TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/TX-87/73+401-4	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle INSTRUMENTATION AND BEHAVIOR OF PRESTRESSED CONCRETE PAVEMENTS	5. Report Date November 1986 6. Performing Organization Code
7. Author(s) Joseph R. Maffei, Ned H. Burns, and B. Frank McCullough	8. Performing Organization Report No. Research Report 401-4
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin Austin, Texas 78712-1075	10. Work Unit No. 11. Contract or Grant No. Research Study 3-8-84-401
12. Sponsoring Agency Name and Address Texas State Department of Highways and Public Transportation; Transportation Planning Division P. O. Box 5051 Austin, Texas 78763-5051	13. Type of Report and Period Covered Interim 14. Sponsoring Agency Code

15. Supplementary Notes

Study conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration. Research Study Title: "Prestressed Concrete Pavement Design—Design and Construction of Overlay Applications"

16. Abstract

Pavements of prestressed concrete are feasible and potentially cost-efficient for highways and airport runways. The design of prestressed concrete pavements requires an accurate knowledge of physical parameters, which include coefficient of base friction, coefficient of thermal expansion of the concrete, modulus of elasticity of the concrete, and temperature changes in the pavement. In order to determine ways of improving the analysis, and consequently the design, of prestressed concrete pavements, a one-mile experimental prestressed concrete pavement was studied. This report describes in detail the development and implementation of an instrumentation program used to monitor the behavior of the experimental prestressed pavement. The measurements taken include continuous measurement of ambient and concrete temperatures, horizontal slab movement, slab curling, and concrete strain. Data are also presented on tendon elongation, very early concrete strength, concrete modulus of elasticity, and slab cracking.

Many aspects of the instrumentation program are ongoing, but an examination of some of the data has revealed:

(1) Very early post-tensioning of prestressed concrete pavements (within 8 to 15 hours after concrete placement) is effective in preventing any pavement cracking, but direct testing of concrete strength at the time of post-tensioning is recommended.

(2) The coefficient of base friction for the prestressed concrete pavement slabs is around 0.48, significantly lower than the value, developed from field tests, that was used in the original design.

(3) Concrete modulus of elasticity at very early ages generally runs higher than values calculated according to the concrete's compressive strength.

17. Key Words concrete, prestressed concrete, pavements, instrumentation	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 158	22. Price

Form DOT F 1700.7 (8-69)

INSTRUMENTATION AND BEHAVIOR OF PRESTRESSED CONCRETE PAVEMENTS

by

Joseph R. Maffei
Ned H. Burns
B. Frank McCullough

Research Report 401-4

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

in cooperation with the
U.S. Department of Transportation
Federal Highway Administration

by the

Center for Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

November 1986

PREFACE

This report describes in detail the development and implementation of an instrumentation program used to monitor the behavior of the experimental prestressed pavement. The measurements taken include continuous measurement of ambient and concrete temperatures, horizontal slab movement, slab curling, and concrete strain. Data are also presented on tendon elongation, very early concrete strength, concrete modulus of elasticity, and slab cracking.

This work is a part of Research Project 3-8-84-401, entitled "Prestressed Concrete Pavement Design--Design and Construction of Overlay Applications." The research was conducted using the resources and facilities of the Center for Transportation Research and the Phil M. Ferguson Structural Engineering Laboratory, both at The University of Texas at Austin. The research was sponsored jointly by the Texas State Department of Highways and Public Transportation and the Federal Highway Administration under an agreement with The University of Texas at Austin and the Texas State Department of Highways and Public Transportation.

The authors express thanks to Albert Mendoza, Brian Dunn, Way Chia, Jim Wesevich, Julie Kemper, and the other graduate students who assisted in this research. The authors also express thanks and appreciation to Bill Wiese, Mike Keahey, and Alvis H. Spence of the Texas State Department of Highways and Public Transportation in Waco for their cooperation.

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, N. 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.

Report No. 401-4, "Instrumentation and Behavior of Prestressed Concrete Pavements," by Joseph R. Maffei, Ned H. Burns, and B. Frank McCullough, describes the development and implementation of an instrumentation program used to monitor the behavior of a one-mile-long experimental prestressed concrete pavement and presents the results of measurements of ambient and concrete temperatures, horizontal slab movement, slab curling, concrete strain, very early concrete strength, concrete modulus of elasticity, and slab cracking.

ABSTRACT

Pavements of prestressed concrete are feasible and potentially cost-efficient for highways and airport runways. The design of prestressed concrete pavements requires an accurate knowledge of physical parameters, which include coefficient of base friction, coefficient of thermal expansion of the concrete, modulus of elasticity of the concrete, and temperature changes in the pavement. In order to determine ways of improving the analysis, and consequently the design, of prestressed concrete pavements, a one-mile experimental prestressed concrete pavement was studied.

This report describes in detail the development and implementation of an instrumentation program used to monitor the behavior of the experimental prestressed pavement. The measurements taken include continuous measurement of ambient and concrete temperatures, horizontal slab movement, slab curling, and concrete strain. Data are also presented on tendon elongation, very early concrete strength, concrete modulus of elasticity, and slab cracking.

Many aspects of the instrumentation program are ongoing, but an examination of some of the data has revealed:

(1) Very early post-tensioning of prestressed concrete pavements (within 8 to 15 hours after concrete placement) is effective in preventing any pavement cracking, but direct testing of concrete strength at the time of post-tensioning is recommended.

(2) The coefficient of base friction for the prestressed concrete pavement slabs is around 0.48, significantly lower than the value, developed from field tests, that was used in the original design.

(3) Concrete modulus of elasticity at very early ages generally runs higher than values calculated according to the concrete's compressive strength.

KEYWORDS: Concrete, prestressed concrete, pavements, instrumentation

SUMMARY

This report describes in detail the development and implementation of an instrumentation program used to monitor the behavior of the experimental prestressed pavement. The measurements taken include continuous measurement of ambient and concrete temperatures, horizontal slab movement, slab curling, and concrete strain. Data are also presented on tendon elongation, very early concrete strength, concrete modulus of elasticity, and slab cracking.

Many aspects of the instrumentation program are ongoing, but an examination of some of the data has revealed:

(1) Very early post-tensioning of prestressed concrete pavements (within 8 to 15 hours after concrete placement) is effective in preventing any pavement cracking, but direct testing of concrete strength at the time of post-tensioning is recommended.

(2) The coefficient of base friction for the prestressed concrete pavement slabs is around 0.48, significantly lower than the value, developed from field tests, that was used in the original design.

(3) Concrete modulus of elasticity at very early ages generally runs higher than values calculated according to the concrete's compressive strength.

Future research on the instrumentation and behavior of the Texas prestressed concrete pavement should be carried out according to the recommendations for continued instrumentation which are presented in Chapter 6. These recommendations include gathering more data on horizontal slab movement, concrete strain, and slab curling due to daily temperature changes and carrying out the program of long-term instrumentation.

IMPLEMENTATION STATEMENT

This report describes in detail the development and implementation of an instrumentation program used to monitor the behavior of the experimental prestressed pavement. The measurements taken include continuous measurement of ambient and concrete temperatures, horizontal slab movement, slab curling, and concrete strain. Data are also presented on tendon elongation, very early concrete strength, concrete modulus of elasticity, and slab cracking.

This report will be of use to anyone interested in prestressed concrete pavement behavior and design, or anyone interested in field instrumentation and data collection.

TABLE OF CONTENTS

PREFACE iii

LIST OF REPORTS v

ABSTRACT vii

SUMMARY ix

IMPLEMENTATION STATEMENT xi

CHAPTER 1. INTRODUCTION

BACKGROUND 1
  Behavior of Prestressed Concrete Pavements 2
  Design of Prestressed Concrete Pavements 9
  Purpose of Monitoring Prestressed Pavement Behavior 14
OBJECTIVES OF THE REPORT 15
OUTLINE OF CHAPTERS 15

CHAPTER 2. INSTRUMENTATION DEVELOPMENT

REVIEW OF THE INSTRUMENTATION OF PREVIOUS PROJECTS 17
INSTRUMENTATION OBJECTIVES FOR THE TEXAS PRESTRESSED PAVEMENT 22
  Objectives of the Short-Term Measurements 22
  Objectives of the Long-Term Measurements 24
PAVEMENT TEST SLAB AT BALCONES RESEARCH CENTER 25
  Construction of the Test Slab 26
  Test Slab Instrumentation 30
  Experimental Procedure for the Test Slab 33
  Test Slab Results 35
  Test Slab Conclusions 44

CHAPTER 3. FIELD IMPLEMENTATION

GENERAL DESCRIPTION OF THE TEXAS PRESTRESSED PAVEMENT PROJECT 45
MEASUREMENTS TAKEN AND EQUIPMENT USED 48
  Short Term Instrumentation 49
  Long Term Measurements 60
INSTALLATION PROCEDURES 60
  Short Term Instrumentation 60
  Long Term Instrumentation 72
EXPERIMENTAL PROCEDURE 72
  Schedule of Measurements 72
  Short Term Instrumentation 76
  Long Term Instrumentation 81

CHAPTER 4. PRESENTATION OF DATA

SHORT-TERM MEASUREMENTS 85
  Ambient and Concrete Temperatures 85
  Horizontal Slab Movement 89
  Concrete Strain 93
  Slab Curling 97
  Tendon Elongations 97
  Concrete Compressive Strength 97
  Concrete Modulus of Elasticity 104
  Slab Cracking 104
LONG-TERM MEASUREMENTS 108
  Joint Opening Width 108
  Other Long-term Measurements 108

CHAPTER 5. DISCUSSION OF RESULTS

HORIZONTAL SLAB MOVEMENT AND CONCRETE STRAIN DUE TO POST-TENSIONING 111
  Initial Post-tensioning of Slab 7 113
  Final Post-tensioning of Slab 14 115
VERY EARLY CONCRETE STRENGTHS 121
CONCRETE MODULUS OF ELASTICITY 122
SLAB CRACKING 122

CHAPTER 6. CONTINUATION OF THE INSTRUMENTATION PROGRAM

SHORT-TERM INSTRUMENTATION 125
  Horizontal Slab Movement and Concrete Strain Due to Temperature Change 125
  Slab Curling Due to Temperature Change 126
LONG-TERM INSTRUMENTATION 127
  Joint Opening Width 127
  Load Transfer Capabilities of the Transverse Joint 129
  Deflection Characteristics of the Pavement 132
  Riding Quality of The Pavement 133

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS 135
RECOMMENDATIONS FOR FURTHER RESEARCH 139

REFERENCES 141

CHAPTER 1. INTRODUCTION

BACKGROUND

Pavements of prestressed concrete are feasible and potentially cost-efficient for highways and airport runways. The Transportation Research Board defined prestressed concrete pavement as "a pavement in which a permanent and essentially horizontal compressive stress has been introduced prior to the application of live load" (Ref 1). Such pavements utilize the advantage of high concrete compressive strength in resisting traffic loads. The advantages of prestressed concrete pavements over continuously reinforced concrete pavements or other conventional pavements include

(1) reduced pavement cracking,
(2) reduced number of joints,
(3) improved pavement performance,
(4) material savings, and
(5) reduced routine maintenance.

A potentially promising use of prestressed concrete pavements is for overlaying existing highway pavements. The deterioration and wear out of existing highway pavements is becoming an increasing problem in this country. The problem is due in part to an inadequate design life, increased legal axle loads, and traffic increase greater than anticipated. This situation makes the advantages of prestressed concrete highway pavements even more pronounced.

Although the use of prestressing is prominent in concrete bridge and building construction, and the first investigations into prestressed concrete pavements took place as early as 1937, the use of prestressed concrete in the pavement industry remains a new idea (Ref 1). Recent prestressed concrete pavement projects have shown, however, that prestressed concrete pavements are now becoming a viable alternative. In the United States, the most recently constructed prestressed concrete pavements include four projects sponsored by the Federal Highway Administration (Ref 2):

(1) two lanes of pavement (one direction) 0.6 mile long, constructed in 1971 in Dulles, Virginia,
(2) four lanes of pavement (divided) 1.5 miles long, constructed in 1973 near Hogeston, Pennsylvania,
(3) four lanes of pavement (divided) 2.5 miles long, constructed in 1976 near Brookhaven, Mississippi, and
(4) four lanes of pavement (divided) 1.2 miles long, constructed in 1977 near Tempe, Arizona.

All four of these projects used pavement slabs 6 inches thick, post-tensioned only in the longitudinal direction using plastic-coated unbonded tendons. In all of the projects, either a single sheet or a double sheet of polyethylene was used as a friction reducing medium between the prestressed concrete pavement slabs and their bases.

The prestressed concrete pavement overlay which is the subject of this experimental program was completed in December of 1985. It is located near Waco, Texas, as part of Interstate Highway 35. There are two lanes of pavement overlay (one direction) one mile long. The pavement slabs are 6 inches thick, cast on a single sheet of polyethylene, and post-tensioned in the longitudinal and transverse directions using plastic-coated unbonded tendons. The tendons used are 0.6–inch–diameter, 7-wire, low-relaxation strands.

Behavior of Prestressed Concrete Pavements

In prestressing, concrete which is weak in tension and strong in compression is compressed by steel strands under high tension, so that the brittle concrete is able to withstand tensile stresses. In general, if there are no tensile stresses in the concrete there can be no cracks, and the concrete is no longer a brittle material: it is now an elastic one (Ref 3).

In a pavement slab, tensile stresses are introduced in the bottom of the slab due to traffic wheel loads. In long pavement slabs, tensile stresses are introduced throughout the thickness of the slab by shrinkage and temperature contraction of the concrete. These tensile stresses are primarily in the longitudinal direction and develop because the contraction of the pavement slab is fully or partially restrained by base friction. The effect of applied prestress, then, is to counteract these tensile stresses so that the net stress in the concrete is either a compressive stress or a small tensile stress below the cracking stress. To describe the behavior of prestressed pavements, we will first consider a long pavement slab without the application of any prestress.

The friction force along the bottom of a pavement slab has been shown to vary with the movement of the slab (Refs 4, 5, 6, 7, and 8). For a pavement slab cast on a single layer of polyethylene, the relationship between movement and the coefficient of friction is shown in Fig 1.1. This relationship can be expressed as

$$\mu = \mu(z) \tag{1.1}$$

where

μ = coefficient of base friction, and

z = local movement of the pavement slab.

When the concrete temperature in a pavement slab drops, the slab contracts, with the local movement of the slab increasing from zero at the center of the slab to a maximum at the end of the slab. Base friction acts to restrain this local movement and cause the build-up of tensile stress in the concrete, which increases from zero at the end of the slab to a maximum value at the center of the slab length. This relationship between slab movement, base friction restraint, and concrete stress for a long pavement slab without prestress is illustrated in Fig 1.2 (Ref 9).

A mathematical relationship between slab movement, base friction restraint, and concrete stress can be found by considering a half-slab, as shown in Fig 1.2(a). Let x be the length coordinate along the slab, starting at the slab centerline. Let z(x) be the local movement (due to temperature drop) of a point x of the slab. Consider a slab element of differential length, dx. The elongation of this slab element due to the movement z(x) is the quantity dz, and the strain in the slab element is the quantity dz/dx. By compatibility, slab movement can be related to temperature drop and concrete stress:

$$dz/dx = \alpha \Delta T + F_c(x)/E_c \tag{1.2}$$

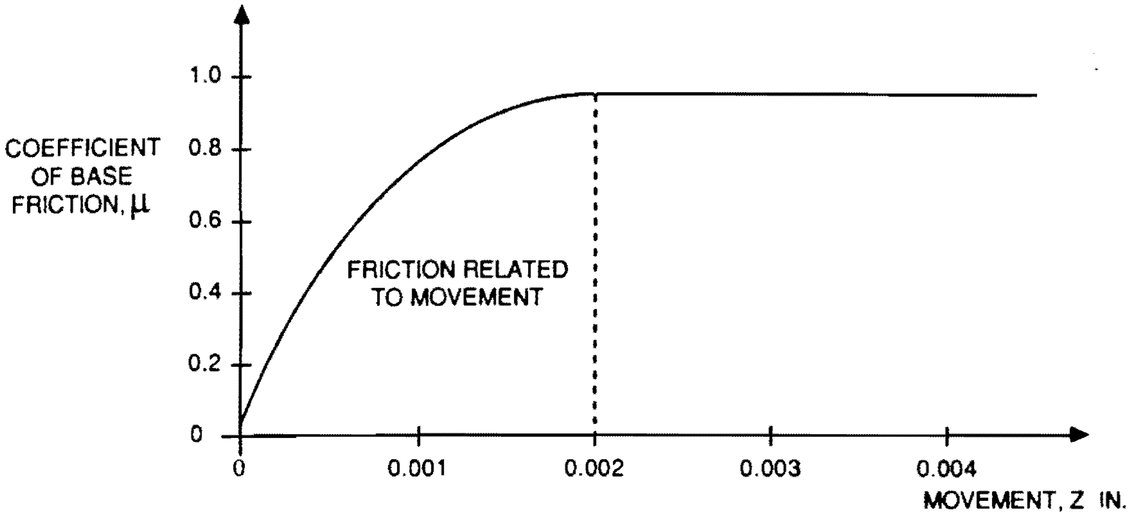


Fig 1.1. Coefficient of base friction versus displacement, single layer polyethylene membrane (Ref 6).

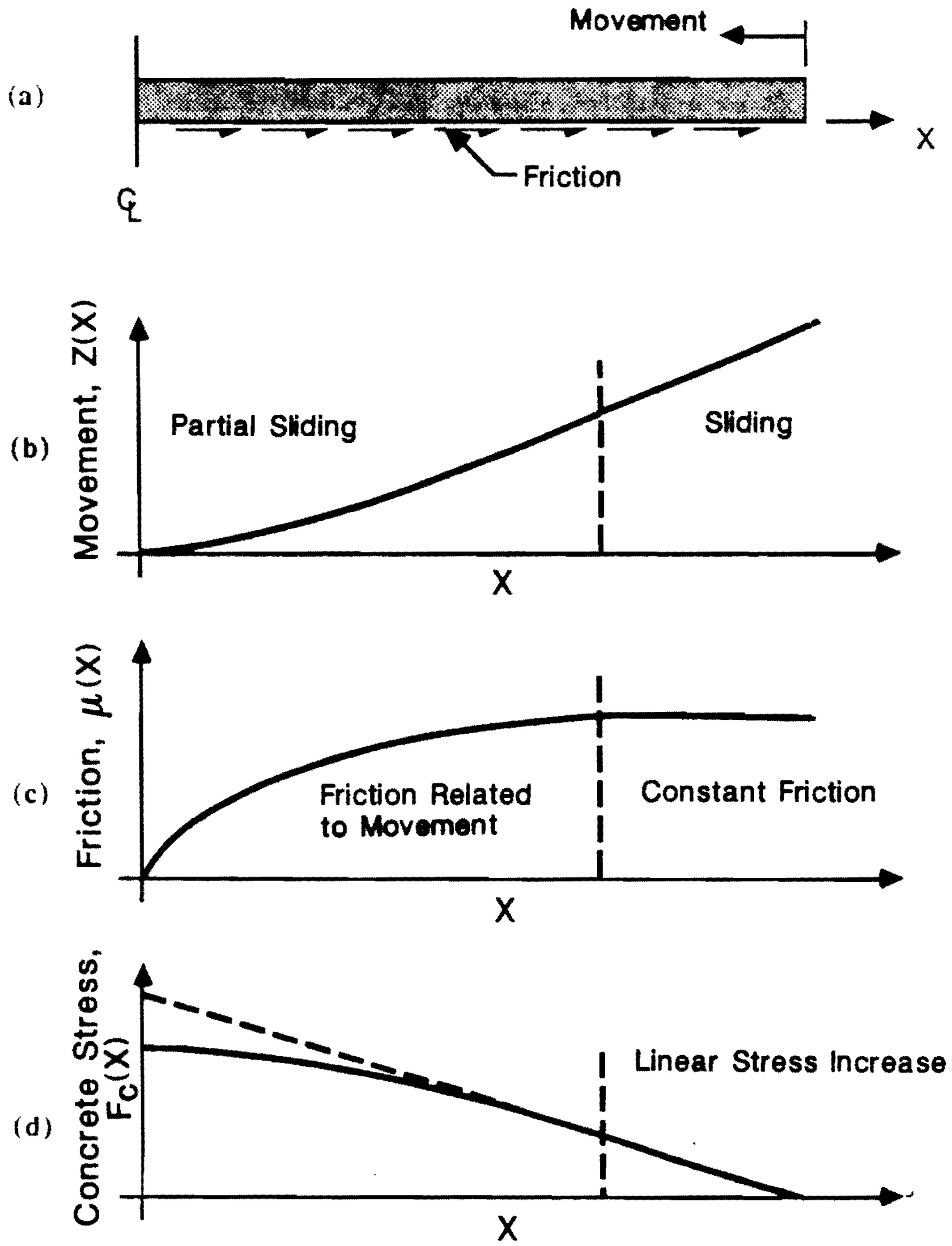


Fig 1.2. Modelling of the pavement half-slab.

where

α = coefficient of thermal expansion for concrete,
ΔT = change in concrete temperature,
$F_c(x)$ = concrete stress (positive for tension), and
E_c = modulus of elasticity for concrete.

The concrete stress, $F_c(x)$, is equal to the accumulation of the friction force between the slab end and the point of interest. Thus, the concrete stress at any point x can be written

$$F_c(x) = \int_x^L \mu(x)\,\gamma dx, \tag{1.3}$$

where

L = length of the half-slab
$\mu(x)$ = coefficient of base friction
γ = unit weight of the concrete

Note that the coefficient of base friction, μ, varies with location, x, because it is a function of movement, $z(x)$.

Equations 1.1, 1.2, and 1.3 are the basic equations relating movement, base friction, and concrete stress in a long pavement slab. Since the three equations are interdependent, and since μ is generally not an analytical function of z, the solution for slab movement and concrete stress must be an iterative one. The following method was proposed by Friberg (Ref 5):

(1) Assume a constant coefficient of friction.
(2) Solve for $F_c(x)$ according to Eq 1.3.
(3) Solve for the movement $z(x)$ according to

$$z(x) = \int_0^x [\alpha\Delta T + F_c(x)/E]dx. \tag{1.4}$$

(4) Solve for $\mu(x)$ based on the relationships for $\mu(z)$ and $z(x)$.

(5) Repeat steps 2 through 4 until convergence.

A computer program has been written by Mendoza-Diaz (Ref 10) which makes use of this method in analyzing the behavior of prestressed concrete pavement slabs.

Distributions of concrete stress in a 440-foot-long pavement slab without prestress are shown in Figs 1.3(a), and 1.3(b). The following values were assumed in the calculation of concrete stress:

maximum coefficient of friction, $m_{max} = 0.96$
coefficient of thermal expansion of the concrete, $a = 5.0 \times 10^{-6}$ inch/inch/°F
concrete modulus of elasticity, $E = 3{,}500{,}000$ psi
concrete unit weight, $\gamma = 145 \text{ lb/ft}^3 = 0.0839 \text{ lb/inch}^3$

Figure 1.3(a) shows a pavement slab subject to a temperature drop of 5°F. The maximum tensile stress in the concrete due to this temperature drop is 88 psi. In the case of Fig 1.3(a), this maximum tensile stress exists throughout a long section of the midslab area. This is because this section of the slab remains fully restrained for a temperature change of 5°F. Thus the maximum tensile stress is the full restraint temperature stress, which is equal to $\alpha \Delta TE$.

Figure 1.3(b) shows the concrete stress variation in the same pavement slab subject to a 15°F temperature drop. The maximum tensile stress in the concrete is now 210 psi. In this case, no finite portion of the slab remains fully restrained against movement, so that tensile stress continues to build to a maximum at midslab. In both cases, the concrete stress at any point is equal to the accumulation of the base friction forces, according to Eq 1.3.

The effect of prestress can be taken into account simply by modifying Eq 1.3:

$$F_c(x) = F_{ps}(x) + \int_x^L \mu(x)\, \gamma dx, \tag{1.5}$$

where

$F_{ps}(x)$ = applied prestress (force/area) in the concrete at any point x.

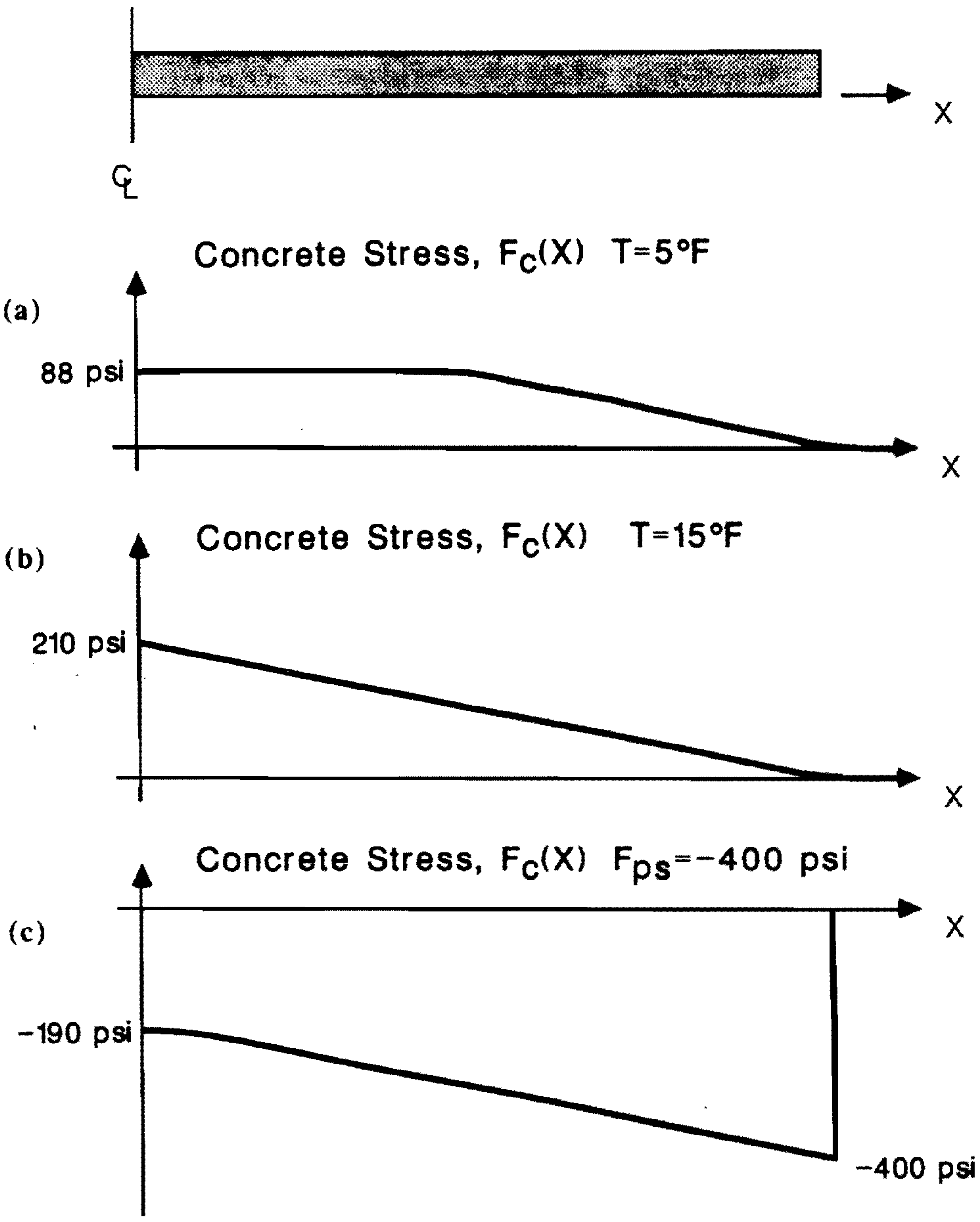


Fig 1.3. Concrete stresses in a 440-foot-long prestressed pavement slab.

Note that, in these equations, $F_{ps}(x)$ will be a negative value because it is a compressive stress. $F_{ps}(x)$ varies with location in the slab because of friction along the post-tensioning tendon.

The effect of applying prestress to a long pavement slab is shown in Fig 1.3(c). This figure reflects the application of 400 psi of compressive stress in the concrete due to prestressing. For simplicity, friction along the post-tensioning tendon is neglected. The concrete stress in the center of the slab is now 190 psi compression. Figure 1.3(c) shows the distribution of concrete stress right after the application of prestressing. The concrete stress will be distributed in this manner regardless of the distribution of stress in the slab before the application of prestressing. This is because the application of prestress causes contraction of any previously restrained portions of the slab.

In considering the effect of cyclic changes in temperature, it is necessary to account for the inelastic nature of the base friction versus movement relationship. Figure 1.4 shows the assumed base friction versus movement relationship for slab movement in two opposing directions. When a reversal in temperature occurs, the ends of the pavement slab react first, changing their direction of movement. Correspondingly, the base friction force at the slab ends changes direction. With continued temperature change, portions of the slab closer to midslab begin to react.

As before, the concrete stress in the pavement slab can be found by integrating the friction force according to Eq 1.5. The effect of a temperature reversal on the concrete stress throughout the length of a 440-foot-long prestressed pavement slab is shown in Fig 1.5. Curve (a) in Fig 1.5 shows the concrete stress in the pavement slab after a temperature decrease. The stress at the slab end is equal to the applied prestress, F_{ps}. Curve (b) in Fig 1.5 shows the concrete stress in the same slab after a subsequent temperature increase. Curves (c) and (d) show the concrete stress in the slab after continued temperature increases. Note that any distribution of concrete stress due to temperature change will fall within the envelope formed by curves (a) and (d) of Fig 1.5.

Design of Prestressed Concrete Pavements

This section gives a brief overview of the design of prestressed concrete pavements. For a more extensive consideration of prestressed pavement design, the reader is referred to

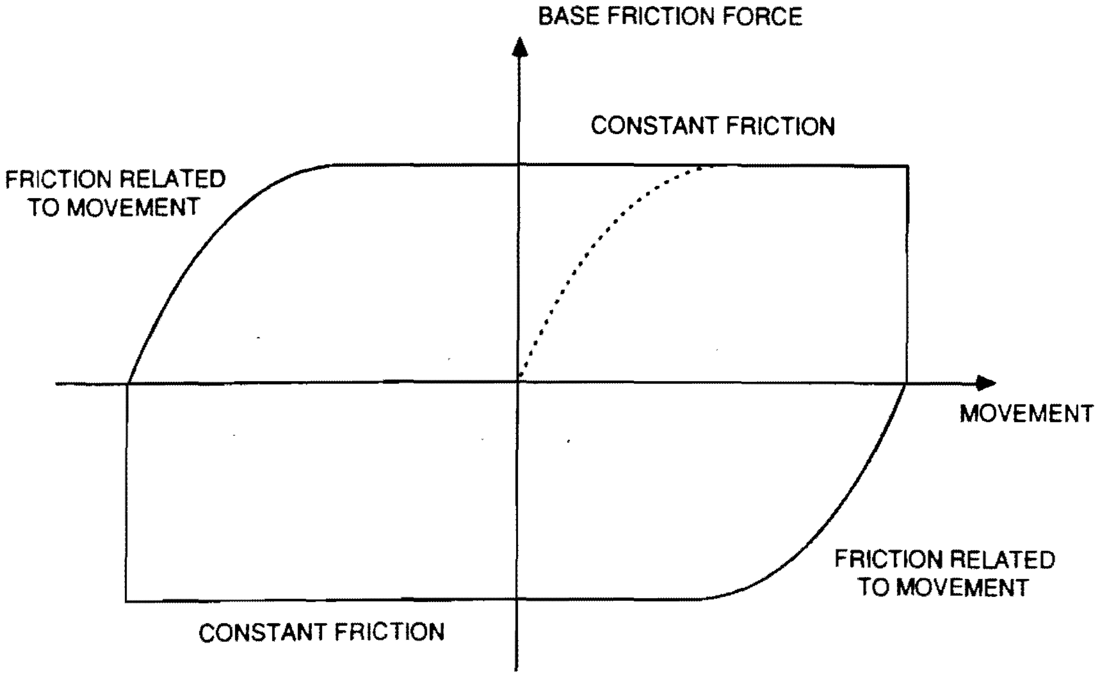


Fig 1.4. Base friction force versus slab movement for cyclic slab movement (Ref 10).

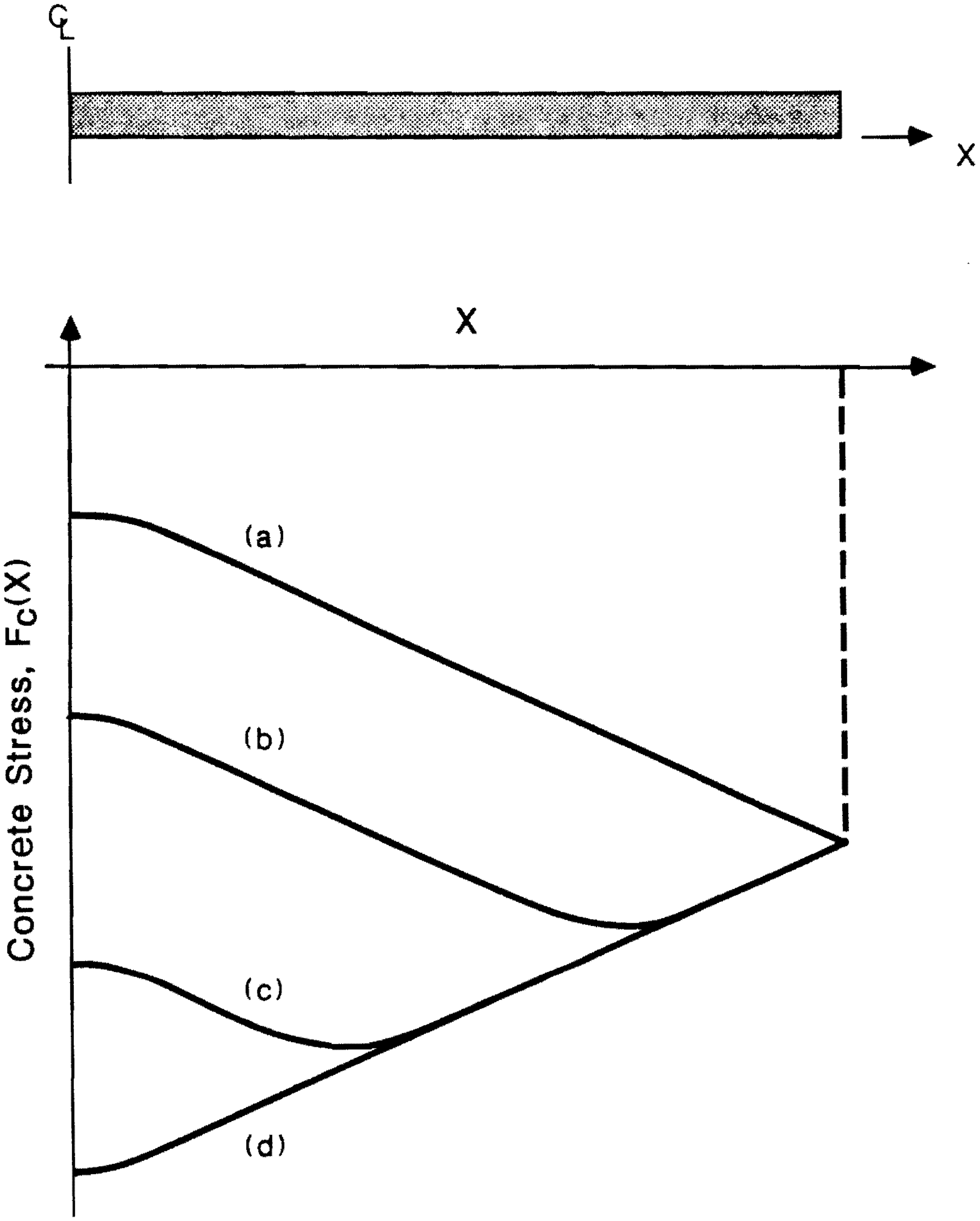


Fig 1.5. Change in concrete stress throughout the length of a prestressed pavement slab due to a temperature increase.

Cable (Ref 1). The design procedure for the Texas prestressed concrete pavement is summarized in Fig 1.6, which shows the sequence of design tasks.

The first design task is to determine the thickness and minimum prestress level, after losses, of the prestressed concrete pavement. The minimum prestress level is the concrete compressive strength in the center of the slab after losses due to base restraint. The design variables of pavement thickness and minimum prestress level are directly interrelated and depend mainly on the foundation strength of the pavement base and projected traffic loading. Concrete strength and minimum allowable cover for prestressing tendons must also be considered. Recent prestressed concrete pavements for highways have been 4 to 6 inches thick, with a minimum prestress level, after losses, of 50 to 200 psi. In the design of the Texas prestressed pavement, three options for thickness and prestress level were considered: a 6-inch-thick pavement with 65 psi minimum prestress force, a 7-inch-thick pavement with 55 psi minimum prestress force, and an 8-inch-thick pavement with 45 psi minimum prestress force (Refs 11 and 12).

