CHARACTERIZATION OF THE SWELLING CLAY PARAMETER USED IN THE PAVEMENT DESIGN SYSTEM

by

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A System Analysis of Pavement Design
and Research Implementation

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PREFACE

This is the third in a series of reports dealing with the findings of Research Project 1-8-69-123, "A System Analysis of Pavement Design and Research Implementation." The report characterizes the swelling clay parameter using data from standard laboratory soil tests and presents a design equation. This report is submitted as a research record and not for general publication.

Grateful acknowledgment is given to the staff members of the Center for Highway Research who helped to edit, type, and compile this report, and also to Mark Goode who helped to prepare the data presented in this document. The authors are grateful to the Texas Highway Department for their sponsorship in this program.

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ABSTRACT

The purpose of this study was to quantify the swelling clay parameter used in the systems approach to pavement design. The quantification of the parameter was to be made using data from standard laboratory soils tests and actual concrete pavements. The pavement sections used in the research were chosen so that only the soil properties of the subgrade varied. To insure that the subgrade soils were different, statistical tests were performed. The quantification of the parameter involved three steps. First, the Present Serviceability Indexes were computed from the average slope variances of the pavement sections at various times. With the PSI versus time data, the swelling clay parameter was characterized using the Serviceability Loss Function. Using the calculated values for the swelling clay parameter and various soil properties, the parameter was quantified. The quantification was made using both single and multiple regression analyses. A design equation for use in the Pavement Design System is presented. It expresses the swelling clay parameter in terms of the plastic, liquid, shrinkage, and linear shrinkage limits.

KEY WORDS: clay, pavements, systems engineering, highway, design.

SUMMARY

The most important result of this research was proving that the swelling clay parameter can be characterized using standard laboratory tests. While single regression analyses cannot adequately predict the variation in the swelling clay parameter, multiple regression analyses can. The results of this study indicate the swelling clay parameter can be adequately characterized using the soil's liquid and plastic limits.

The research also showed that the construction procedure used in preparing the subgrade had an important effect on the swelling clay parameter. The following procedures appeared beneficial in reducing the swelling clay parameter:

(1) compacting of subgrade in wet condition,
(2) ponding of water over the swelling clay,
(3) deep time treatments for subgrade, and
(4) keeping the pavement surface sealed.

The swelling clay parameter, as shown by this research, has a pronounced effect on the pavement's serviceability. For this reason, the highway designer should make every effort to incorporate the proper parameter into this design.

IMPLEMENTATION STATEMENT

The characterization of the swelling clay parameter should be of great assistance to users of the pavement design system. Probably its most useful purpose will be to help identify potential trouble areas along the pavement. If the designer knows in advance that certain areas of the subgrade are more likely to swell, he can take measures to prevent this trouble by either working on the subgrade itself or adjusting the design of the pavement in this area.

The proper swelling clay parameter will allow the designer to determine if it is more economical to improve the subgrade in potential trouble areas or to adjust the pavement design in these areas.

A design equation for evaluating the swelling clay parameter is presented. This equation was derived from lightly reinforced, jointed concrete pavements. It may be equally applicable to flexible pavements and continuously reinforced pavements, but proper care should be used in any such undertaking.

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CHAPTER 1. INTRODUCTION

Background

In the past, a pavement design has generally been based on its initial cost; however, designers are now realizing that the total cost of the pavement system must be considered over a period of time in choosing the pavement design.

The Center for Highway Research at The University of Texas at Austin, the Texas Highway Department, and the Texas Transportation Institute are developing a systems approach to the design of pavements (Ref 1). A procedure for the design of flexible pavement systems has been developed by TTI (Refs 2, 3, and 4), and a procedure for the design of rigid pavement systems is currently being developed at the Center for Highway Research. This systems approach will make it possible to judge a pavement design on not only its initial construction cost, but also, and more importantly, on its most probable overall cost during the design life.

Flexible pavement structures are often designed for periods of 20 to 25 years; however, at the present time a design is often chosen only on the basis of its first cost (Refs 5 and 6). Most design methods used do not have procedures for evaluating the subsequent maintenance and user costs during its design life.

The systems approach uses physical variables such as traffic and material properties to predict the serviceability history of the pavement with time. From this history it may be possible to determine how long a given pavement will last before it needs an overlay or maintenance. By knowing how the serviceability of the pavement deteriorates with time, the designer will know how many overlays a given design will need. With this approach, other costs associated with any design can be determined, including the following: initial construction cost, maintenance cost, user cost due to traffic delays during overlay construction, and salvage value. Knowing the overall cost of the design for a specified analysis period in addition to the first cost, the designer can choose the most economical design for a given situation.

A computer program was chosen as the best method for incorporating these variables into the design procedure. In addition to being able to consider many of the variables, the designer, through the computer program, can provide many designs and compare them on a cost basis. To be worthwhile, the computer program, aside from being a tool to the design engineer and an aid to the research engineer in determining where research should be performed, should also be easy to update as new information on flexible pavements becomes available.

Statement of Problem

A sensitivity analysis presently being conducted at the Center for Highway Research shows one of the more important input variables required for making a flexible pavement design with FPS to be the swelling clay parameter. The swelling clay parameter was derived after a newly constructed pavement on I.H. 35 in San Antonio, Texas, could not be opened to traffic, because the pavement's riding quality had deteriorated to an unsatisfactory level. This serviceability loss was attributed to movements of the subgrade, which was classified as a swelling clay. In order to incorporate the effect of swelling clays into the pavement design system, a mathematical model was developed at TTI by Frank Scrivner (Ref 4). The effect of various swelling clay values on the present serviceability time curve of a pavement as described by the Scrivner model is shown in Fig 1. The more active the swelling clay, the larger the swelling clay parameter (i.e., rate of serviceability loss) becomes. The rate and amount of pavement serviceability lost because of a swelling clay increase as the swelling clay parameter increases.

It is important to remember that the curves in Fig 1 define a mathematical relationship assumed to exist for the loss of serviceability due to swelling action of clays. While a swelling clay value of zero to .02 would cause little loss of pavement serviceability in 20 years, a swelling clay value of .32 could lower the serviceability to an unsatisfactory level in less than two years. For this reason, the swelling clay value used influences the thickness of materials used in the pavement structure, the number of overlays a given pavement design will require over a 20-year period, and more importantly, the cost of the design. While the swelling clay parameter is very important in the systems approach to pavement design, the highway designer, at the present time, must rely only on experience and judgment in assigning values to the swelling clay

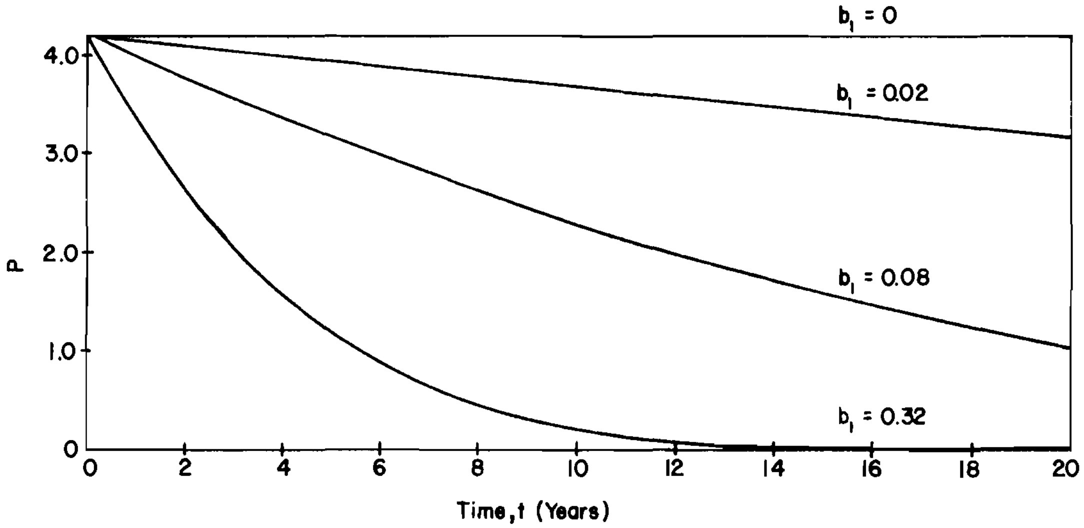

Fig 1. Four performance curves illustrating the effect of foundation movements in the absence of traffic. These curves approach lower limit of $P'_2 = 0.0$ (Ref 4).

parameter. Reasonable estimates of the swelling clay parameter, perhaps the best available at the present time, are given in Table 1.

Objective

This report describes research conducted to provide the highway designer with a better means of evaluating the swelling clay parameter than the qualitative criteria presently available (~~Table 1~~)., It shows that with a characterization of the swelling clay parameter, from a correlation with standard laboratory tests, the highway designer can determine what swelling clay value should be used in a design.

Scope

In characterizing the swelling clay parameter, research data developed from in-service pavement sections are used rather than experimental data obtained from laboratory tests. Discussion of these data is divided into three basic parts. First, the serviceability-time data are derived from actual pavement sections. Then the swelling clay parameter is quantified using the models proposed in the systems approach to pavement design. The serviceability-time model is discussed in Chapter 2. Finally, the derived swelling clay parameters are characterized using various soil properties.

TABLE 1. QUALITATIVE CRITERIA FOR EVALUATING THE SWELLING CLAY PARAMETER (REF 2)

Expected Non-traffic associated loss of serviceability	B
Light	0.02
Moderate	0.06
Heavy	0.12

CHAPTER 2. THEORY OF PAVEMENT SERVICEABILITY

Two important concepts are utilized in quantifying the swelling clay parameter, Present Serviceability Index (PSI) and the Serviceability Loss Function (Q). The first was developed at the AASHO Road Test (Ref 8) and the second was developed at TTI (Ref 4).

Present Serviceability Index

The AASHO officials recognized the need for a standard method of evaluating the condition of a pavement and developed the Present Serviceability Index, which evaluates a pavement's condition at a given time but tells nothing about its serviceability before or after. The first step in developing the PSI method was to select a panel of men representing all the important groups of highway users to rate various pavements on a numerical scale. The numerical rating system and the pavement conditions represented by it are shown in Fig 2.

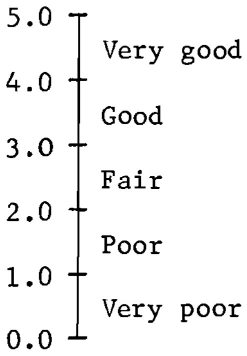

Fig 2. Numerical rating system.

The rating panel is known as the Present Serviceability Rating.

The ultimate goal of AASHO officials was to produce a mathematical model which would predict the panel's rating from various physical pavement measurements. As the panel rated the test sections, measurements designed to describe longitudinal and transverse roughness, summarize surface cracking, and measure the patched areas of the pavement were taken. Later, a regression analysis was made to find which physical pavement characteristics best predicted the performance rating the panel had given. From this, the Pavement Serviceability Index was obtained, using the mathematical expressions given below.

For flexible pavements:

$$\mathrm{PSI} = 5.03 - 1.91 \operatorname{Log} (1 + \overline{\mathrm{SV}}) - 1.38\, \overline{\mathrm{RD}}^2 - .01 \sqrt{C + P} \qquad (2.1)$$

For rigid pavements:

$$\mathrm{PSI} = 5.41 - 1.78 \operatorname{Log} (1 + \overline{\mathrm{SV}}) - .09 \sqrt{C + P} \qquad (2.2)$$

where

PSI = Present Serviceability Index,

$\overline{\mathrm{SV}}$ = mean slope variance $\times 10^6$,

$\overline{\mathrm{RD}}$ = mean rut depth (in inches), and

C+P = total cracking and patching (per 1000 feet^2).

Serviceability Loss Function

The Present Serviceability Index provides a standard method of evaluating the condition of a pavement, but the systems approach to pavement design entails an additional function, to predict the effect of various variables on the pavement's performance. Among the factors considered important in determining how a pavement's serviceability decreases with time are the materials used for the pavement and subbase, the volume of traffic carried by the pavement, the temperature variation in the region where the pavement is constructed, and the type of subgrade upon which the pavement is built. In order to satisfy the need for determining their effect, the serviceability loss function was introduced (Ref 4). It is used to predict the amount of the pavement's initial serviceability which has been lost at any given time. There are two ways to calculate this loss. The first is a historical method and involves the measurement of the present serviceability index of a pavement at two different times. One is at any time after construction of the pavement or overlay and the second is any later time desired. Equation 2.3 shows how the serviceability loss is calculated by this method.

$$Q = \sqrt{5 - P} - \sqrt{5 - P_1} \qquad (2.3)$$

where

Q = Serviceability Loss Function,

P = Present Serviceability Index of pavement at desired time,

P_1 = Present Serviceability Index of pavement at initial time.

The second method is a predictive procedure which involves the use of the various variables known to cause serviceability to decrease with time. Equation 2.4 shows how the serviceability loss is calculated by this method.

$$Q_2 = \frac{53.6\,(N_k - N_{k-1})S^2}{\bar{\alpha}} + Q_2'\left(1 - e^{-b_k(t_k - t_{k-1})}\right) \qquad (2.4)$$

The variables in Eq 2.4 are defined in Appendix 1. The definitions are taken directly from Ref 4. In this second method, the serviceability loss function is the sum of two terms. The first represents the effects of the quantity of traffic carried by the pavement, the strength of the materials used in the pavement and subbase, and the variation of temperature in the region where the pavement is built. The second term represents the contribution the swelling clay makes to the serviceability loss function.