The second important design task is to devise a means of reducing friction between the prestressed concrete pavement and its base. The reduction of base friction reduces the magnitude of the prestress loss and allows longer slabs to be constructed. Several friction reducing media have been explored (Refs 1, 6, 7, and 8). Recent prestressed concrete pavement projects have used sand-asphalt bases or polyethylene sheeting to reduce base friction. When a friction reducing medium is used, the coefficient of base friction usually ranges between 0.4 and 1.0.

Determination of slab length is based mainly on projected daily temperature variation and the amount of friction between the prestressed pavement slab and the base. The temperature drop in the concrete due to the daily temperature cycle tends to cause a contraction of the pavement slab, which is resisted by friction along the bottom of the pavement slab. This base friction causes a reduction of the minimum effective prestress. Longer slab lengths cause this reduction in effective prestress stress to be greater, while shorter slab lengths are costlier because more transverse joints are needed. Also, slab lengths may be limited because of a maximum allowable transverse joint opening. Recent prestressed concrete pavement projects have used slab lengths from 240 feet to 760 feet. On the Texas prestressed pavement, the computer analysis program written by Mendoza (Ref 10) was used to determine practical slab lengths.

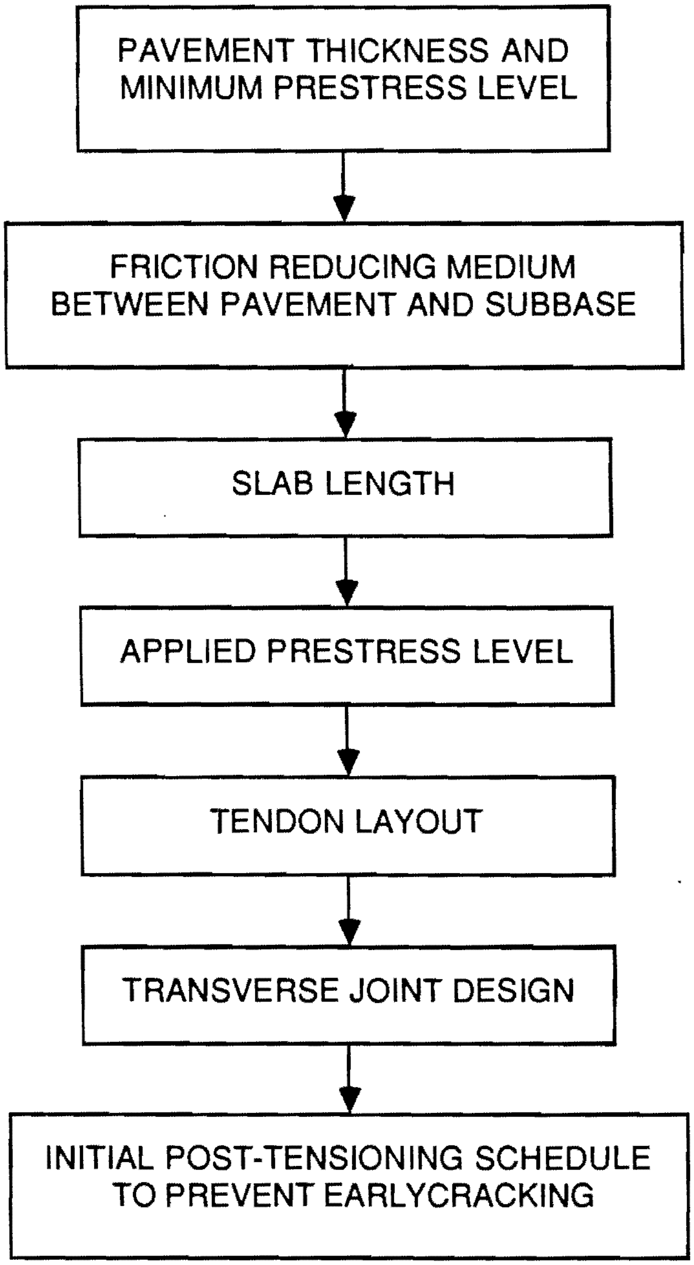


Fig 1.6. Sequence of design tasks for the Texas prestressed concrete pavement.

Sufficient applied prestress force must be provided so that the minimum effective prestress level, after losses, will be maintained. The amount of applied longitudinal prestress necessary is determined according to the stress model described in the previous section. The applied longitudinal prestress on recent projects has ranged from 200 psi to 490 psi. Applied transverse prestress has ranged from 0 to 200 psi.

The layout of the longitudinal prestressing tendons in the pavement slab must be designed to provide sufficient applied prestress force so that the minimum effective prestress level, after losses, will be maintained. Recent prestressed pavements have used 0.5-inch and 0.6–inch–diameter 7-wire prestressing strand spaced at intervals of 16 to 24 inches

Additional design tasks include the design of the transverse joints between pavement slabs. Since the slabs are as long as 440 feet, the transverse joint must allow as much as 3 inches of expansion and contraction of the joint opening but transmit the vertical shear forces due to traffic loads. The Texas prestressed pavement uses an armored joint with stainless steel encased dowels for load transfer (Ref 13).

One of the most important design tasks is to prevent any early temperature or shrinkage cracking of the pavement slab. On all of the four previous prestressed concrete pavements, transverse cracks developed in several pavement slabs during the first morning after concrete placement. The likelihood of such cracks occurring can be determined with the help of the stress model described in the previous section, using the expected temperature variation and shrinkage strain In the Texas prestressed pavement, early cracks were prevented by applying very early initial post-tensioning--within 8 to 15 hours after placement of the concrete. The specified initial post-tensioning force varied from 20 to 50 percent of the final post-tensioning force, depending on the concrete compressive strength at the time of the post-tensioning.

Purpose of Monitoring Prestressed Pavement Behavior

As can be seen from the previous section, the design of prestressed concrete pavements requires an accurate knowledge of many aspects of the behavior of such pavements. The most effective design is based on an accurate knowledge of physical parameters, which include coefficient of base friction, coefficient of thermal expansion of the concrete, modulus of elasticity of the concrete, and expected daily temperature cycles. Using assumed values of these parameters, the movement and stress variation with time in a prestressed pavement can be predicted analytically; by measuring movement and stress experimentally, these design assumptions can be evaluated. In addition, the collection of performance data of the pavement over the long term should provide valuable information on the effectiveness of the pavement design. Thus the main purpose in monitoring the Texas prestressed pavement was to determine ways in which the analysis, and consequently the design, of prestressed pavements can be improved.

OBJECTIVES OF THE REPORT

The objective of this report is to describe in detail the instrumentation and behavior of an experimental prestressed concrete pavement. More specific objectives of the report are

(1) to give the reader a background in the general principles of behavior and design of prestressed concrete pavements,
(2) to explain what aspects of prestressed concrete pavement behavior it is of interest to measure experimentally,
(3) to describe in depth the field implementation of mechanical and electronic monitoring equipment on the Texas prestressed concrete pavement, and
(4) to present some of the important findings of the instrumentation program.

This report should be of use to anyone interested in prestressed concrete pavement behavior and design, or anyone interested in field instrumentation and data collection in general.

OUTLINE OF CHAPTERS

Chapter 2 describes the development of the instrumentation program for the Texas prestressed pavement. This instrumentation development is based on a review of the instrumentation of previous projects, an examination of instrumentation objectives, and the testing of instrumentation on a pavement test-slab.

Chapter 3 describes the implementation of the instrumentation plan on the Texas prestressed pavement. An overall description of the project is given, and the instrumentation and its installation are described in detail.

Chapter 4 presents the data collected to date, in summarized form. The data include ambient and concrete temperature data, horizontal slab movement data, concrete strain data, tendon elongation data, concrete strength data, concrete modulus of elasticity data, slab cracking data, and joint opening width data. The chapter also includes some evaluation of the accuracy of the data. The complete tabulations of all of the data (printouts of the continuously recorded data, etc.) are not included in this report but comprise another report, "Compendium of Information on the Instrumentation and Behavior of Prestressed Concrete Pavements" (Ref 23).

Chapter 5 is a discussion of results. The chapter includes an examination of horizontal slab movement and concrete strain due to post-tensioning, discussions of concrete strength and modulus of elasticity results, and the observation of slab cracking.

Chapter 6 presents recommendations for the continuation of the instrumentation program. The recommendations include suggestions for gathering more data on slab behavior due to daily temperature cycles, and recommendations for a program of long term instrumentation. The long term instrumentation includes the continued measurement of joint opening width, and the measurement of the load transfer capabilities of the transverse joints, the deflection characteristics of the pavement, and the riding quality of the pavement.

Chapter 7 presents the conclusions and recommendations of the report.

CHAPTER 2. INSTRUMENTATION DEVELOPMENT

This chapter describes the development of the instrumentation program for the Texas prestressed concrete pavement. This instrumentation development is based on a review of the instrumentation of previous projects, an examination of instrumentation objectives, and the testing of instrumentation on a pavement test-slab.

REVIEW OF THE INSTRUMENTATION OF PREVIOUS PROJECTS

Before proposing an instrumentation scheme for the Waco site, instrumentation arrangements used on similar pavement projects were reviewed. These projects include prestressed concrete pavement installations in Pennsylvania, Virginia, Mississippi, and Arizona, and slab tests conducted at Rolla, Missouri, and Slidell, Louisiana (Refs 14,15,16,17,18,19). Reports of these projects provided useful information on instrumentation equipment and procedures. The instrumentation used in three of these projects is summarized in Tables 2.1, 2.2, and 2.3. In these projects, the following items were monitored: ambient temperature, concrete temperature, concrete strain, absolute horizontal movement, curling movements, and joint opening width.

Thermocouples have proved effective in measuring both ambient temperature and concrete temperature. For concrete temperatures, the thermocouples are fixed at known depths of the slab to obtain the temperature gradient through the thickness of the slab. It is best to position these gages in "block-out" regions after the concrete has been placed with the paver. In the above projects, the thermocouple leads were carried through PVC conduit out the side of the slab. This conduit was put into place before the paving operations. In the case of the Virginia pavement, the temperature gages were placed in 12 inch by 12 inch block-outs before the placement of the concrete. After the slip-form paver had passed, concrete was placed and vibrated around the arranged gages.

All three of the above projects attempted to record concrete strain using embedment gages. For each of the projects, the strain gages were installed in the same manner as the temperature gages, with the gage leads carried through PVC conduit to the edge of the pavement. All three of the projects reported trouble in recording concrete strain. In explaining the failure to obtain usable data from the strain gages, the reports from the

TABLE 2.1. PAVEMENT INSTRUMENTATION FOR THE PRESTRESSED CONCRETE PAVEMENT PROJECT AT DULLES, VIRGINIA

Measurement	Instrumentation
Concrete Temperature	Thermocouples at 4 depths. Held in place in vertical plexiglass rods. 12-Channel continuous temperature recorder. 4 locations total in 3 slabs.
Concrete Strain	(1) Vibrating wire gages at 3 depths. "Have not produced usable data." 12 locations each in 3 slabs. (2) 50-inch length change gage. Mechanically measures surface length change between two countersunk points. 10 locations total in 4 slabs.
Horizontal Movement	Pipe-wire-scale. Accurate to 1/2 mm (0.02-inch). 17 locations total, all slabs.
Curling Movements	(1) Profiler beam. Profile lines 140-inch long with 15 profile points. Vertical deflection to 0.0001-inch. 10 locations each in 4 slabs. (2) 20-inch clinometer. Measures slope change along profile lines. 10 locations each in 4 slabs.
Joint Opening Width	(1) 96-inch length change gage. Measures relative movement of prestressed slabs. Measured across gap slab. Measured at all joints. (2) Dial equipped slide caliper. Measures the movement of one prestressed slab relative to the gap slab. Measured at all joints.

TABLE 2.2. PAVEMENT INSTRUMENTATION FOR THE PRESTRESSED CONCRETE PAVEMENT PROJECT AT BROOKHAVEN, MISSISSIPPI

Measurement	Instrumentation
Ambient Temperature	Continuous Temperature Recorder
Concrete Temperature	Temperature sensors at 4 depths. Micro measurements type ETG-50D gage bonded to copper tubing. Recorded at 1°F.
Concrete Strain	(1) Concrete embedment gages at 3 depths. Did not produce usable data. 4 slabs. (2) strain gaged bars. 3 feet long, 1/2-inch diameter steel bars with strain gages attached. 12 locations total in 4 slabs.
Horizontal Movement	Pipe-wire-scale. Measured on 3 slabs, at both ends of each slab.
Curling Movements	Survey equipment. Measured evaluation change in 3 foot intervals along slab ends and 5 foot intervals along length of slab. Measured to nearest 0.001 inch. 2 slabs.
Joint Opening Width	Dial calipers and reference plugs. Accurate to 0.001 inch. Most slabs.
Other	Tendon elongation, modulus of elasticity of the concrete, Dynaflect deflection, PCA roadmeter, skid resistance.

TABLE 2.3. PAVEMENT INSTRUMENTATION FOR THE PRESTRESSED CONCRETE PAVEMENT PROJECT AT TEMPE, ARIZONA

Measurement	Instrumentation
Ambient Temperature	Thermistors recorded to 1°F.
Concrete Temperature	Embedded Thermistors at 3 depths. Continuously recorded with a timed auto data acquisition device. Recorded to 1°F. Installed in 3 slabs near slab end, 1 slab near mid-slab.
Concrete Strain	Embedment gages placed at 3 depths. Ailtech CG-129 gages. Continuously recorded. Data was "questionable". Installed in 3 slabs near slab end, 1 slab near mid-slab.
Horizontal Movement	Slab length change found by "distance measuring equipment." Recorded to 0.001-inch. 1 slab.
Curling Movements	Dial gage at slab corner. Referenced to iron pin driven into subgrade. Accurate to 0.001-inch. 2 slabs.
Joint Opening Width	Extensometer bar. Accurate to 0.001-inch. 5 slabs.
Other	Visual crack survey. All slabs.

Virginia and Mississippi projects described the particular gages as being "not sufficiently rugged" for field use. Concrete strain measurements were successfully recorded in slab tests at Slidell, Louisiana, using strain gages made by T.M.L., Inc. The gages used were polyester mold gages, model PML-60.

In Arizona, temperature and strain data were continuously recorded using a timed automatic data acquisition device. In the Virginia project, concrete temperatures were recorded using a 12-channel continuous temperature recorder. In Mississippi, only ambient temperature was continuously recorded. Readings of concrete temperature and strain were taken intermitantly using a digital strain indicator.

The Mississippi project also installed strain–gaged bars to measure concrete strain. This apparatus was made in-house from a 1/2 inch-diameter steel bar, 3 feet long, with steel plates welded to the ends of the bar to provide positive bond with the concrete. Strain gages were attached to the bar to compensate for bending, temperature, and Poisson's effect. The strain taken by the steel bar was assumed equal to the strain in the concrete.

In the Virginia project, concrete strain was found by mechanically measuring the surface length change of the concrete slab. The length change was measured between countersunk profile points, 50 inches apart, mounted to the slab surface. The measuring apparatus used a Nilvar bar and a movement dial gage. Concrete strain at the interior of the slab was calculated using measurements of surface curvature and a straight line projection of surface strains.

On two previous projects, horizontal slab movement was found using a pipe-wire-scale apparatus. The reference for this measurement is a wire stretched across the pavement between two posts. The wire is tightened to a specified tension to minimize variance due to wind. A scale is mounted in a pre-set position in the pavement surface so that movement of the pavement can be read according to where the wire crosses the scale.

Slab curling movements have been measured in a variety of ways. For the Virginia project and for slab tests at Rolla, Missouri, slab curvature was found along profile lines. For the Mississippi project, survey equipment was used to measure elevation changes across sections of the pavement slab. In the Arizona project, movement of the slab corners was measured with dial gages. Iron pins driven into the subgrade were used to mount the dial gages and thus served as a reference.

For the projects in Virginia, Mississippi, and Arizona, the changes in width of the transverse joints were measured mechanically using an extensometer or a similar device. All of these projects measured the joint opening between the prestressed slab and the gap slab. In Virginia, the width across the gap slab was also measured.

In the Mississippi project, tendon elongation was measured to verify the magnitude of the prestressing force. In Arizona, a visual crack survey was reported. All pavement slabs were inspected for cracks before the application of the prestress, and intermitantly thereafter.

INSTRUMENTATION OBJECTIVES FOR THE TEXAS PRESTRESSED PAVEMENT

Before specifying an instrumentation scheme or any instrumentation equipment, the particular objectives of the instrumentation were defined. The instrumentation for the Texas prestressed pavement project is intended to serve two main purposes: (1) to provide a verification of predicted values of concrete stress and slab movements due to prestressing and daily changes in temperature and (2) to periodically monitor the condition and behavior of the pavement over the long term. Accordingly, the instrumentation objectives are divided into two categories: objectives of the short-term measurements and objectives of the long-term measurements.

Objectives of the Short-Term Measurements

In general, short-term instrumentation is needed to verify the values of slab movement and concrete stress. This verification is important because the design of the slab lengths and the amount of prestressing are based on the critical stressses predicted analytically by the method discussed in Chapter 1. In addition, slab length design and transverse joint design are based on expected horizontal movement of the pavement slab. The objectives of the short-term measurements are outlined as follows:

I. Verify the effect of the daily temperature cycle (ambient temperature) on
   -- slab temperature and slab temperature gradients
   -- longitudinal restraint stresses in the concrete
   -- horizontal slab movements

-- gradient of longitudinal stresses in the concrete
-- vertical movement of the slab corners.

II. Measure the effect of longitudinal prestress application on
-- concrete stress throughout the slab
-- gradient of concrete stress
-- horizontal slab movement.

III. Verify prestress force and tendon friction by recording tendon elongation.

IV. Determine concrete strength at early ages and at 28 days.

V. Determine concrete modulus of elasticity at early ages.

VI. Check for any early cracking of the slabs

It is important to record slab temperature and ambient temperature. Changes in slab temperature are the cause of significant movements and stresses in prestressed concrete pavement slabs. The stresses arise because temperature movement of the slab is partially restrained by base friction. Based on the assumed cycle of slab temperature, concrete stress and slab movement are calculated by the method dicussed in Chapter 1. The recording of actual temperature cycles in the slab is needed to verify this analytical method. Also, the relationship between slab temperature and ambient temperature (determining the time lag between ambient temperature changes and slab termperature changes) is useful in relating slab behavior to expected ambient temperature cycles. Finally, slab temperature should be recorded because it affects the strength gain of the concrete.

The stresses in a long pavement slab arise because movement of the slab is partially restrained by base friction. Based on given values for the coefficient of thermal expansion and the coefficient of base friction, slab movement and concrete stress can be calculated by the method discussed in Chapter 1. The measurement of the actual slab movements and concrete strains enables the assumed values for coefficient of base friction and coefficient of thermal expansion to be verified.

It is also important to record the gradient of temperature in the slab. Temperature gradients through the depth of the slab are the driving force behind curling stresses and movement. When the slab is restrained by its own weight, the gradient of temperature causes a stress gradient through the depth of the slab. Near the slab ends, where there is less restraint against curling, slab temperature gradients can cause uplift of the slab. This correspondence between temperature gradients, stress gradients, and vertical movement of the slab ends can be predicted by computer model (Ref 10). The measurement of temperature gradients, strain gradients and vertical movement verifies the curling and warping behavior of the slab.

If the above measurements are continuously recorded during the application of longitudinal prestress, the effect of the prestress can be determined. Before and after measurements of concrete strain and horizontal slab movement indicate the amount of prestress loss due to friction. In this way, the assumed value for the coefficient of base friction can be checked. Measurements of the gradient of concrete strain and the vertical movement of the slab corners indicate the effect of the eccentricity of the prestressing tendons.

Concrete strength tests provide a verification of the assumed strength gain curve of the concrete used in the pavement design. Measurements of concrete modulus of elasticity at early ages can be used to convert values of concrete strain to values of stress. A survey of crack formation in the pavement slabs is important. If early cracks are found in the slab, the time of the crack formation can be correlated with the measured temperature cycle, and the concrete stresses which caused the cracking can be examined.

Objectives of the Long-Term Measurements

Objectives of the long-term measurements were outlined as follows:

Measure the effect of time and seasonal temperature change on

- -- transverse joint opening width
- -- load transfer capabilities of the transverse joints
- -- deflection characteristics of the pavement
- -- ride quality of the pavement.

The purpose of the long-term measurements is to determine how the pavement holds up over time. Readings of transverse joint openings will indicate whether or not the friction properties of the base are changing with time, and will show the effects of creep and shrinkage of the concrete. Load transfer measurements at the transverse joint can show if joint opening width affects load-transfer, and if the effects of traffic have caused any deterioration of the joint. Measurements of the deflection characteristics of the prestressed overlay can be compared to similar measurements taken on the pavement before the overlay construction and thus indicate the increase in pavement stiffness due to the overlay. All of these measurements will give an indication of the long-term performance of prestressed concrete pavements.

PAVEMENT TEST SLAB AT BALCONES RESEARCH CENTER

Before installing the instrumentation in the pavement at Waco, a pavement test slab was built to test the functioning of the instrumentation. This slab was constructed at the Balcones Research Center at The University of Texas at Austin, on an existing asphalt base. A single sheet of polyethylene, 6 mils thick, was used for reducing friction between the slab and the asphalt base. The test slab was 6 inches thick, 8 feet wide and 26-1/2 feet long, post-tensioned in the longitudinal and transverse directions. It incorporated the following instrumentation:

Electronic Instrumentation:

1 ambient temperature thermocouple
6 embedded thermocouples
10 embedment strain gages
2 surface strain gages
3 displacement transducers

Mechanical Instrumentation:

3 movement dial gages
2 sets of Demac strain reference points

The purpose of the test slab was three-fold. It provided an opportunity to (1) get familiar with the procedures for implementing the instrumentation, (2) verify that the electronic instrumentation functioned accurately, and (3) program the data acquisition system. The test slab was also used for other purposes, including testing post-tensioning anchor-zone strength and pocket stressing techniques.

Construction of the Test Slab.

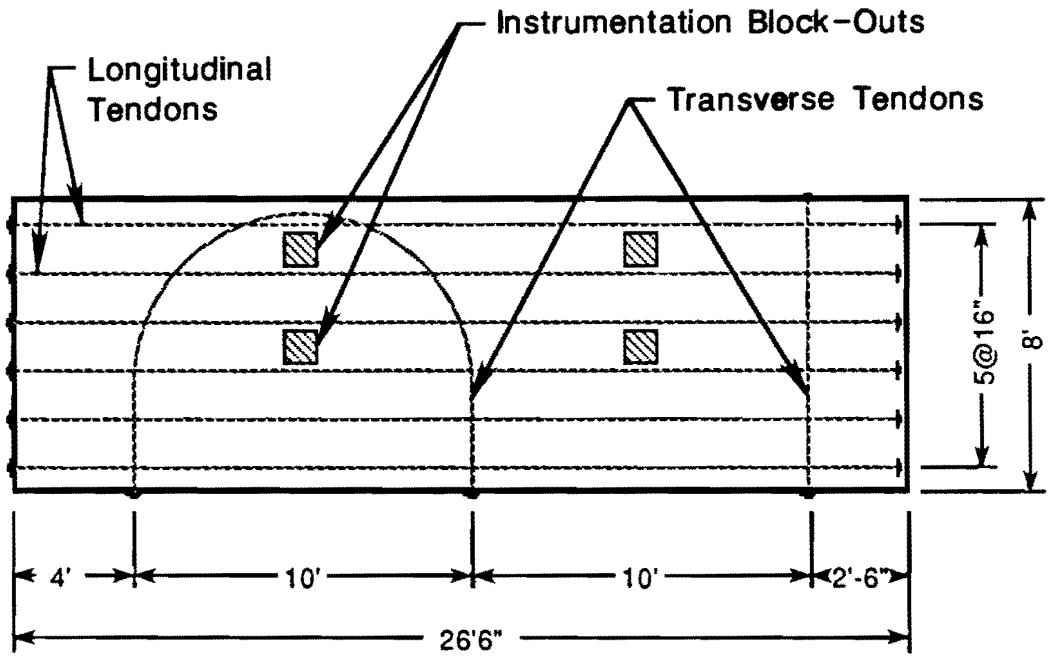
A drawing of the test slab is shown in Fig 2.1. The dimensions of the slab are 6 inches thick by 8 feet wide by 26–1/2 feet long. The slab is cast on a 3-inch-thick asphalt base layer. A single layer of 6-mil polyethylene sheeting serves as a friction reducing medium between the prestressed concrete slab and the asphalt base. The thicknesses of the slab and base layer and the friction reducing medium are the same as those used in the Texas prestressed pavement.

The last 3 feet of the west end of the slab is keyed in to the asphalt at a depth of 3 inches. There are two vertical dowel bars anchoring this end of the slab to the subbase. This key-in detail is identical to that used at midslab of the Texas prestressed pavement slabs. By anchoring the west end of the test slab, all horizontal movement of the slab is forced to occur at the east end of the slab. Thus, the test slab actually models half of a 50-feet-long pavement slab.

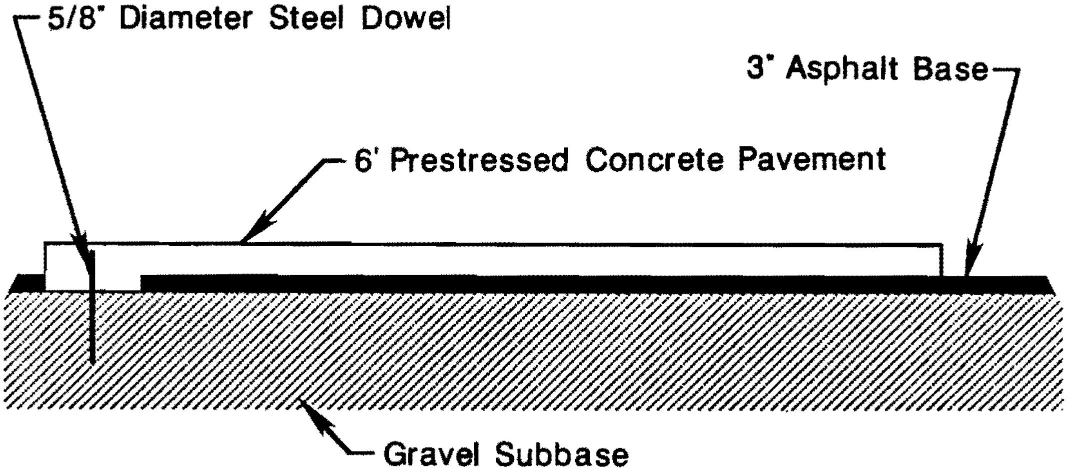
There are six longitudinal post-tensioning tendons in the test slab. They are 0.6-inch-diameter plastic-coated unbonded tendons. The tendons are spaced on 16-inch centers. This longitudinal tendon layout is the same as that used in the 440-foot slabs of the Texas prestressed pavement.

The test slab contains one looped transverse tendon, and one straight-through transverse tendon. The spacing between transverse tendons is 10 feet. This is similar to the transverse tendon layout for the Texas prestressed pavement.

The concrete for the test slab was placed on August 23, 1985. The concrete was specified to be "Class S," according to the specifications of the Texas State Department of Highways and Public Transportation (Ref 20). This is the same concrete specification used for the Texas prestressed pavement. The concrete had a cement content of 6 sacks per yard, 5 percent air entrainment, and a 2-inch slump. Placement of the concrete for the test slab is shown in Fig 2.2. The completed test slab is pictured in Fig 2.3.



Plan

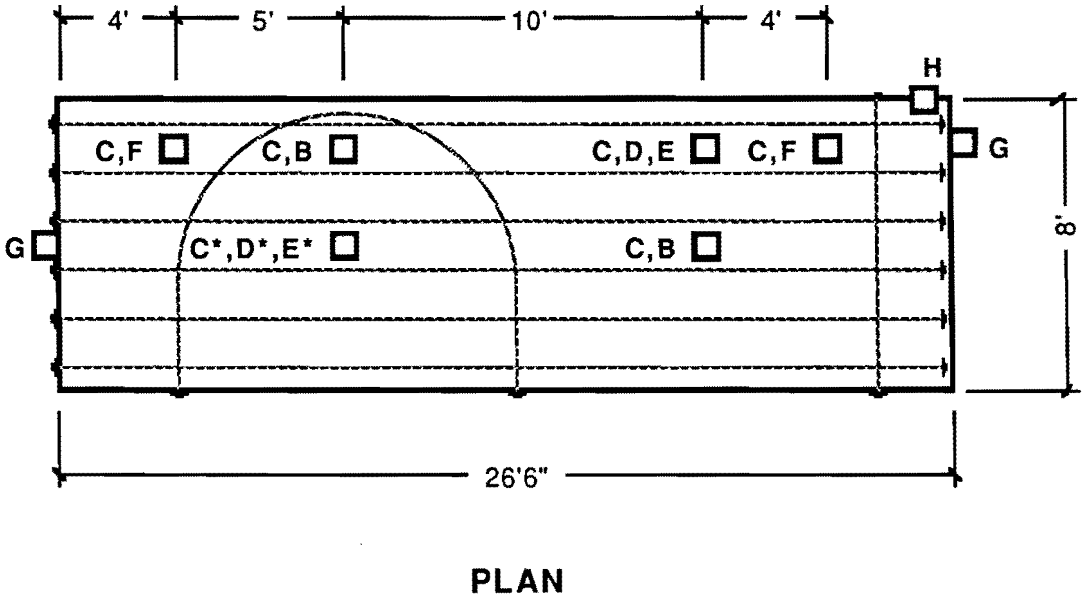


Section

Fig 2.1. Pavement test slab.

Fig 2.2. Concrete placement for the test slab.

Fig 2.3. Test slab completed.



MEASUREMENT	NO. OF LOCATIONS	APPARATUS
A. AMBIENT TEMPERATURE	1	THERMOCOUPLE
B. SLAB TEMPERATURE AT 3 DEPTHS	2	EMBEDMENT GAGE
C. MID-DEPTH CONCRETE STRAIN	6	"
D. 1/2 IN. DEEP CONCRETE STRAIN	2	"
E. 5 1/2 IN. DEEP CONCRETE STRAIN	2	"
F. SURFACE CONCRETE STRAIN	2	SURFACE GAGE
G. HORIZONTAL SLAB MOVEMENT	2	DISPL. TRANSDUCER
H. VERTICAL SLAB MOVEMENT	1	"

* INDICATES GAGES POSITIONED TRANSVERSELY

Fig 2.4. Test slab instrumentation.

Test Slab Instrumentation

The layout of test slab instrumentation is shown in Fig 2.4. Thermocouples were used to monitor ambient temperature and slab temperature at three depths. The embedded thermocouples were placed in two locations in the slab. In each location there was a thermocouple at a depth of 1/2 inch, one at a depth of 3 inches, and one at a depth of 5–1/2 inches The thermocouples were placed in plexiglass chairs which held them at the correct depths, as shown in Fig 2.5. The chairs were positioned in 12–inch by 12–inch block-outs while the concrete was placed. Immediately after the concrete was placed, the block-outs were removed and additional concrete was placed and vibrated around the thermocouples.

Embedment gages were used to measure longitudinal and transverse concrete strain. The gages used were polyester mold gages , model PML 60, made by T.M.L., Inc. The gage is pictured in Fig 2.6. It has an overall length of 125 mm and a gage length of 60 mm. These gages were placed in six locations in the test slab, as shown in Fig 2.4. In five locations the gages were placed longitudinally, and in one location the gages were placed transversely. In two locations, gages were placed at three depths: 1/2 inch, 3 inches, and 5 1/2 inches. As with the thermocouples, the embedment strain gages were held in place using plexiglass chairs. (see Fig 2.5.). As with the thermocouples, block-outs were used to protect the gages during concrete placement. Figure 2.7 shows embedment strain gages during the placement of the concrete.

Surface strain gages were also used to measure concrete strain. These gages were also made by T.M.L., Inc., model PL-60. Two gages were placed on the test slab. Concrete strain at the slab surface was also measured mechanically using a Demac extensometer with an 8-inch gage length. This strain measurement was made between Demac reference points in the locations of the two surface strain gages.

Horizontal and vertical movements of the slab were recorded electronically using displacement transducers. The transducers were mounted to 5/8-inch-diameter steel rods driven 2 feet into the pavement base. Three transducers were used: one was positioned horizontally at the west end of the slab, one was positioned horizontally at the east end of the slab, and one was positioned vertically at the northeast corner of the slab. In all three of these locations, a dial gage was positioned alongside the displacement transducer as a back-up measurement.

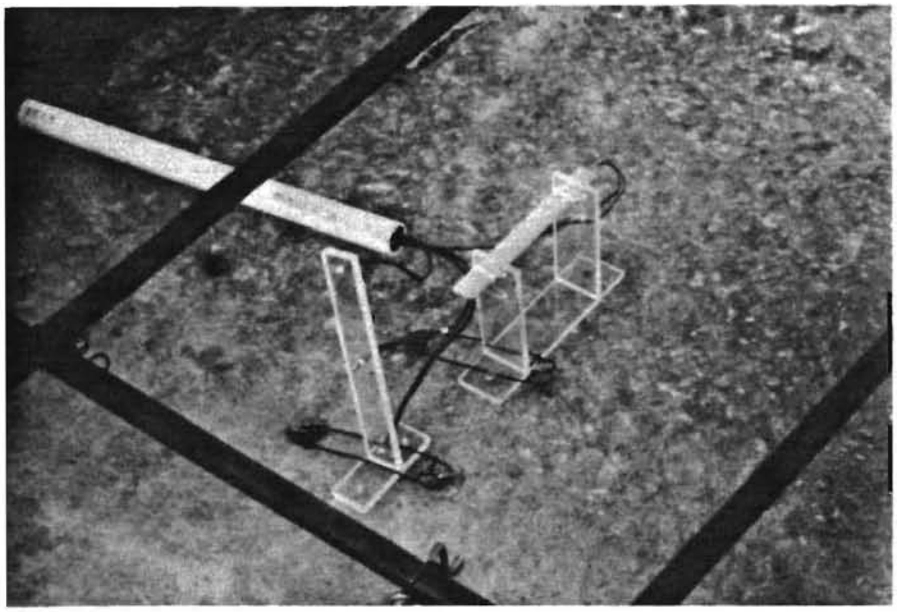


Fig 2.5. Thermocouples and embedment strain gages on plexiglass chairs before concrete placement.

Fig 2.6. Embedment gage used for measuring concrete strain.

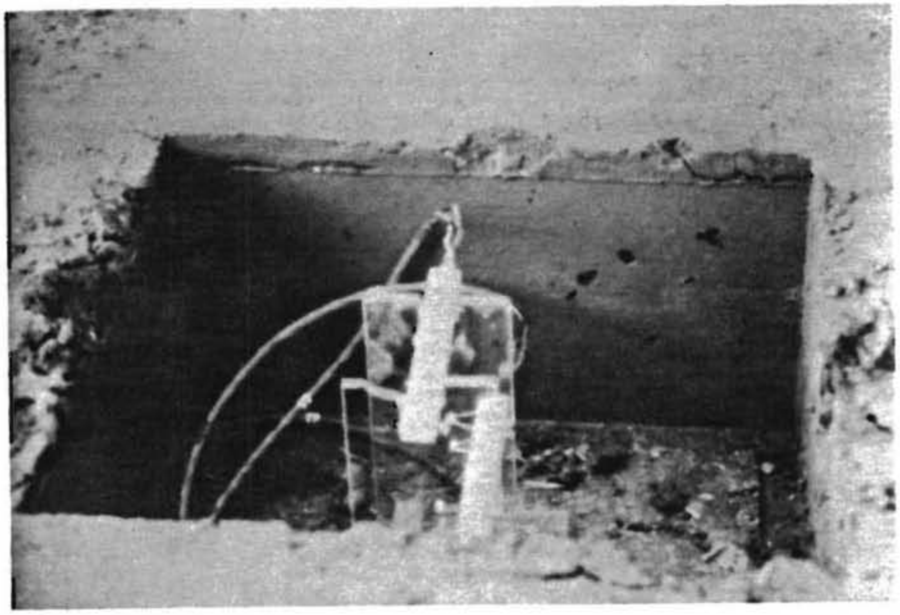


Fig 2.7. Installation of embedded strain gages in the test slab.

The output of the thermocouples and strain gages was recorded by a Hewlett-Packard 3497 data acquisition system controlled by a Hewlett-Packard 150 desk-top computer.

Experimental Procedure for the Test Slab

The experimental procedure for the test slab involved the recording of ambient and concrete temperature changes, and the recording of horizontal slab movements and concrete strain due to post-tensioning.

(1) Temperature Change. Ambient temperature and slab temperature were monitored during part of a daily temperature cycle. Five sets of readings were taken between 10:43 A.M. and 7:30 P.M. on the day of casting.