Relationship Between Q and PSI

While the Serviceability Loss Function and the Present Serviceability Index have been treated separately thus far, they are actually directly related. By replacing the Q terms in Eq 2.4 with their corresponding PSI values, the Serviceability Loss Function can be given in terms of measured PSI values:

$$\sqrt{5 - P} - \sqrt{5 - P_1} \approx \frac{53.6(N_k - N_{k-1})S^2}{\bar{\alpha}} + (\sqrt{5 - P_2'} - \sqrt{5 - P_1})\left(1 - e^{-b_k(t_k - t_{k-1})}\right) \tag{2.5}$$

If the effect of the swelling clay alone is desired, Eq 2.5 can be reduced to

$$\sqrt{5 - P} - \sqrt{5 - P_1} = (\sqrt{5 - P_2'} - \sqrt{5 - P_1})\left(1 - e^{-b_k(t_k - t_{k-1})}\right) \tag{2.6}$$

A representation of the relationship between the Present Serviceability Index and the Serviceability Loss Function when only the effects of the swelling clay are considered (Ref 4) shows that as the PSI reading decreases, the Q function increases (Fig 3).

In this research, Eq 2.6, which assumes that all of the pavement's serviceability losses are due to swelling clay, is used for quantification of the swelling clay parameter. PSI values at various times are calculated, and with this data a regression analysis is made using Eq 2.6.

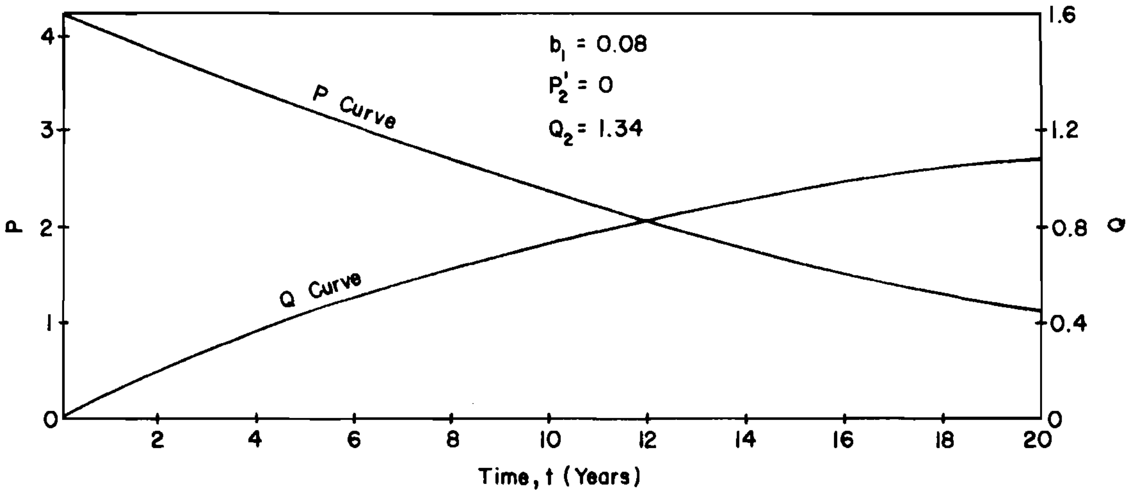

Fig 3. A performance curve and its corresponding serviceability loss curve, with no traffic operating (Ref 4).

CHAPTER 3. SELECTION OF DATA SOURCE

Chapter 3 explains the data necessary to use the available theories and the source of the data used. Research data is developed from in-service pavement sections.

Type of Data Desired

To use the Present Serviceability Index and the Serviceability Loss Function to evaluate the swelling clay parameter, a data source which met the following criteria was needed:

(1) The pavement should be on a swelling clay.
(2) The properties of the soil under the pavement should be known.
(3) The condition of the riding surface at various times should be known.
(4) The traffic over the pavement should be negligible or traffic data should be available to evaluate its effect.

The first two are important because the purpose of this research is to characterize the swelling clay parameter with respect to standard laboratory soil's tests. The third consideration is important because the swelling clay parameter is best quantified using the Present Serviceability Index and the Serviceability Loss Function. The fourth consideration is important to insure that the losses in the pavement's serviceability are due to swelling clay.

A series of recently constructed pavement which had not been opened to traffic and had been subjected only to environmental changes would have provided the needed data. The pavement chosen should have had PSI readings taken at regular intervals over several years of life. At least four or five years would be required in order to develop a trend for the swelling clay action upon the pavement's serviceability. No such ideal recently built pavement could be located. There was available, however, a well documented research study by the Texas Highway Department on a series of test sections in Guadalupe County, Texas from 1933 to 1937, which satisfied all the above requirements (Ref 9).

Guadalupe County Project

As early as 1928, the Texas Highway Department had noticed that surface irregularities were developing in certain concrete pavements across Texas as the result of unequal vertical movements at joints and cracks in the pavements. After their study, conducted in the 1930's, of the data available on these pavements, the following observations were reported (Ref 9):

(1) "No irregularities had developed on sand foundations."

(2) "Such warping, or bending or twisting out of plane, that existed had occurred on clay soils (soil classifications A-6 and A-7)."

(3) "The major portion of the irregularities developed in cuts, on hill slopes, and crests."

In an effort to determine what could be done to prevent such surface irregularities, the Texas Highway Department decided to build an experimental pavement. In 1932, Mr. Gibb Gilchrist, the Texas State Highway Engineer, outlined the purposes of the research pavement as follows (Ref 9):

(1) "A complete study, utilizing all available technical and practical information, augmented by an experimental construction project awarded to contract on plans and specifications drafted for this express purpose, which would embody all possible designs that might throw light on the subject."

(2) "The selection of a location where the natural soil and climatic conditions were similar to those where pavements in Texas and warped; and where local materials were economically available."

(3) "The compiling of costs of the different designs involved for comparative purposes."

With these objectives in mind, the Texas Highway Department began looking for a suitable site. State Highway 3A, in Guadalupe County, Texas, between Seguin and San Antonio, was selected for the following reasons:

(1) A clay soil, which would be classified as A-7, existed along the entire test section.

(2) A 9 by 6 by 9-inch concrete pavement with a 1-inch bituminous surface, located on a similar clay subgrade, had been built on a project near the proposed Guadalupe County Project. This pavement had warped within nine months after its completion.

The Texas Highway Department did not know whether the pavement warping was the result of improper pavement design, of improper construction methods, or of the clay subgrade. To determine why the pavements were warping, the Guadalupe County Project, which was 13.5 miles in length, was divided into

39 separate test sections in which there were 12 different slab designs, 7 different concrete mixes, and 18 different subgrade treatments. The variables involved in these test sections were:

(1) subgrade preparation,
(2) concrete mix design,
(3) joint spacing,
(4) amount of longitudinal reinforcing steel,
(5) thickness of slab, and
(6) waterproofing of the bottom and sides of the slab.

A complete description of each of the 39 test sections may be found in Ref 9.

The Texas Highway Department decided to record any data from the Guadalupe County Project which might help explain the swelling clay problem, feeling that it was better to record too much data than too little. The following general types were recorded:

(1) description of construction methods,
(2) paving construction progress,
(3) history of subgrade moisture contents,
(4) class and characteristics of the soil foundation,
(5) history of vertical movements of the pavement,
(6) progressive pictures of construction methods and observations,
(7) concrete design and strength,
(8) detailed cost,
(9) fluctuations in widths of expansion joints,
(10) meterological,
(11) temperature fluctuations between top and bottom of slab,
(12) slab condition surveys, and
(13) miscellaneous.

An expansion of two of the above categories is given here to emphasize the vast amount of data recorded on the Guadalupe County Project. To record meterological data, a complete meterological unit was installed and operated continuously until the project ended. Among the meterological data recorded were a continuous record of the fluctuations in temperature, wind velocity, and humidity; a daily record of when and how much precipitation fell on each test section; sunrise and sunset times for each day; and finally, the character of each day. Among the types of data recorded under the general category of miscellaneous are (1) the pressure existing between the pavement and subbase, determined by pressure cells installed in some of the test sections, and (2) any creep of the pavements on a hillside, detected by markers installed in the pavement. The Guadalupe County Project contains a wealth of other information on concrete pavements.

From the Guadalupe County Project, much of the information required to characterize the swelling clay parameter could be obtained or estimated. Although it was not constructed recently, it was the best source of data which could be found. The criteria used to determine which of the data provided by the Guadalupe County Project should be used are discussed in Chapter 4.

CHAPTER 4. SELECTION AND EVALUATION OF APPLICABLE DATA

Data Selection

Because of the large amount of data available from the Guadalupe County Project, it was desirable to select and use only that data which would be important in this research. The following general categories were considered pertinent to characterization of the swelling clay parameter:

(1) description of construction methods,
(2) history of subgrade moisture contents,
(3) class and characteristics of the soil foundation,
(4) history of vertical movements of the pavements, and
(5) slab condition surveys.

The construction methods data contained such important information as (1) whether the pavement section was on a cut or on a fill, (2) the general terrain in the area, (3) the way the roadway was formed, (4) the condition of the subgrade when it was compacted, and (5) any troubles encountered in building the pavement. This information was important because it was necessary that all of the test sections used in this research study be built in the same way.

The history of the subgrade moisture content furnished information on variations in the moisture content from the initial construction of the pavement to the end of the project.

The class and characteristics of the soil foundation data furnished information about the soil on which the pavement was constructed, data were obtained by taking samples approximately every 300 feet along the entire length of the project. These samples were taken at depths of 0, 6, 12, 24, and 36 inches below the natural ground line. The soil was also sampled at intervals perpendicular to the center line of the pavement up to a distance of 20 feet, which was 10 feet beyond the pavement's edge in each direction. These samples were sent to Austin, and laboratory tests were conducted to determine the following data:

(1) liquid limit,
(2) plastic limit,
(3) plasticity index,
(4) shrinkage limit,
(5) linear shrinkage limit,
(6) field moisture equivalent,
(7) centrifugal moisture equivalent, and
(8) soil classification.

Data on the vertical movements of the pavements and slab condition surveys data were required to quantify the swelling clay parameters. The vertical movements of the pavements were recorded by taking rod readings along the length of the pavement. The slab condition surveys furnished data on the number and width of cracks that developed in the pavement, along with the date the cracks occurred, and also identified any leaking joints.

Selection of Test Sections

The Guadalupe County Project furnished plentiful data to use in the characterization of the swelling clay parameter. The next step was to decide which of the 39 test sections would be used. The project had attempted to test so many variables that a full factorial would have required over one million test sections. Since there were only 39 different test sections on the project, all the test variables could not be adequately evaluated. For the swelling clay analysis the test sections needed as many of the design variables as possible constant.

The main concern of this study was the effect of the swelling clay on the pavement; therefore, two requirements were placed on the test sections selected. First, all the design variables for the test sections had to be the same; and secondly, the soil properties of the subgrades under the different test sections had to be different. Six sections, which had the same design variables, were found if the concrete mixes were considered the same because their flexural strengths were the same. Sections 2, 14, 16, 21, and 33 met the first requirement. The sections on the Guadalupe County Project were consecutive. All had a natural earth subgrade, a concrete pavement thickness of 9 by 6 by 9 inches, regular slab reinforcement, one dummy joint per slab, and a concrete flexural strength of 600 psi. The pavement slabs were lightly reinforced by 1/2-inch-diameter bars around the perimeter and dowel bars, 4 feet in length and 1/2 inch in diameter, perpendicular to the center line of the pavement on 5-foot ceneters (Fig 4).

Testing of Selected Sections

After the test sections which had the same design variables were selected, a means of determining whether the subgrade soil properties were different under the various test sections was required. The Scheffe Test, which is given in Appendix 2, was used to test for a significant difference in the subgrade properties. The average plastic index PI for each section was determined from the available data. The means and standard deviations of the plastic index for each section were used with the Scheffe Test to determine if there was a significant difference in the subgrade soil properties of the test sections. The Scheffe Test, with $\alpha = .05$* , showed that there was not a significant difference between Sections 16 and 21, and 14 and 21. While the Scheffe Test showed that the subgrade soil properties in Sections 14 and 21 were not significantly different, the vertical profiles in the sections were greatly different; therefore, these sections were retained in the research. Sections 16 and 21 both had the same subgrade soil properties and the same vertical profiles; therefore, only Section 21 was retained. The average PI values for each section and the results of the Scheffe Test are shown in Appendix 2.

Each test section contained at least 15 slabs, each of which was 78.5 feet long. The slabs within each section were numbered consecutively. Many of the slabs within a section did not have vertical profile readings recorded for them, while other slabs had only a few vertical profiles recorded. For estimating the Present Serviceability Index of a pavement, it was felt that there should be at least two adjacent slabs which could be used and that soil samples should have been taken from the subgrade under these slabs. While the test slabs were short for estimating PSI changes, they offered an advantage in that the soil properties would remain fairly constant under the slabs. In Sections 2, 14, and 33, two sets of slabs satisfied all of the above requirements. The two sets of slabs in each of the three sections had varying vertical

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*A level of significance, α , of .05 means that the Scheffè Test will give the correct answer in 95 percent of the cases tested.