(2) Horizontal Slab Movement. Because the length of the slab is only 26–1/2 feet, horizontal movement due to diurnal temperature changes was expected to be negligible during the period when the test slab was being monitored. Horizontal movement due to the application of longitudinal prestress, however, was expected to be significant.

During the application of longitudinal prestress, horizontal slab movement was monitored using displacement transducers and dial gages. The six longitudinal tendons were post-tensioned to 20 kips each, and horizontal slab movement was recorded after each post-tensioning operation. The tendons in the center of the slab were stressed first, according to the order of stressing operations shown in Fig 2.8. Thus after every second stressing operation, the applied prestress was symmetric across the slab. The prestress level in the concrete after all six tendons were stressed was calculated to be 162 psi (assuming a 1/4–inch–loss of tendon elongation due to anchor seating.)

(3) Longitudinal Concrete Strain. Concrete strain due to the application of longitudinal prestress was recorded after every stressing operation. This time the longitudinal tendons were stressed to 40 kips each. The applied prestress level in the concrete after all six tendons were stressed was 371 psi.

(4) Transverse Concrete Strain. Concrete strain in the transverse direction was recorded during the release of longitudinal prestressing and the application of transverse prestressing. In this case there were four stressing operations: (1) the release of the longitudinal prestress of 371 psi, (2) the stressing of the looped transverse tendon to 40 kips, (3) the stressing of the straight-through transverse tendon, and (4) the release of

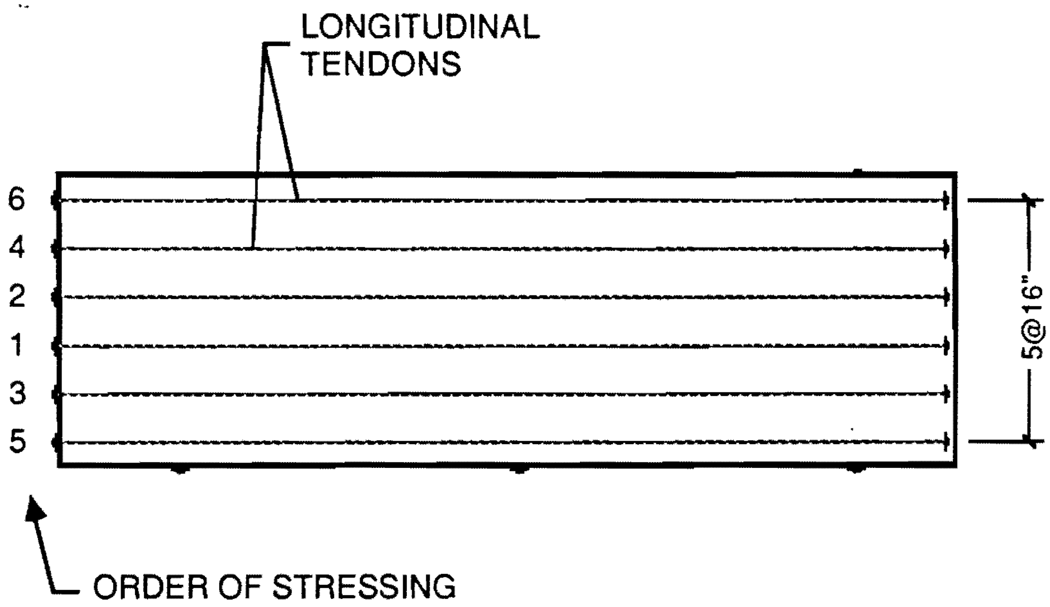


Fig 2.8. Order of stressing for the longitudinal tendons.

prestress in both transverse tendons. The transverse prestress level in the slab after both transverse tendons were stressed was 55 psi.

Test Slab Results

The experimentation on the test slab yielded results which indicate the effectiveness of measurements of temperature change, horizontal slab movements, and concrete strain.

(1) Temperature Change. Figure 2.9 shows the output of thermocouples 1, 2, and 3. These three thermocouples were in the same location in the slab. Thermocouple 1 was 5–1/2 inches deep, thermocouple 2 was 3 inches deep, and thermocouple 3 was 1/2 inch deep. It can be seen from Fig 2.9 that during the middle of the day the top thermocouple shows the highest temperature and the bottom thermocouple shows the lowest temperature. In the evening hours, the temperature of the top thermocouple drops quickest, and the temperature of the bottom thermocouple is most stable. Figure 2.9 shows that the maximum positive temperature gradient occurs at 12:30 and that the temperature gradient is about 2°F/inch. Thermocouples 4, 5, and 6 were also positioned at 3 depths in the slab but were located in a different slab location. The output of thermocouples 4, 5, and 6 corresponded very closely to that of thermocouples 1, 2, and 3

(2) Horizontal Slab Movement. Horizontal slab movement at the east end of the test slab after every second stressing operation is shown in Fig 2.10. It can be seen from this figure that the measurements of the displacement transducer and the dial gage correspond very closely. It can also be seen that the contraction movement progresses almost linearly (as expected) over the three increments of prestress application.

The final amount of movement, after all six tendons have been stressed, was 0.0102 inch (contraction.) From this final movement, the modulus of elasticity of the concrete can be back-calculated. Assuming a constant coefficient of base friction of 0.96, a concrete unit weight of 145 pcf, and a prestress level in the concrete at the east end of the slab of 162 psi, the average concrete stress is calculated to be 150 psi. The slab movement indicates an average concrete strain of 0.000034 inch/inch. This gives a concrete modulus of elasticity of 4,400,000 psi.

(3) Longitudinal Concrete Strain. Figure 2.11 shows the concrete strain, after every second stressing operation, at four different mid-depth strain gages. It can be seen

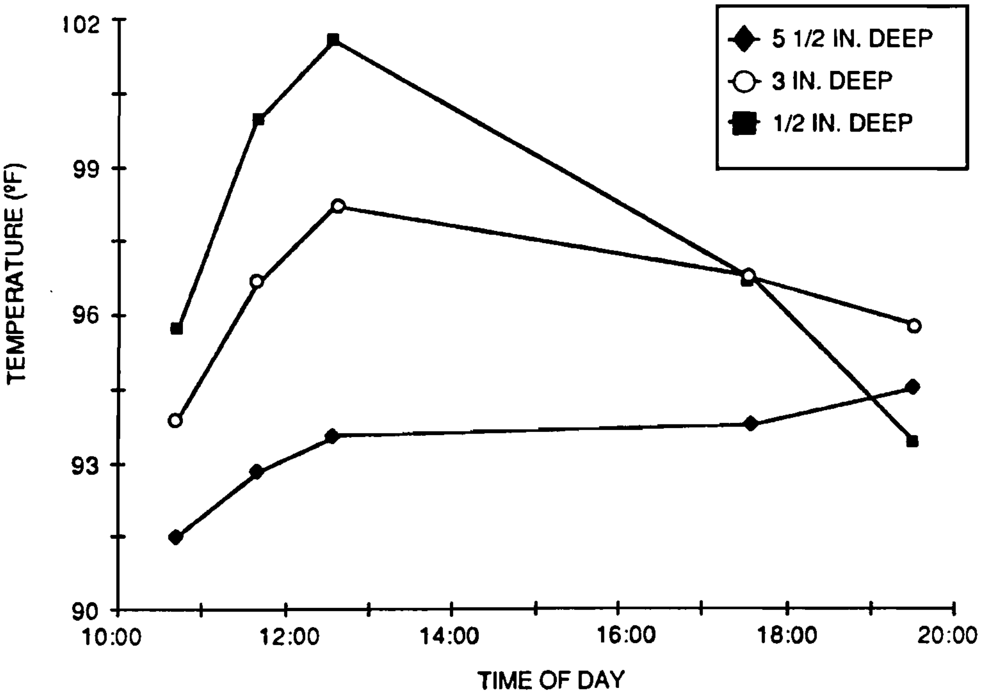


Fig 2.9. Temperature changes in the test slab, August 23, 1985, thermocouple channels 1, 2, and 3.

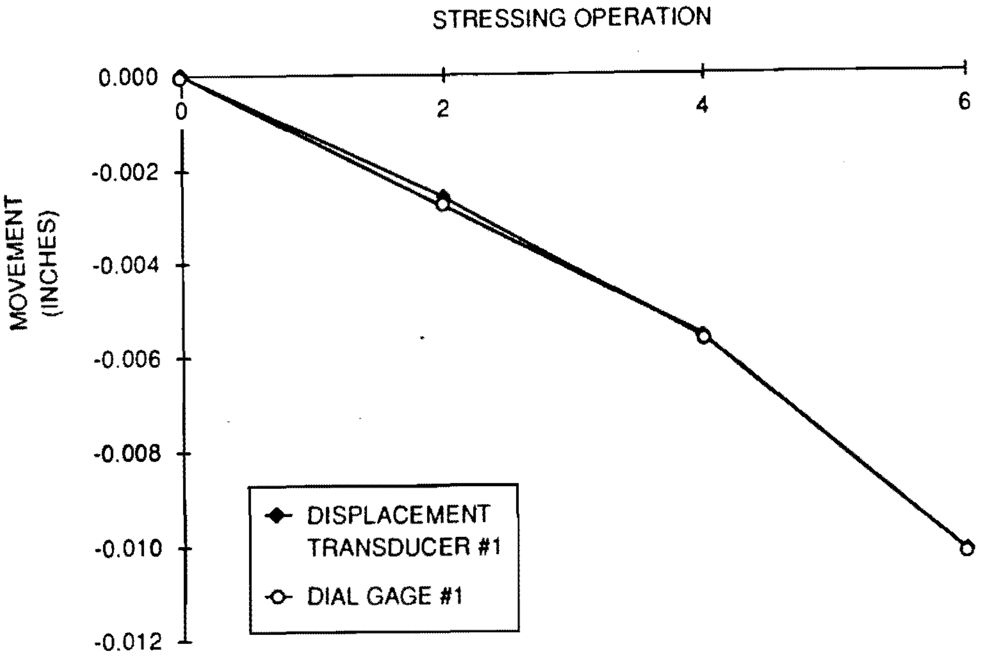


Fig 2.10. Horizontal movement of the test slab as measured by displacement transducer and dial gage.

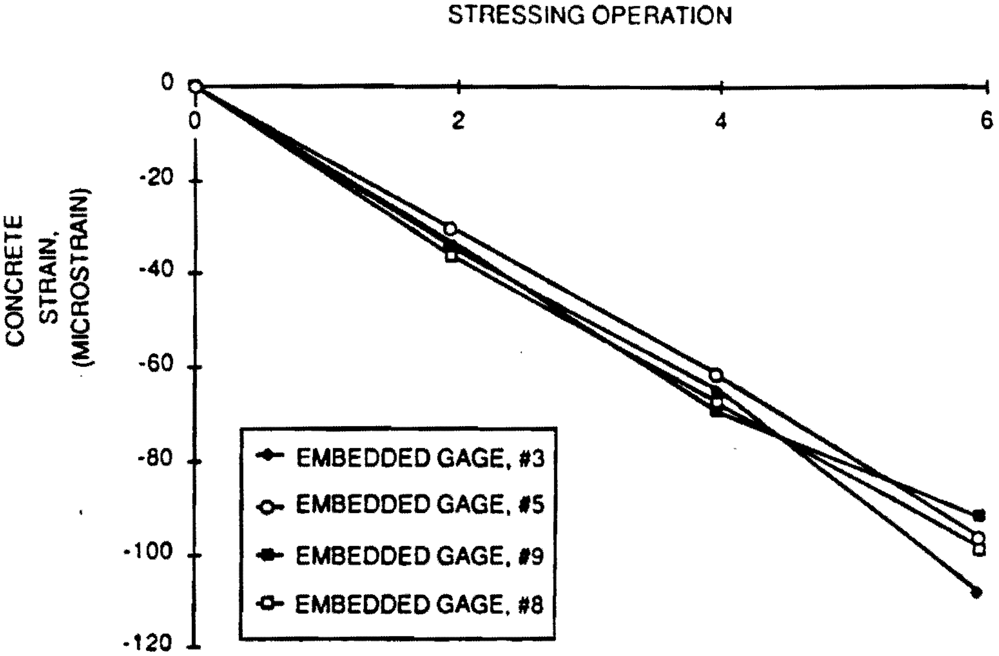


Fig 2.11. Mid-depth concrete strain in the test slab.

from this figure that the gages correspond closely and that compressive strain progresses linearly (as expected) over the three increments of prestress application.

Figure 2.12 shows the output of three strain gages placed at different depths at the same location. The gage at mid-depth and the gage near the concrete surface show nearly the same strain, but the gage near the bottom of the slab shows a strain 35 percent greater than the other two gages. This increased strain cannot be explained as the result of the eccentricity of the prestressing force because the slab self-weight counteracts this effect. The output of this embedment gage is not considered accurate, perhaps due to improper gage placement, an error in the data acquisition software, or a defective gage. This was the only strain gage, of the 12 gages in the test slab, to show errant results.

Figures 2.13 and 2.14 show the output of the two surface strain gages. It can be seen from Fig 2.13 that the surface strain corresponds closely to the strain measured at mid-depth of the slab. In Fig 2.14 it can be seen that surface strain gage output also corresponds closely to the mechanically measured strain using the Demac gage.

Values of strain can be used to back-calculate the modulus of elasticity of the concrete. The average concrete stress in the slab after all six tendons were stressed was calculated to be 359 psi. The strain gages, on average, showed a concrete strain of 0.000095 inch/inch after all tendons were stressed. This gives a concrete modulus of elasticity of 3,800,000 psi.

(4) Transverse Concrete Strain. Because the transverse tendons are spaced so far apart, the stress introduced in the concrete from transverse post-tensioning is about 1/7 that introduced by the longitudinal post-tensioning. Figure 2.15 shows the output of the three strain gages which were positioned transversely in the test slab. Stressing operation 1 in this figure is the result of the 371 psi of longitudinal prestress. It is evident from this figure that the longitudinal post-tensioning affects the transversely-oriented strain gages (due to Poisson's effect) almost as much as the transverse post-tensioning does. It appears that the magnitude of strain changes in the concrete due to transverse post-tensioning is too small in comparison to the resolution capabilities of the gages and cannot be recorded effectively.

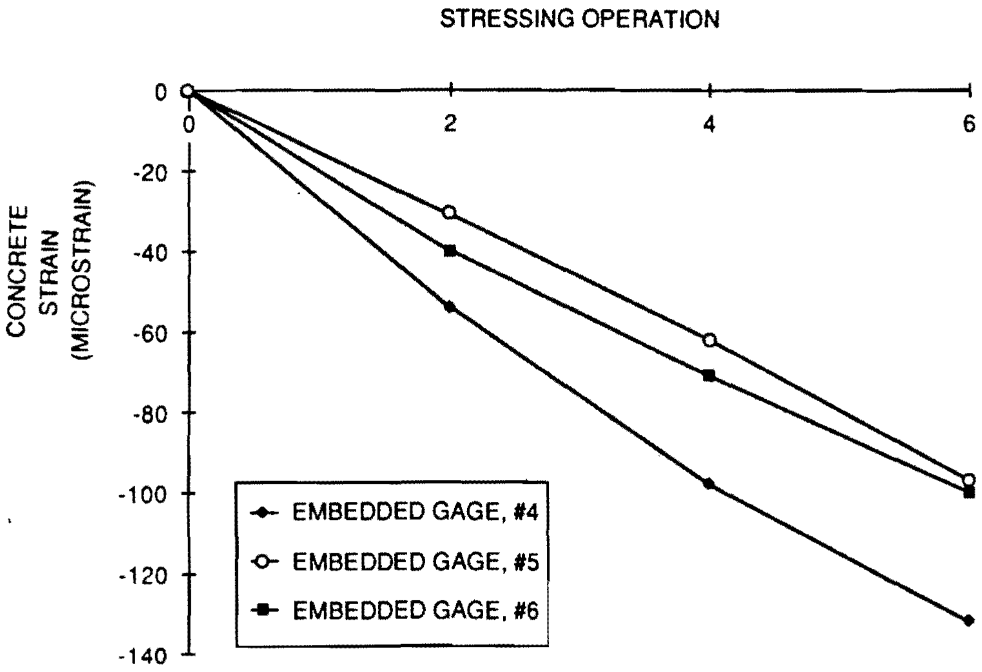


Fig 2.12. Concrete strain at three depths in the test slab.

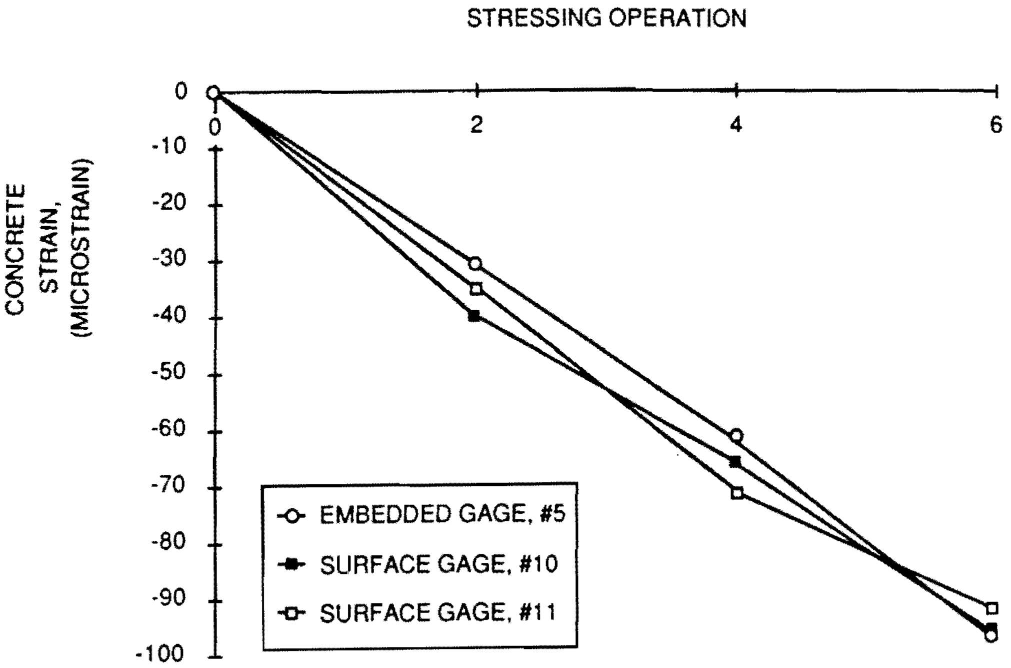


Fig 2.13. Comparison of mid-depth concrete strain and surface concrete strain for the test slab.

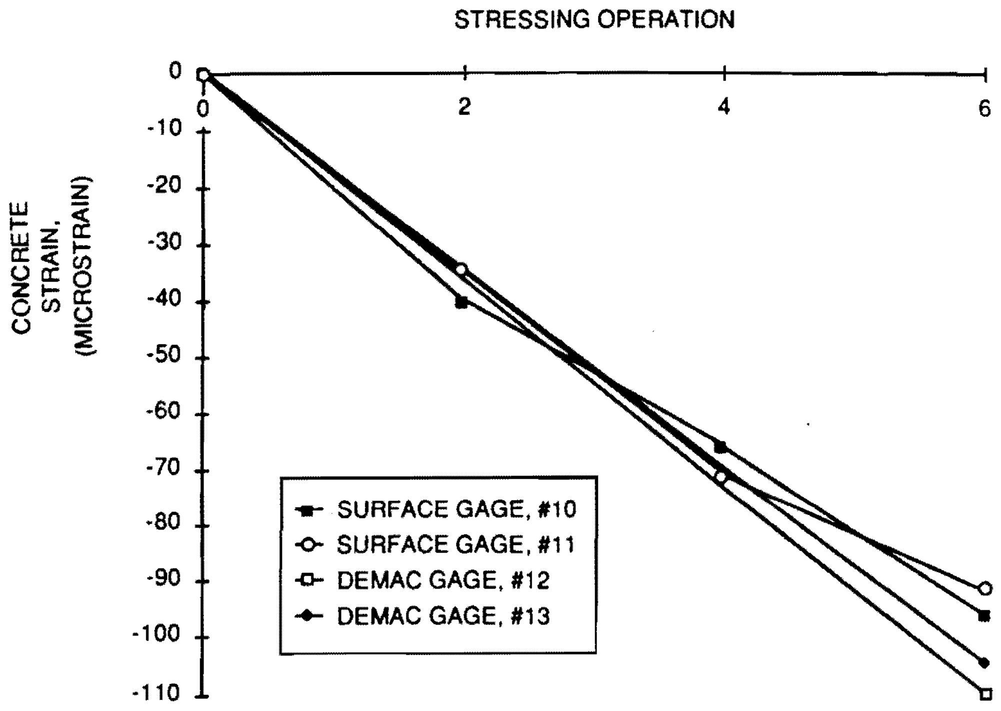


Fig 2.14. Surface concrete strain of the test slab as measured by resistive gage and demac gage.

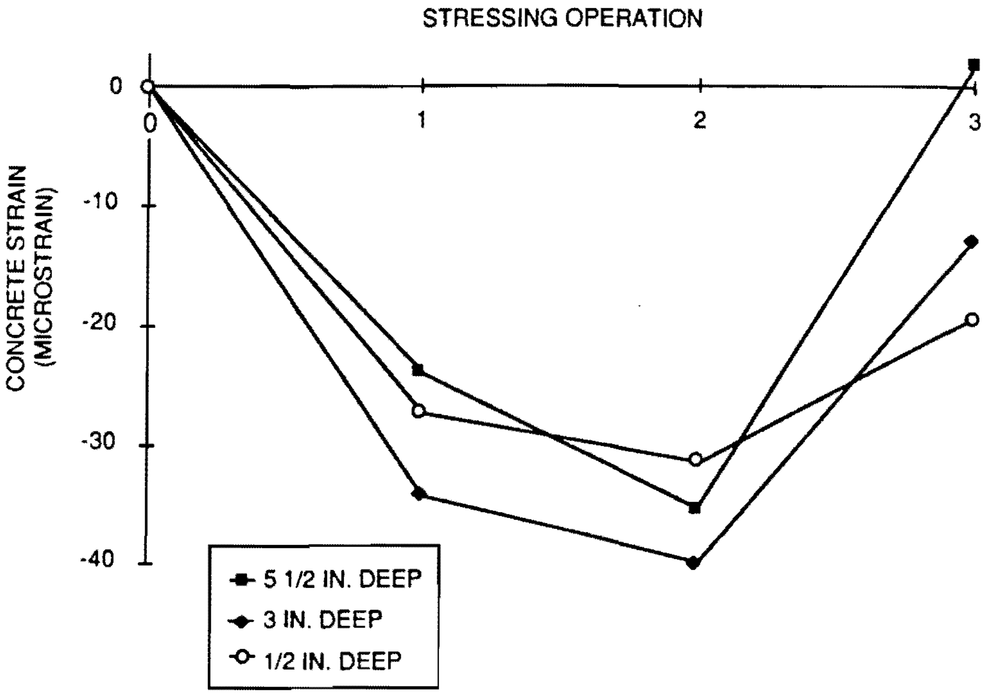


Fig 2.15. Concrete strain in the transverse direction in the test slab.

Test Slab Conclusions

The results of the experimentation on the test slab indicate the following conclusions:

(1) Thermocouples are effective in recording both ambient and concrete temperatures and can be considered accurate to 1°F or better.

(2) Displacement transducers are very effective in recording horizontal slab movement. The transducers are capable of resolving slab movements accurately to the nearest 0.001 inch

(3) Embedded and surface strain gages, positioned longitudinally, are generally effective in recording changes in concrete strain due to longitudinal post-tensioning. One embedment strain gage, however, gave errant results which cannot fully be explained. In most cases, the strain gages could resolve accurately strain changes of 5 microstrain.

(4) Embedded strain gages positioned transversely were not effective or consistent in recording the changes in concrete strain due to transverse post-tensioning. This is probably because the change in strain due to the transverse post-tensioning is small in comparison to the resolution capabilities of the gages.

CHAPTER 3. FIELD IMPLEMENTATION

This chapter describes the implementation of instrumentation on the Texas prestressed concrete pavement. An overall description of the project is given, and the instrumentation and its installation are described in detail.

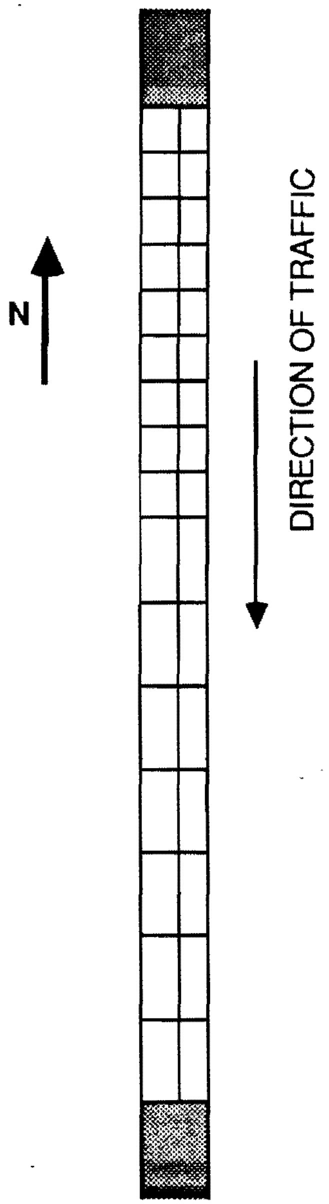
GENERAL DESCRIPTION OF THE TEXAS PRESTRESSED PAVEMENT PROJECT

The design of the Texas prestressed pavement is described in detail in Ref 21. The project consists of 32 prestressed concrete pavement slabs which make up a one-mile stretch of Interstate 35 in McClennan County, Texas. Underlying the prestressed pavement is a 4-inch-thick asphalt-concrete pavement on top of a 12-inch-thick jointed concrete pavement. Underlying this is a 5-inch-thick granular base and a 6-inch-thick lime-stabilized subbase.

There are two lanes of prestressed concrete pavement overlay one mile long. The two lanes were placed in separate operations. The first lane placed was 17 feet wide, including a 4-foot-wide shoulder. The second lane placed was 21 feet wide, including a 10-foot-wide shoulder. The prestressed concrete pavement slabs are either 240 feet or 440 feet in length, as shown in Fig 3.1. The numbering scheme used to identify the slabs is shown in Fig 3.2.

The pavement slabs are 6 inches thick, cast on a single sheet of 6-mil polyethylene, and post-tensioned in the longitudinal and transverse directions. The midslab section of each pavement slab is anchored to the base using a 3-inch-deep by 3-foot-long key-in with 5/8-inch-diameter vertical dowels driven into the subgrade. This assures that horizontal slab movements will be the same at either end of the slab.

The post-tensioning tendons are 0.6-inch-diameter unbonded tendons. In the 240-foot slabs the longitudinal tendons were spaced on 24-inch centers. In the 440-foot slabs the tendons were spaced on 16-inch centers. Each longitudinal tendon was stressed from a pre-formed 10–inch by 48-inch pocket near the center of the pavement slab. This central stressing from pockets eliminated the need for short gap slabs between the prestressed slabs (which were necessary on earlier projects). After the final stressing of the tendons, the stressing pockets were filled with concrete and finished to the surface of the surrounding pavement.



TOTAL OF 32 PRESTRESSED CONCRETE PAVEMENT SLABS:

9 SLABS 240 FT. X 21 FT. (OUTSIDE LANE)
7 SLABS 440 FT. X 21 FT. (OUTSIDE LANE)
9 SLABS 240 FT. X 17 FT. (INSIDE LANE)
7 SLABS 440 FT. X 17 FT. (INSIDE LANE)

Fig 3.1. Layout of prestressed concrete pavement slabs for the Texas prestressed pavement.

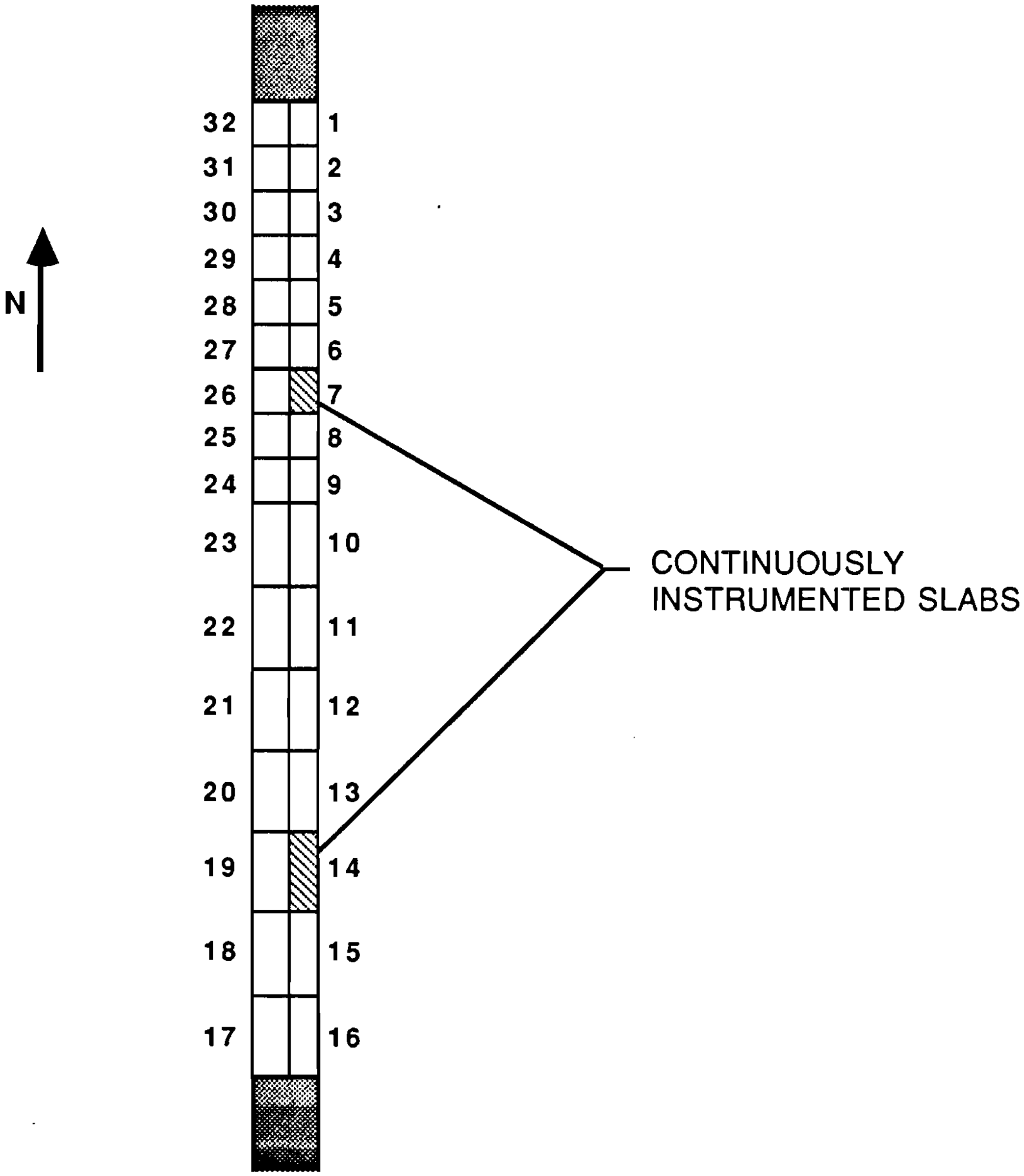


Fig 3.2. Numbering system for the prestressed concrete pavement slabs for the Texas prestressed pavement.

The transverse tendons were spaced on 10-foot centers. To reduce the number of stressing operations, the tendons were placed in a looped configuration. The transverse tendons were stressed from pockets in the pavement shoulder.

The transverse joints between pavement slabs were designed to permit free expansion and contraction of the pavement slabs. At the same time the joints are designed to transfer vertical shear forces from one pavement slab to another. An armored joint section is anchored to the ends of each pavement slab, and 1-1/4 inch-diameter stainless steel encased dowels are used for load transfer.

In previous prestressed concrete pavement projects, transverse cracks developed in the pavement slabs during the first night after placement. On the Texas prestressed pavement, early cracking of the pavement slabs due to overnight temperature drops was prevented by applying an initial amount of longitudinal prestress. This initial prestress was applied to the pavement slabs within 8 to 15 hours after concrete placement. The amount of initial prestress applied to the concrete varied from 70 psi to 200 psi. This value was determined according to the concrete strength at the time of the initial post-tensioning.

Also unique to this project is the computer-based method of analysis. The computer program written by Mendoza-Diaz (Ref 10), predicts the stresses and slab movement in a prestressed pavement slab due to daily temperature changes. The input to this program includes the dimensions of the pavement slab, the properties of the concrete used, the friction characteristics of the underlying material, and the assumed cycle of slab temperatures. Thus, for a given pavement design and any selected temperature cycle, the resulting concrete stresses and slab movement can be estimated.

MEASUREMENTS TAKEN AND EQUIPMENT USED

According to the objectives described in Chapter 2, the instrumentation for the Texas prestressed pavement is divided into two categories: short-term instrumentation and long-term instrumentation.

Short Term Instrumentation

The short-term instrumentation for the Texas prestressed pavement consists of (1) continuously recorded electronic instrumentation, (2) mechanical instrumentation to back-up the continuously recorded measurements, and (3) intermitantly recorded measurements. During construction in the fall of 1985, short-term instrumentation was implemented on two of the prestressed pavement slabs. Since the slabs are staked at mid-length, behavior of the two halves of a slab is symmetric, and only one half of the pavement slab needs to be monitored. One 240-foot-long slab and one 440-foot-long slab were instrumented. The instrumented slabs are slabs 7 and 14 in Fig 3.2. The same instrumentation was used for the 240-f00t-slab and the 440-foot-slab.

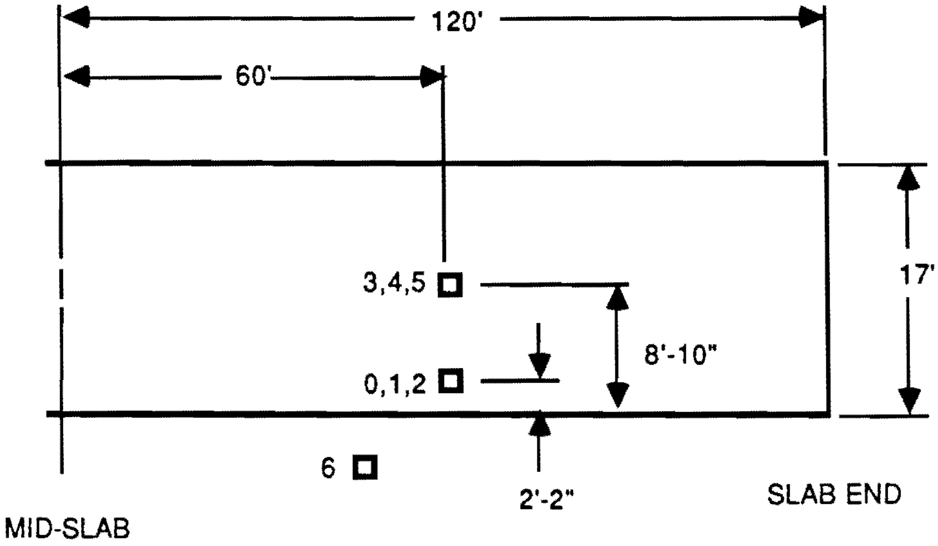
A listing of the continuously recorded electronic instrumentation used in the two instrumented slabs is shown in Table 3.1. This instrumentation consists of thermocouples for measuring temperature, strain gages for measuring concrete strain, and displacement transducers for measuring horizontal and vertical slab movements.

Thermocouples were used to monitor both ambient temperature and concrete temperature. For concrete temperatures, the thermocouples were placed at three depths in the slab to obtain the temperature gradient through the thickness of the slab. For each pavement slab monitored there were two locations for the embedded thermocouples: one near the center of the pavement slab and one near the slab edge. The ambient temperature measurement device consisted of a thermocouple placed in the shade outside of the slab. The thermocouples used 20-gage copper-constantine thermocouple wire with crimp-on junctions. The locations of the thermocouples installed in slab 7 are shown in Fig 3.3. On slab 7, data from three of the thermocouples (input channels 1, 2, and 3) were not used because the thermocouples were damaged during construction. The locations of the thermocouples installed in slab 14 are shown in Fig 3.4.

Movement of the slab was monitored using displacement transducers mounted at the slab corners. At each of the two corners of the half-slab, there were a transducer to record vertical deflection and a transducer to record horizontal deflection. In addition there were four transducers mounted along the pavement edge, equally spaced between the slab edge and mid-slab, to record horizontal movement. Four-conductor, 18-gage shielded wire was used for the displacement transducer leads. The locations of displacement transducers for slabs 7 and 14 are shown in Figs 3.5 and 3.6. On slabs 7 and 14 data from three of the displacement

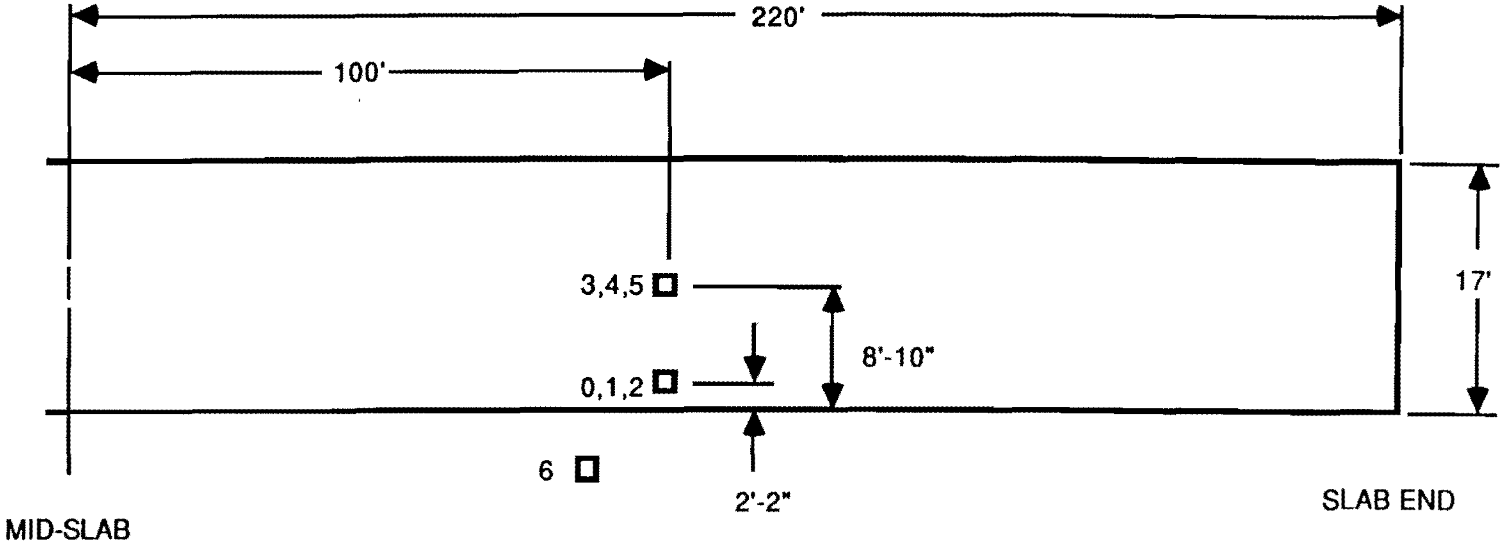
TABLE 3.1. CONTINUOUSLY RECORDED ELECTRONIC INSTRUMENTATION

Measurement	Number of Locations Each Slab	Apparatus
Ambient Temperature	1	Thermocouple
Slab Temperature at 3 Depths	2	Thermocouple
Mid-Depth Concrete Strain	6	Embedment Gage
1/2-inch Deep Concrete Strain	3	Embedment Gage
5-1/2 inch Deep Concrete Strain	3	Embedment Gage
Horizontal Slab Movement	6	Displ. Transducer
Vertical Slab Movement	2	Displ. Transducer



INPUT CHANNEL	THERMOCOUPLE LOCATION
0	5 1/2 IN. DEEP
1	3 IN. DEEP
2	1/2 IN. DEEP
3	5 1/2 IN. DEEP
4	3 IN. DEEP
5	1/2 IN. DEEP
6	AMBIENT

Fig 3.3. Location of thermocouples for slab 7.



INPUT CHANNEL	THERMOCOUPLE LOCATION
0	5 1/2 IN. DEEP
1	3 IN. DEEP
2	1/2 IN. DEEP
3	5 1/2 IN. DEEP
4	3 IN. DEEP
5	1/2 IN. DEEP
6	AMBIENT

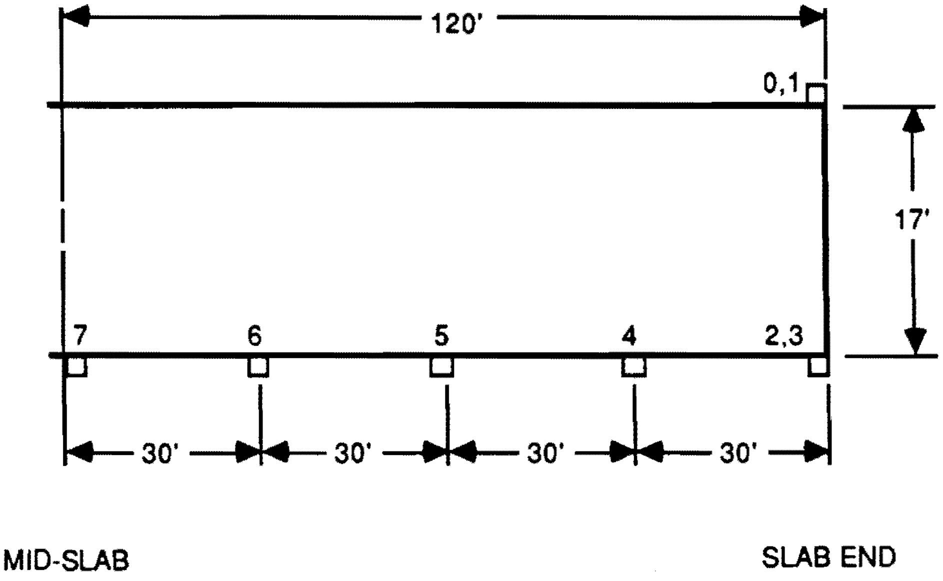
Fig 3.4. Location of the thermocouples for slab 14.

transducers (input channels 5, 6, and 7) were not recorded due to an error in the data acquisition software.

Concrete strain was recorded using polyester mold embedment gages (made by T.M.L., Inc., model PML-60) For each slab these gages were placed in six locations in the concrete. In three of the locations the gages were placed at three depths to obtain the strain gradient through the thickness of the slab. In the other three locations there was only one embedment gage, placed at mid-depth. There were six surface strain gages mounted to the pavement surface in the same locations as the embedment gages. The surface gages were made by T.M.L., Inc., model PL-60. Three-conductor, 18-gage wire was used for all of the strain gage leads. The locations of strain gages for slabs 7 and 14 are shown in Figs 3.7 and 3.8. On slab 7, data from one of the embedment strain gages (input channel 4) were not used because the gage was damaged during construction. On slabs 7 and 14, data from 8 of the strain gages (input channels 10 through 17) were not successfully recorded due to an error in the data acquisition software. These lost channels include all channels for the surface strain gages.

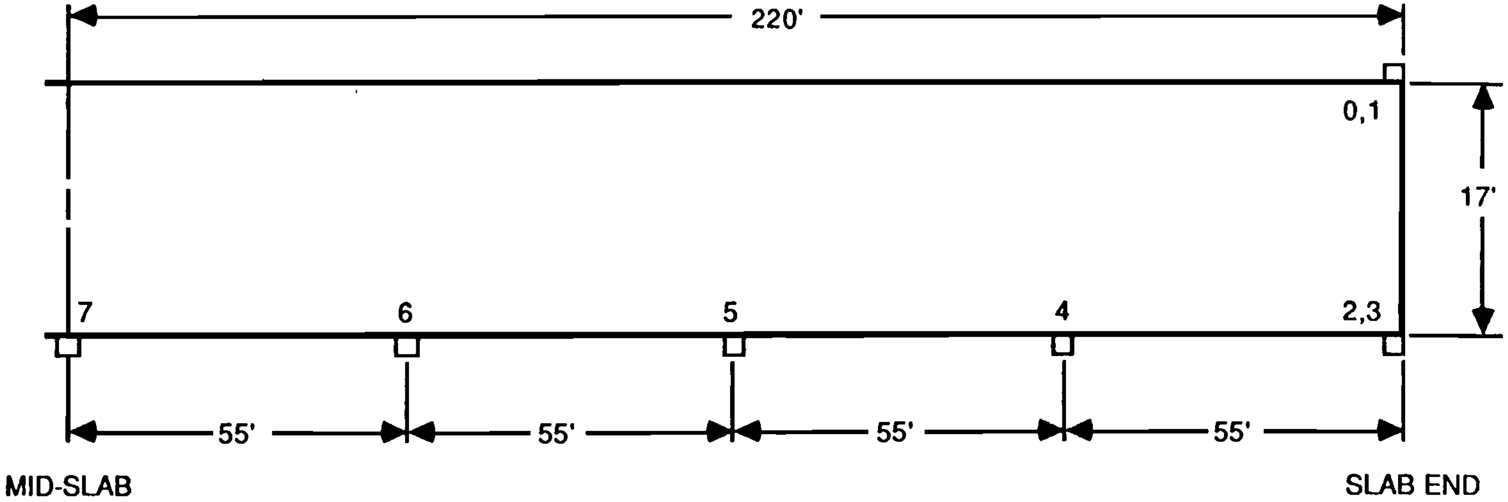
The data from this instrumentation were continuously recorded over several daily temperature cycles. The automatically timed recording of several channels of data input necessitated the use of a data acquisition system. The system is shown schematically in Fig 3.9. The voltage signals from the thermocouples, transducers, and strain gages are carried into the front end of the data acquistion device. In the case of the remote gages, the voltage signal may need to be amplified by a pre-amp located near the gages. (Because of the low resistance of the gage leads, a pre-amp was not used on the Texas prestressed pavement.) In the front-end of the data acquisition system, the input buffer conditions the signal by adjusting the amplitude of the signal voltage. Subsequently, the multiplexer allows the different inputs to be read in sequence, and the analog/digital converter records the voltage signal in binary code. This procedure is programmed by the controller, which also directs the storage and printing of the data. On this project, a Hewlett-Packard 3497 data acquisition system was used, controlled by a Hewlett-Packard 150 desk-top computer.

Measurements of ambient temperature, slab movement, and concrete strain were also recorded mechanically, as shown in Fig 3.10. Ambient temperature readings were checked intermittantly using a thermometer. Horizontal movement was checked at the slab ends by periodically measuring the width across the transverse joint, using a scale and reference marks on either side of the joint. Using a Demac gage, concrete strain was measured



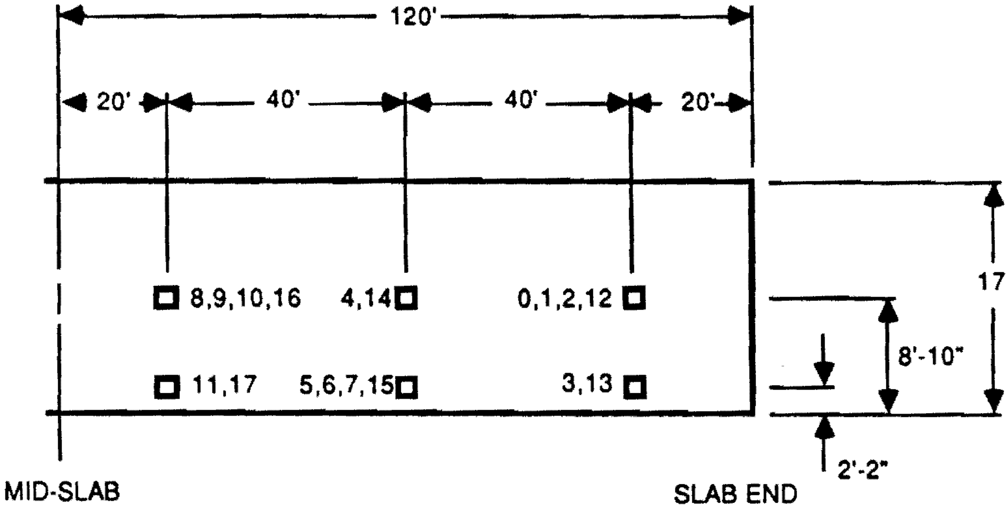
INPUT CHANNEL	TRANSDUCER ORIENTATION
0	VERTICAL
1	HORIZONTAL
2	VERTICAL
3	HORIZONTAL
4	HORIZONTAL
5	HORIZONTAL
6	HORIZONTAL
7	HORIZONTAL

Fig 3.5. Location of displacement transducers for slab 7.



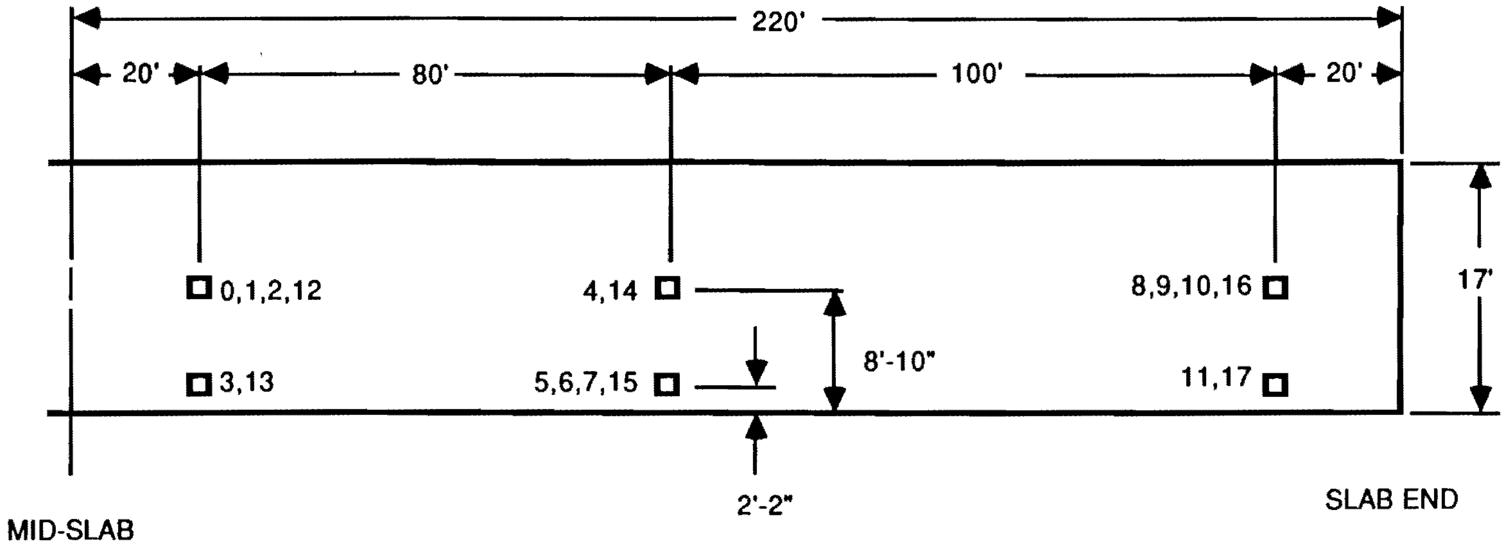
INPUT CHANNEL	TRANSDUCER ORIENTATION
0	HORIZONTAL
1	VERTICAL
2	HORIZONTAL
3	VERTICAL
4	HORIZONTAL
5	HORIZONTAL
6	HORIZONTAL
7	HORIZONTAL

Fig 3.6. Location of displacement transducers for slab 14.



INPUT CHANNEL	STRAIN GAGE LOCATION
0	5 1/2 IN. DEEP
1	3 IN. DEEP
2	1/2 IN. DEEP
3	3 IN. DEEP
4	3 IN. DEEP
5	5 1/2 IN. DEEP
6	3 IN. DEEP
7	1/2 IN. DEEP
8	5 1/2 IN. DEEP
9	3 IN. DEEP
10	1/2 IN. DEEP
11	3 IN. DEEP
12	SURFACE
13	SURFACE
14	SURFACE
15	SURFACE
16	SURFACE
17	SURFACE

Fig 3.7. Location of strain gages for slab 7.



INPUT CHANNEL	STRAIN GAGE LOCATION	INPUT CHANNEL	STRAIN GAGE LOCATION
0	5 1/2 IN. DEEP	9	3 IN. DEEP
1	3 IN. DEEP	10	1/2 IN. DEEP
2	1/2 IN. DEEP	11	3 IN. DEEP
3	3 IN. DEEP	12	SURFACE
4	3 IN. DEEP	13	SURFACE
5	5 1/2 IN. DEEP	14	SURFACE
6	3 IN. DEEP	15	SURFACE
7	1/2 IN. DEEP	16	SURFACE
8	5 1/2 IN. DEEP	17	SURFACE

Fig 3.8. Location of strain gages for slab 14.

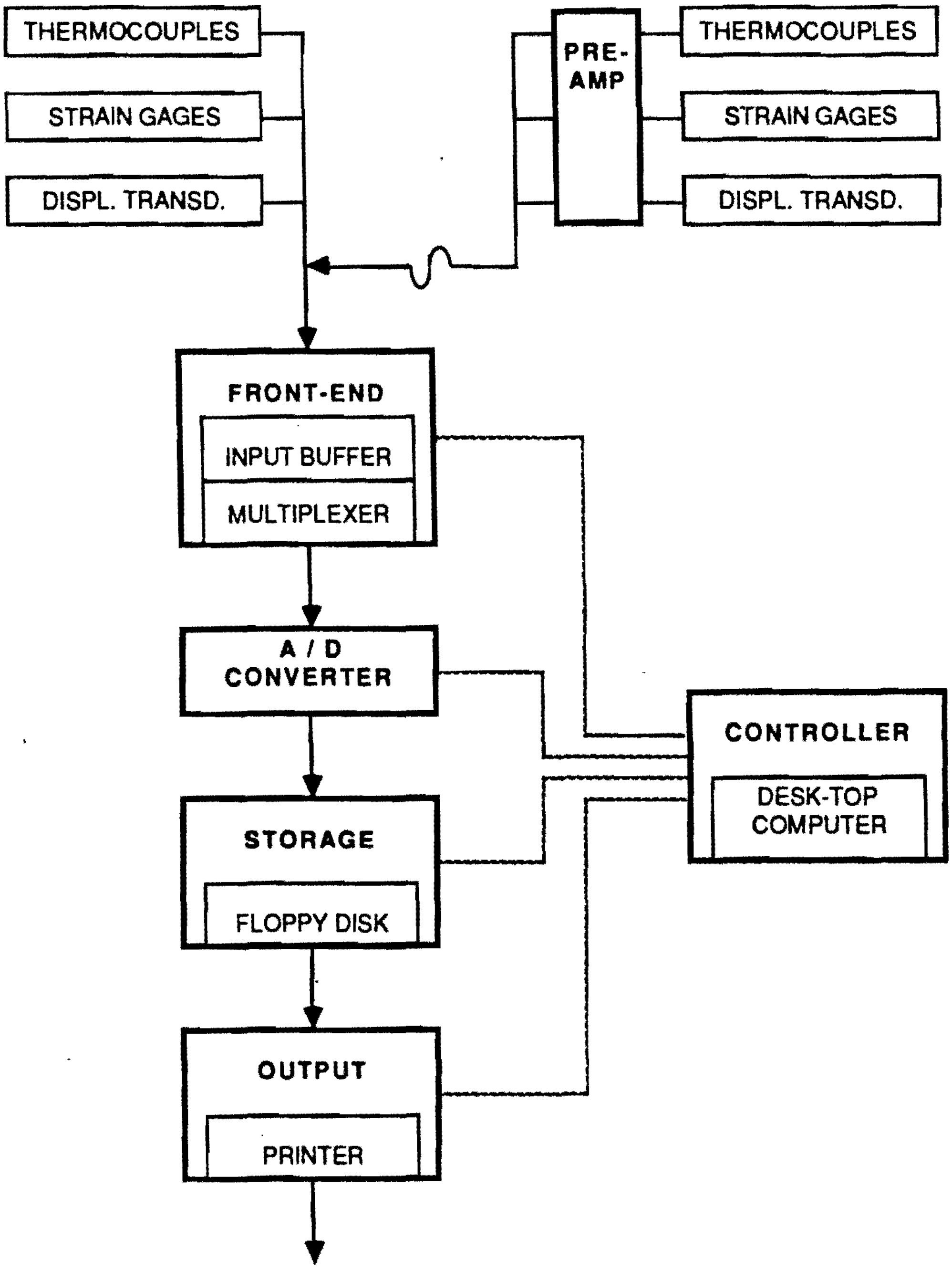
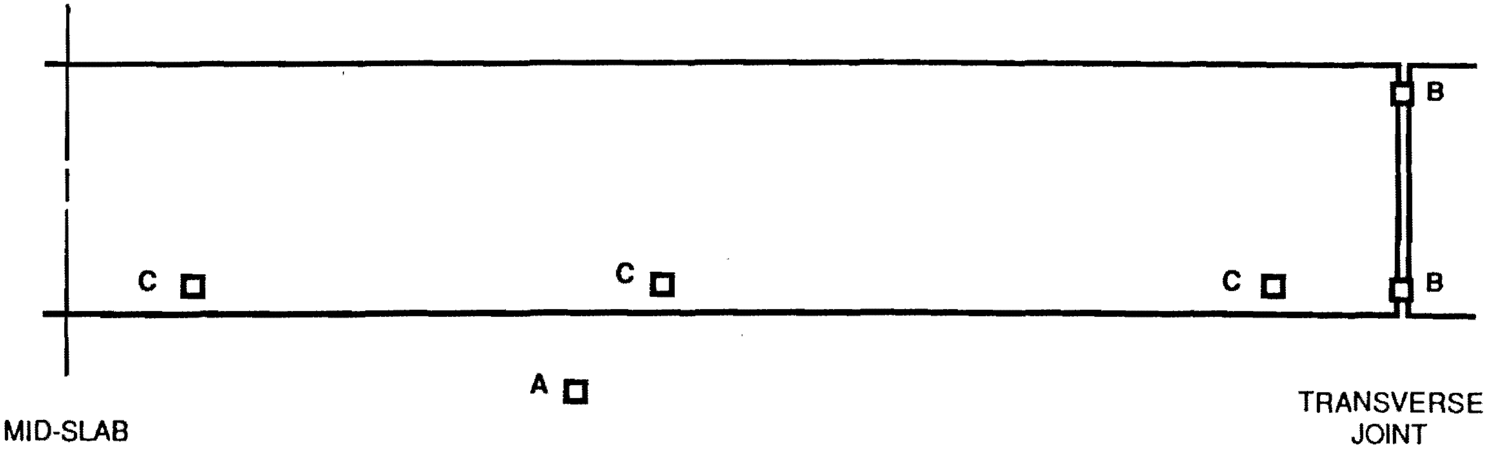


Fig 3.9. Schematic view of data acquisition system.



MEASUREMENT	NO. OF LOCATIONS	APPARATUS
A. AMBIENT TEMPERATURE	1	THERMOMETER
B. JOINT OPENING WIDTH	2	SCALE AND SCRIBE MARKS
C. SURFACE CONCRETE STRAIN	3	DEMAC GAGE

Fig 3.10. Mechanical instrumentation used on slabs 7 and 14.

periodically at three locations on the slab surface. For both slabs, Demac strain was measured in the locations of surface strain gages 13, 14, and 17 as indicated in Figs 3.7 and 3.8.

Intermitantly recorded measurements include the measurement of tendon elongations, concrete compressive strength, and concrete modulus of elasticity and an inspection of slab cracking. Tendon elongations during initial and final post-tensioning were measured to the nearest 1/8 inch using tape marks and a ruler. Tendon elongations were recorded on all tendons on all slabs. Concrete compressive strength at very early ages was measured using a compression testing machine at the job-site. For each pavement slab, six cylinders were tested at ages of 8 to 12 hours. Concrete modulus of elasticity at very early ages was measured on six cylinders total. Inspection of slab cracking was carried out regularly on all pavement slabs.

Long Term Measurements

Joint width was measured at all transverse joints, using a scale accurate to 0.01 inch. The load transfer capabilities of the transverse joint will be measured using two devices: the Dynaflect and the falling weight deflectometer. These devices will also be used to determine the deflection characteristics of the overlay.

INSTALLATION PROCEDURES

The installation of the pavement instrumentation includes the installation of short-term instrumentation and long-term instrumentation.

Short Term Instrumentation

Embedded instrumentation--thermocouples and embedment strain gages--was put in position before the concrete for the pavement slabs was placed. During concrete placement the gages were protected in 10-inch by 30-inch block-outs attached to the pavement base. The leads from the gages were protected in lengths of 1/2-inch-diameter PVC pipe. A section of steel channel protects the leads under the path of the paver tread. Figures 3.11, 3.12, and 3.13 show the block-outs for protecting pavement instrumentation.

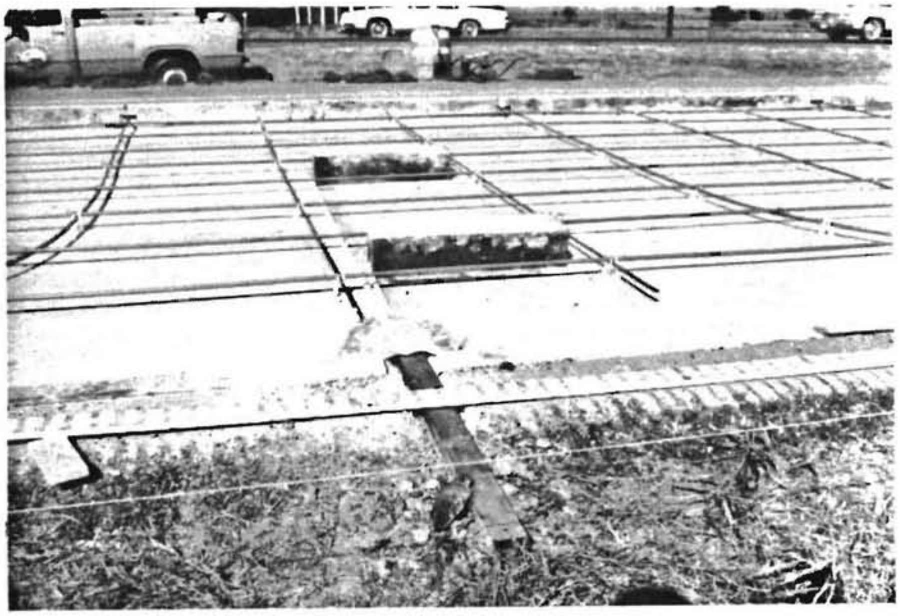


Fig 3.11. Blockouts for protecting embedded instrumentation; PVC conduit and steel channel section for protecting instrumentation leads.

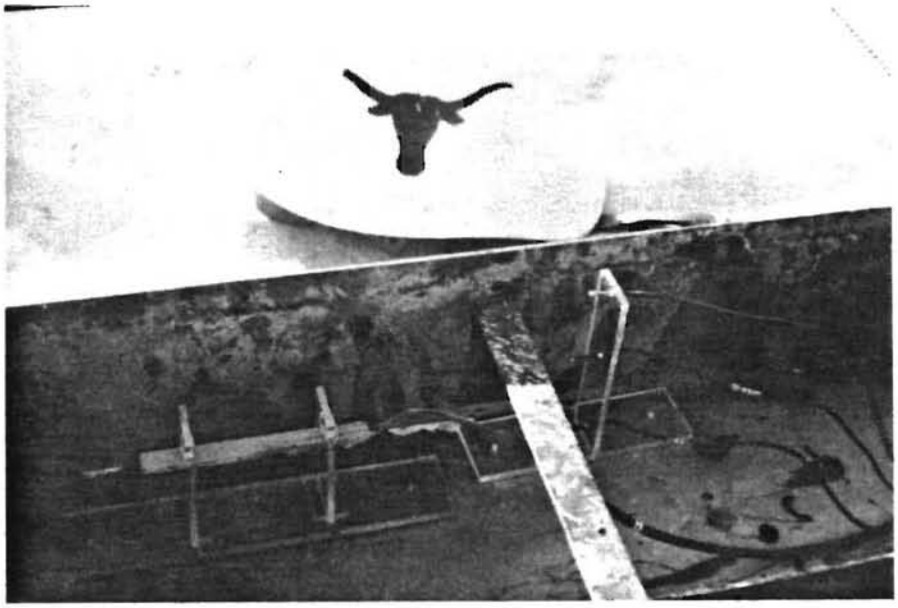


Fig 3.12. Close-up view of thermocouples and embedment strain gages in block-out.

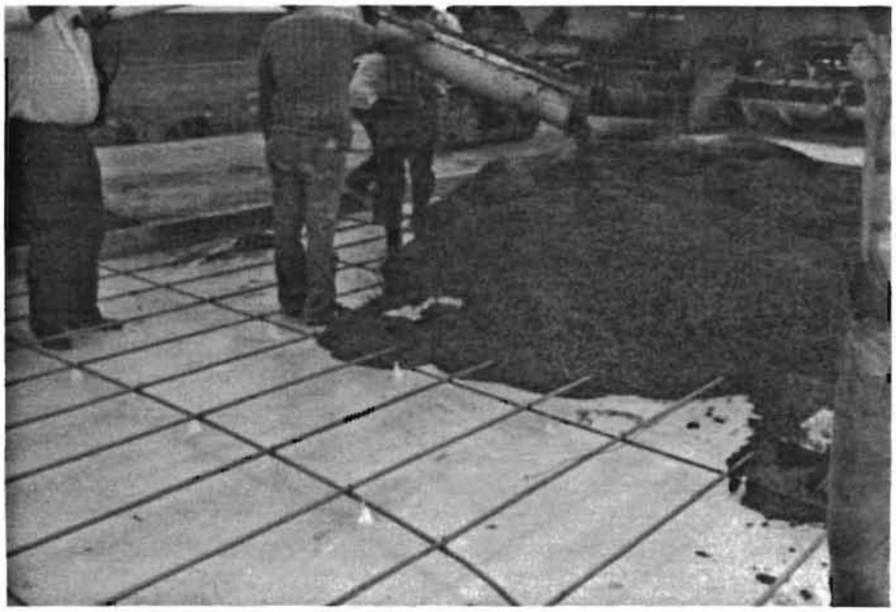


Fig 3.13. Paving operation around instrumentation block-outs.

Immediately after the paving operation the instrumentation block-outs were removed and the gages were secured in position (see Figs 3.14 and 3.15). Additional concrete was placed and vibrated around the gages, and finished to the surrounding pavement surface (see Figs 3.16, 3.17, and 3.18).

During the paving operation for slab 7, two of the block-outs protecting the embedded instrumentation were struck by the finishing screed of the slip-form paver. In the process, one embedment strain gage and 3 thermocouples were damaged. Thus, for slab 7, no data are reported for strain gage 4 and thermocouples 1, 2, and 3.

Displacement transducers were mounted near the edges of the pavement slabs. Before the concrete had set, a steel angle was mounted to the slab surface, as shown in Fig 3.19. A 5/8-inch-diameter steel rod was driven into the pavement base to a depth of 30 inches, as shown in Fig 3.20. Displacement transducers for recording the horizontal movement of the slab were mounted to the steel rod so that they reacted against the steel angle, as shown in Figs 3.21 and 3.22.

Displacement transducers for recording vertical movement of the slab were mounted to the steel rods in a vertical position so that they reacted against the slab surface. The displacement transducers were covered to protect against rain or accidental jarring.

Surface strain gages must be applied to a smooth concrete surface. For this reason, in the location of each surface gage, a small area of the grooved pavement surface was troweled smooth before the concrete set (see Fig 3.23). Four to six hours after the concrete was placed, the surface strain gages were mounted using a quick-setting epoxy. A mounted surface strain gage is shown in Fig 3.24. The surface strain gages were covered to protect then against weather.

Surface concrete strain was also measured mechanically using a Demac gage with an 8-inch gage length. The reference points for the Demac gage were epoxied to the pavement surface in the same locations as the surface strain gages. The measurement of concrete strain using the Demac gage is shown in Figs 3.25 and 3.26.

The leads for all electronic instrumentation were run alongside the pavement slab to the data acquisition unit. The data acquisition unit was set up in a van parked alongside the pavement slab, as shown in Figs 3.27 and 3.28. An overall view of an instrumented slab is given in Fig 3.29.

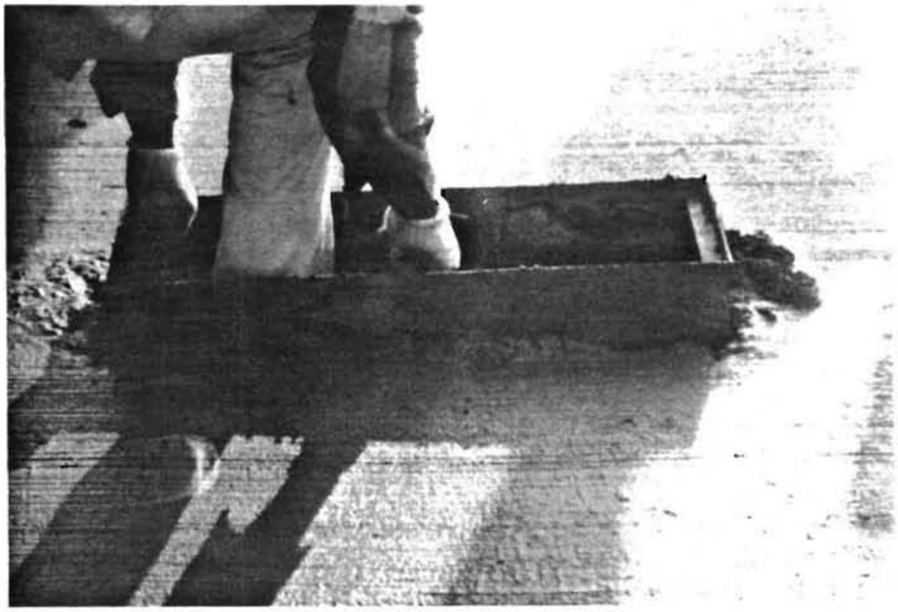


Fig 3.14. Removal of the instrumentation block-out after paving.

Fig 3.15. Final positioning of embedded gages.

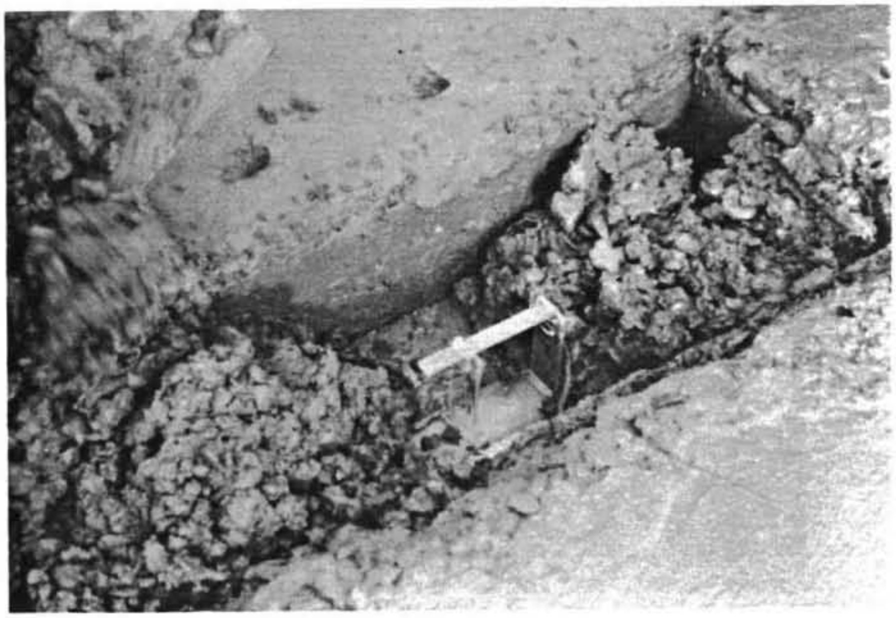


Fig 3.16. Placement of concrete around embedded gages.

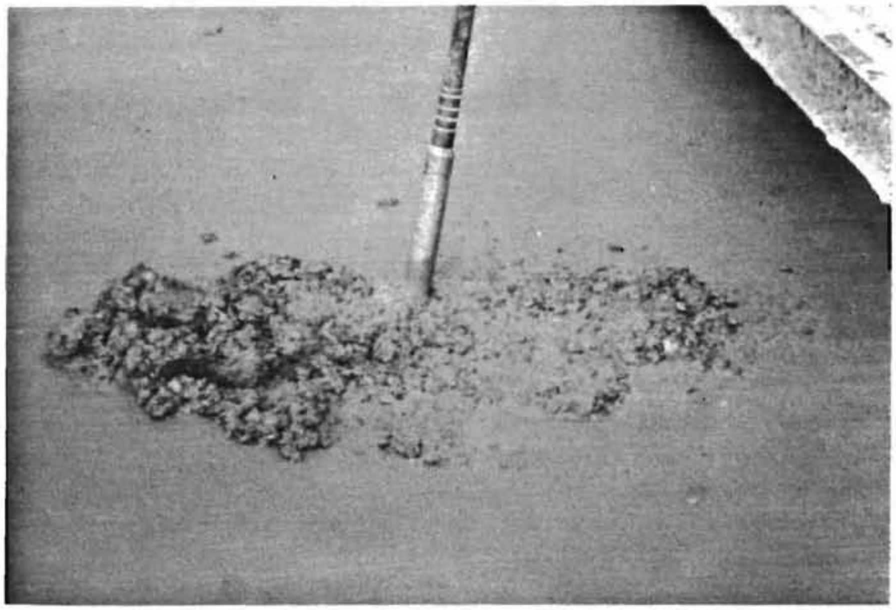


Fig 3.17. Vibration of concrete around embedded instrumentation.