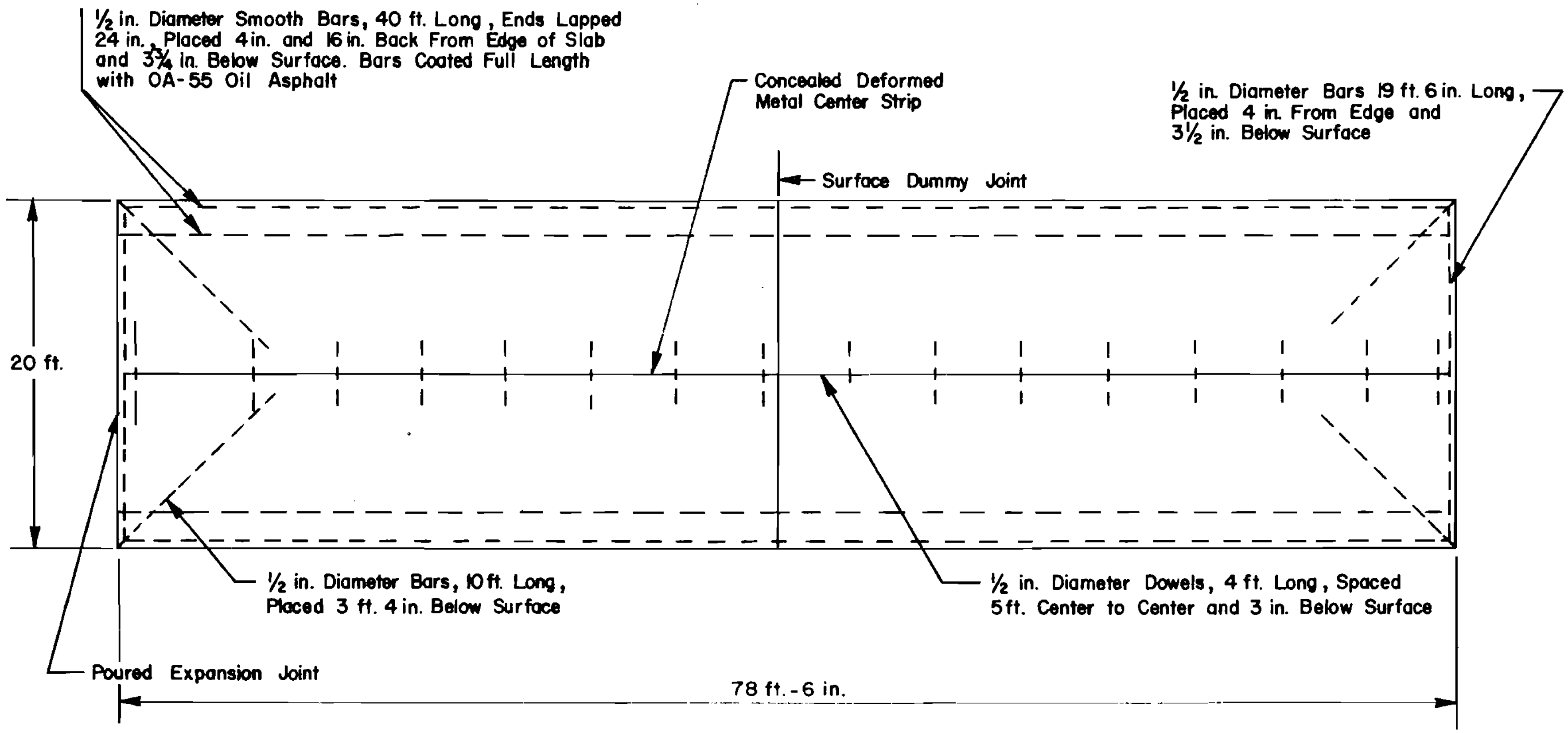


Fig 4. Regular reinforcement.

profiles; therefore, the average value of the PI of the soil under each set of slabs was calculated and found to vary within a given section. The Student "t" test was used to determine that the PI differences were really significant, and by calculating the PI values under the test slabs, eight different test slab sets were found (Table 2). The average PI values used for test test slabs and the results of the Student "t" test are given in Appendix 2.

The condition of the pavement at various times was given as vertical profiles rather than directly as PSI readings. Although the vertical profile readings were not the desired data, from them an estimate of the slope variance could be obtained. PSI values are a function of a pavement's average slope variance and the amount of cracking and patching which has taken place (Eq 2.2).

During the Guadalupe County Project, crossmarks were put in the pavement when the concrete was placed, and, thus, it was possible to take rod readings at the same spot every time. In running the levels, temporary benchmarks were placed every half mile. The rod readings were spaced at 1/4, 5, 10, 20, and 39 1/4 feet from each end of the test slabs (Fig 5).

Vertical profile data were available for several dates during the life of the pavement, and it was necessary to determine the dates on which it would be worthwhile to convert the vertical profiles to PSI readings. The necessary criteria required that the vertical profile readings be available for both adjacent slabs on the same date.

Profiles were not usually recorded for both slabs before two years after pouring. The times at which the vertical profiles for each test slab set were analyzed are shown in Fig 6, as the number of days after the concrete was poured.

Based on these data selected from the Guadalupe County Project, it was possible to quantify the swelling clay parameters for the selected sections as discussed in Chapter 5.

TABLE 2. SECTIONS AND SLABS USED IN THE STUDY

Section Number	Slab Numbers
2	3, 4
2	8, 9
14	4, 5
14	14, 15
21	1, 2
33	3, 4
33	13, 14, 15

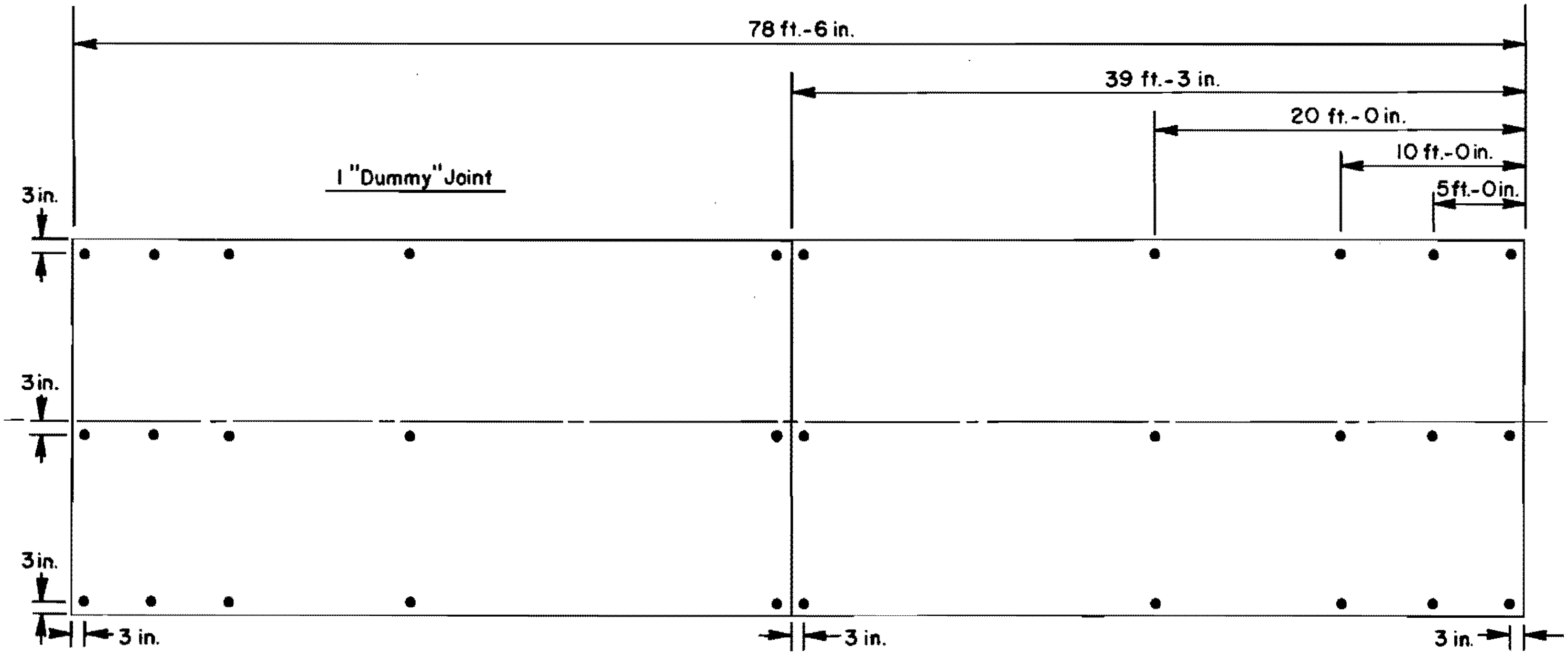


Fig 5. Spacing of rod readings for slab profiles.

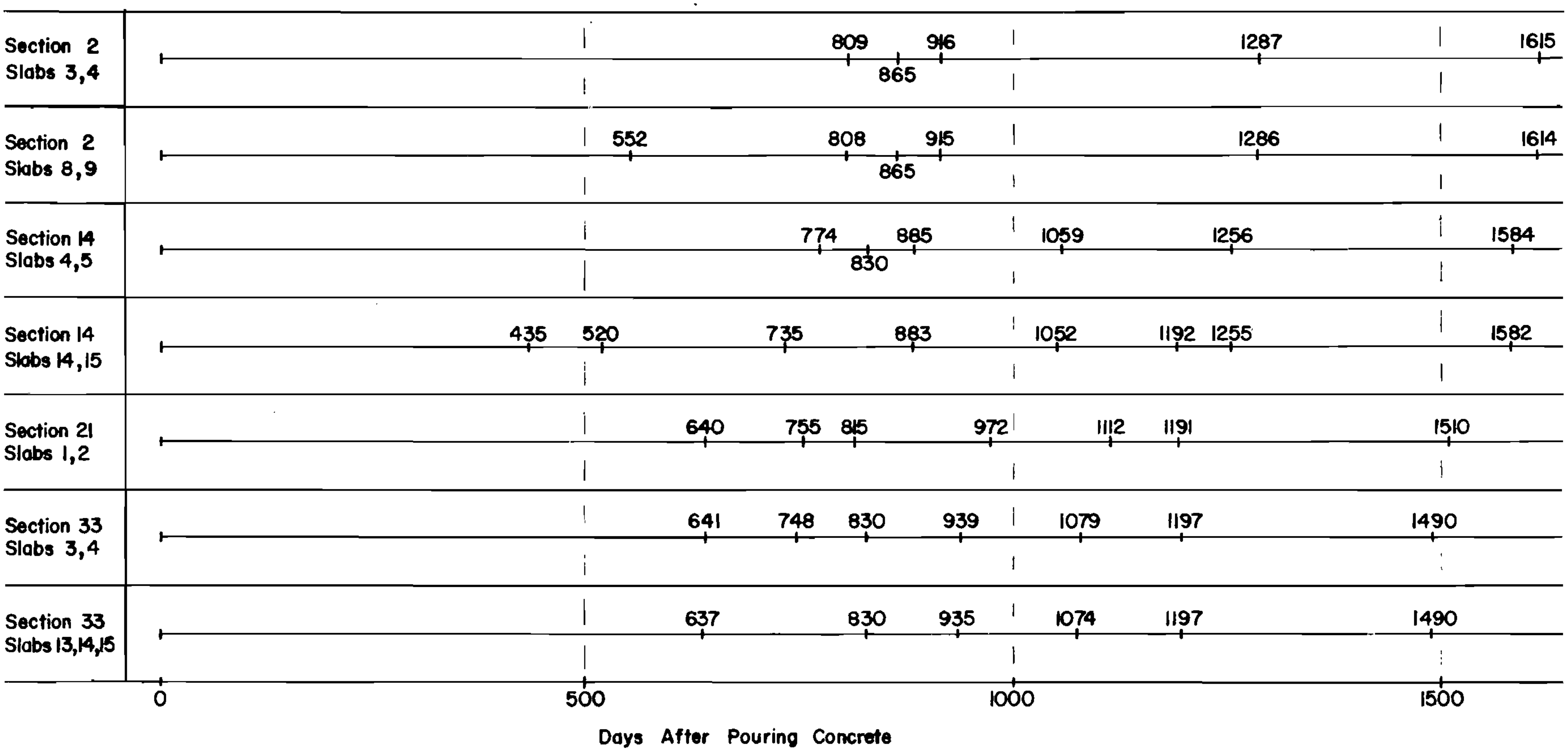


Fig 6. Age of slabs when vertical profiles were taken.

CHAPTER 5. QUANTIFICATION OF SWELLING CLAY PARAMETER

Quantification of the swelling clay parameter was divided into three stages. First, the vertical profiles were converted into average slope variances. Then the average slope variances were converted into PSI values for each data. The resulting PSI versus time data were used to quantify the swelling clay parameter as discussed below.

Conversion of Vertical Profiles to Slope Variance

For each test slab, three different vertical profiles were recorded — north, center, and south. The north and south profiles were taken along the north and south edges of the slab, and the center profile was taken just to the right of the pavement center line. A typical vertical profile is given in Appendix 3.

A computer program was written to convert the vertical profile readings for each section into average slope variances. Slope variance is the variance of the pavement slopes calculated from one of the vertical profiles. The average slope variance is the average value of the three vertical profiles taken from each slab set. The average slope variances computed from the vertical profiles are based on vertical distances taken over a longer horizontal distance than the AASHO Road Test. The AASHO Road Test took vertical measurements every 9 inches, and the Guadalupe County Project took vertical measurements up to 20 feet apart. While the average slope variance values obtained from each method may vary slightly, the project data will be useful. Basically, the program computed the slope variance for each of the three profiles and then used the average of the three values as the average slope variance for that particular time. Appendix 3 gives a description of the computer program and how to use it. Figures 7, 8, 9, and 10 show how the slope variance changed with time. While the slope variance generally increased with time, the increase was not smooth.

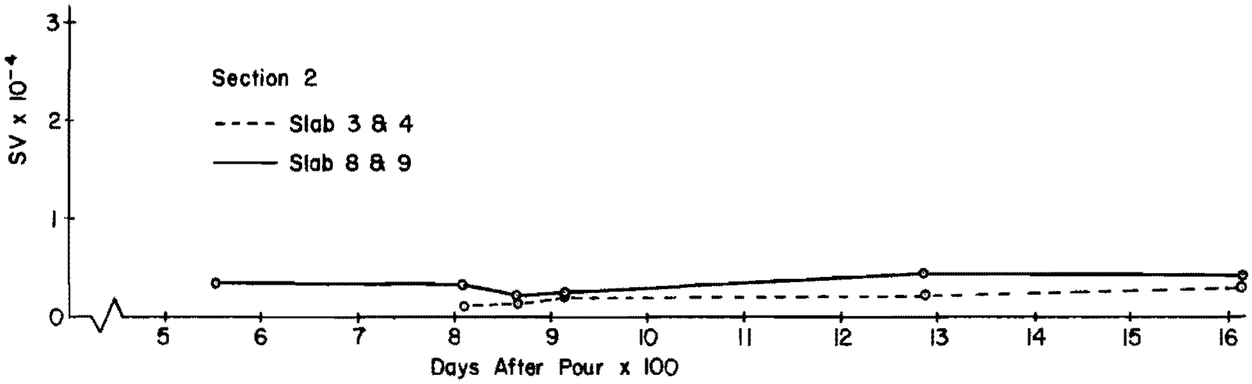


Fig 7. Slope variance versus pavement age.

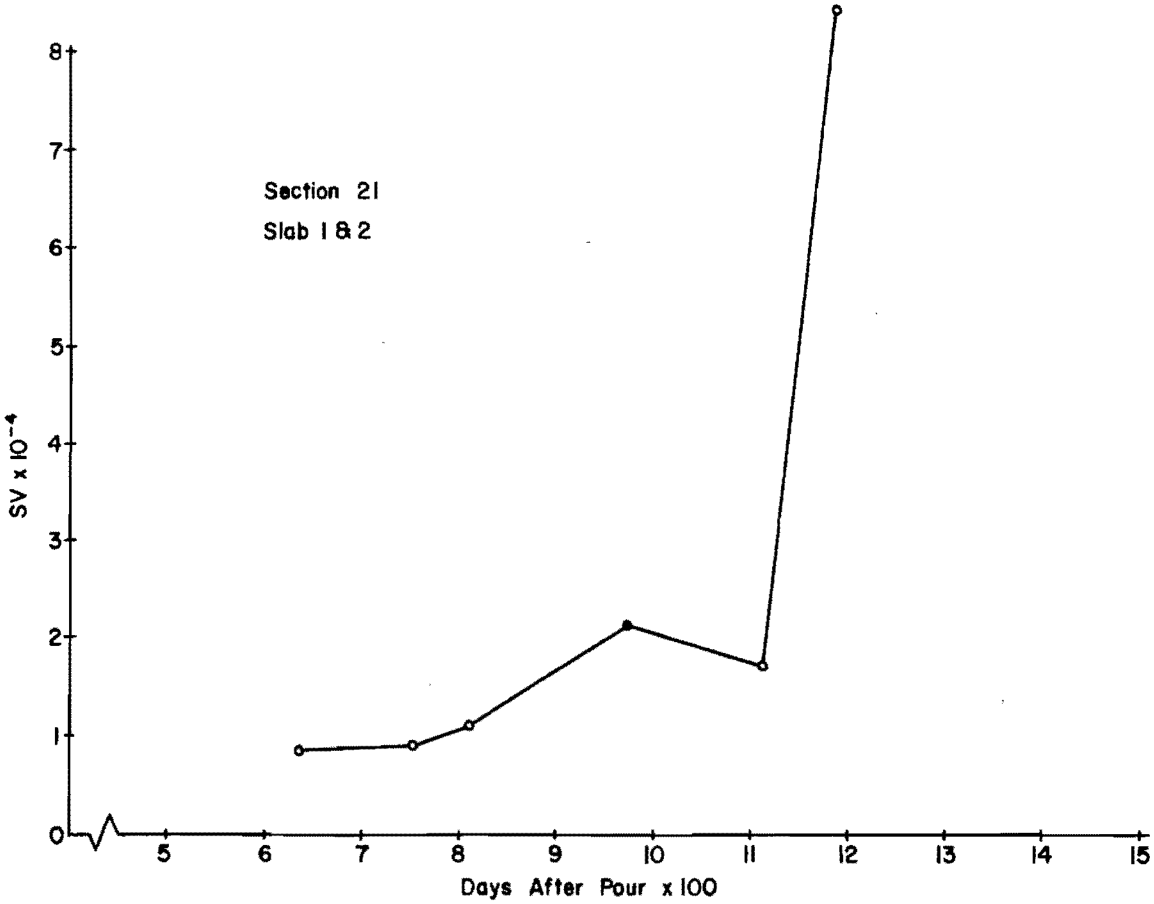


Fig 8. Slope variance versus pavement age.

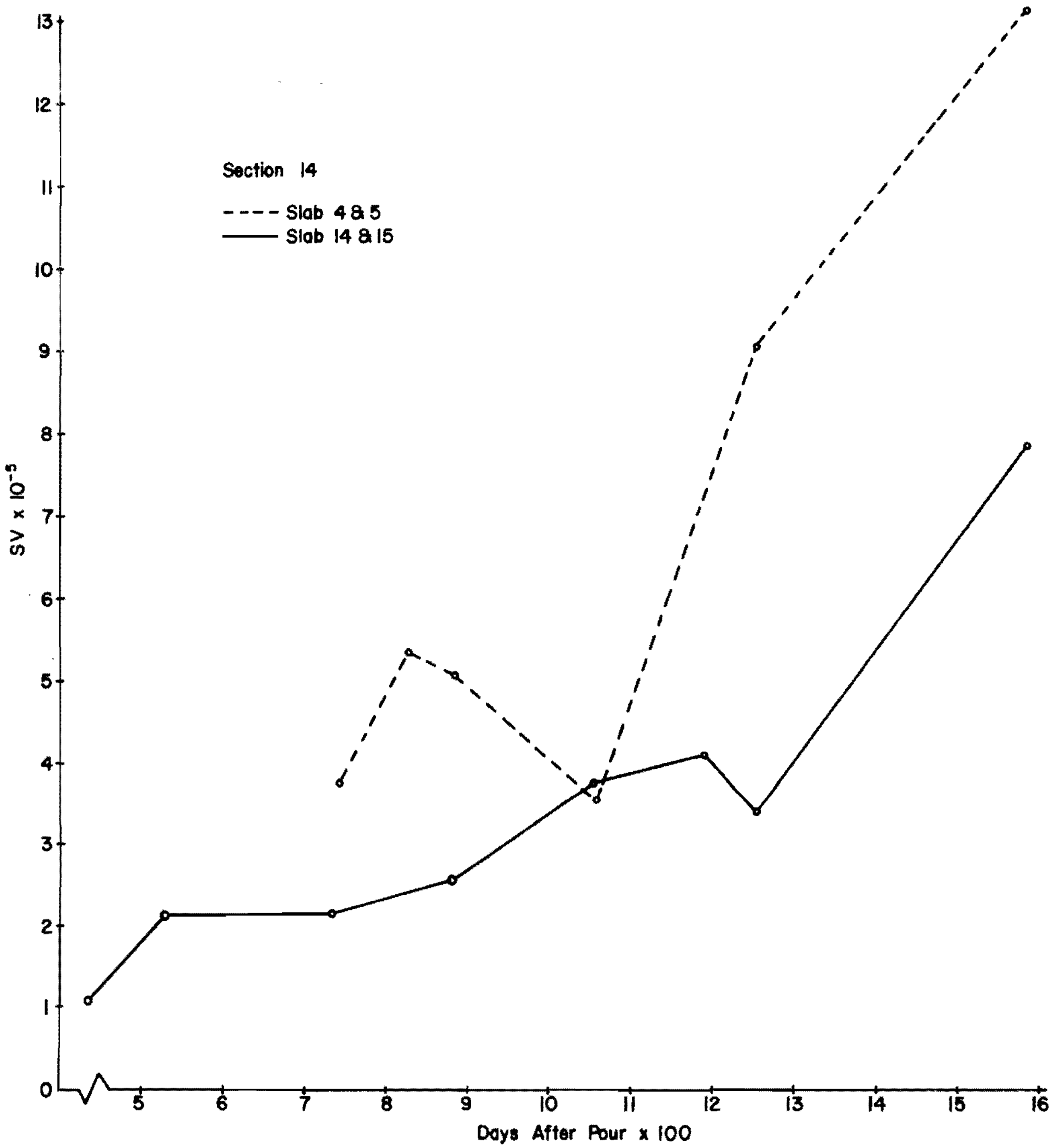


Fig 9. Slope variance versus pavement age.

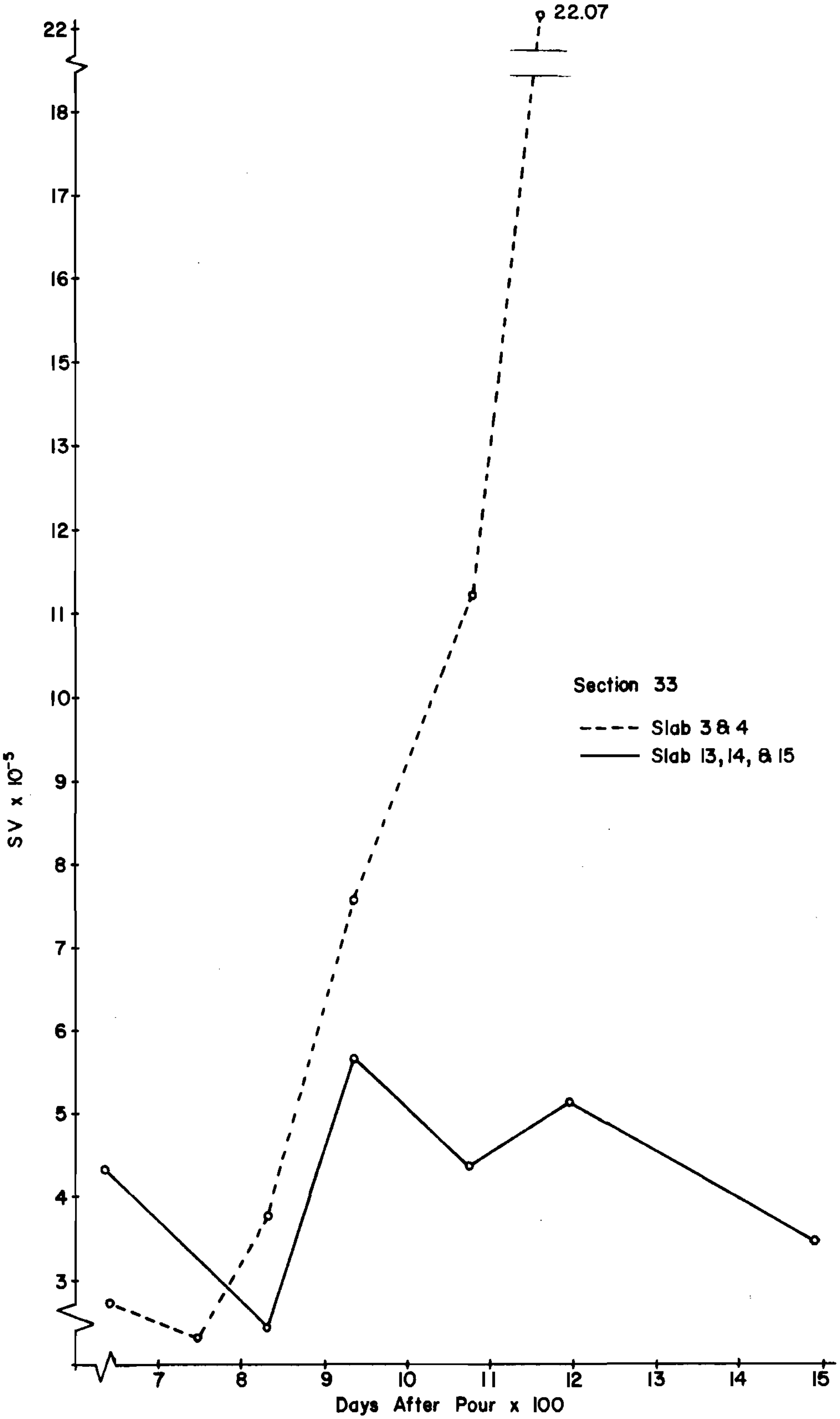


Fig 10. Slope variance versus pavement age.

Conversion of Slope Variance to Present Serviceability Index

After the average slope variance for each test slab had been computed for each of the readings, the variances were converted to Present Serviceability Index values. With the slab survey data and the slope variance values, the psi values could have been calculated:

$$\text{PSI} = 5.41 - 1.78 \text{ Log } (1 + \overline{\text{SV}}) - .09 \quad C + P \tag{5.1}$$

The definition of each of the terms in this AASHO equation is given in Chapter 2. If each slab had four transverse cracks 1/16 inch wide, the PSI of the slab would be decreased by only .055. The slope variance, which contributes largely to the quality of the riding surface, is greatly influenced by the swelling clays. Since the cracking and patching contributed so little to the PSI in comparison with the slope variance, the last term in Eq 5.1 was omitted, and the PSI values were calculated with Eq 5.2.

$$\text{PSI} = 5.41 - 1.78 \text{ Log } (1 + \overline{\text{SV}}) \tag{5.2}$$

By substituting the slope variance computed from the vertical profile readings into Eq 5.2, the PSI values for the test sections were computed. Figures 11, 12, 13, and 14 show how the PSI values varied with time. The PSI of the test slabs generally decreased with time.