Fig 3.18. Finishing of concrete over embedded instrumentation.

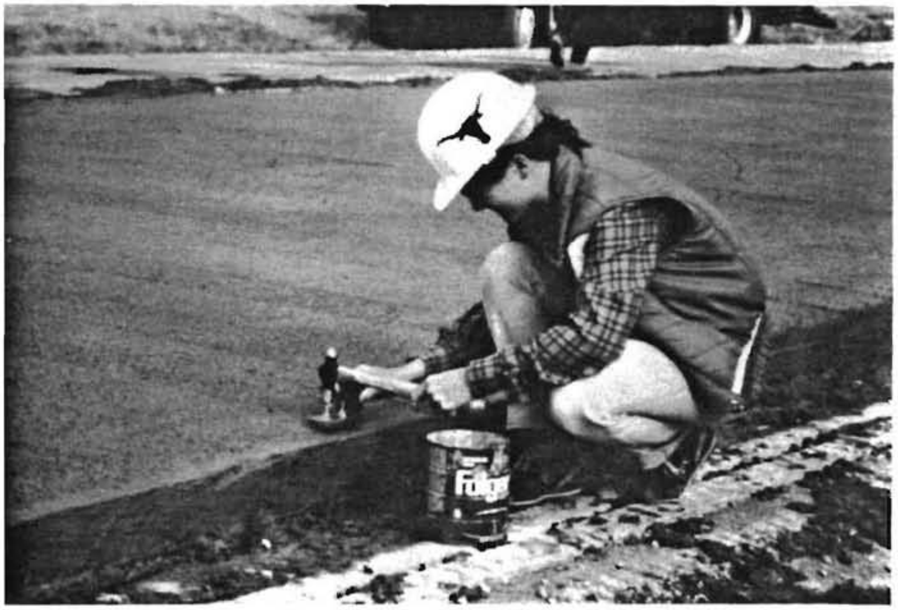


Fig 3.19. Attachment of steel angle for displacement transducer.

Fig 3.20. Installation of steel rod for mounting displacement transducer.

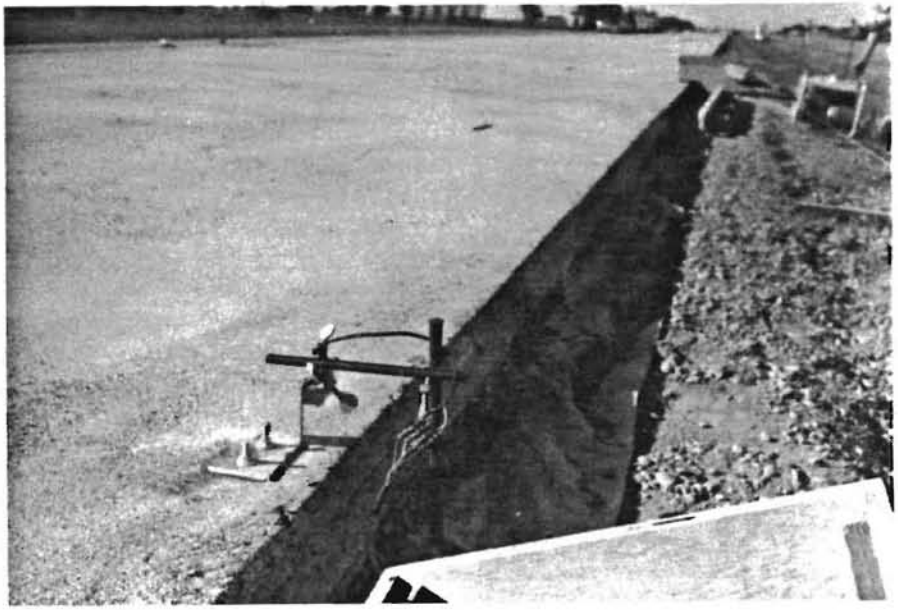


Fig 3.21. Displacement transducer for measuring horizontal slab movement.

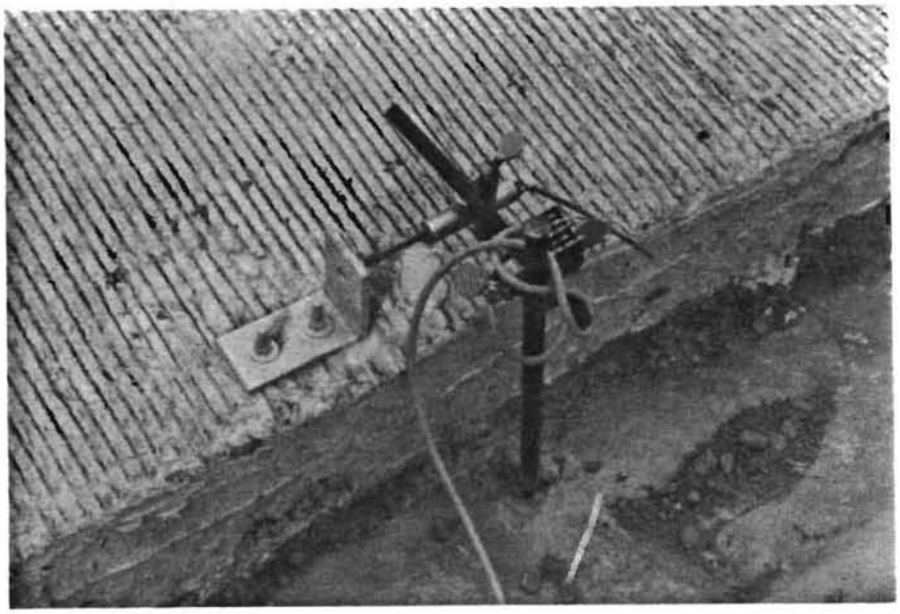


Fig 3.22. Displacement transducer for measuring horizontal slab movement.

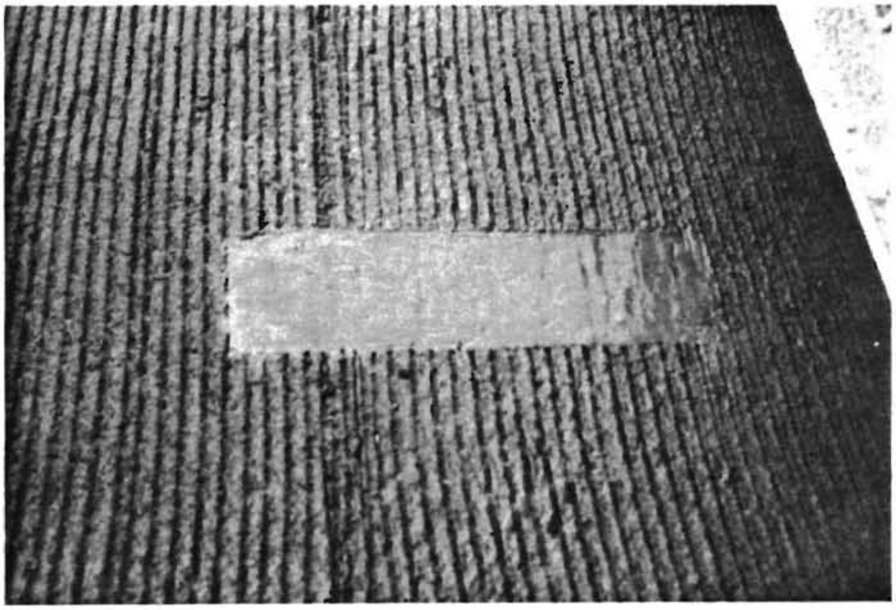


Fig 3.23. Pavement surface prepared for the attachment of surface strain gage.

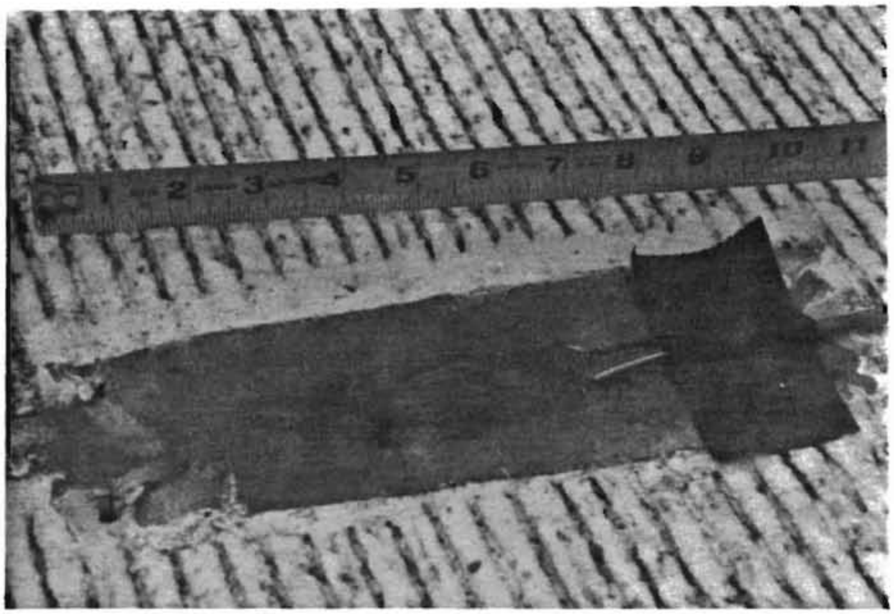


Fig 3.24. Surface strain gage.

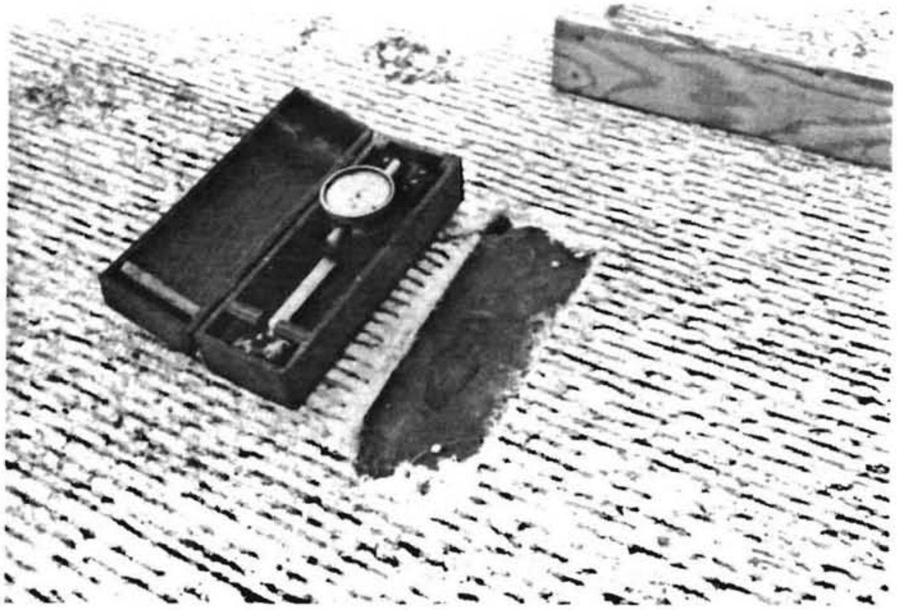


Fig 3.25. Demac gage and reference points.

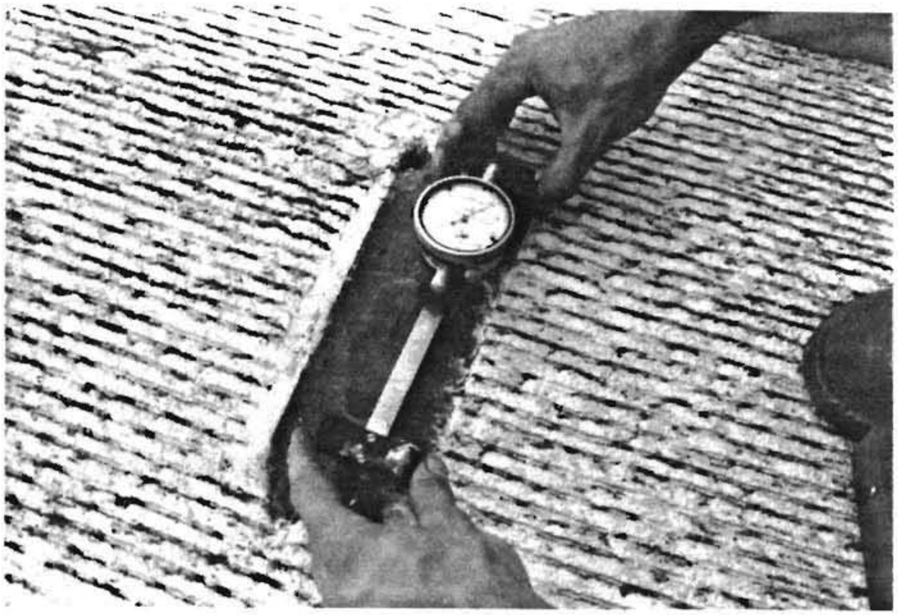


Fig 3.26. Measurement of concrete strain using the Demac gage.

Fig 3.27. Van used for the set-up of the data acquisition unit.

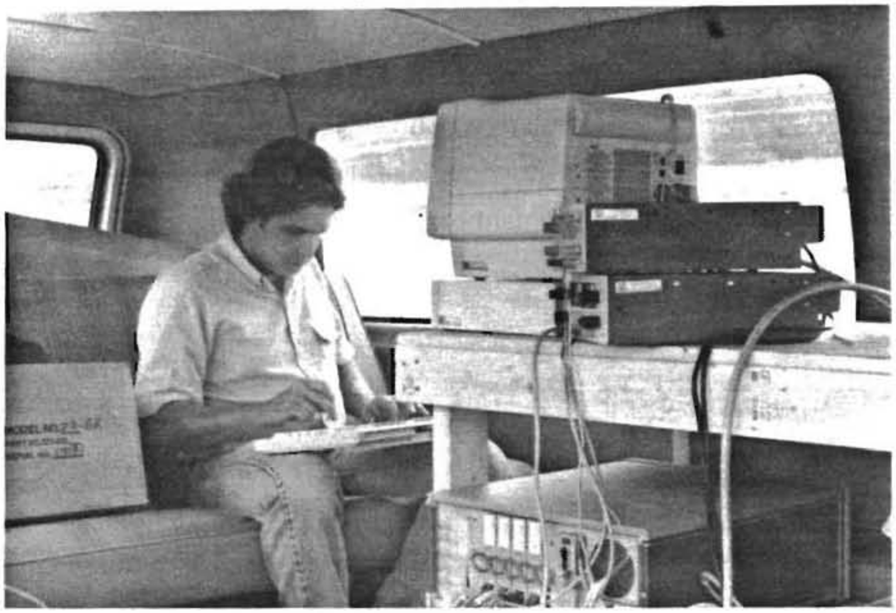


Fig 3.28. Data acquisition system.

Fig 3.29. Overall view of the instrumentation for slab 14.

Long Term Instrumentation

The change in joint opening width for the transverse joints was measured using a scale between reference scribe marks. Scribe marks 1 inch long were etched into the top surface of the steel of the transverse joints, as shown in Figs 3.30 and 3.31. Three pairs of scribe marks were etched into each transverse joint--two locations on the east lane and one location on the west lane. The measurement of joint opening width between scribe marks is shown in Fig 3.32.

EXPERIMENTAL PROCEDURE

The experimentation on the Texas prestressed concrete pavement was carried out according to an overall schedule of measurements which includes short-term experimentation and long-term experimentation.

Schedule of Measurements

An overall schedule of the measurements is shown in Fig 3.33. Concrete placement for the pavement slabs of the east lane began on September 19, 1985, and was finished on October 10, 1985. Concrete placement for the pavement slabs of the west lane began on November 12, 1985, and was finished on November 22, 1985. Concrete strength at early ages was measured on all pavement slabs. Tendon elongation was recorded during all stressing operations. The initial stressing of the longitudinal tendons was done on the day of placement for each slab. The final stressing for each slab was done two days later. The transverse stressing for all slabs was done on November 29, 1985, and November 30, 1985. Concrete modulus of elasticity was measured on October 8, 1985, and October 9, 1985. Electronic instrumentation was set up on slab 7 on September 26, 1985, and on slab 14 on October 8, 1985. A complete set of joint opening measurements was taken on 13 different occasions.

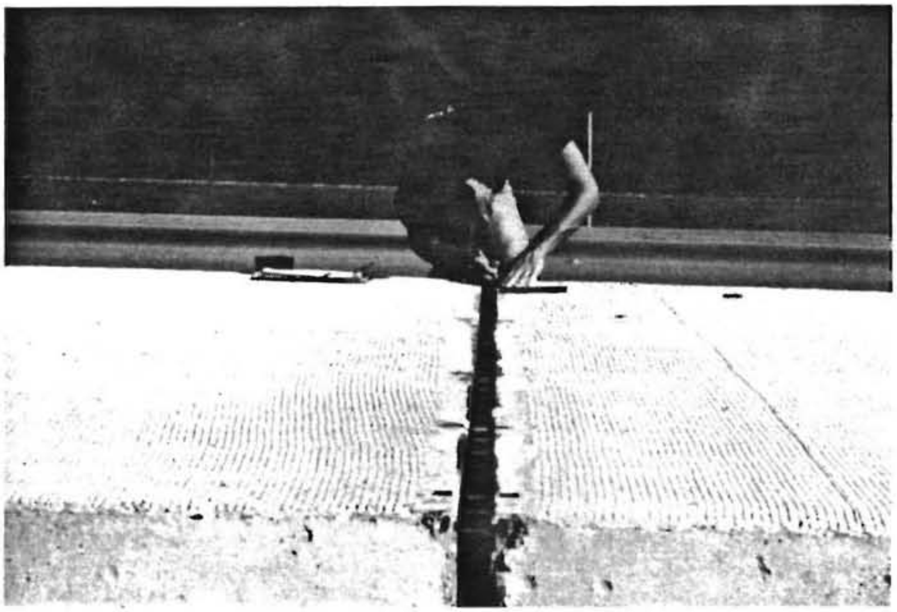


Fig 3.30. Etching of scribe marks used as a reference for measuring

Fig 3.31. Etching of scribe marks used for measuring changes in joint opening width.

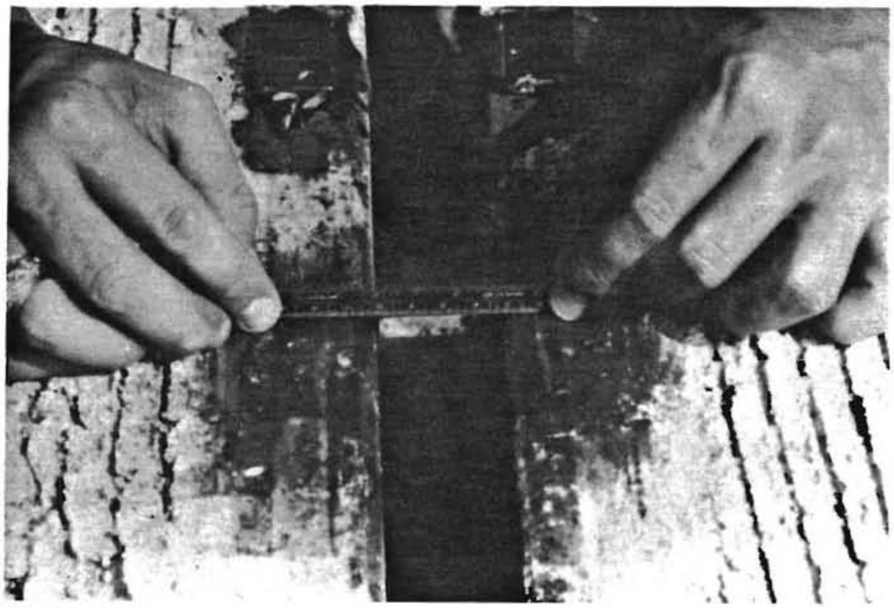


Fig 3.32. Measurement of joint opening width.

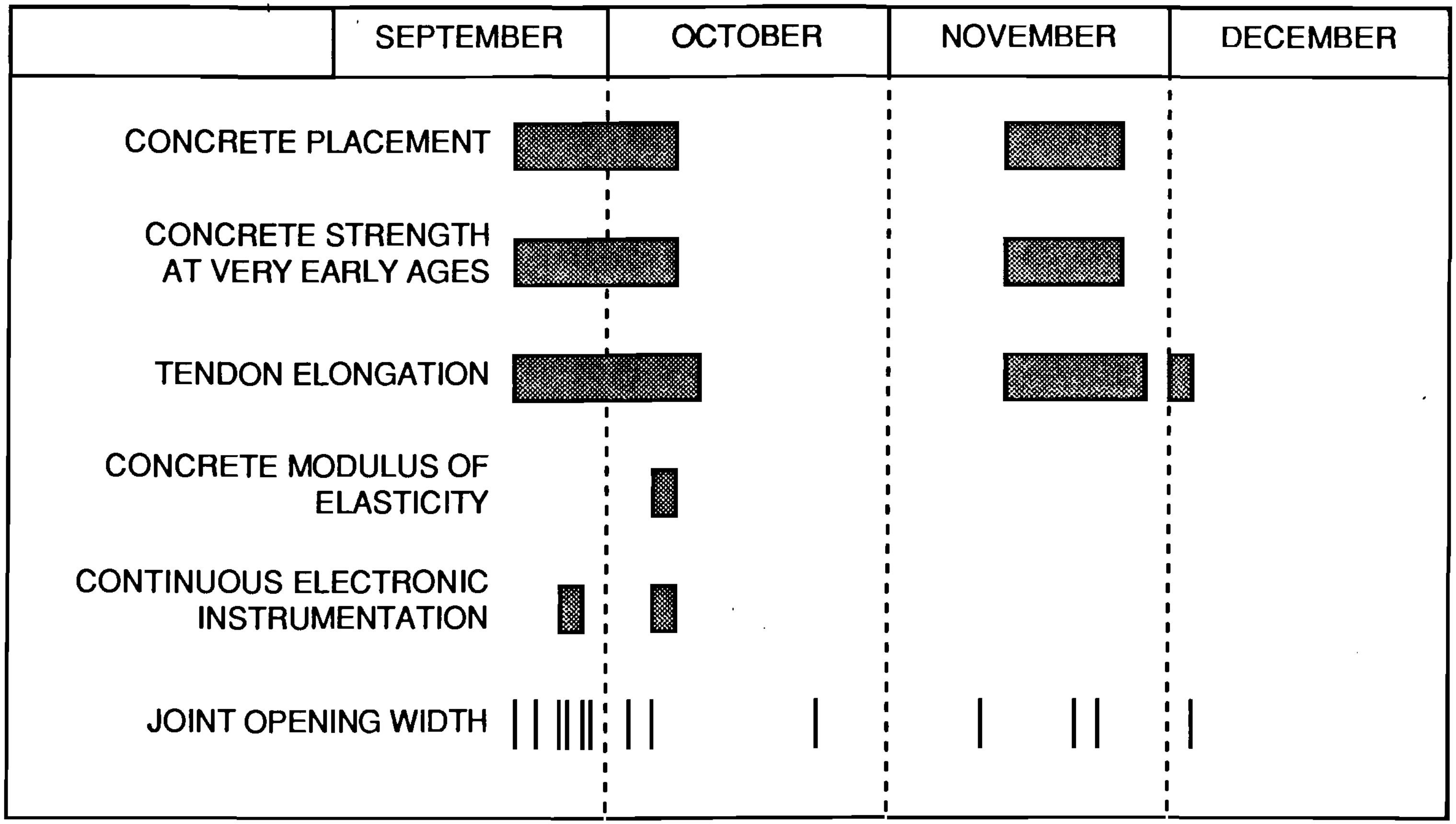


Fig 3.33. Schedule of measurements taken in the fall of 1985.

Short Term Instrumentation

Continuously recorded instrumentation was implemented on slabs 7 and 14. On slab 7, 20 hours of continuously recorded measurements were successfully recorded according to the timetable shown in Fig 3.34. Concrete placement for slab 7 began at 10:22 and was finished at 13:15. The recording of strain gage and thermocouple output began at 13:29 and was terminated at 16:13 to install the displacement transducers. Continuous recordings were resumed at 19:36. Seven channels of temperature data, 18 channels of strain data, and 8 channels of displacement data were recorded approximately every 8 minutes by the data acquisition system. The data acquisition system was set up to record continuously for 40 hours. Unfortunately, due to operator error, data from the last 23 hours of recording were written to the disk without proper formatting. There is a question as to whether or not these data can be retrieved. The continuously recorded data which are presented are from the period between 13:29 and 16:13 on September 26, 1985, and the period between 19:36 on September 26, 1985, and 12:50 on September 27, 1985. Initial post-tensioning of the slab was applied within this period, between 11:45 on September 26, 1985, and 12:08 on September 27, 1985. The jacking force for the initial post-tensioning was 15.8 kips per tendon. Final post-tensioning for slab 7 was applied between 21:20 and 21:40 on September 28, 1985. The jacking force for the final post-tensioning was 46.4 kips per tendon.

Throughout the period of the instrumentation of slab 7, mechanical measurements were made to back up the continuously recorded electronic measurements. Ambient temperature was recorded by thermometer 14 times during the interval. Surface concrete strain in three locations was recorded three times, using a demac gage.

On slab 14, 34 hours of continuously recorded measurements were successfully recorded according to the timetable of Fig 3.35. Concrete placement for slab 14 began at 7:55 and was finished at 11:55. The recording of strain gage and thermocouple output began at 15:14 and was terminated at 17:30 to install the displacement transducers. Continuous recordings were resumed at 21:40. As with slab 7, 7 channels of temperature data, 18 channels of strain data, and 8 channels of displacement data were recorded approximately every 8 minutes. The data acquisition system was set up to record continuously for 48 hours, but, again due to operator error, some data were written to the disk without proper formatting. The continuously recorded data which are presented are from the period between 15:14 and 17:30 on October 8, 1985, the period between 21:40 on October 8, 1985, and

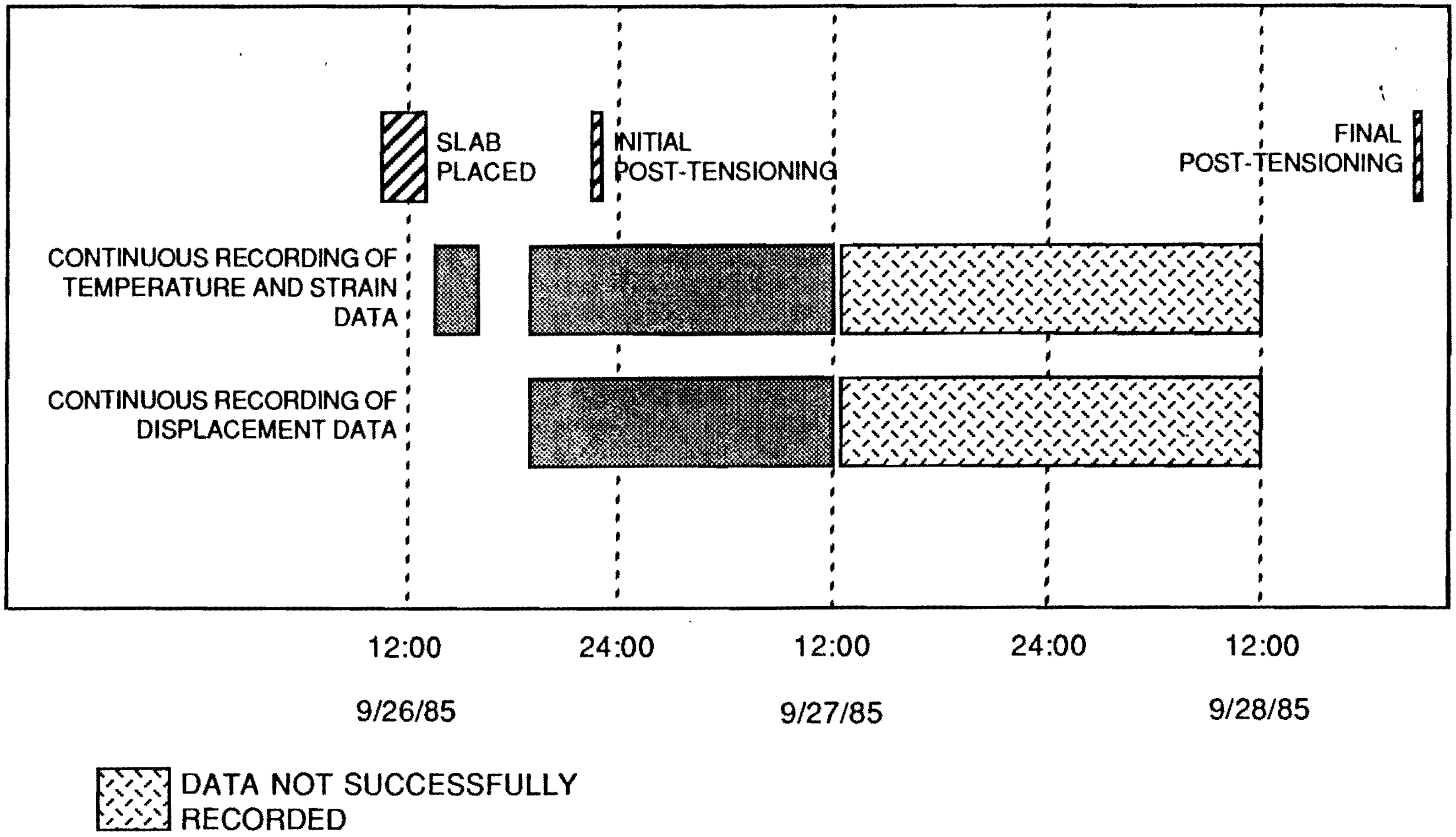


Fig 3.34. Timetable for continuously recorded measurements for slab 7.

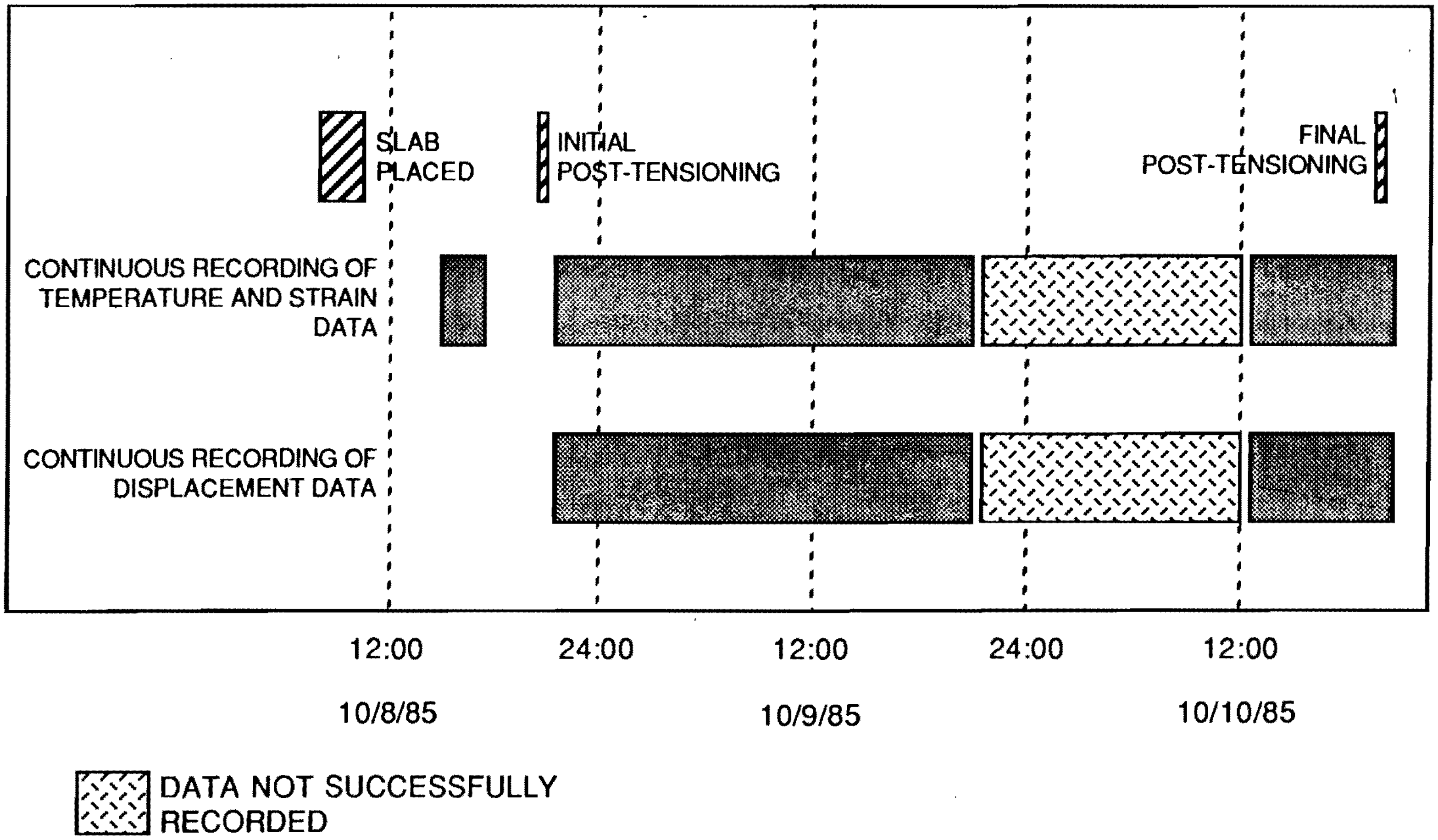


Fig 3.35. Timetable of continuously recorded measurements for slab 14.

21:47 on October 9, 1985, and the period between 12:49 and 20:30 on October 10, 1985. The final post-tensioning of the slab was applied within this last period, between 19:35 and 20:25 on Octrober 10, 1985. The jacking force for the final post-tensioning was 46.4 kips per tendon. The initial post-tensioning was applied to the slab between 20:40 and 21:10 on October 8, 1985. The jacking force for the initial post-tensioning of slab 14 was 16.5 kips per tendon.

On both slab 7 and slab 14, three channels of displacement transducer input and eight channels of strain gage input were not recorded because of an error in the data acquisition software. Thus, the data from displacement transducers 5, 6, and 7 and strain gages 10 through 17 are not reported.

Back-up mechanical measurements were also made for slab 14. Ambient temperature was recorded by thermometer 12 times. Surface concrete strain in three locations was recorded four times using a Demac gage.

Additional instrumentation sessions for the continuous measurement of slab temperature and movement have been scheduled. The continuation of this instrumentation is discussed in Chapter 6.

On all slabs, tendon elongations were recorded for each stressing operation. The tendon elongations for the stressing of each tendon were measured as follows: (1) A 5-kip jacking force was applied to the tendon in order to take up any slack in the tendon and its anchorages. (2) With the 5 kips still acting, the tendon was marked at the points where it protruded into the stressing pocket. (3) The jacking force was brought up to the specified value according to the pump pressure gage. (4) The elongation of the tendon was measured at each end of the stressing pocket using a ruler. The measurements were made to the nearest 1/8 inch A more detailed description of the procedure for measuring tendon elongation is given in Ref 22. Tendon elongations were measured and recorded by personnel from the Texas State Department of Highways and Public Transportation (SDHPT).

Concrete strength at very early ages was measured using a compression testing machine located at the jobsite (see Fig 3.36). For each pavement slab at least six test cylinders were made for testing at very early ages. The cylinders were tested in compression at ages of 8 to 15 hours. In addition, for each pavement slab, two cylinders were made for testing at 28 days. Concrete strength testing was carried out by the project contractor and supervised by SDHPT personnel.

Fig 3.36. Testing machine for measuring concrete compressive strength.

Six of the concrete cylinders were used to measure the modulus of elasticity of the concrete at very early ages. To measure modulus of elasticiy, each cylinder was loaded in the testing machine while the compressive movement of the cylinder was measured using the extensiometer device pictured in Fig 3.37. Each cylinder was loaded to approximately half its ultimate strength, while compressive movement was monitored at 6 to 10 load levels.

A survey of slab cracking was made by SDHPT inspectors. All pavement slabs were inspected regularly, especially in the period before the application of initial prestress.

Long Term Instrumentation

Measurements of the change in joint opening width of the transverse joints were carried out 13 times during the fall of 1985. For each set of readings all joints that had been placed were measured. For identification, the transverse joints were given numbers, as shown in Fig 3.38. The opening of each transverse joint of the east lane was measured in two locations on the joint as shown in Fig 3.38. Location A was 6 to 12 inches from the east shoulder of the lane, and location B was 6 to 12 inches from the longitudinal joint between lanes. On the west lane, the opening of each transverse joint was measured in one location, 6 to 12 inches from the west shoulder of the lane--location C of Fig 3.38.