Conversion of PSI Versus Time Data into Swelling Clay Values

With the PSI versus time data available, the quantification of the swelling clay parameter required the use of the Serviceability Loss Function, discussed in Chapter 2. The Serviceability Loss Function is a function of the amount of traffic the pavement carries and the swelling clay parameter. For light traffic volumes, the traffic's contribution to the loss in pavement serviceability is negligible in the first years of a pavement's life; however, the major portion of a pavement's serviceability lost due to swelling clay generally occurs

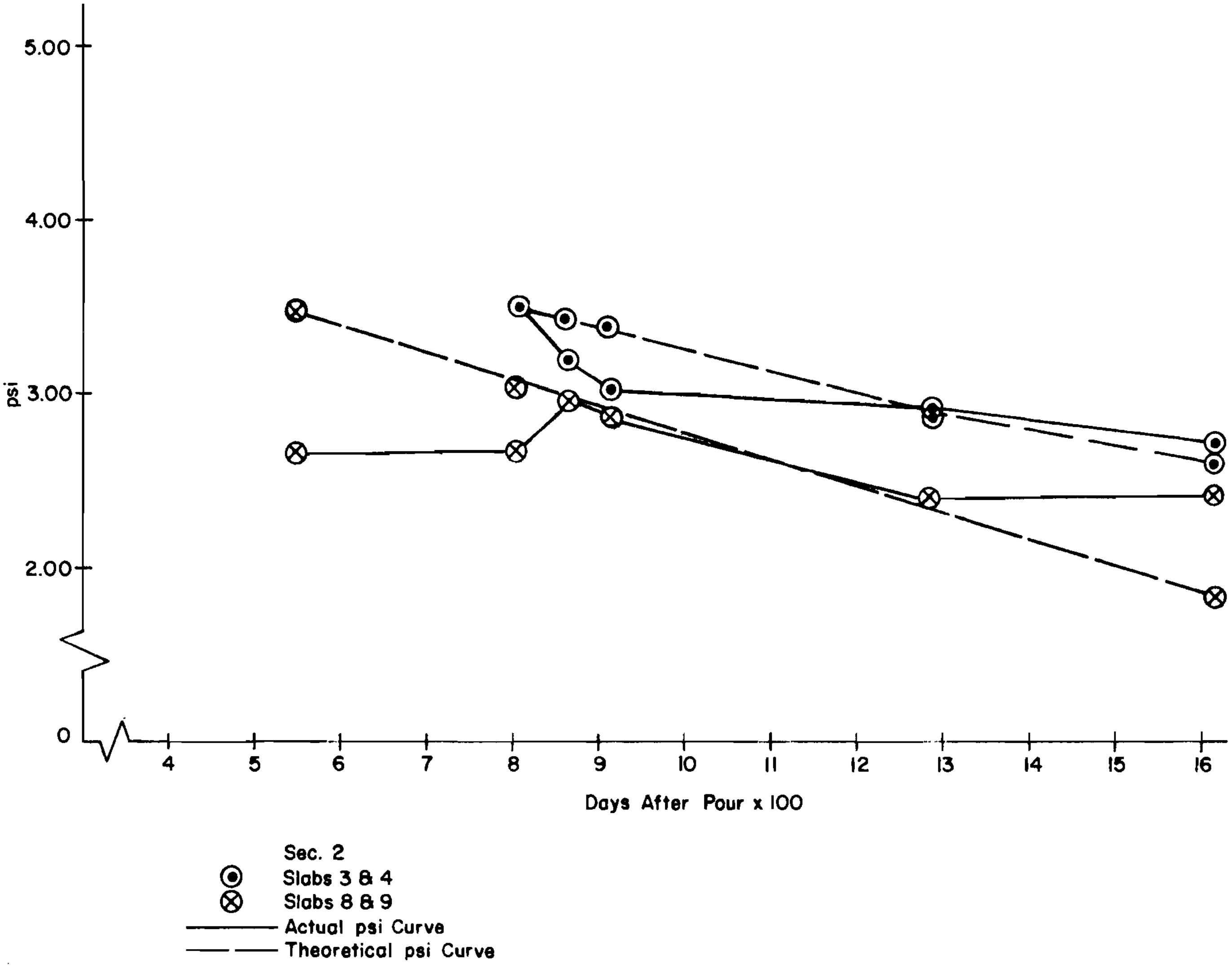


Fig 11. PSI versus pavement age.

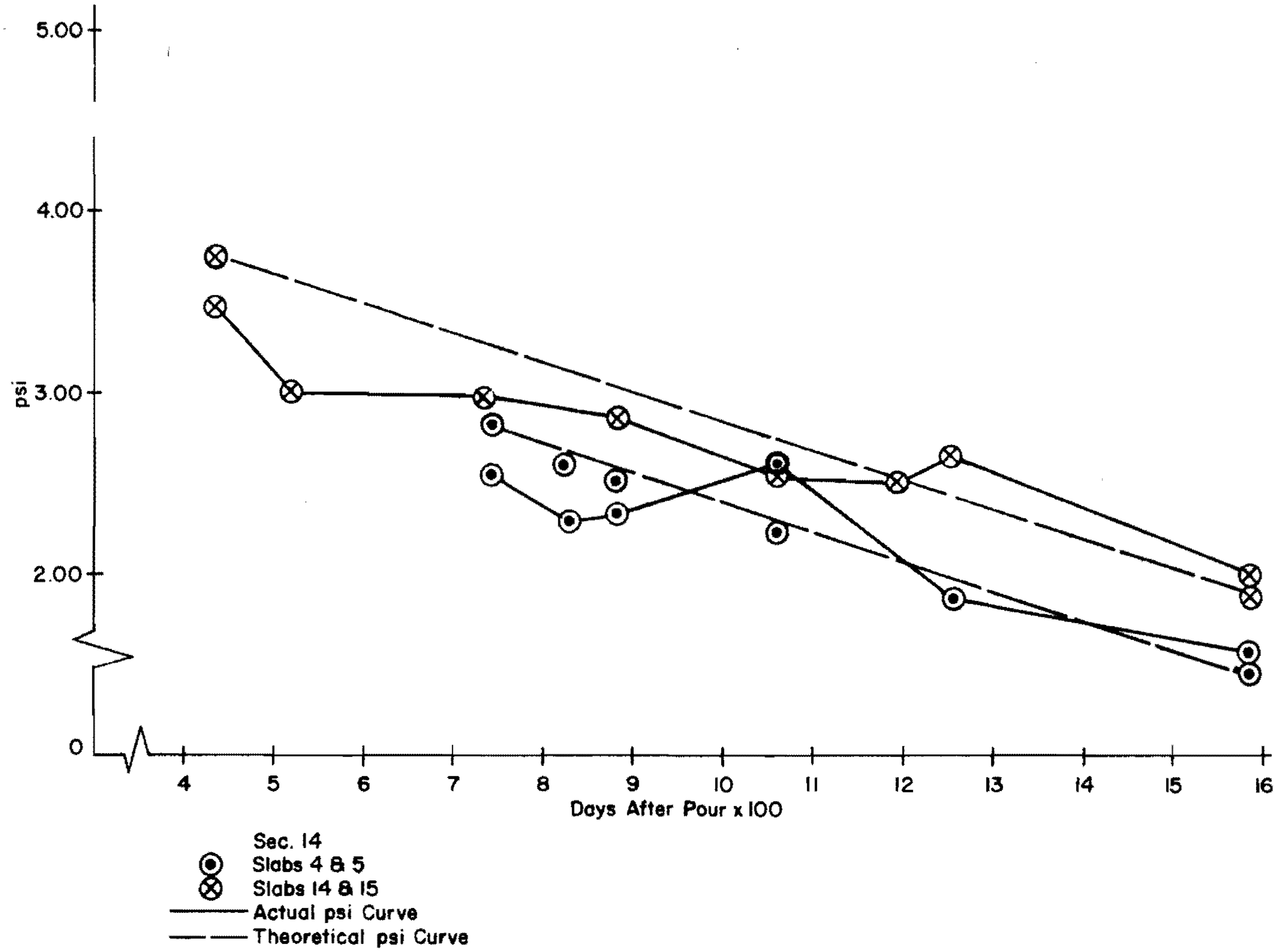


Fig 12. PSI versus pavement age.

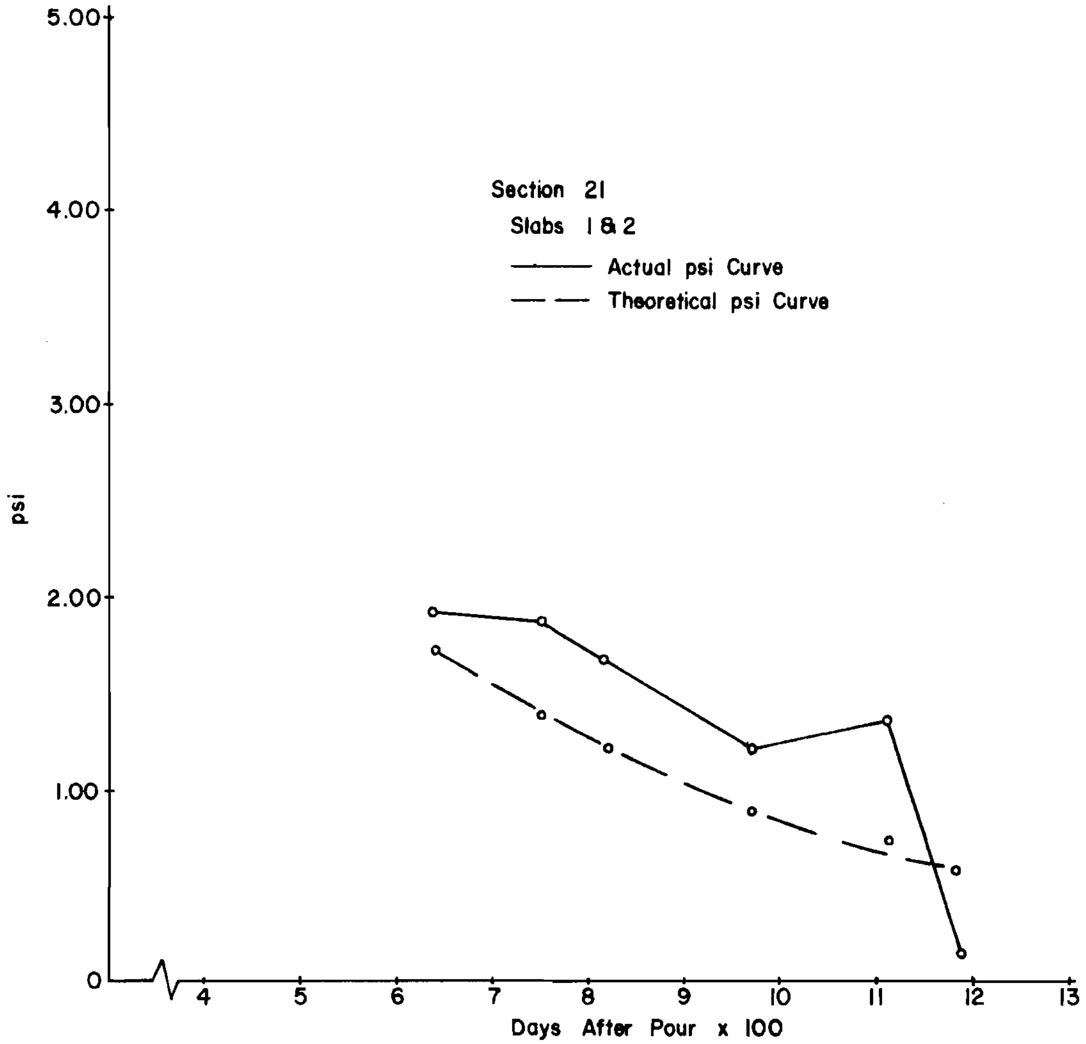


Fig 13. PSI versus pavement age.

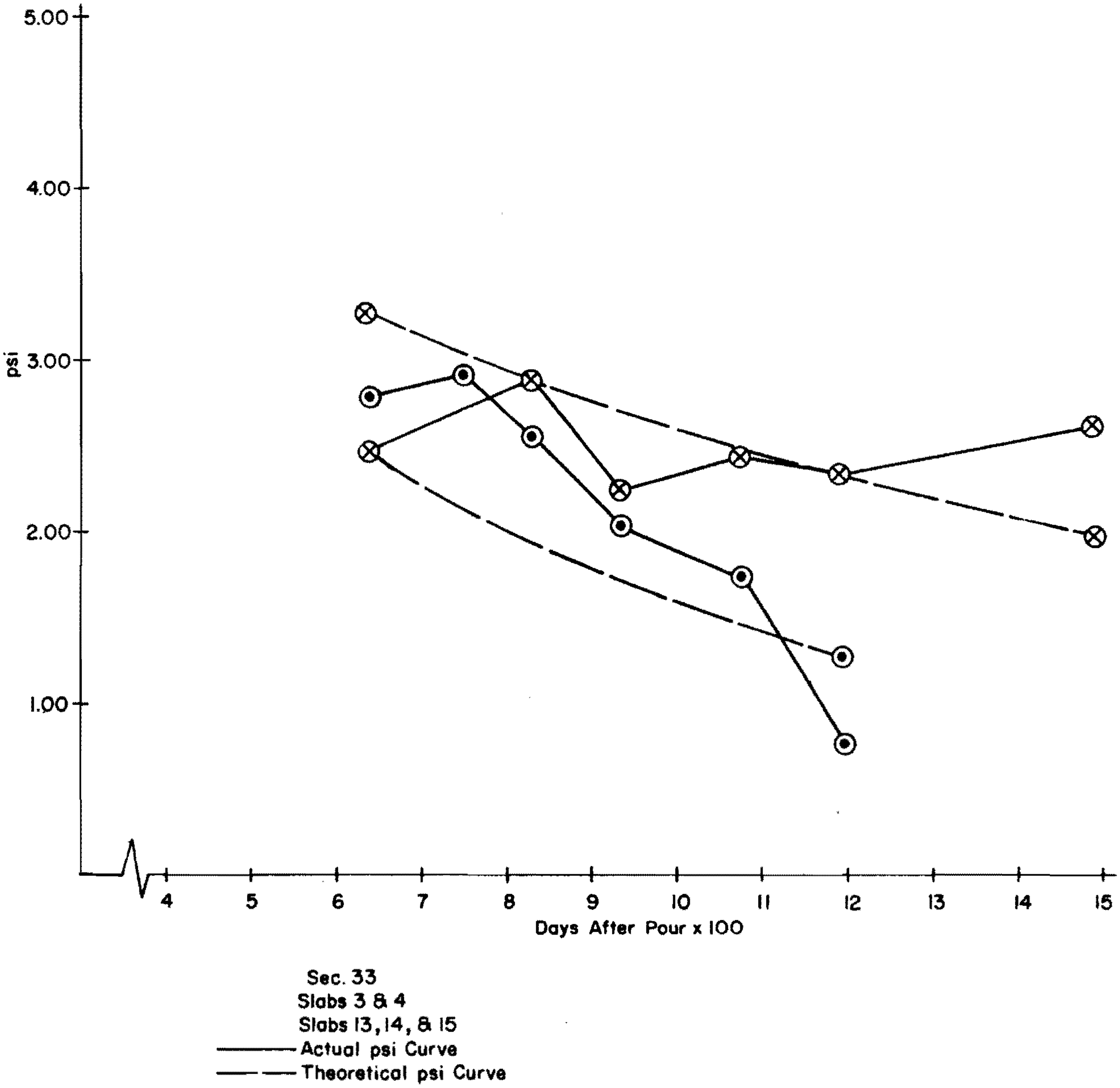


Fig 14. PSI versus pavement age.

during the first five years of the pavement's life. Since a pavement which was near the Guadalupe County Project and on the same type of soil warped within nine months after construction, the assumption that the loss in the pavement's serviceability was due to swelling clay is probably valid. Assuming that the swelling clay accounts for all the pavement's loss in serviceability, the Serviceability Loss Function can be defined by

$$Q_2 = Q_2' \left[1 - e^{-b_k(t_k - t_{k-1})} \right] \tag{5.3}$$

The pavement's initial PSI value (P_1) was taken as 4.5 while the lowest PSI value (P_2'), due to swelling clay, was taken as 0.0. With the Serviceability Loss Function defined as a function of the swelling clay alone and P_1 and P_2' defined as 4.5 and 0.0, respectively, a regression analysis could now be made to quantify the swelling clay parameter. Initially the regression analysis was made using a P_2' of 1.0; however, this yielded beta values which seemed too high. Equation 5.3 was converted into a linear equation for use in the regression analysis. For the derivation of the equation used in the regression analysis, see Appendix 4. While this regression could have been made using hand calculations, it was considered best to use a statistical computer program Step-01, a computer program developed by UCLA and modified by the Center for Highway Research at The University of Texas at Austin. The program is capable of performing both single and multiple linear regressions. In a multiple regression analysis, a series of regressions are made by adding one new variable after each regression. Besides computing the linear regression equation, the program also calculates the coefficient of correlation and standard deviation which correspond to that equation. For a full description of Step-01 and the type of output it generates, see Appendix 5. The results of the regression analyses are given in Table 3. After the beta values were quantified, the theoretical PSI versus time curves were plotted on the actual PSI versus time graphs (Figs 11, 12, 13, and 14).

Discussion of Swelling Clay Values

After the regression analyses characterizing the swelling parameter had been completed, it was noted that the beta values given for slabs 1 and 2 of

TABLE 3. RESULTS OF REGRESSION ANALYSES TO DETERMINE BETA

Section and Slab Number	Beta	R^2	Standard Deviation	R^2 Required for $\alpha = .05$
Section 2 Slabs 3 and 4	.189	.9807	.0927	.8783
Section 2 Slabs 8 and 9	.270	.9010	.2861	.8114
Section 14 Slabs 4 and 5	.337	.9835	.1443	.8114
Section 14 Slabs 14 and 15	.268	.9787	.1186	.7067
Section 21 Slabs 1 and 2	.729	.8817	.7483	.8114
Section 33 Slabs 3 and 4	.488	.9545	.2959	.8114
Section 33 Slabs 13, 14, and 15	.283	.9237	.2590	.8114

Section 21, and slabs 3 and 4 of Section 33 were higher than the other sections. In order to try to account for these differences, the construction procedure used for each of the test sections was reviewed (Table 4). Each of the three high beta values could be traced back to the construction procedure. Section 21 had a leaky joint at the end of slab 1 which allowed free water to enter the subgrade during rainy periods and cause additional swelling of the subgrade. Slabs 3 and 4 of Section 33 had high beta values because 14 feet of slab 4 had been subjected to ponding, while the remaining portion and slab 3 had not been. As a result of the ponding, the last 14 feet of slab 4 did not move as much as the remaining portion. A new beta was calculated considering just slab 3, and a lower value of .433 was obtained.

TABLE 4. CONSTRUCTION PROCEDURE FOR EACH OF THE SECTIONS

	Scarified	Sprinkling	Compaction	Comments
Section 2, Slabs 3 and 4 Station 83 + 57.1 to Station 85 + 14.3 Slabs 8 and 9 Station 87 + 50 to Station 89 + 7.1	6 inches	1860 gallons per station	Rolled twice with 5-ton 3-wheel roller	Ponded Station 91 + 00 to Station 93.0. Terrain was flat and uniform, light fill 1 1/2 inch deep. After soil was scarified to 6 inches and pulverized with a tooth harrow, soils was thoroughly wetted and pulverized with a scarifier and tooth harrow again. Soil wet again and forms set in place.
Section 14, Slabs 4 and 5 Station 225 + 95.5 to Station 227 + 52.5 Slabs 14 and 15 Station 233 + 80.5 to Station 235 + 40.0	Not scarified or harrowed	1050 gallons per station rain one week before pour add 950 gallons per station	Rolled twice with 5-ton 3-wheel roller after rain	Embankment ponded Station 224 + 00 to Station 235 + 40 comparatively high-fill because section in low area adjacent to the Santa Clara Creek. Fill = 2 feet to 8 feet, average 6 feet. After soil swelled considerably, 1/2 to 3/4 inch soil removed and compacted. During paving, numerous mixer delays because of inadequate water supply flat.

(Continued)

TABLE 4. (CONTINUED)

	Scarified	Sprinkling	Compaction	Comments
Section 17, Slabs 7 and 8 Station 272 + 91.0 to Station 274 + 48.0	Not scarified or harrowed	1270 gallons per station rain five days before pour 87 gallons per station	Wet lightly, rolled twice with 5-ton 3-wheel roller	Embankment contained some gravel, gypsum, and rock. Fill = 1 foot deep. Section on hillside. 4.066 percent grade.
Section 21, Slabs 1 and 2 Station 315 + 40 to Station 316 + 97	Not scarified or harrowed	1775 gallons per station	Wet lightly, rolled twice with 5-ton 3-wheel roller	Terrain fairly flat, .52 percent grade. 2 1/2-foot cut to fill. In preparation of subgrade, numerous shrinkage cracks noticed in shoulders and slopes. Trace of gypsum in Slab 1. The pavement rose noticeably at a transverse open crack. Leaky crack, whole pavement rose. Ponded Station 326 + 50 to Station 327 + 20.
Section 33, Slabs 3 and 4 Station 458 + 57 to Station 460 + 14.0	No	1700 gallons per station .53-inch rain	Wet lightly, rolled twice with 5-ton 3-wheel roller	Light fill = 1 to 1.8 foot. After embankment construction, embankment was jetted and ponded from Station 460 + 00 to Station 463 + 00. Encompasses 14 feet of Slab 4.
Slabs 13, 14, and 15 Station 466 + 42 to Station 468 + 80	No	1700 gallons per station .53-inch rain	Wet lightly, rolled twice with 5-ton 3-wheel roller	

CHAPTER 6. CHARACTERIZATION OF SWELLING CLAY PARAMETER

Having quantified the swelling clay parameter, Chapter 6 characterizes this parameter. Various soil data are used in the characterization. Both single and multiple regression analyses are performed.

Soil Data Considered

The Guadalupe County Project provided a wealth of information which could be used for characterizing the swelling clay parameter. The beta value was expressed as a function of the soil properties in the regression analysis. The soil properties could be broken down into three categories. The first two categories are useful in predicting soil behavior and are thus known as predictive soils tests. The first category concentrates on present-day laboratory tests and the second on outmoded laboratory tests. The third category is historical, giving a history of the behavior of the subgrade over a period of time.

The first category was soil data obtained from standard laboratory tests performed on soil samples before the pavement was constructed. In this first group are the liquid limit (LL), the plastic limit (PL), the plasticity index (PI), the shrinkage limit (SL), and the linear shrinkage limit (LSATLLI). The second category was data obtained from obsolete laboratory tests performed on soil samples before the pavement was constructed. In this group are the field moisture equivalent (FME), used to predict the maximum obtainable soil moisture content under the pavement; and the centrifugal moisture equivalent (CME), used to predict the minimum obtainable soil moisture content under the pavement.

The third category of data provided was soil data taken on the subbase after the pavement was placed. These data provided information on how the moisture content in the subbase varied with time. From these data the observed maximum and minimum moisture contents were obtained.

Single Regression Analysis

The single regression analysis was performed to see how much of the variation in beta could be explained by any one soil variable and to give guidance in conducting the multiple regression analyses. Before running any single regression analysis, the swelling clay parameters were plotted against the various soil variables to determine what type of line might best fit the data. A straight line was felt to be a good assumption for the line of fit, based on examination of the various plots. Figures 15 and 16 show the data points and the line of best fit found by the regression analyses.

Table 5 shows the regression equations produced for each of the variables, along with the coefficient of correlation and standard error for each equation. Generally, the single regression analyses showed very little correlation with the swelling clay parameter. Only two variables were able to predict over 30 percent of the variation in beta. The observed maximum moisture change predicted 59 percent of the variation in beta, while centrifugal moisture equivalent predicted 33 percent of the variation in beta. Since no one single variable predicted the beta value very well, multiple regression analyses were used.

Multiple Regression Analysis

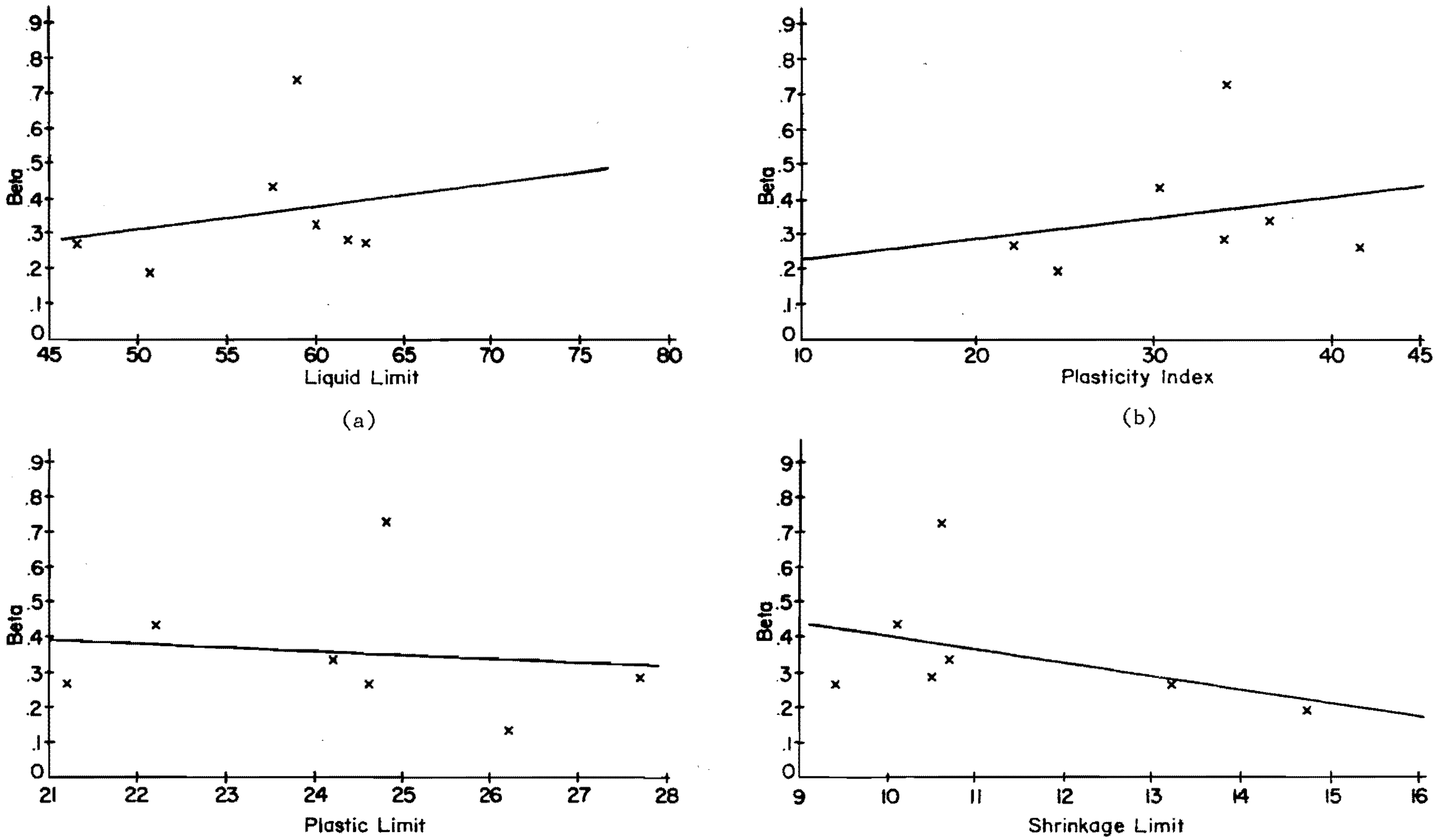
The multiple regression analysis was made to determine what combination of soil data would give the best characterization of the swelling clay parameter. The multiple regression, like the single regression, was made using Step-01 which is described in Appendix 5.