The continuation of measurements of the change in joint opening width of the transverse joints has been scheduled. Measurements of the load transfer capabilities of the transverse joints and measurements of the deflection characteristics of the pavement have also been scheduled. These joint opening and load transfer measurements are discussed in Chapter 6.

Fig 3.37. Extensiometer device for measuring concrete modulus of elasticity.

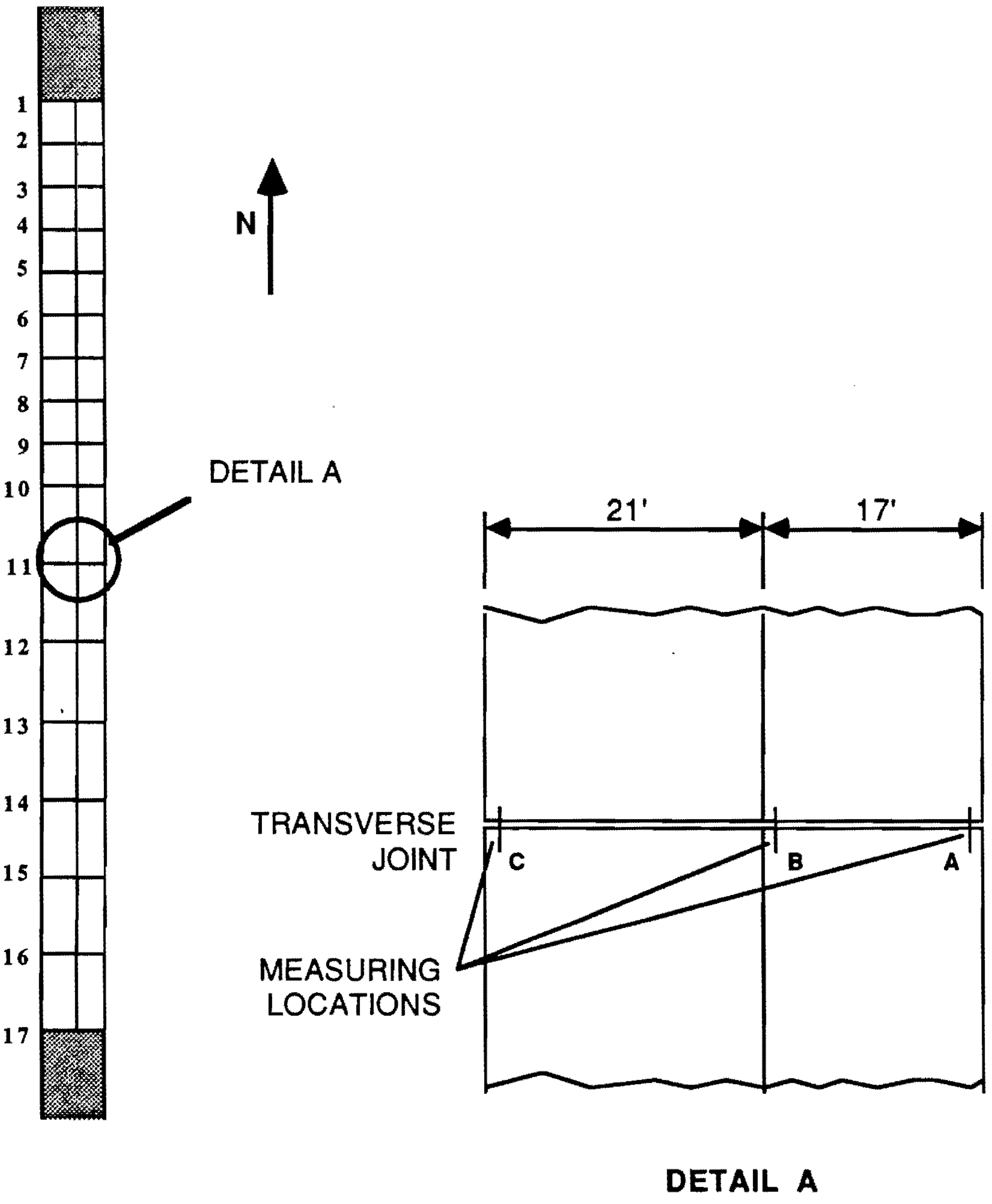


Fig 3.38. Measurement locations and numbering of transverse joints.

CHAPTER 4. PRESENTATION OF DATA

This chapter presents the data collected to date, in summarized form. The data include ambient and concrete temperature data, horizontal slab movement data, concrete strain data, vertical slab movement data, tendon elongation data, concrete strength data, concrete modulus of elasticity data, slab cracking data, and joint opening width data. This chapter also includes some evaluation of the accuracy of the data.

SHORT-TERM MEASUREMENTS

For the short-term measurements, data are presented on ambient and concrete temperatures, horizontal slab movement, concrete strain, slab curling, tendon elongations, concrete strength, concrete modulus of elasticity, and slab cracking.

Ambient and Concrete Temperatures

Figure 4.1 shows the electronically recorded temperatures for slab 7 over a 17-hour time period from 19:36 on September 26, 1985, to 12:50 on September 27, 1985. These data are for thermocouple channels 0, 4, 5, and 6. As was mentioned, the thermocouples for channels 1, 2, and 3 were damaged during the paving operation. The electronically recorded ambient temperatures shown in Fig 4.1 were checked against thermometer readings taken in the field. The readings were found to correspond closely. It should be noted that Fig 4.1 shows concrete temperatures within 5 hours after concrete placement, so that the heat of hydration due to the concrete curing causes a greater difference between concrete temperatures and ambient temperatures.

Figure 4.2 shows the continuously recorded temperatures for slab 14 over a 24-hour time period from 21:40 on October 8, 1985, to 21:49 on October 9, 1985. Figure 4.3 shows additional values of continuously recorded temperatures for slab 14 over an 8-hour time period, from 12:49 to 20:30 on October 10, 1985. The slab temperatures shown in these figures are from thermocouple channels 4, 5, and 6. These temperatures correspond very closely to the slab temperatures from thermocouples 0, 1, and 2 of slab 14 located at the same depths (see Fig 3.4 for thermocouple locations). Also, the electronically recorded ambient

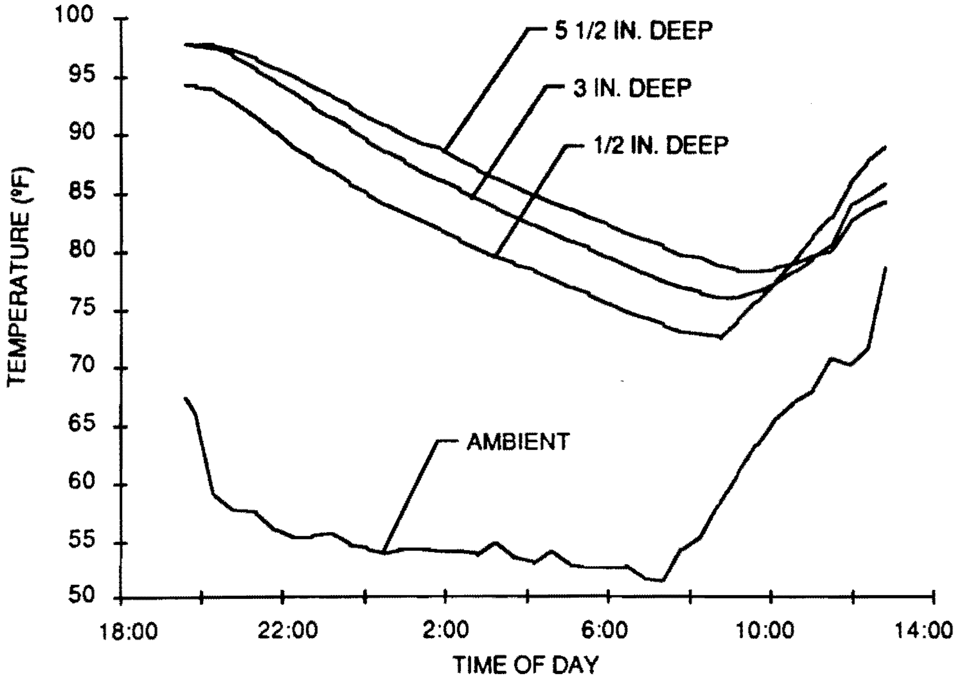


Fig 4.1. Ambient and concrete temperatures for slab 7, September 27, 1985, channels 0, 4, 5, and 6 (concrete placement time 14:00 hours).

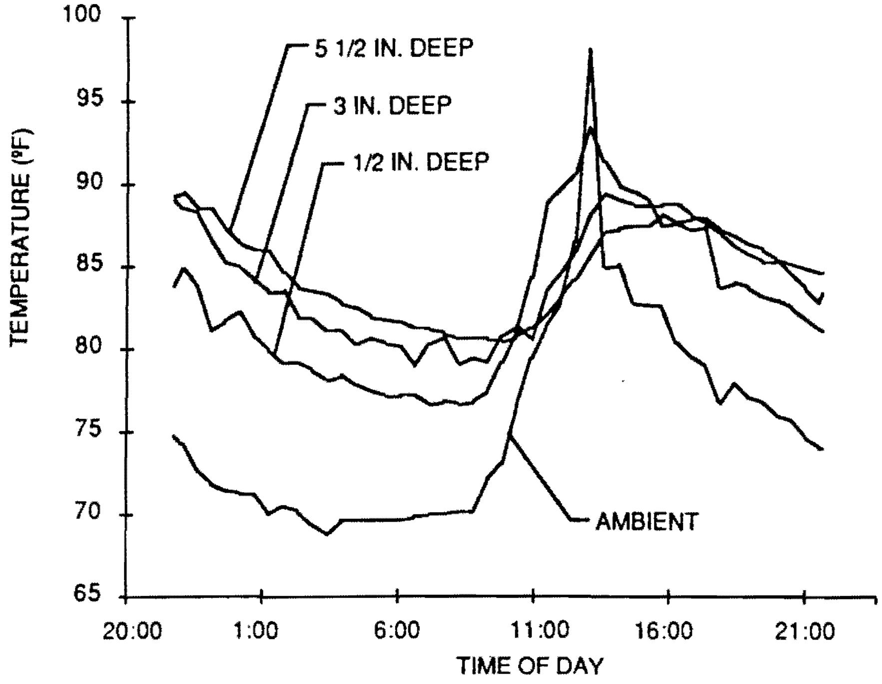


Fig 4.2. Ambient and concrete temperature for slab 14, October 9, 1985, channels 0, 4, 5, and 6.

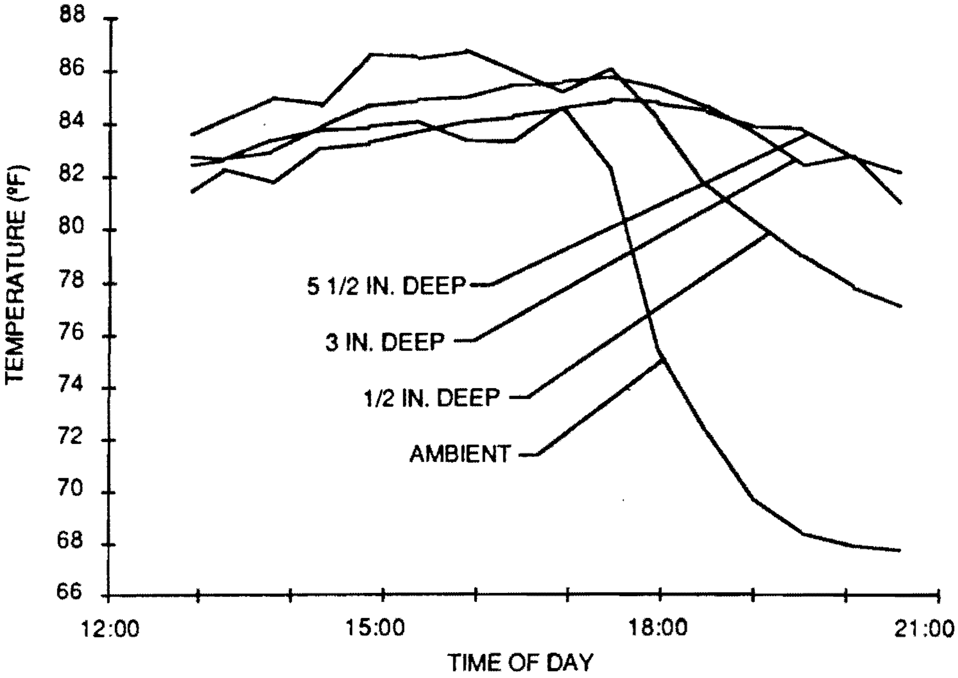


Fig 4.3. Ambient and concrete temperatures for slab 14, October 10, 1985, channels 0, 4, 5, and 6.

temperatures were checked against thermometer readings taken in the field and were found to correspond closely.

The temperature data for slabs 7 and 14 agree with the expected characteristics of slab temperature changes. It can be seen from Figs 4.1, 4.2, and 4.3 that the topmost thermocouple of the slab shows the highest temperature during the day, between 9:00 and 17:00 hours, and shows the lowest temperature during the night. The maximum negative temperature gradient for the slabs occurs between 1:00 and 9:00. The maximum positive temperature gradient occurs between 12:00 and 15:00. In both cases the maximum temperature difference between the bottom thermocouple and the top thermocouple is about 7°F. This corresponds to a slab temperature gradient of 1.4°F/inch. The fugires in this report are plots of electronically recorded data which are part of the project files.

Horizontal Slab Movement

Figure 4.4 shows the recorded values of horizontal slab displacement for slab 7, recorded continuously over a 17-hour period. The rapid change in displacement seen in Fig 4.4 around 23:50 corresponds to the initial post-tensioning operation. Displacement transducer channels 1, 3, and 4 correspond to the slab locations indicated on the figure itself and also shown in Fig 3.5.

There is something of a discrepancy between the output of channels 1 and 3 of this figure. Channel 1 shows movements about 10 to 20 percent less than channel 3 even though both channels are for transducers located at the slab end. The discrepancy may be due to varying friction properties of the pavement base.

Figure 4.5 shows the recorded values of horizontal slab displacement for slab 14, recorded continuously over a 24-hour period. Figure 4.6 shows additional values of horizontal slab displacement for slab 14, recorded continuously over an 8-hour period. The rapid change in displacement seen in Fig 4.6 around 20:10 corresponds to the final post-tensioning operation for slab 14. Displacement transducer channels 0, 2, and 4 in Figs 4.5 and 4.6 correspond to the slab locations indicated in the figures themselves and in Fig 3.6.

All channels of displacement data of Fig 4.5 show a movement of the slab of about 0.04 inch at 8:00. This movement does not correspond to either a sudden temperature change or to any post-tensioning operation. Most likely, this movement is due to the freeing-up of the transverse joint against base friction which had previously hindered its movement.

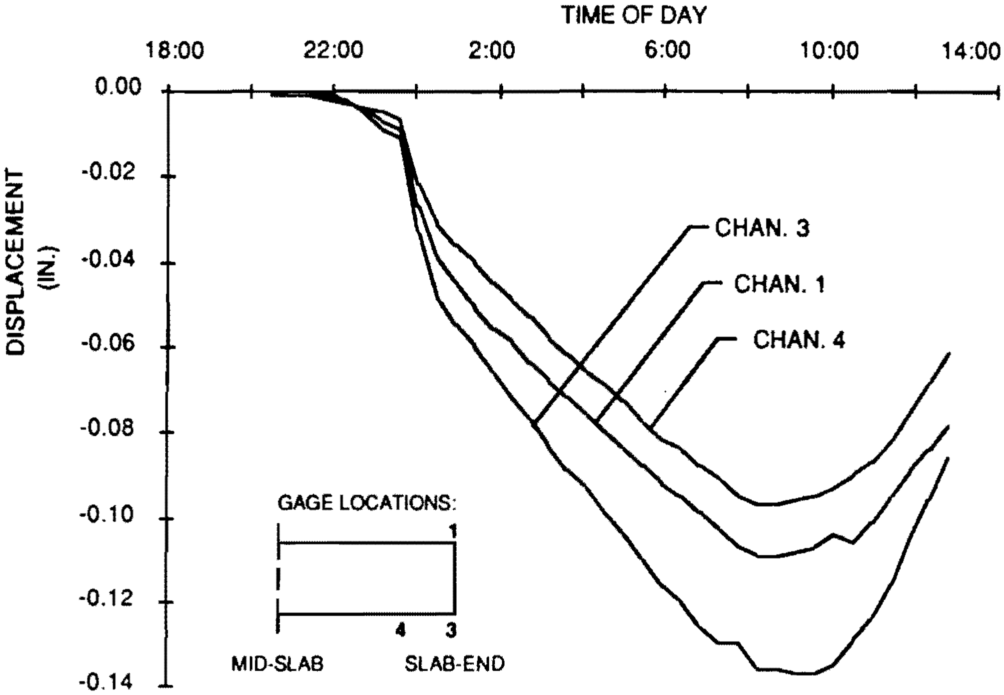


Fig 4.4. Horizontal slab displacement of slab 7, September 27, 1985.

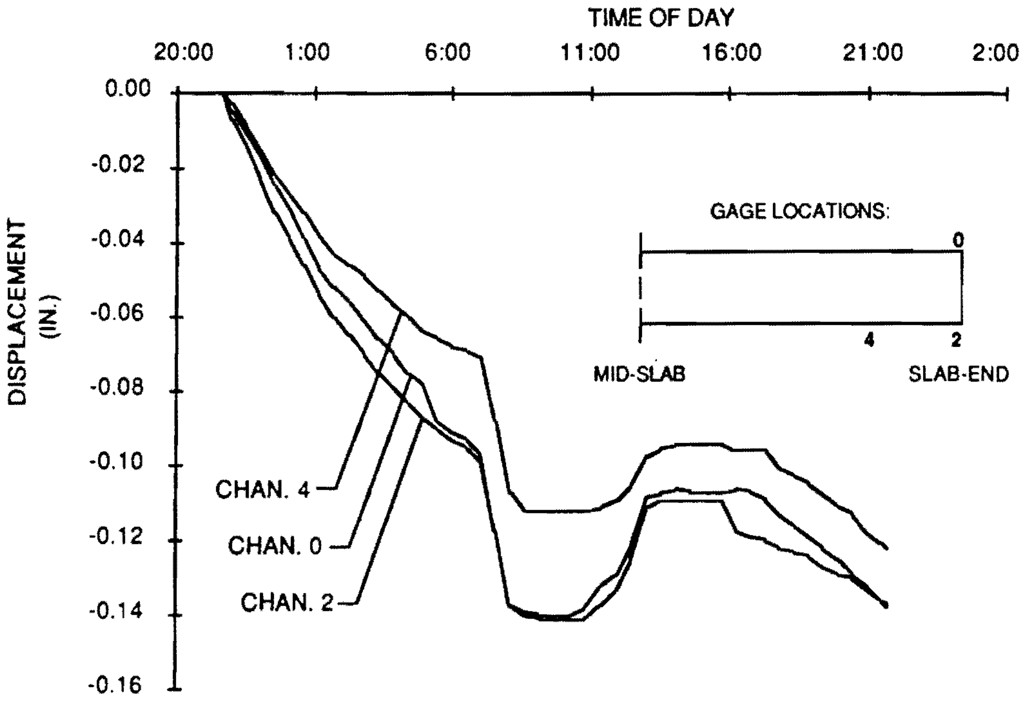


Fig 4.5. Horizontal slab displacement of slab 14, October 9, 1985.

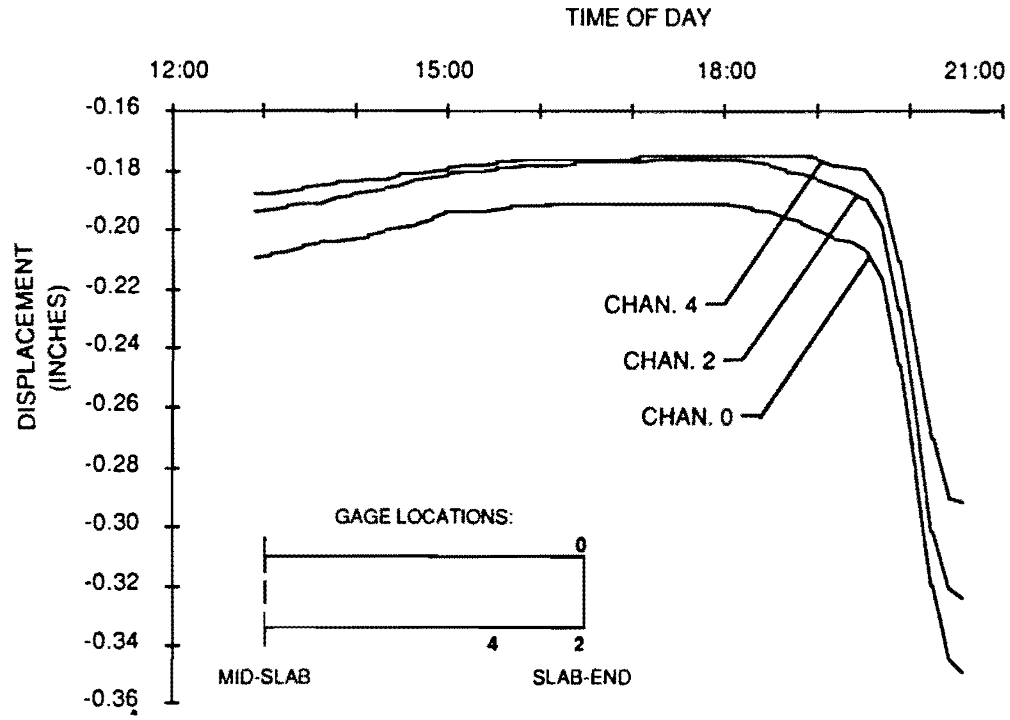


Fig 4.6. Horizontal slab displacement of slab 14, October 10, 1985.

Mechanical measurements of joint opening width covering the same time periods as the electronic data show good correspondence with the displacement readings.

Concrete Strain

In general the data for concrete strain are less consistent and less accurate those that for horizontal slab movement. The embedment strain gages were effective in recording the change in concrete strain due to initial post-tensioning but were less consistent in recording the more gradual strain changes due to temperature change.

The output of three of the embedment strain gages for slab 7, recorded continuously over a 17-hour period, is shown in Fig 4.7. The strain gage locations are as indicated on the figure and as shown in Fig 3.7. The effect of the initial post-tensioning for slab 7 is evident in Fig 4.7 by the drop in concrete strain, by about 25 microstrain, of all of the channels corresponding to the post-tensioning time, 23:45 to 00:08.

Figures 4.8 and 4.9 show the output of three of the embedment strain gages for slab 14, recorded continuously over a 24-hour period and an 8-hour period. The strain gage locations are as indicated on Figs 4.8 and 4.9 and as shown in Fig 3.8. The effect of the final post-tensioning for slab 14 is evident in Fig 4.9 by the drop in concrete strain, by about 60 microstrain, at all of the strain gage locations, corresponding to the post-tensioning time, 19:35 to 20:25.

It can be seen from Figs 4.7, 4.8, and 4.9 that, compared to the concrete strain near midslab, the concrete strain near the slab ends reaches greater values in both expansion and contraction due to daily temperature cycles. This demonstrates the effect of the base friction which restrains expansion and contraction near midslab. It can also be seen from Fig 4.7 that the effect of the initial post-tensioning is felt to a greater extent by strain gages near the slab end. This again shows the effect of the base friction, which causes the prestress in the concrete to diminish toward midslab.

It should be noted that the values of Figs 4.7, 4.8, and 4.9 have been adjusted to show the change in strain from the beginning of each time period (i.e., the initial strain value of each time period was subtracted from all of the strain values). This was done for ease of comparison. For both slab 7 and slab 14, Demac strain measurements verified the general trend of the strain data.

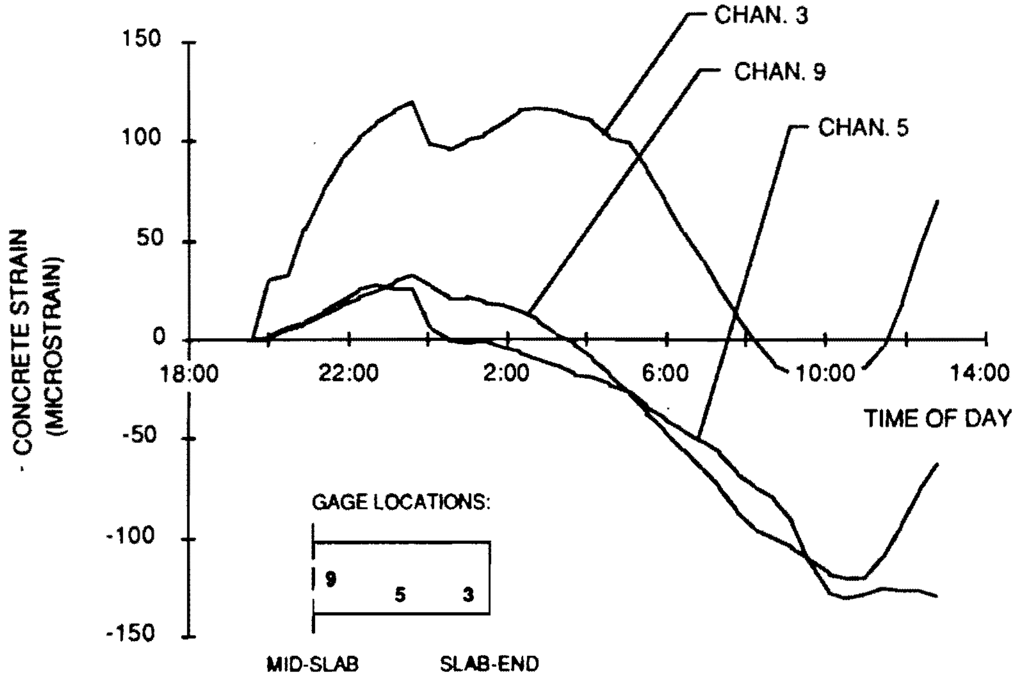


Fig 4.7. Concrete strain for slab 7, September 27, 1985.

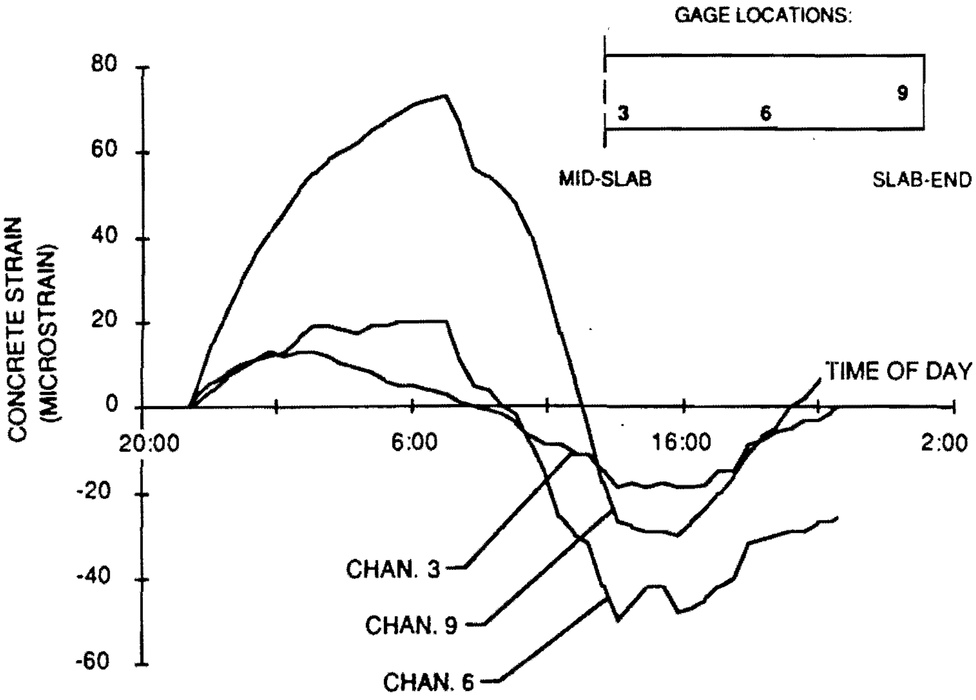


Fig 4.8. Concrete strain for slab 14, October 9, 1985.

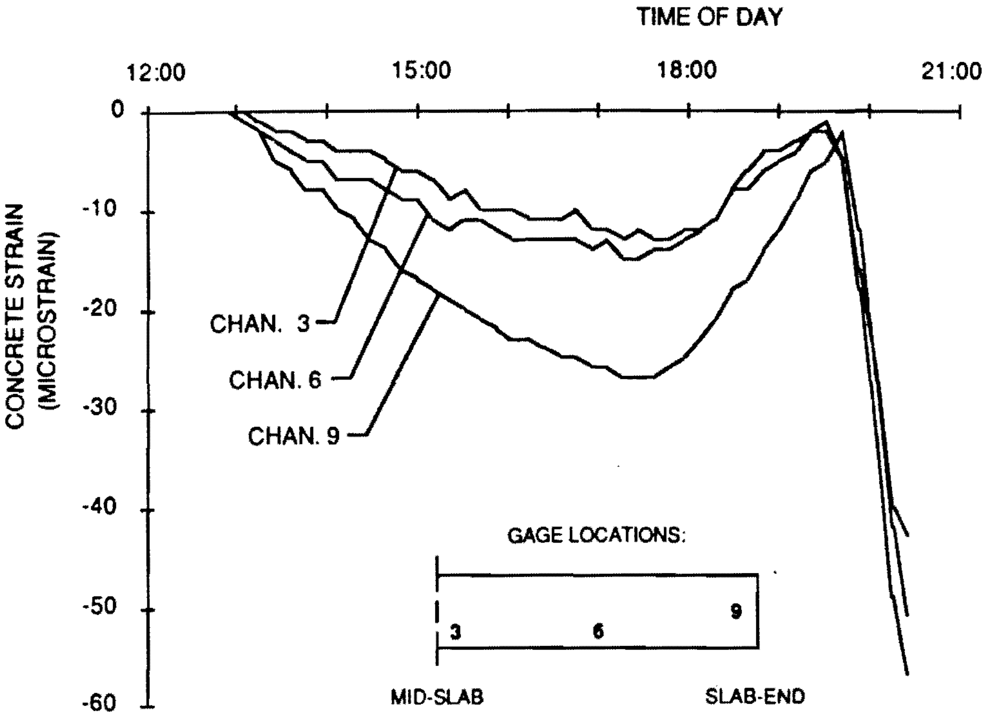


Fig 4.9. Concrete strain for slab 14, October 10, 1985.

Slab Curling

Figure 4.10 shows the continuously recorded vertical displacement of the slab corners for slab 7. It should be noted here that the displacement transducer connected to the recorder channel 0, upon examination, was found to be slightly defective because its spring mechanism was damaged and movement of the transducer was somewhat hindered. It can be seen from Fig 4.10 that between the hours of 24:00 and 10:00 that transducer registered no change in movement. If the gage for channel 0 had not been defective, the two curves of Fig 4.10 would correspond more closely. It can be seen from this figure, however, that the upward curling of the slab ends reaches its maximum around 9:00 hours. This corresponds to the time when the maximum negative temperature gradient in the pavement occurs (see Fig 4.1).

In agreement with the data for slab 7, Fig 4.11 shows that the maximum upward curling for slab 14 occurs at 9:00 hours. Figure 4.12 shows that the downward curling for slab 14 is greatest between the hours of 14:00 and 18:00 hours. This corresponds to the time when the maximum positive temperature gradient in the slab is acting (see Fig 4.2). In both slabs 7 and 14, the maximum vertical movement of the slab corners is about 0.03 inch

Further analysis and discussion of slab curling results is not included in this report but will be included in a future report.

Tendon Elongations

Tendon elongation measurements for each tendon for each stressing operation were recorded in the project field notes. The averaged values of tendon elongation for each slab and the tabulation of tendon elongations versus. jacking force are available in the project files.

Figure 4.13 shows the tendon elongation per unit tendon length (average strain in the tendon) plotted against jacking force. The analysis and discussion of the tendon elongation results are not included in this report but are the topic of another report: "Friction Loss in Unbonded Post-tensioning Tendons" (Ref 23).

Concrete Compressive Strength

The results of the compressive strength testing of the concrete at very early ages are shown in Figs 4.14 and 4.15. These figures show the concrete compressive strength plotted

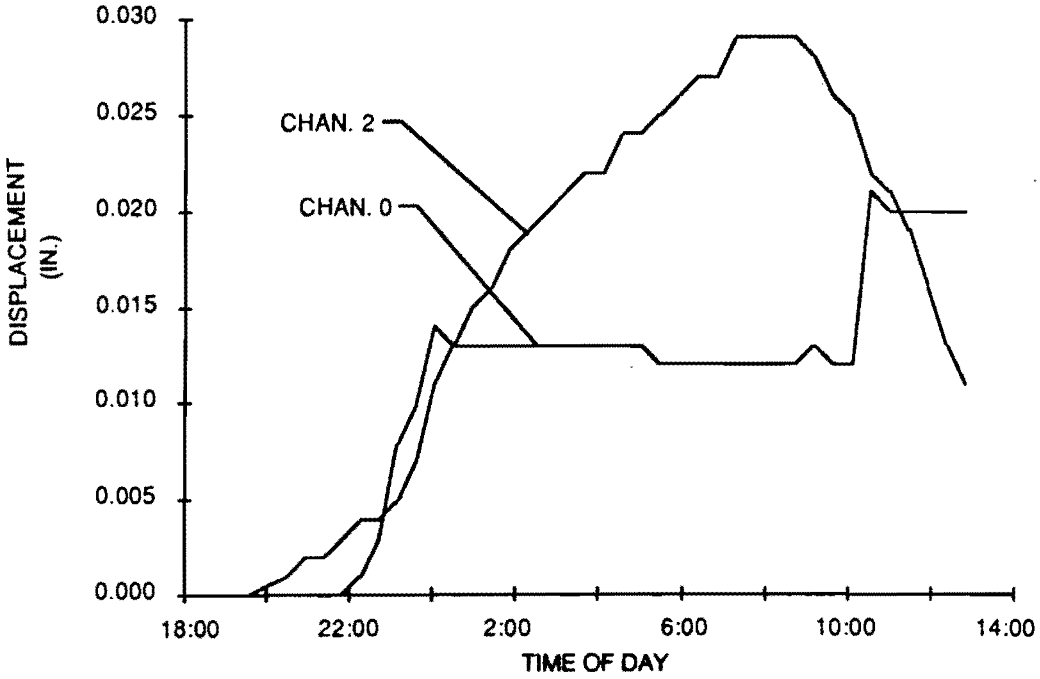


Fig 4.10. Vertical movement of the slab corners for slab 7, September 27, 1985 (for gage locations see Fig 3.7).

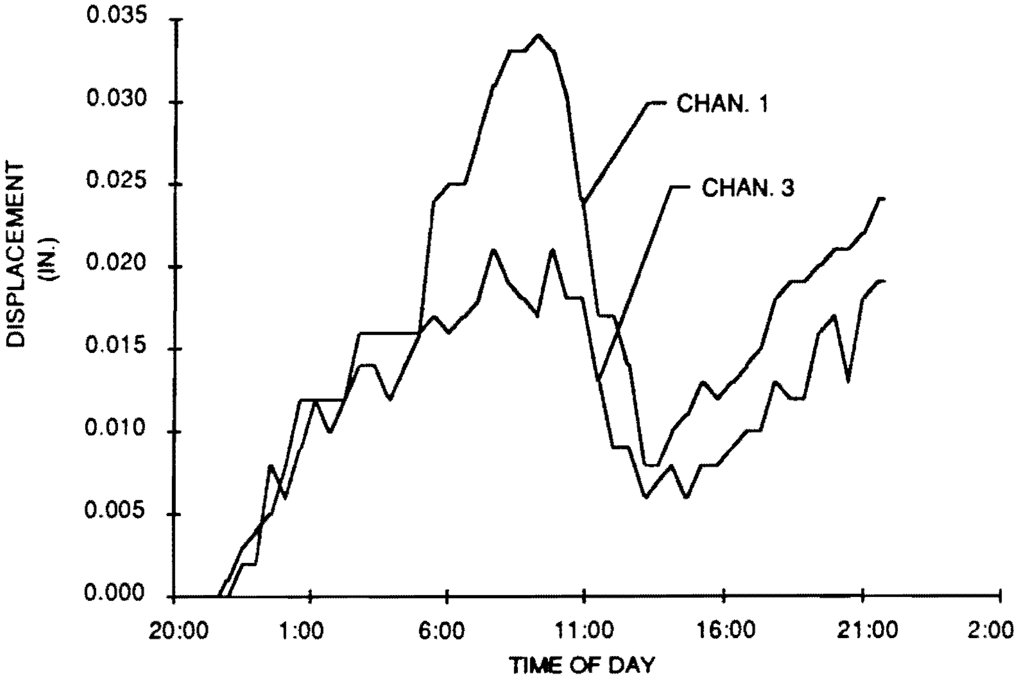


Fig 4.11. Vertical movement of the slab corners for slab 14, October 9, 1985 (for gage location see Fig 3.8).