It was necessary to decide how many of the eight variables should be listed at one time. Since there were only seven beta values available, the largest number of variables, not counting the beta value, that could be tested at one time was four. While groups of four variables would have required 35 analyses, it was felt that 35 regression analyses were too many because the single regression analysis showed that some of the soil variables explained little of the variation in beta. Also, 35 regression analyses would involve undue computer time. Therefore, elimination of some of the required regressions was desired.

Since the purpose of the research was to develop a reasonable characterization of the swelling clay parameter with respect to some standard laboratory

TABLE 5. RESULTS OF SINGLE REGRESSION ANALYSES

Soil Property Used	R^2	Standard Deviation
Beta versus liquid limit (LL)		
B = .02226 + .00598(LL)	.0438	.1925
Beta versus plastic limit (PL)		
B = .60196 - .00997(PL)	.0151	.1953
Beta versus plasticity index (PI)		
B = .16315 + .00614(PI)	.0542	.1914
Beta versus shrinkage limit (SL)		
B = .80037 - .03906(SL)	.1710	.1792
Beta versus linear shrinkage limit (LSATLLI)		
B = -.02092 + .02013(LSATLLI)	.0890	.1879
Beta versus field moisture equivalent (FME)		
B = -.40567 + .0200(FME)	.0900	.1878
Beta versus centrifugal moisture equivalent (CME)		
B = -.43001 + .02027 (CME)	.3349	.1605
Beta versus actual maxiumum moisture change (AMC)		
B = -.62540 + .09306 (AMC)	.5907	.1259



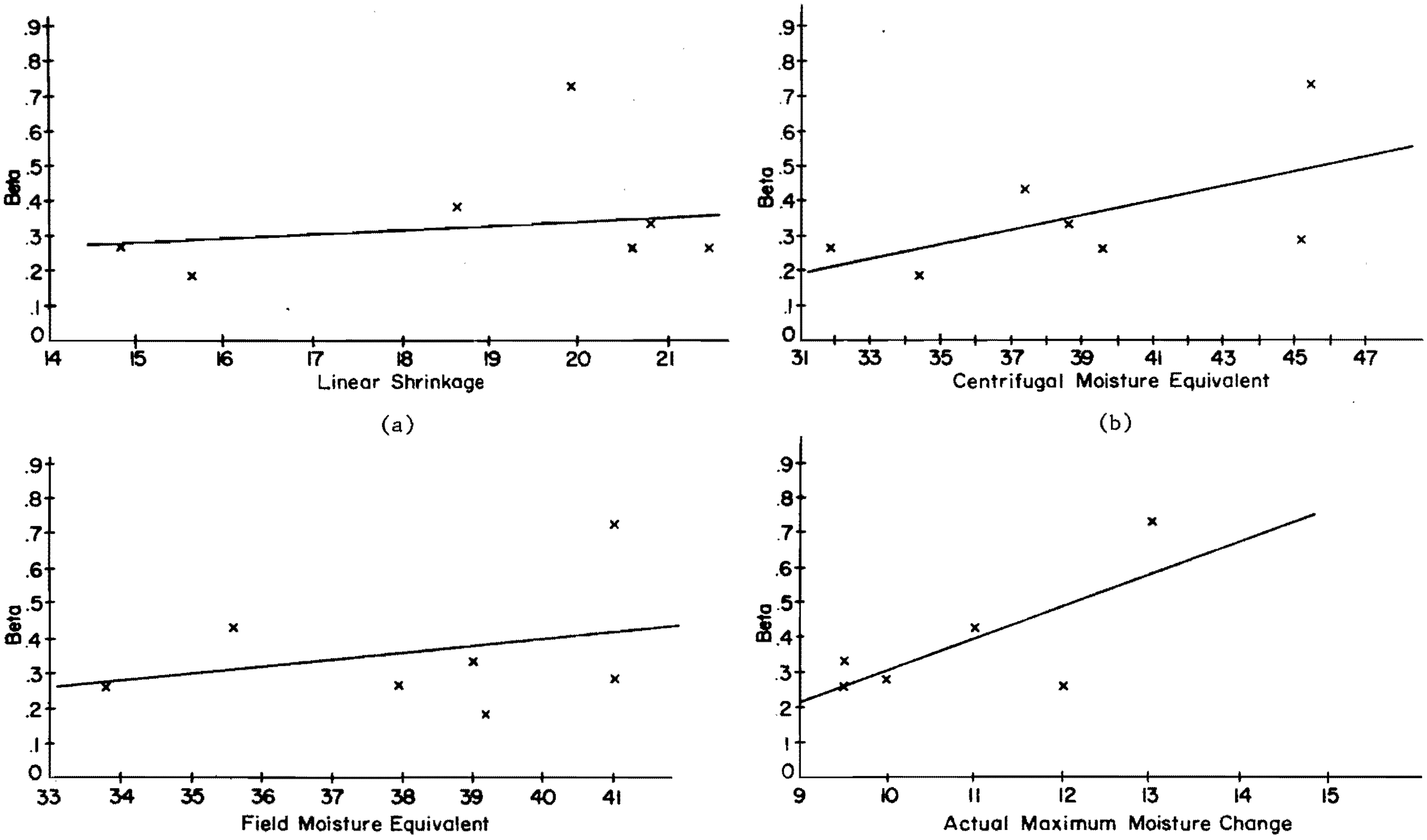
(a)

(b)

(c)

(d)

Fig 15. Results from single regression analyses.



(a)

(b)

(c)

(d)

Fig 16. Results from single regression analyses.

TABLE 6. DATA USED IN CHARACTERIZING THE SWELLING CLAY PARAMETER

	Beta	L.L.	LPL	PI	SL	LSATLLI	FME	CME	AMC Actual Maximum Moisture Change
Section 2									
Slabs 3,4	.189	50.6	26.2	24.4	14.7	15.6	39.2	34.3	9.0
Slabs 8,9	.270	46.6	24.6	22.0	13.2	14.8	37.9	31.8	9.5
Section 14									
Slabs 4,5	.337	60.6	24.2	36.4	10.7	20.8	39.0	38.6	9.5
Slabs 14,15	.268	62.7	21.2	41.5	9.4	21.6	33.8	39.6	12.0
Section 21									
Slabs 1, 2	.729	58.9	24.8	34.1	10.6	19.9	41.0	45.5	13.0
Section 33									
Slabs 3,4	.433	52.4	22.2	30.2	10.1	18.6	35.6	37.3	11.0
Slabs 13,14,15	.283	61.7	27.7	34.0	10.5	20.6	41.0	45.2	10.0

tests, the first regression analyses involved only soil data, which would be started. This group of data consisted of the liquid limit (LL), the plastic limit (PL), the plastic index (PI), the shrinkage limit (SL), and the linear shrinkage limit (LSATLLI). The second group of regression analyses involved using combinations of all the variables available to see what the best possible correlation was.

Initially, the multiple regression analysis was made using the data presented in Table 6. The results of these multiple regression analyses showed that the swelling clay parameter could be characterized by using various combinations of the soil data selected; however, combinations of the various data obtained from present clay laboratory tests did not adequately predict the swelling clay parameter (Table 7). The equation which gave the best correlation with the swelling clay parameter is given below.

$$B = .02070 - .02250(LL) - .12496(PL) + .08541(FME) + .03572(CME) \qquad (6.1)$$

where

B = swelling clay parameter,
LL = liquid limit,
PL = plastic limit,
FME = field moisture equivalent, and
CME = centrifugal moisture equivalent.

This equation had a coefficient of determination of .9988 and a standard deviation of .0108. While this equation gave the best correlation, the field moisture equivalent (FME) and the centrifugal moisture equivalent (CME) are derived from obsolete laboratory tests.

A suitable correlation involving the standard laboratory tests was not obtained from the data in Table 6; however, it was felt that there was a discretancy in the data. The data were examined and it seemed that the beta value measured for Section 21 was not the result of swelling clay action alone. The history of the construction procedure and maintenance required for this section

TABLE 7. RESULTS OF MULTIPLE REGRESSION ANALYSES

Soil Properties Used	R^2	Standard Deviation
Beta versus LL, PL, FME, and AMC		
$B = -1.88258 + .03018(FME + .10290(AMC)$	.7888	.1011
$B = -1.58057 - .08842(PL) + .09046(FME) + .06061(AMC)$	.9252	.0695
$B = -1.45751 - .00615(LL) - .08361(PL) + .08913(FME) + .07539(AMC)$	.9607	.0617
Beta versus LL, PL, FME, and CME		
$B = -.05868 - .02078(LL) + .04075(CME)$	.5213	.1523
$B = -1.08539 - .03216(LL) - .04544(PL) + .05630(CME)$	.7639	.1235
$B = -.02250(LL) - .12496(PL) + .08541(FME) + .03572(CME)$	.9988	.0108
Beta versus LL, PL, SL, and LSATLLI		
$B = 1.36783 - .00673(LL) - .05579(SL)$	.1950	.1975
$B = 1.42069 - .01201(LL) + .02189(PL) - .08146(SL)$	.2354	.2222
$B = .83526 - .03347(LL) + .02568(PL) - .04909(SL) + .07075(LSATLLI)$	.2439	.2706
Beta versus LL, PL, SL, and LSATLLI (B = .283 for Sec. 21)		
$B = 1.47080 - .01067(LL) - .05093(SL)$	.7306	.0476
$B = .43464 - .04647(LL) + .01320(SL) + .12329(LSATLLI)$	.8989	.0337
$B = 1.8103 - .05999(LL) + .01465(PL) + .01391(SL) + .15768(LSATLLI)$	.9901	.0129
Beta versus LL, PL, and SL (B = .283 for Sec. 21)		
$B = 1.47080 - .01067(LL) - .05093(SL)$	.7306	.0476
$B = 1.48581 - .01217(LL) + .00622(PL) - .05822(SL)$	.7464	.0530

were reviewed and this revealed that the joint between the two slabs used in the research was allowing free water to seep into the subgrade. For this reason, the swelling clay subgrade in Section 21 was subjected to greater variations in moisture content than the subgrades under the other test slabs. The soil data showed that the beta value for Section 21 should have been similar to the beta value measured for Section 33, slabs 13, 14, and 15.

A second regression analysis was made with the original beta value of Section 21 replaced by a beta value of .283. This multiple regression analysis showed that the swelling clay parameter could be characterized using combinations of the various data from the standard laboratory tests (Table 7). The equation which gave the best correlation with the swelling clay parameter is given below.

$$\begin{aligned} B = {} & .18103 - .05999(LL) + .01465(PL) + .01391(SL) \\ & + .15768(LSATLLI) \end{aligned} \tag{6.2}$$

where

B = swelling clay parameter,

LL = liquid limit,

PL = plastic limit,

SL = shrinkage limit, and

LSATLLI = linear shrinkage limit at the liquid limit.

This equation had a coefficient of determination of .9901 and a standard deviation of .0129.

The regression analyses showed that the swelling clay parameter could be characterized by the soil variables available. The single regression analyses indicated that no single soil variable could adequately explain the variation in beta. The best single regression analysis involved the actual maximum moisture content change and could explain only 59 percent of beta's variation. The multiple regression analyses could explain the variation in beta, as shown by Eqs 6.1 and 6.2.

This chapter characterized the swelling clay parameter; Chapter 7 discusses utilization of the results of this characterization.

CHAPTER 7. DISCUSSION OF RESULTS OF STUDY

The preceding chapter characterized the swelling clay parameter with respect to standard soil tests. This chapter discusses use of the results of this characterization in the systems approach to pavement design.

Application of Results

The regression analyses showed that there is a definite relationship between the swelling clay parameter and the various soil data used. The single regression analysis showed that no single soil property could adequately predict the swelling clay parameter. The multiple regression analyses proved that the swelling clay parameter could be adequately predicted by standard laboratory tests. Equations 6.1 and 6.2, from the multiple regression analyses, give correlations with the swelling clay parameter. The standard deviations from Eqs 6.1 and 6.2 were .0108 and .0129. The coefficient determinations were .9988 and .9901.