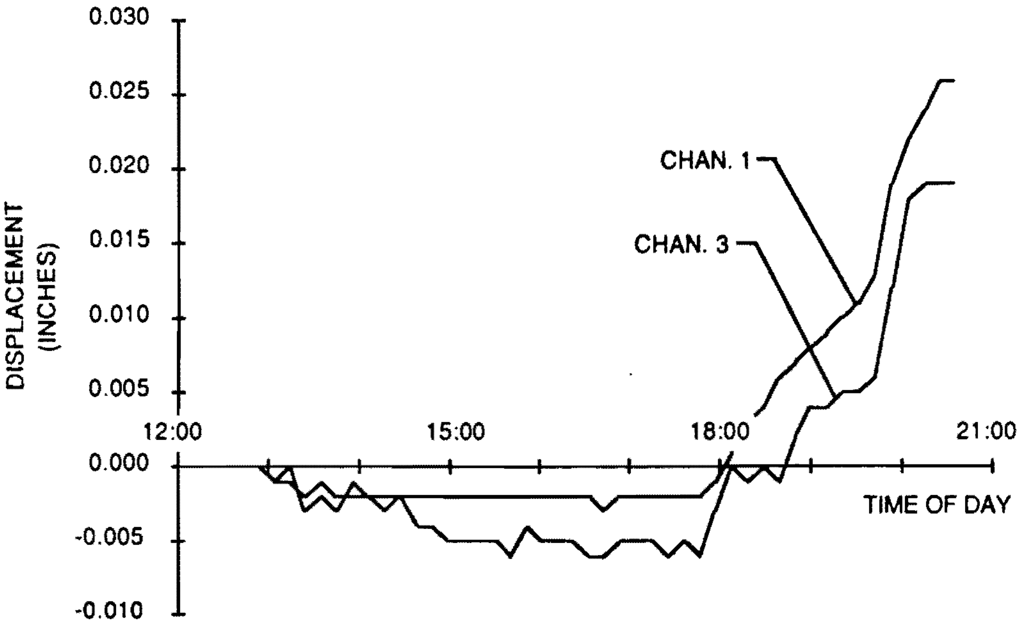


Fig 4.12. Vertical movement of the slab corners for slab 14, October 10, 1985 (for gage locations see Fig 3.8).

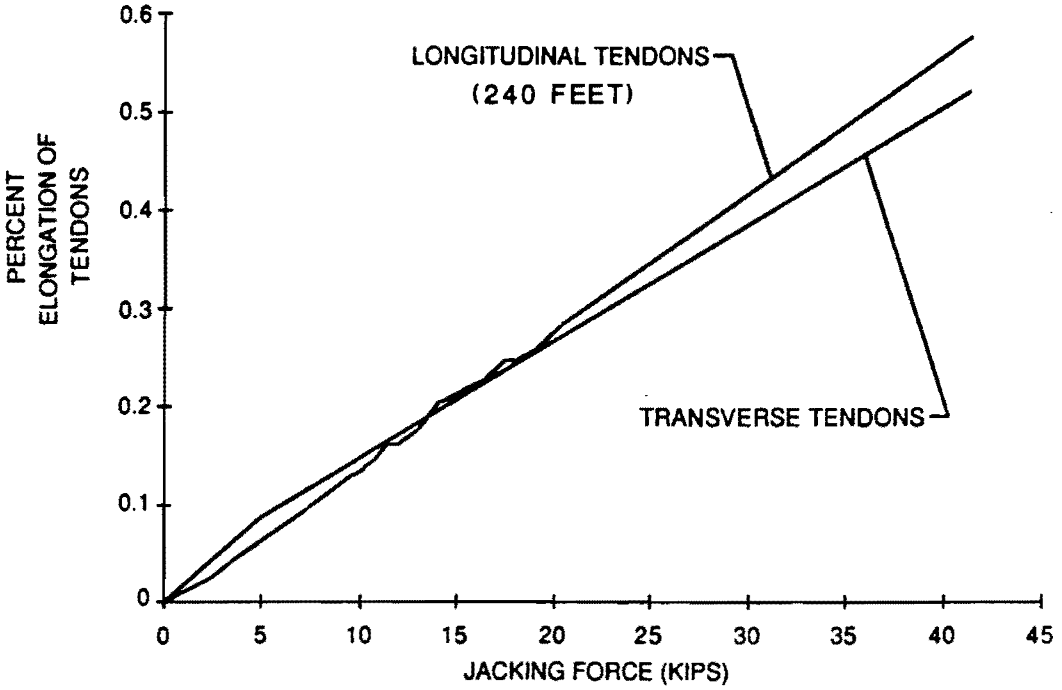


Fig 4.13. Percent tendon elongation versus jacking force for the post-tensioning tendons.

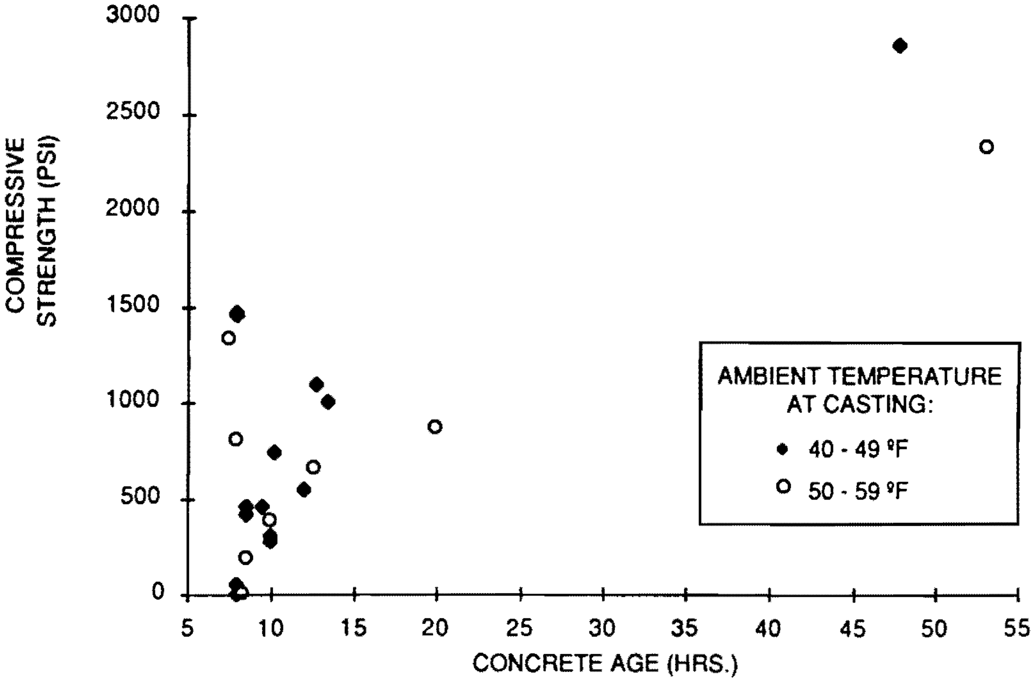


Fig 4.14. Concrete compressive strength at very early ages for curing temperatures of 40-50°F.

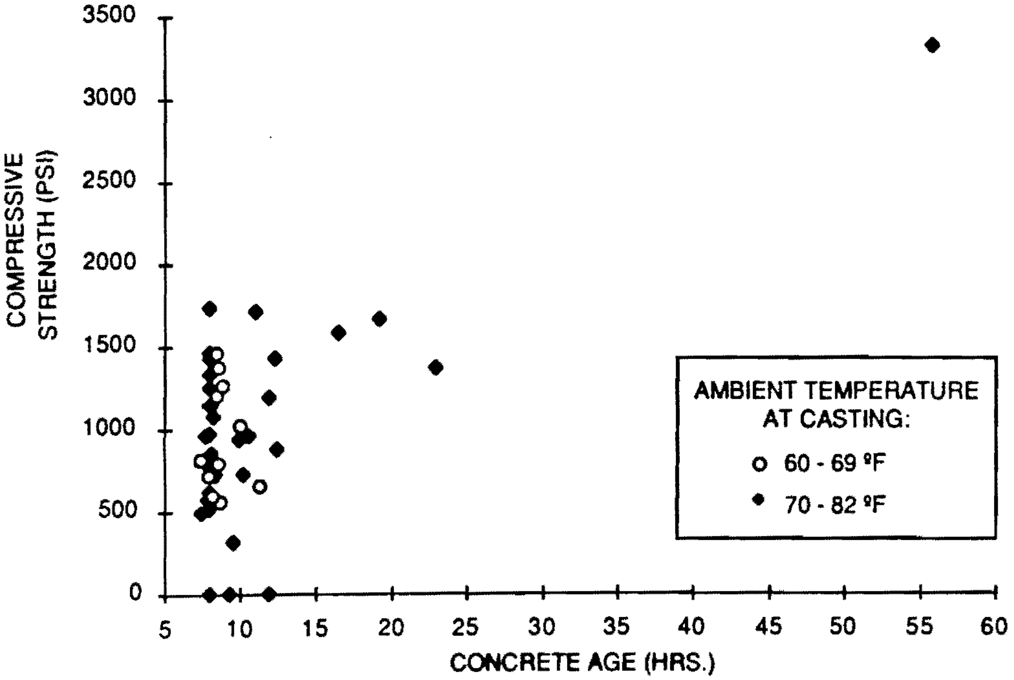


Fig 4.15. Concrete compressive strength at very early ages for curing temperatures of 60-82°F.

vs. the age of the concrete when tested. The data are separated into four groups to show the effect of curing temperature on concrete strength. Figure 4.14 shows data from cylinders that were made at an air temperature of 40-49°F and at an air temperature of 50-59°F. Figure 4.15 shows data from cylinders that were made at an air temperature of 60-69°F, and at an air temperature of 70-82°F.

It should also be noted that a set retarder was used in the concrete mix design. In addition to age of concrete and temperature at curing, the dosage of set retarder in the mix was an important variable affecting concrete strength at very early ages. From observations of the time it took for the concrete to set, it appeared that the dosage of set retarder in different loads of concrete varied.

The results of the 28-day compressive strength tests, for the concrete used in slabs 1 through 16 are shown in Fig 4.16.

Concrete Modulus of Elasticity

The results of the six modulus of elasticity tests are summarized in Table 4.1 and Fig 4.17. Figure 4.17 shows the measured modulus of elasticity plotted vs. the measured compressive strength. For comparison, the figure also shows a modulus of elasticity vs. compressive strength curve which is calculated according to specifications of the American Concrete Institute (Ref 24) using the equation

$$E_c = 57{,}000 \sqrt{f'_c}$$

The stress-strain data used in determining the modulus of elasticity for the six cylinders are included in project files.

Slab Cracking

The only pavement slab in which transverse cracking occurred was slab 5. This was the only slab to which initial post-tensioning was not applied on schedule. Because of insufficient concrete strength, slab 5 was not post-tensioned during the day of casting as was recommended. In the morning after casting, a transverse crack formed in slab 5 about 10

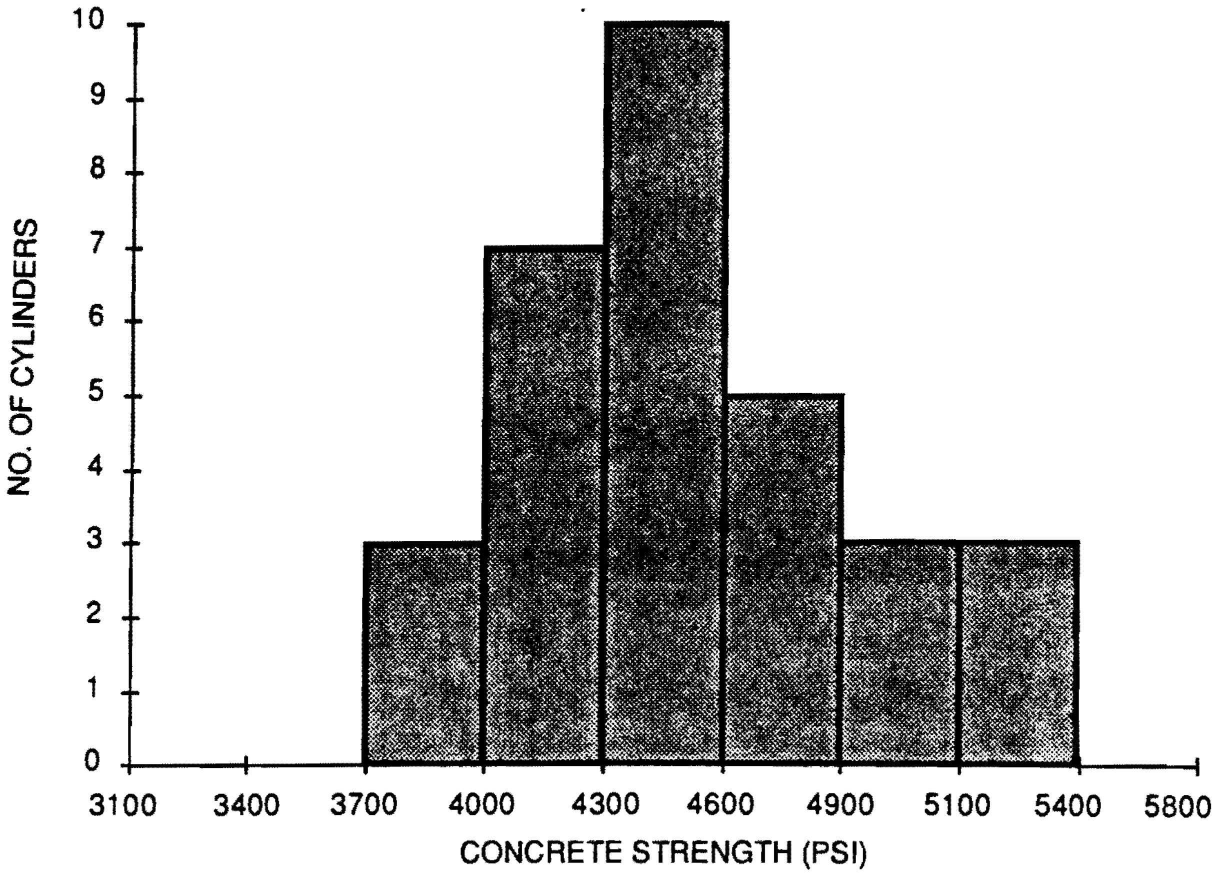


Fig 4.16. Twenty-eight day concrete strengths.

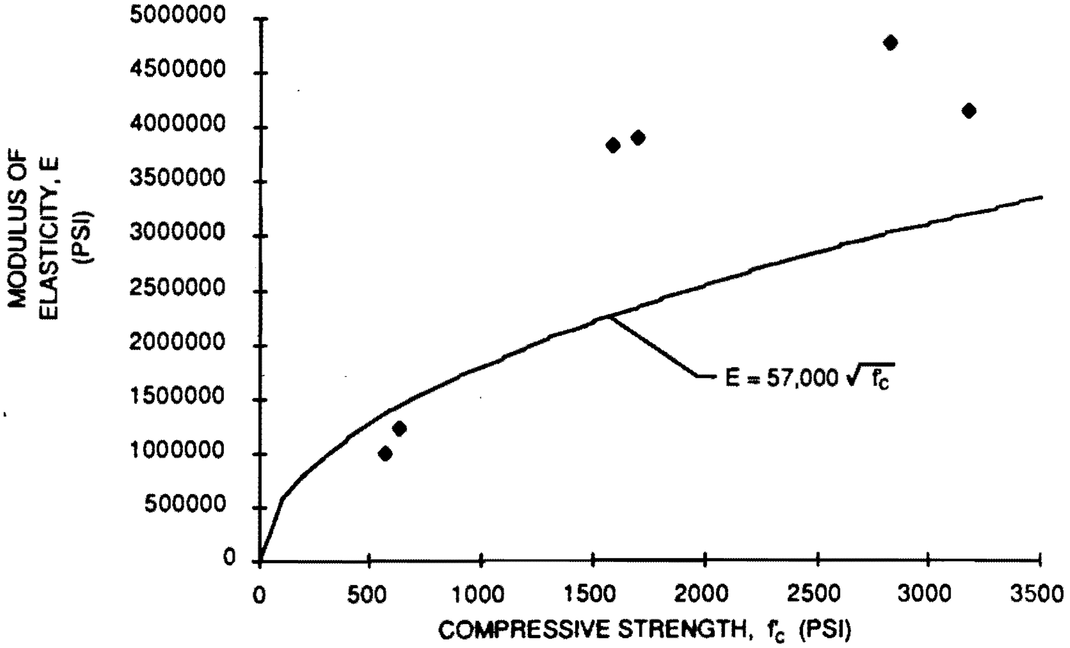


Fig 4.17. Modulus of elasticity versus compressive strength for concrete at early ages.

TABLE 4.1. SUMMARY OF CONCRETE MODULUS OF ELASTICITY TESTS

Cylinder Number	Age When Tested (Hours)	Compressive Strength (PSI)	Modulus of Elasticity (PSI)
8	346	3180	4,160,000
7	8.2	580	998,000
9	8.5	640	1,220,000
4	9.2	1700	3,890,000
5	9.5	1590	3,820,000
6	30	2830	4,750,000

feet south of midslab. The crack was seen to form at 8:45 hours. The crack traversed 3 stressing pockets and opened up to a width of about 1/8 inch. The initial post-tensioning was eventually applied to slab 5 at 11:00 in the morning with a jacking force of 22.6 kips per strand. This post-tensioning caused the crack to close completely.

LONG-TERM MEASUREMENTS

Long-term measurements include measurements of joint opening width and other measurements.

Joint Opening Width

Figure 4.18 shows the change in joint opening over time for four different transverse joints. The opening of each joint was measured in two locations according to Fig 3.44. It can be seen from Fig 4.18 that (1) measurements taken on the two different locations of the same joint (e.g., measurement locations 8A and 8B) correspond closely, (2) joint opening measurements on similar joints (e.g., joints 8 and 9) correspond closely, and (3) the movement of the joints between the 440-foot-long slabs is about twice the movement of the joints between the 240-foot-long slabs.

Since long-term measurements of joint-opening width are ongoing, a complete discussion of joint-opening width results is not included in this report. Mendoza (Ref 10) has begun a statistical analysis of the joint-opening width data to quantify the creep and shrinkage occurring in the pavement slabs.

Other Long-term Measurements

Data on the load transfer capabilities of the transverse joints, the deflection characteristics of the pavement, and the ride quality of the pavement are not included in this report. The data from these measurements will be included in future reports.

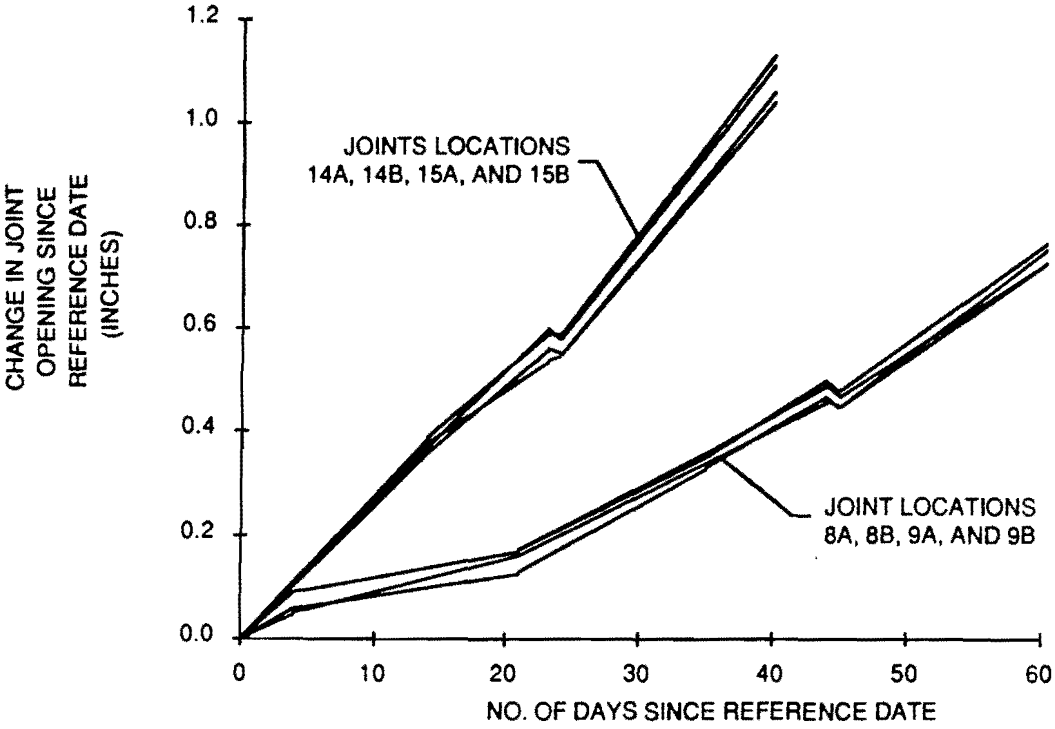


Fig 4.18. Comparison of the movement of joints 8, 9, 14, and 15.

CHAPTER 5. DISCUSSION OF RESULTS

This chapter is a discussion of the results, in accordance with the instrumentation objectives outlined in Chapter 2. The present chapter includes an examination of horizontal slab movement and concrete strain due to post-tensioning and discussions of concrete strength and modulus of elasticity results and the observation of slab cracking.

A discussion of the results of tendon elongation data is not included here but is included in another report (Ref 23). Also, the results concerning slab curling, horizontal slab movement, and concrete strain due to temperature change, and the results of the long-term measurements are not discussed in this report but are discussed in later reports.

HORIZONTAL SLAB MOVEMENT AND CONCRETE STRAIN DUE TO POST-TENSIONING

Concrete strain along the length of the pavement slab due to post-tensioning is not constant because of (1) friction along the post-tensioning tendon and (2) base friction. Friction along the post-tensioning tendon causes the prestressing force to diminish as the distance away from the stressing location increases. This decay in prestress force is given by the equation

$$P_x = P_s e^{-Kx} \tag{5.1}$$

where

x = distance away from the stressing location
P_x = post-tensioning force per tendon at any location x
P_s = applied post-tensioning force per tendon, at the stressing location
K = wobble coefficient for the friction loss in the tendons.

Note that, for central stressing, x can be considered to be the length coordinate of the slab starting at midslab.

From Eq 5.1 it is easy to see that, neglecting base friction, the concrete strain at any point x in the slab can be written

$$\varepsilon(x) = \left(1/E_c\right)\left(\left[-P_s/A_c e^{-Kx}\right]\right) \tag{5.2}$$

where

x = length coordinate of the slab starting at midslab
$\varepsilon(x)$ = concrete strain at x (negative for contraction)
E_c = concrete modulus of elasticity
A_c = concrete cross-sectional area for each tendon.

The effect of the base friction is to resist the contraction of the pavement due to post-tensioning. For slab displacements greater than 0.003 inch it has been shown that the coefficient of base friction acts at a constant maximum value (Refs 6, 7, and 8). Thus it can be assumed that for post-tensioning operations the base friction restraint is uniform along the length of the slab. Acccordingly, the accumulation of base friction restraint causes the compressive stress due to prestressing to diminish linearly as the distance away from the slab end increases. The decrease in concrete compressive strain at any point x of the slab due to base friction restraint can be written

$$\Delta\varepsilon(x) = 1/E_c\left[\mu\gamma\left(L_o/2 - x\right)\right] \tag{5.3}$$

where

$\Delta\varepsilon(x)$ = change in compressive strain at any point x (positive for decrease)
μ = coefficient of base friction
γ = concrete unit weight
L_o = slab length.

Taking into account both friction along the post-tensioning tendon and base friction (assumed to be constant), concrete strain due to post-tensioning can be calculated according to the equation

$$\varepsilon(x) = 1/E_c\left[-P_s/A_c\, e^{-Kx} + \mu\gamma\,(L_o/2 - x)\right] \qquad (5.4)$$

where

$\varepsilon(x)$ = concrete strain at x (negative for contraction)

An expression for horizontal slab movement at any point x can be found by integrating the expression of concrete strain, Eq 5.4. The expression can be written

$$z(x) = 1/E_c\left[P_s/A_cK\left(1 - e^{-Kx}\right) - \mu\gamma/2\left(L_ox - x^2\right)\right] \qquad (5.5.)$$

where

$z(x)$ = horizontal slab movement at x (negative for contraction).

Initial Post-tensioning of Slab 7

The applied initial post-tensioning force for slab 7 was 15.8 kips. This post-tensioning was applied 13 hours after the placement of concrete at the north end of the slab. Compressive test cylinders tested at an age of 10 hours showed a compressive strength of 940 psi.

The effect of the initial post-tensioning on the horizontal slab movement and concrete strain of slab 7 was recorded. Table 5.1 shows the measured horizontal slab movement due to the initial post-tensioning, and Table 5.2 shows the measured concrete strain due to the initial post-tensioning.

The measured values of horizontal slab movement and concrete strain due to the initial post-tensioning were used in conjunction with Eqs 5.4 and 5.5 to back-calculate values of coefficient of base friction, μ, and concrete modulus of elasticity, E_c. These are two of the most important parameters in the analysis and design of prestressed concrete pavements.

In this calculation the wobble coefficient, K, was assumed to be 0.002 foot^{-1}. This value was selected in accordance with the results of the tendon elongation data (see Ref 24).

TABLE 5.1. HORIZONTAL SLAB MOVEMENT DUE TO THE INITIAL POST-TENSIONING OF SLAB 7

Distance From Midslab (Feet)	Transducer Number	Horizontal Slab Movement (Inch)
90	4	- 0.023
120	1	- 0.027
120	3	- 0.033

TABLE 5.2. CONCRETE STRAIN DUE TO THE INITIAL POST-TENSIONING OF SLAB 7

Distance From Midslab (Feet)	Gage Number	Concrete Strain (Microstrain)
20	8	- 9
20	9	- 12
60	5	- 25
60	6	- 22
60	7	- 17
100	0	- 23
100	1	- 16
100	3	- 27

The best fit of the measured data to Eqs 5.4 and 5.5 was found using a stepwise multiple linear regression program. The values of m and E_c which give the best fit to the strain data only are $\mu = 0.629$ and $E_c = 3,240,000$ psi. When all of the displacement data are included in the regression, the value of μ does not converge. When the data point for displacement transducer channel 1 is removed from the regression, the values of μ and E_c which give the best fit to both the strain and displacement data are $\mu = 0.510$ and $E_c = 2,909,000$ psi.

The value of the coefficient of friction, 0.51, is much lower than the conservative design value of 0.96, but it compares more closely to the coefficient of friction measured in friction push-off tests (Refs 6, 7, and 8). The value for concrete modulus of elasticity, 2,909,000 psi corresponds with the results of the modulus of elasticity tests.

The correlation of data for the initial post-tensioning of slab 7 is shown in Figs 5.1 and 5.2. Figure 5.1 shows the calculated values of horizontal slab movement over the length of slab 7 due to the initial post-tensioning, plotted against measured values of slab movement. Figure 5.2 shows the calculated values of concrete strain over the length of slab 7 due to the initial post-tensioning, plotted against measured values of concrete strain. It should be kept in mind when examining these figures that the curves for the calculated values are based on one regression analysis made of both strain and displacement data.

Final Post-tensioning of Slab 14

The applied final post-tensioning force for slab 14 was 16.5 kips. The final post-tensioning of 46.4 kips increased the post-tensioning level by 29.9 kips. The final post-tensioning was applied 60 hours after the placement of concrete at the north end of slab 14. The effect of this final post-tensioning on horizontal slab movement and concrete strain was recorded. Table 5.3 shows the measured horizontal slab movement due to the final post-tensioning, and Table 5.4 shows the measured concrete strain due to the final post-tensioning.

The value of the coefficient of friction, 0.45, is much lower than the conservative design value of 0.96, but it compares more closely to the coefficient of friction measured in friction push-off tests, and with the value found for slab 7. The value for concrete modulus of elasticity, 3,655,000 psi, corresponds with the results of the modulus of elasticity tests.

The correlation of data for the final post-tensioning of slab 14 is shown in Figs 5.3 and 5.4. Figure 5.3 shows the calculated values of horizontal slab movement over the length of slab 14 due to the final post-tensioning, plotted against measured values of slab movement.

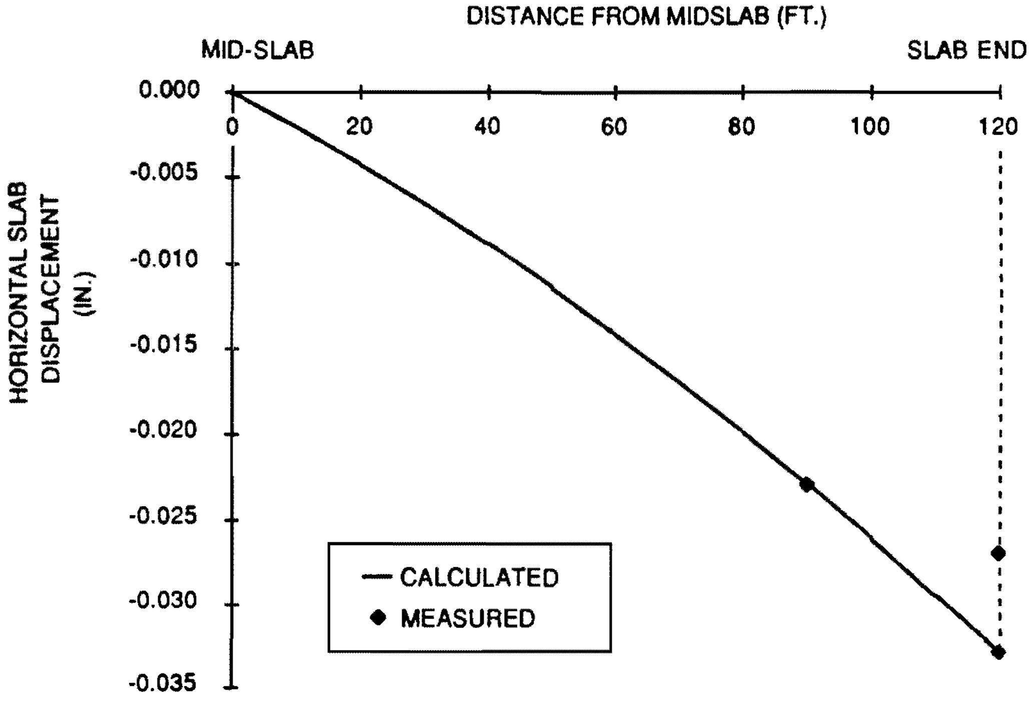


Fig 5.1. Correlation of calculated and measured slab displacements due to the initial post-tensioning of slab 7.

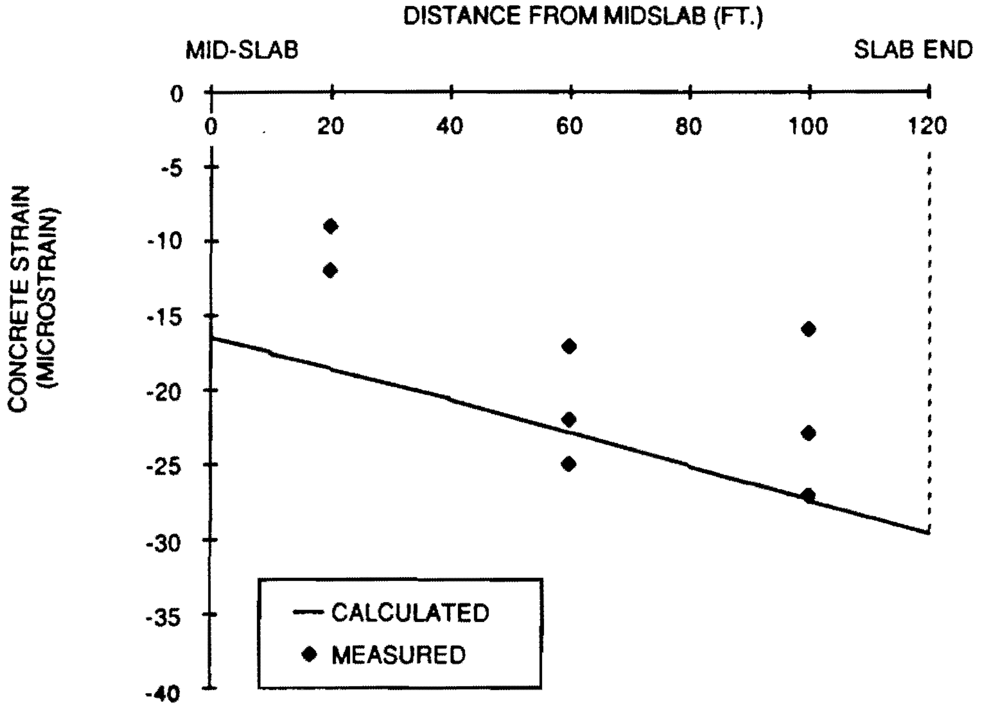


Fig 5.2. Correlation of calculated and measured concrete strain values due to the initial post-tensioning of slab 7.

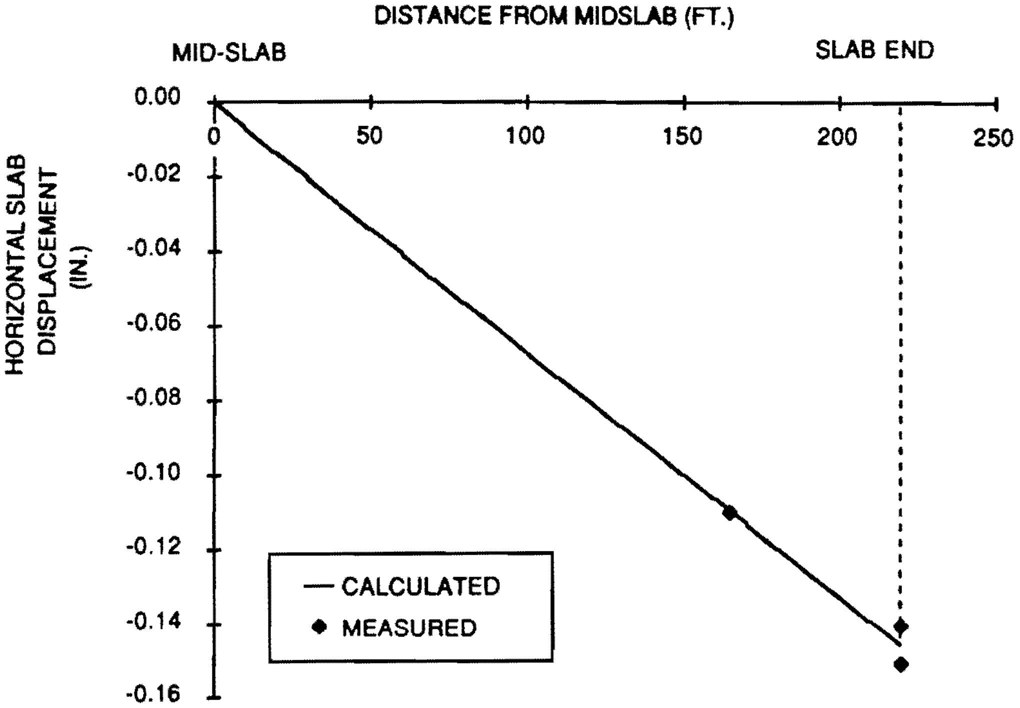


Fig 5.3. Correlation of calculated and measured slab displacements due to the final post-tensioning of slab 14.

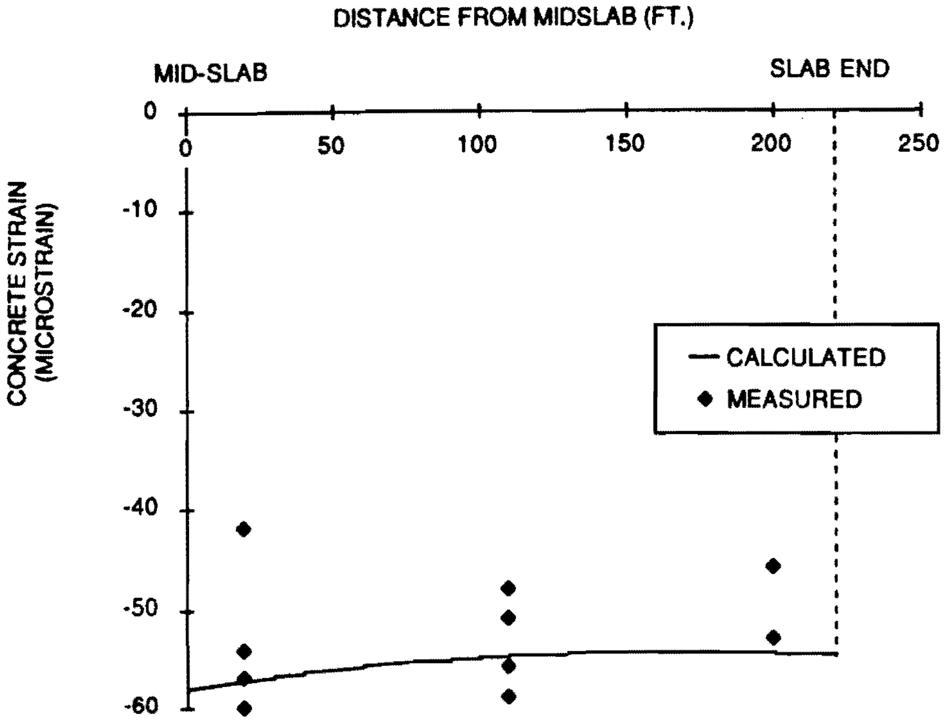


Fig 5.4. Correlation of calculated and measured concree strain due to the final post-tensioning of slab 14.

TABLE 5.3. HORIZONTAL SLAB MOVEMENT DUE TO THE FINAL POST-TENSIONING OF SLAB 14

Distance From Midslab (Feet)	Transducer Number	Horizontal Slab Movement (Inch)
165	4	- 0.110
220	0	- 0.141
220	2	- 0.151

TABLE 5.4. CONCRETE STRAIN DUE TO THE FINAL POST-TENSIONING OF SLAB 14

Distance From Midslab (Feet)	Gage Number	Concrete Strain (Microstrain)
20	0	- 60
20	1	- 57
20	2	- 54
20	3	- 42
110	4	- 51
110	5	- 48
110	6	- 56
110	7	- 59
200	8	- 53
200	9	- 46

Addition of 29.9 kips post-tensioning to final value of 46.4 kips at 60 hours following placement.

Figure 5.4 shows the calculated values of concrete strain over the length of slab 14 due to the final post-tensioning, plotted against measured values of concrete strain. It should be kept in mind when examining these figures that the curves for the calculated values are based on a single regression analysis made of both strain and displacement data.

VERY EARLY CONCRETE STRENGTHS

From the data shown in Figs 4.14, 4.15, 4.16, and 4.17, concrete strength at very early ages was not significantly affected by curing temperature. For all curing temperatures (ranging from 40ΥF to 82ΥF) concrete compressive strength at 8 hours varied widely. Values ranged from 0 psi to 1800 psi.

It is likely that the most-significant variable affecting very early concrete strengths was the dosage of set retarder. The set retarder was needed because the concrete was delivered from a remote batch plant. If set retarder is not used, very early concrete strength results will be higher and vary less. It can be concluded, however, that, in all slabs except one, the concrete reached sufficient strength during the day of casting to allow an effective initial post-tensioning to be applied to the pavement.

It had been suggested that in future prestressed concrete pavement projects, where very early initial post-tensioning is applied, maturity curves could be used to estimate concrete strength at very early ages. Based on the evidence of the compressive cylinder strength results, it can be concluded that the maturity curve approach would not have worked on the Texas prestressed pavement.

It should also be noted that, in cases when the concrete was very slow in setting, the lack of sufficient concrete strength for initial post-tensioning could be determined visually simply by scratching the concrete surface. This indicates that an in-situ method of concrete testing, such as using a rebound hammer or Windsor probe, could be used to determine concrete compressive strength at very early ages. This would eliminate the need for a compression testing machine at the job site and would save labor in casting and testing cylinder specimens.

CONCRETE MODULUS OF ELASTICITY

Figure 4.19 shows the measured modulus of elasticity in comparison with that calculated according to the ACI formula (Ref 24). It can be seen from this figure that, for concrete strengths around 600 psi, the measured and calculated values for concrete modulus of elasticity correspond closely. But, for concrete strengths of 1500 to 3300 psi, the measured values exceed the calculated values by as much as 68 percent .

This discrepancy is probably due to the fact that the measured data are for concrete at early ages. It has been noted elsewhere that the modulus of elasticity for concrete reaches mature values relatively early compared to the compressive strength gain. That is, concrete at very early ages gains stiffness faster than it gains strength (Ref 9). Thus, the ACI formula may underpredict the modulus of elasticity of concrete at very early ages.

It is important to note that, when calculating concrete stresses due to restrained temperature and shrinkage movement, using too low a value for concrete modulus of elasticity is unconservative. Assuming too low a value of concrete modulus of elasticity in designing a prestressed pavement would underpredict the restraint stresses in the pavement.

Thus it is recommended that, in the analysis and design of prestressed pavements, the most accurate data available for determining concrete modulus of elasticity should be used. If the ACI formula is used the designer should account for the fact that the formula may underpredict the modulus of elasticity for concrete at very early ages.

SLAB CRACKING

The transverse crack which formed in slab 5 gives evidence of the importance of very early initial post-tensioning. Slab 5 was the only one of the pavement slabs in which initial post-tensioning was not applied during the day of concrete placement. Not coincidentally, slab 5 was also the only pavement slab to develop a transverse crack.

The time of crack formation corresponds closely to the lowest temperature of the daily cycle (see Figs 4.1 and 4.2). Assuming a coefficient of base friction of 0.64, the maximum uniform tensile stress in the concrete at the time of cracking was 82 psi. The location of this maximum tensile stress corresponds to the location near midslab where the crack actually formed. It can be concluded that even a small amount of initial post-tensioning applied during the day of casting would have prevented the transverse cracking.

CHAPTER 6. CONTINUATION OF THE INSTRUMENTATION PROGRAM

This chapter presents recommendations for the continuation of the instrumentation program. The recommendations for the short-term instrumentation include suggestions for gathering more data on horizontal slab movement, concrete strain, and slab temperature gradients and slab curling due to ambient temperature changes. Recommendations for long-term instrumentation include a program for the continued measurement of joint opening width and recommendations for measuring the load transfer capabilities of the transverse joints, the deflection characteristics of the pavement, and the riding quality of the pavement.

SHORT-TERM INSTRUMENTATION

Recommendations for the continuation of short-term instrumentation include recommendations for gathering more data on horizontal slab movement and concrete strain due to temperature change, and on slab curling due to temperature change.

Horizontal Slab Movement and Concrete Strain Due to Temperature Change

Continued measurement of the effect of daily temperature changes on the horizontal movement and concrete strain of the pavement slabs will give a better indication of several factors important in the design of prestressed concrete pavements. These factors include (1) the coefficient of thermal expansion, (2) the coefficient of base friction, and (3) the concrete modulus of elasticity. Also, the measurements can be used to verify the inelastic nature of the base friction force.

Continued instrumentation should include thermocouples for measuring ambient and slab temperatures. Ambient temperatures should be measured continuously using one or two thermocouples and should be checked intermitantly using a thermometer. Concrete temperature should be measured at a slab depth of 3 inches using embedded thermocouples in two separate locations.

The measurement of horizontal slab movement using displacement transducers has proven more accurate and more reliable than the measurement of concrete strain using strain gages. Although both types of measurements should provide useful data, the measurement of horizontal slab movement should be considered the more important measurement. Horizontal slab movements should be measured with displacement transducers mounted along the shoulder edge of the pavement slab according to the procedures outlined in Chapter 3. The transducers should be mounted in at least four locations equally spaced between mid-slab and the slab end. The joint opening width of one of the transverse joints adjacent to the instrumented slab should be measured periodically on a continuous basis.

Concrete strain should be measured using surface strain gages. For the application of these gages it is necessary that an area of the pavement surface be ground smooth. It is suggested that at least three strain gages be used: one near mid-slab, one at the slab quarterpoint, and one near the slab end. Strain measurements can be verified mechanically using the Demac gage as was done previously (see Chapter 3).

It is best if the recordings of temperature, movement, and concrete strain are carried out continuously over a 48-hour period. One short slab and one long slab of the west lane should be instrumented. The new data should be compared with that reported in Chapter 4 of this report and evaluated to determine the concrete coefficient of thermal expansion, coefficient of base friction, and concrete modulus of elasticity. Also, the data can be used to characterize the inelastic nature of the base friction force.

Slab Curling Due to Temperature Change

Vertical temperature gradients are the cause of significant stresses in prestressed concrete pavements. At the ends of the pavement slabs, the temperature gradients will cause the upward or downward curling of the slab. This curling of the slab ends may have a detrimental effect on the performance of the transverse joints of the pavement. Away from the slab ends, curling movements are restrained by the pavement's self weight and give rise to tensile and compressive stresses in the concrete.

The continued measurement of slab temperature gradients will help give a better indication of the magnitude of the temperature gradients and their relationship to ambient temperature cycles. The data will help refine analytical models which can predict slab temperature gradients based on ambient temperature changes and the thermal conductivity of the concrete pavement. Measurement of slab temperature gradients should be made using thermocouples embedded in the concrete at three depths.

Curling of the slab ends should be measured using vertically oriented displacement transducers as described in Chapter 3. On previous implementations, the transducers were located only very close to the slab ends. For the continued measurement of slab curling, it is suggested that one displacement transducer be placed as close as possible to the slab end and that three other displacement transducers be positioned at 12-inch intervals away from the slab end, as shown in Fig 6.1. This arrangement of transducers will give a profile of the shape of the slab as it curls upwards. This arrangement will also indicate if the downward curling of the slab when restricted by the pavement base causes the uplift of portions of the pavement a short distance away from the slab end.

It is recommended that readings of slab temperature at three depths and vertical movements of the slab corners be recorded continuously over a 48-hour period. The new data should be compared with that presented in Chapter 4 of this report and should be evaluated to determine the coefficient of thermal expansion of the concrete. Analytical models which predict temperature gradients in pavement slabs should be explored, and the effect of temperature gradients on concrete strain should be examined.

LONG-TERM INSTRUMENTATION

Recommendations for the continuation of long-term instrumentation include a program for the continued measurement of joint opening width, and recommendations for measuring the load transfer capabilities of the transverse joints, the deflection characteristics of the pavement, and the riding quality of the pavement.

Joint Opening Width

The continued measurement of joint opening width will give an indication of (1) long-term shortening of the pavement slabs due to creep and shrinkage of the concrete, (2) changes in joint opening width due to seasonal temperature changes, and (3) any change in the friction characteristics of the pavement base.

The measurements should be carried out according to the procedures that have been used to date, recording the ambient temperature when measuring the joints. As a minimum, joint opening width should be measured at the following transverse joints:

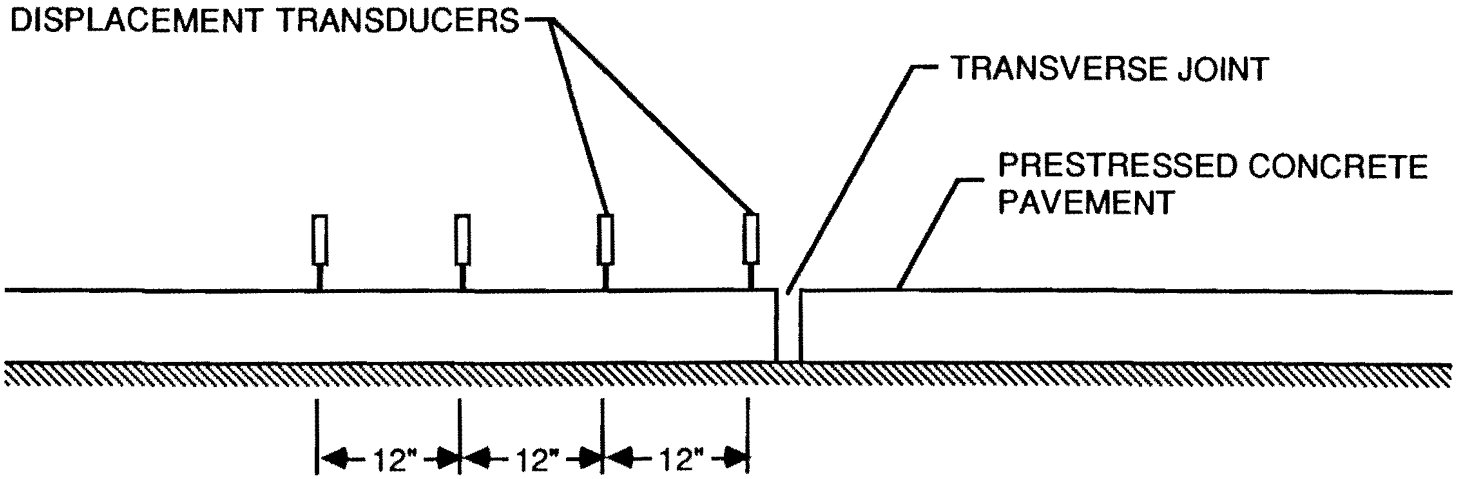


Fig 6.1. Recommended displacement transducer locations for measuring slab curling.

-the approach joints (joints 1 and 17),
-two typical joints between short slabs,
-the transition joint (joint 10), and
-two typical joints between long slabs.

If the joint opening readings are taken along the shoulder of the west lane only, location C of Fig 3.44, the measurements can be carried out without interrupting traffic. It is recommended that joint opening readings be taken monthly through December 1986 (i.e., for the first year after construction), and twice yearly thereafter.

Mendoza (Ref 10) has set up a program to statistically analyze the joint opening width data. This analysis uses the data to back-calculate values for the coefficient of thermal expansion and creep and shrinkage coefficients for the pavement. This analysis should be continued with the inclusion of the new data.

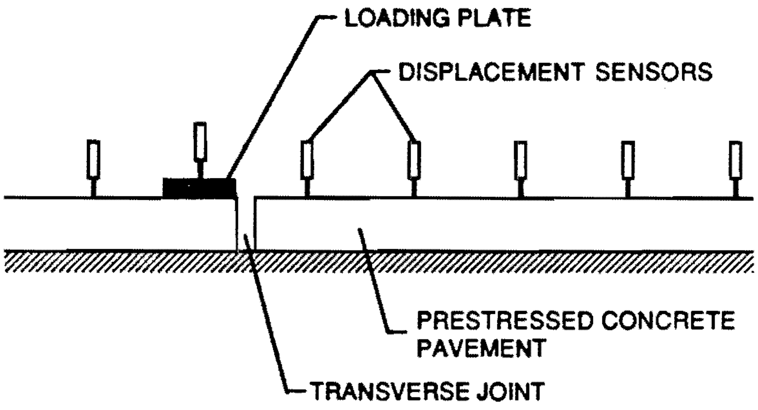
Load Transfer Capabilities of the Transverse Joint

Measuring load transfer of the transverse joints indicates the effectiveness of the joints in carrying shear loads due to traffic. This measurement can be accomplished by measuring slab surface deflections near the joints under generated dynamic loads. Two devices are available for this measurement: (1) the falling weight deflectometer and (2) the Dynaflect apparatus.

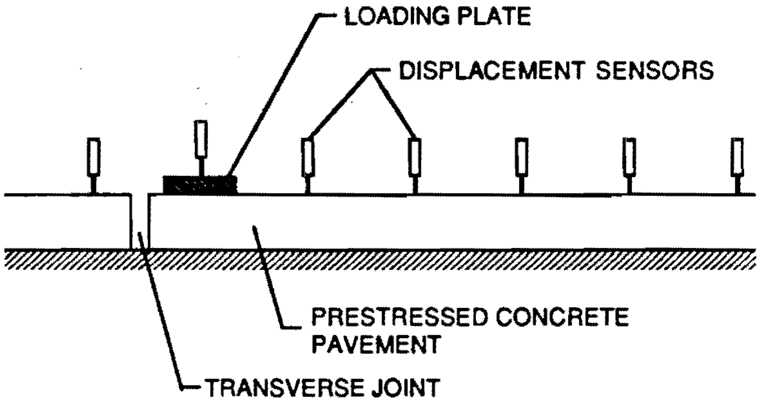
In using these devices the load must be applied on one side of the joint and deflections measured on the other side of the joint. If possible, the load transfer of the joints should be measured in both directions; i.e,. first with the load applied on the north side of the joint (and deflections measured on the south side of the joint) and then with the load applied on the south side of the joint (and deflections measured on the north side of the joint). Figure 6.2 shows the recommended set-up of the falling weight deflectometer, and Fig 6.3 shows the recommended positioning of the Dynaflect apparatus.

As a minimum, load transfer should be measured at the following joints:

-the approach joints (joints 1 and 17),
-two typical joints between short slabs,



U-POSITION (LOAD UPSTREAM OF JOINT)



D-POSITION (LOAD DOWNSTREAM OF JOINT)

Fig 6.2. Recommended positioning of the Falling Weight Deflectometer for load transfer measurements.

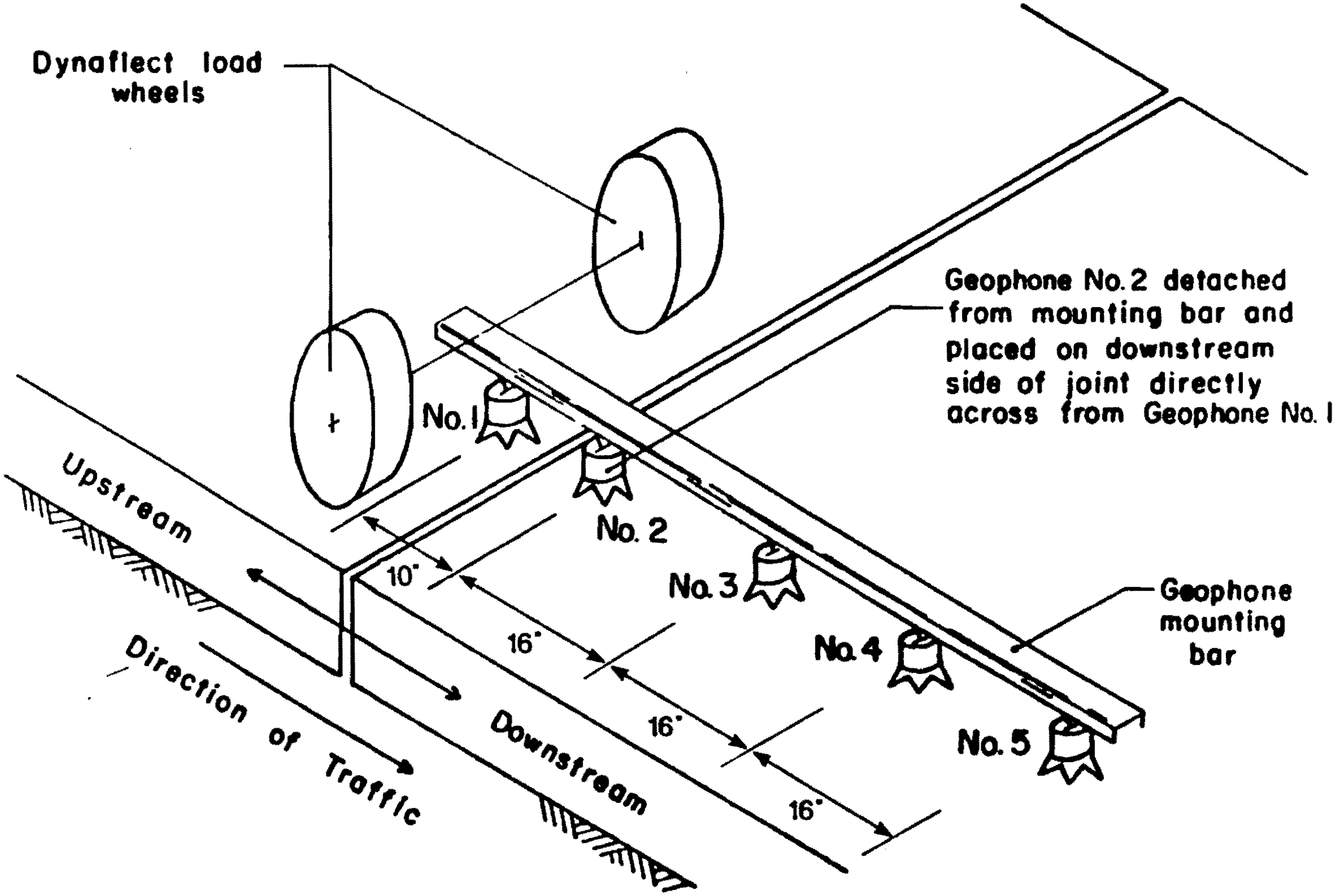


Fig 6.3. Recommended positioning of Dynaflect wheel loads and geophones for load transfer measurements.

-the transition joint (joint 10), and
-two typical joints between long slabs.

The load transfer readings should be taken for both lanes of traffic.

It is expected that the load transfer capabilities of the transverse joints will be dependent upon joint opening width. It is important that a measurement of joint opening width for each joint be taken at the same time that each measurement of load transfer is made. This measurement should be taken between opposite lips of the armored joint. This will indicated the "absolute" joint opening width.

In addition, it is recommended that the joint openings for the west lane be measured from the reference scribe marks at the same time as the load transfer measurements are taken. This measurement will show the joint opening width in comparison with that of previous months.

It is also expected that load transfer across the joints may be influenced by curling of the slab ends. Slab curling in the downward direction will be greatest in the early morning, 1 to 3 hours after sunrise. This is when the top of the slab will be at a higher temperature than the bottom of the slab and downward curling of the slab ends will result. Conversely, upward curling of the slab ends will be greatest around sunset and for a few hours afterwards. This is when the top on the slab will be at a cooler temperature than the bottom of the slab and upward curling will result.

Thus it is recommended that the deflection readings of load transfer at the joints be taken at two times in the same day. Another possibility is that load transfer readings can be taken at regular intervals throughout an entire day. Time of day and ambient temperature should be recorded when taking all of the load transfer measurements.

These series of measurements should be taken twice yearly, It is recommended that the load transfer measurements be taken in the coldest possible weather (winter condition), when joint openings are greatest, and again in hot weather (summer condition), when joint openings are smallest.

Deflection Characteristics of the Pavement

The relationship between a concentrated load on a pavement and the deflections it produces gives an indication of the load carrying capacity of the pavement. Using the Dynaflect apparatus, this relationship can be established. Deflection readings of the Texas prestressed pavement overlay can be compared with those that were taken on the old pavement before the overlay was constructed. This will indicate the gain in pavement strength due to the construction of the prestressed concrete overlay. Also, if the Deflection measurements are taken near the stressing pockets, it can be determined whether or not the pockets constitute a weak zone in the pavement.

As a minimum, the Deflection readings should be taken on at least two 240-foot pavement slabs and two 440-foot pavement slabs. The readings should be taken near the transverse joints and at several points along the length of each slab and at the stressing pockets. It is recommended that these Deflection readings be taken on both lanes of traffic.

The Deflection readings throughout the pavement should be taken twice yearly. Because the prestress level in the pavement will vary with temperature, it is recommended that the Deflection readings throughout the pavement be carried out in the coldest possible weather (winter condition) and again in hot weather (summer condition).

Riding Quality of The Pavement

The evaluation of riding quality requires a roughness measurement which can be taken using the surface dynamic profilometer 690-D. This measurement should be taken twice yearly to determine if deterioration of the pavement and/or joints is occurring and to determine to what extent this deterioration affects pavement serviceability.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Pavements of prestressed concrete are feasible and potentially cost-efficient for highways and airport runways. The advantages of prestressed concrete pavements over continuously reinforced concrete pavements or other conventional pavements include the following:

(1) reduced pavement cracking,
(2) reduced number of joints,
(3) improved pavement performance,
(4) material savings, and
(5) reduced routine maintenance.

A potentially promising use of prestressed concrete pavements is for overlaying existing highway pavements.

In the United States, five prestressed pavement demonstration projects have been built since 1971. The most recent of these projects, the Texas prestressed pavement, is the subject of the research program described in this report. This pavement was completed in December of 1985 and consists of two lanes of highway pavement overlay one mile long.

The design of prestressed concrete pavements requires an accurate knowledge of many aspects of the pavement's behavior. The most effective design is based on an accurate knowledge of physical parameters, which include coefficient of base friction, coefficient of thermal expansion of the concrete, modulus of elasticity of the concrete, and expected daily temperature cycles. Using assumed values of these parameters, the movement and stress in a prestressed pavement can be predicted analytically; by measuring movement and stress experimentally, these design assumptions can be evaluated. In order to determine ways of improving the analysis, and consequently the design, of prestressed concrete pavements, an instrumentation plan was implemented on the Texas prestressed pavement.

The instrumentation plan for the Texas prestressed pavement was developed based on a review of the instrumentation arrangements on previous projects, an examination of instrumentation objectives, and the testing of instrumentation on a pavement test-slab. Based on the instrumentation objectives, the instrumentation scheme was divided into short-term measurements and long-term measurements. The main objective of the short-term measurements was to provide a verification of predicted values of concrete stress and slab movement due to prestressing, and due to daily changes in temperature. The main objective of the long-term measurements is to determine how the pavement holds up over time.

An 8-foot by 26-foot pavement test-slab was used to test the installation and functioning of instrumentation which was planned for use in the field. The results of the experimentation on the test slab indicated the following conclusions:

(1) Thermocouples are effective in recording both ambient and concrete temperatures.
(2) Displacement transducers are very effective in recording horizontal slab movements.
(3) Embedded and surface strain gages, positioned longitudinally, are generally effective in recording changes in concrete strain due to longitudinal post-tensioning.
(4) Embedded strain gages positioned transversely were not effective or consistent in recording the small changes in concrete strain due to transverse post-tensioning.

The Texas prestressed pavement project consists of 32 prestressed concrete pavement overlay slabs, of either 240 feet in length or 440 feet in length. The pavement slabs are 6 inches thick, cast on a single sheet of polyethylene over the previous pavement, and post-tensioned in the longitudinal and transverse directions using 0.6-inch-diameter, 7-wire, unbonded tendons. Early cracking of the pavement slabs was prevented by applying an initial amount of longitudinal prestress within 8 to 15 hours after concrete placement. The amount of this initial prestress applied to the concrete ranged from 70 to 200 psi, depending on the concrete strength at the time of stressing.

The short-term instrumentation used on the Texas prestressed pavement was installed on one 240-foot slab (slab 7) and one 440-foot slab (slab 14). The short-term instrumentation consisted of thermocouples for measuring ambient and concrete temperatures, embedded and surface strain gages for measuring concrete strain in the longitudinal direction, and displacement transducers for measuring horizontal and vertical slab movements. Mechanical measurements were also made to back up these electronic measurements. Short-term instrumentation also included measurement of tendon elongations, very early concrete strengths, and concrete modulus of elasticity.

The long-term measurements proposed consist of (1) a program to periodically measure the joint opening width of the transverse joints, (2) a program to periodically measure the load transfer capabilities of the transverse joints, (3) measurement of the deflection characteristics of the pavement, and (4) measurement of the riding quality of the pavement.

Data from the short-term measurements include the following:

(1) Continuously recorded ambient and concrete temperature data which correspond closely to back-up readings taken by thermometer and agree with expected temperature variations according to slab depth.

(2) Horizontal slab movement data which effectively show the contraction of the pavement slab due to post-tensioning and show the cyclic movement of the pavement slab due to daily temperature cycles.

(3) Concrete strain data which effectively show the contraction of the pavement slab due to post-tensioning. The data are less consistent, however, in showing cyclic changes in strain due to daily temperature changes.

(4) Slab curling data which show the vertical displacement of the slab corners due to daily temperature cycles. The data show that, as should be expected, the maximum upward curling of the slabs corresponds to the time when the maximum negative temperature gradient in the slab is acting.

(5) Data on tendon elongations, which are discussed in another report (Ref 24).

(6) Data on concrete compressive strength at very early ages and at 28 days.

(7) Data on concrete modulus of elasticity.

(8) Observations of slab cracking.

The program of long-term measurements is ongoing at this time. The only long-term data included in this report are a sampling of joint opening width data taken in the Fall of 1985. These data show the behavior of similar joints to be very consistent. Data on the load transfer capabilities of the transverse joints, deflection characteristics of the pavement, and riding quality of the pavement are presented in later reports.

A statistical analysis of slab movement and concrete strain data, corresponding to the post-tensioning of the pavement slabs, yielded important results in the calculation of coefficient of base friction and concrete modulus of elasticity for the pavement. The coefficient of base friction was found to be 0.51 according to the initial post-tensioning of slab 7, and 0.45 according to the final post-tensioning of slab 14. Although these values are much lower than the conservative design value of 0.96, they are considered an accurate indication of the actual coefficient of base friction.

The concrete modulus of elasticity for the initial post-tensioning of slab 7, was found to be 2,900,000 psi. The age of the concrete at the time of this post-tensioning was about 13 hours. For the final post-tensioning of slab 14, the concrete modulus of elasticity was found to be 3,700,000 psi. The age of the concrete at the time of this final post-tensioning was about 60 hours. These values are in line with the results of the concrete modulus of elasticity tests performed on concrete cylinder specimens.

The results of 61 compressive cylinder tests showed that very early concrete strengths for the project did not depend solely on age and curing temperature. The dosage of set retarder in the concrete appears to have been a factor. It had been suggested that, in future prestressed concrete pavement projects where very early initial post-tensioning is applied, maturity curves could be used to estimate concrete strength at very early ages. Based on the evidence of the compressive cylinder strength results, it can be concluded that the maturity curve approach would not have worked on the Texas prestressed pavement. It is possible however that concrete strength at very early ages could be effectively determined with an in-situ method of testing, such as the use of a rebound hammer. This would eliminate the need for a compression testing machine at the jobsite and would save labor in casting and testing cylinder specimens.

The results of concrete modulus of elasticity tests performed on compressive cylinder specimens were compared to the ACI formula in which concrete modulus of elasticity is written as a function of compressive strength:

$$E_c = 57,000 \sqrt{f'c}$$

For concrete strengths around 600 psi, the measured values of concrete modulus of elasticity correspond closely to those calculated by the ACI formula. But for concrete strengths of 1500 to 3300 psi, the measured values exceed the calculated values by as much as 68 percent. Since it has been noted that concrete at very early ages gains stiffness faster than it gains strength, the discrepancy is probably due to the fact that all of the data are for concrete at early ages. It is recommended that, in the analysis and design of prestressed concrete pavements, the determination of concrete modulus of elasticity should be based on the most accurate data available.

A transverse crack which formed in slab 5 gave positive evidence of the importance of very early initial post-tensioning. Slab 5 was the only one of the pavement slabs in which initial post-tensioning was not applied during the day of concrete placement. Not coincidentally, slab 5 was the only pavement slab to develop a transverse crack. Although the crack closed after the application of prestress, even a small amount of initial prestress applied during the day of casting would have prevented the crack from ever forming.

RECOMMENDATIONS FOR FURTHER RESEARCH

Further research on the instrumentation and behavior of the Texas prestressed concrete pavement should be carried out according to the recommendations for continued instrumentation, which are presented in Chapter 6. These recommendations include (1) gathering more data on horizontal slab movement, concrete strain, and slab curling due to daily temperature changes and (2) carrying out the program of long-term instrumentation.

Recommendations for the instrumentation of future prestressed concrete pavements can also be made:

(1) The testing of instrumentation prior to field implementation is recommended. The test slab used in this research project was immensely helpful.

(2) Thermocouples are very effective in recording ambient and concrete temperatures.

(3) In general, displacement transducers give better results than strain gages in recording the contraction or expansion of the pavement. If strain gages are used they should be tested extensively prior to field implementation. Surface strain gages are easier to install and will record approximately the same strain as embedment strain gages.

(4) A well planned program for long-term instrumentation is recommended. Such a program should be very useful in evaluating the performance of prestressed concrete pavements in comparison with conventional pavements.

REFERENCES

1. Cable, Neil D.; Burns, Ned H.; and McCullough, B. Frank. "New Concepts in Prestressed Concrete Pavement." Research Report 401-2, Center for Transportation Research, The University of Texas at Austin, August 1985.
2. Gramling, Wade L.; Teng, T. Paul; Morris, Gene R.; and Sheffiels, Joe. Prestressed Pavement Performance in Four States, A Panel Report. U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA/RD-82/169. Springfield, Va.: NTIS, 1983.
3. Lin, T.Y., and Burns, N.H. Design of Prestressed Concrete Structures. 3rd Ed. New York: John Wiley & Sons, 1981.
4. Friberg, Bengt F. "Frictional Resistance Under Concrete Pavements and Restraint Stresses in Long Reinforced Slabs." Proceedings, V. 33, Highway Research Board, 1954, pp 167-184.
5. Friberg, Bengt F. "Restrained Temperature Movements in Long Slabs," ACI Journal, April 1968, pp. 258-265
6. Mendoza, Alberto, and Cable, Neil D. "Field Tests Conducted Near Valley View, Texas, for the Design of the Prestressed Highway Pavement Demonstration Projects in Cooke and McLennan Counties." Technical Memorandum 401-17, Center for Transportation Research, The University of Texas at Austin, September 1984.
7. Mendoza, Alberto. "Repetition of the Friction Tests on the Test Slabs Constructed Near Valley View, Texas, for the Design of the Prestressed Highway Pavement Project in Cooke County." Technical Memorandum 401-20, Center for Transportation Research, The University of Texas at Austin, October 1984.
8. Maffei, Joseph R. "Third and Final Series of Friction Tests on the test slabs Constructed Near Valley View, Texas." Technical Memorandum 401-27, Center for Transportation Research, The University of Texas at Austin, August 1985.
9. O'Brien, J. Scott; Burns, Ned H.; and McCullough, B. Frank. "Very Early Post-tensioning of Prestressed Concrete Pavements." Research Report 401-1, Center for Transportation Research, The University of Texas at Austin, June 1985.
10. Mendoza Diaz, Alberto, Ned H. Burns, and B. Frank McCullough, "Behavior of Long Prestressed Pavement Slabs and Design Methodology," Research Report 401-3,

Center for Transportation Research, The University of Texas at Austin, September 1986.

11. O'Brien, J. Scott. "Procedure for Calculating the Slab Thickness and Prestress Level for the Prestressed Concrete Pavement Overlays." Technical Memorandum 401-4, Center for Transportation Research, The University of Texas at Austin, November 1983.

12. Mendoza, Alberto. "Design of Thickness and Prestress Level for the Prestressed Pavement in McClennan County." Technical Memorandum 401-11, Center for Transportation Research, The University of Texas at Austin, February 1984.

13. O'Brien, J. Scott. "Design of Transverse Joint for Prestressed Pavement in McLennan County." Technical Memorandum 401-15, Center for Transportation Research, The University of Texas at Austin, February 1984.

14. Brunner, Raymond, J. Prestressed Pavement Demonstration Project, Research Project No. 72-22(2). Pennsylvania Department of Transportation, Bureau of Materials, Testing, and Research. Annual Meeting of the Transportation Research Board, 1975.

15. Friberg, Bengt F., and Pasko, T.J. Prestressed Concrete HighwayPavement at Dulles International Airport: Research Progress Report to 100 Days. U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-RD-72-29, August 1973.

16. Albrittion, Gayle E. Prestressed Concrete Highway Pavement: Construction--As Built Performance, Brookhaven, Mississippi (Research Supplement). U.S. Department of Transportation, Federal Highway Administration, Region 15, Demonstration Projects Division. Arlington, Va., August 1978.

17. Morris, Gene R., and Emery, Hal C. The Design and Construction of Arizona's Prestressed Concrete Pavement. Research Section, Highway Division, Arizona Department of Transportation. Fifteenth Paving Conference, University of New Mexico, Department of Civil Engineering, Albuquerque, New Mexico, January 1978

18. Friberg, Bengt F. "Investigations of Prestressed Concrete for Pavements." Bulletin No. 332, Highway Research Board, 1962, pp. 40-94.

19. Wray, Warren K. (Principal Investigator). "Interim Report: Measurement of Slab-Subgrade Friction on a Full Scale 80 ft. x 150 ft. Slab at Slidell, La." Department of Civil Engineering, Texas Tech University, October 3, 1984.

20. Texas State Department of Highways and Public Transportation. Standard Specifications for the Construction of Highways, Streets, and Bridges. 1982.

21. "Plans and Specifications for the Prestressed Pavement Overlay to be Built in McClennan County, Texas." Texas State Department of Highways and Public Transportation, Waco, Texas, 1985.

22. Maffei, Joseph R. "Recommendations for the Initial Post-tensioning of the Waco Prestressed Concrete Pavement." Technical Memorandum 401-26, Center for Transportation Research, The University of Texas at Austin, July 1985.

23. Dunn, Brian; Burns, Ned H.; and McCullough, B. Frank. "Friction Losses in Unbonded Post-tensioning Tendons." Research Report 401-6, Center for Transportation Research, The University of Texas at Austin, November 1986.

24. American Concrete Institute, Committee 318. Building Code Requirements for Reinforced Concrete (ACI 318-83), 2nd Printing, September 1984.