Although Eq 6.2 has a slightly higher standard deviation, it is recommended over Eq 6.1 because all the variables in Eq 6.2 can be calculated from standard laboratory tests. Eq 6.2 contains four variables in the regression analyses. These variables are the liquid limit (LL), the plastic limit (PL), the shrinkage limit (SL), and the linear shrinkage at the liquid limit. Another regression analyses was made using only the liquid limit, plastic limit and shrinkage limit. This regression showed that 75 percent of the variation in the swelling clay parameter could be explained by these three variables (Table 7).

Confidence Limits for Equations

It should be recognized that the swelling clay parameter predicted by Eq 6.2 does not give the only answer possible for a given set of data. Since there is a standard deviation association with Eq 6.2, there will be a range of values for any given data. This range of values will depend on the level of confidence the user desires. Table 8 gives the range of values for different confidence levels.

TABLE 8. CONFIDENCE TABLE

Level of Significance, α	Range for Beta
.01	± .0320
.05	± .0253
.10	± .0211
.15	± .0186

The level of confidence, or confidence coefficient, is defined as $(1 - \alpha)$.

For example, if $B = 0.15$ and a $\alpha = 0.05$, then the range for B will be

$$0.15 - 0.0253 \leqq B \leqq 0.15 + 0.0253$$

i.e.,

$$0.1247 \leqq B \leqq 0.1753$$

This means that 95 percent of the time Eq 7.2 gives a values of 0.15 for beta. The true value of beta will be between 0.1247 and 0.1753. The larger the confidence coefficient $(1 - \alpha)$, the larger the range for the calculated beta value (Table 8).

Design Equation

Equation 7.2 could be used for design purposes, but it is not recommended, because the designer must risk a 50 percent chance that the average beta value predicted by Eq 7.2 will be too low. As explained in the previous section, the predicted beta value actually gives the designer a range of values into which the beta value might fall. For design purposes, it is necessary to make sure that the average beta value predicted by Eq 7.2 will not be less than the true value. For this reason, it is recommended that Eq 7.2 be modified so that the beta value will be less than the actual values only 15 percent of the time. While the designer has the option of choosing whatever confidence level he desires, the 85 percent level is recommended, because other work used in the systems approach to pavement design is based on this value. In order to insure that the average beta value produced by Eq 7.2 is greater than or equal to the true beta value, the equation is changed so that 85 percent of the area under the normal probability distribution curve is left of the beta value predicted by the equation. To accomplish this, the following must be true:

$$\frac{x - u}{\sigma} = 1.03$$

where

u = the average beta value,

x = the desired value,

σ = the standard deviation of u.

For Eq 7.2, σ is equal to 0.0129; therefore

$$x = u + 0.0013$$

For Eq 6.2 to predict the desired beta value, it must be increased as shown:

$$B = 1.8103 - .05999(LL) + .01465(PL) + .01391(SL) + .15768(LSATLLI) + .0013$$

$$B = 1.8116 - .05999(LL) + .01465(PL) + .01391(SL) + .15768(LSATLLI) \tag{7.1}$$

Equation 7.1 will yield a beta value less than the true value only 15 percent of the time.

Utilization

Caution should be used with Eq 7.1 because this equation was derived from lightly reinforced, jointed concrete pavements. With continuously reinforced pavements, the effects of the swelling clay may not be as severe because more slab action is allowed. The characterization of the swelling clay parameter given in Eq 7.1 should be of great assistance to users of the systems approach to pavement design. It will probably be most useful in helping to identify potential trouble areas along the pavement. If the designer knows in advance that certain areas of the subgrade are more likely to swell, he can take measures to prevent this trouble by either working on the subgrade itself or adjusting the design of the pavement in this area. Using the flexible pavement design system, the user will find that as the swelling clay parameter increases the initial pavement thickness decreases. This approach is used because the effects of the swelling clay are most critical in the early years of the pavement. 7 As time passes, the moisture conditions under the pavement stabilize, and the effects of swelling clay are minimized. The thinner initial pavement design is increased with overlays as time passes. Therefore, by waiting until the swelling clay has stabilized, money is not spent unnecessarily on the initial pavement. It is recommended that Eq 7.1 be used in conjunction with Table 1. By using both, the designer will be able to have a feel for what these beta values mean. If the pavements in the area tend to show less activity than is predicted by Eq 7.1, then the low side of the beta range should be used. Conversely, if the pavements show more activity than predicted by Eq 7.3, the high side of the beta range should be used. As stated earlier, the most important use of this equation will be in identifying potential trouble spots before the pavement is constructed. If a high swelling clay value predicts excessive costs, treatment of the subgrade may be justified. McDowell has recommended several methods of reducing the detrimental effects of swelling clay (Ref 12):

(1) compaction of subgrade in wet condition,
(2) pond water over the swelling clay, and
(3) deep lime treatments for subgrade, because top portions of swelling clay causes most of harmful effects.

Chapter 7 proved that the swelling clay parameter could be adequately characterized using standard laboratory tests. The plastic limit, liquid limit, shrinkage limit, and linear shrinkage limit are the parameters needed. Equation 6.2 is recommended for predicting the swelling clay parameter; however, Eq 7.1 is recommended for pavement design. The characterization of the swelling clay parameter should be beneficial in designing pavements. Chapter 8 deals with the conclusions of this research.

CHAPTER 8. CONCLUSIONS

The most important result of this research was proving that the swelling clay parameter can be characterized using standard laboratory tests. While single regression analyses cannot adequately predict the variation in the swelling clay parameter, multiple regression analyses can. Table 5 shows the results of the single regression analyses, and Table 7 shows the results of the multiple regression analyses. Equation 6.1, which provided the best correlation with beta, made use of two obsolete laboratory tests. Equation 6.2, the next most satisfactory equation, had a slightly higher standard deviation. Equation 6.2 was considered the better equation because it involved only the plastic limit, liquid limit, shrinkage limit, and the linear shrinkage limit, which are standard laboratory tests.

For design purposes, a modification of Eq 6.2 was necessary to insure a conservative beta value. With the unmodified Eq 6.2, the designer has a 50 percent chance of using a beta value which was too low. Equation 7.1 (the modification of Eq 6.2) insures that the true beta value will be lower than the predicted value only 15 percent of the time.

It should be noted that these equations were derived using lightly reinforced jointed concrete pavements poured on highly active swelling clay. The coefficients in these equations may change for various pavement types; however, the characterization of the swelling clay parameter should remain a function of the soil's liquid and plastic limits.

This research verified that the PSI reading of a pavement generally decreases with time, due to the action of swelling clay (see Figs 11 through 14). The Serviceability Loss Function currently being used in the systems approach to pavement design seems reasonable because it demonstrates a good correlation with the actual PSI values (see Table 3).

The research also showed that the construction procedure used in preparing the subgrade had an important effect on the swelling clay parameter. The ponding of water over swelling clay is beneficial, as shown by the relatively low beta values found in Section 2. Section 14 showed that ponding should be done carefully, because of the differential settlements at the interface of ponded and non-ponded subgrades. Section 17 showed that compacting a subgrade in a wet condition, rather than in a dry condition, is much more desirable. Section 21 showed that pavement cracks which might allow free water to reach the subgrade had an undesirable effect on the pavement's serviceability. Therefore, these cracks should be sealed as soon as possible.

The swelling clay parameter, as shown by this research, has a pronounced effect on the pavement's serviceability. For this reason, the highway designer should make every effort to incorporate the proper swelling clay parameter into his design.

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APPENDIX 1

DEFINITION OF VARIABLES IN SERVICEABILITY LOSS FUNCTION, EQ 2.4

APPENDIX 1. DEFINITION OF VARIABLES IN SERVICEABILITY LOSS FUNCTION, EQ 2.4

Design Variables

a_i = the strength coefficient of the i^{th} layer of a pavement,

$i = 1, 2, \ldots, n + 1$

D_i = the thickness of the i^{th} layer in inches. $D_{n+1} = \infty$.

Deflection Variables

$S = W_1 - W_2$

S = Curvature index

$$W_j = \sum_{k=1}^{n+1} \Delta_{jk}$$

$$\overset{v}{\Delta}_{jk} = \frac{C_o}{a_k{}^{c_1}} \left[\frac{1}{r_j{}^2 + C_2\left(\sum\limits_{i=0}^{k-1} a_i D_i\right)^2} - \frac{1}{r_j{}^2 + C_2\left(\sum\limits_{i=0}^{k} a_i D_i\right)^2} \right]$$

$C_o = 0.891,$

$C_1 = 4.503,$

$C_2 = 6.25,$

$a_o = D_o = 0.$

W_j = the deflection sensed by the j^{th} sensor of the Dynaflect,

r_j = distance, in inches, from the point of application of either Dynaflect load, to the j^{th} sensor, $r_1^2 = 100$, $r_2^2 = 244$.

Traffic Variables

$$N_k = \frac{N_c}{C(r_o + r_c)} \left[2r_o t_k + \left(\frac{r_c - r_o}{G} \right) t_k^2 \right]$$

t = time (years) since initial construction,

N = total number of equivalent applications of an 18-kip axle axle that will have been applied in one direction during the time, t; N is expressed in millions,

C = length in years of the analysis period,

N_c = N when $t = C$,

N_k = N when $t = t_k$ (defined below),

r_o = ADT (one direction) when $t = 0$,

r_c = ADT (one direction) when $t = C$.

Performance Variables

P = the serviceability index at time, t,

P_1 = the expected **maximum** value of P, occurring only immediately after initial or overlay construction,

P_2 = the specified value of P at which an overlay will be applied.

P_2', a swelling clay parameter = the assumed value of P at $t = \infty$, in the absence of traffic. In general, $0 \leqq P_2' \leqq P_1$.

b_k, a swelling clay parameter applying to the k^{th} performance performance period. A value between zero and 0.3 must be specified for b_1, depending on the expected activity of foundation clays.

$$b_{k+1} = b_k e^{-b_k(t_k - t_k - 1)}$$

t_k = the value of t at the end of the k^{th} performance period, or the beginning of the next period, $t_o = 0$,

Q, the serviceability loss function = $\sqrt{5 - P} - \sqrt{5 - P_1}$

$Q_2 = Q$ when $P = P_2$,

$Q_2' = \sqrt{5 - P_2'} \quad \sqrt{5 - P_1}$

α, a daily temperature constant = 1/2 (maxiumum daily temperature + minimum daily temperature) - 32^o F,

$\bar{\alpha}$ = the effective value of α for a typical year in a given locality, defined by the formula for the harmonic mean=

$$\frac{n}{\sum_{i=1}^{n} \left(\frac{1}{\alpha_i}\right)}$$

where n is the number of days in a year, and α_i is the value of α for the i^{th}

day of the year. To obtain an approximate value of $\bar{\alpha}$ for this report, the formula was used with $n = 12$, and α_i = the mean value of α for the i^{th} month averaged over a ten year period.

APPENDIX 2

TEST OF SIGNIFICANCE

APPENDIX 2. TEST OF SIGNIFICANCE

TABLE A1. DATA FOR TEST OF SIGNIFICANCE FOR TEST SECTIONS

Section Number	n_i, Number Of Data Values	$\bar{x}_i$, Average PI	s_i^2, Variance	F(5,200) For $\alpha = .05$
2	45	23.4	10.0	4.38
14	43	41.7	24.8	4.38
16	43	37.9	19.7	4.38
21	43	41.7	28.0	4.38
33	43	30.3	14.2	4.38

SCHEFFE TEST (REF 11)

For the hypothesis that there is no difference between two groups of data, i.e., $(\bar{x}_1 - \bar{x}_2) = 0$, the Scheffe Test states that

$$\frac{(\bar{x}_i - \bar{x}_j)^2}{(t-1)s_{ij}^2} < F_{\alpha}(t-1,v)$$

where

$\bar{x}$ = average value for group,

t = number of different groups,

$$v = \sum_{i=1}^{t} n_i$$

$$s_{ij}^2 = \left[\frac{n_i\bar{x}_i + n_j\bar{x}_j}{(n_i + n_j - 2)}\right]\left[\frac{n_i + n_j}{n_i n_j}\right]$$

n_i = number of data points in each group,

F = value from F tables.

<u>Section 16 Versus Section 21</u>

$n_1 = 43.0$ $n_2 = 43.0$

$\bar{x}_1 = 37.9$ $\bar{x}_2 = 41.7$

$s_1^2 = 19.7$ $s_2^2 = 28.0$

$$\hat{s}_{12}^{2} = \frac{n_1 s_1^{2} + n_2 s_2^{2}}{n_1 + n_2 - 2} = \left[\frac{43(19.7 + 28.0)}{84}\right]$$

$$\hat{s}_{12}^{2} = 24.4$$

$$s_{12}^{2} = \hat{s}_{12}\left(\frac{n_1 + n_2}{n_1 n_2}\right) = 24.4\left(\frac{86}{43^2}\right) = 1.1$$

$$C = \frac{(x_1 - x_2)^2}{(t-1)(s_{12}^{2})} = \frac{(37.9 - 41.7)^2}{(5)(1-1)} = 2.6 < F = 4.38$$

There is no significant difference between sections.

Section 2 Versus Section 33

$n_1 = 45$ $\qquad$ $n_2 = 43.0$

$\bar{x}_1 = 23.4$ $\qquad$ $\bar{x}_2 = 30.3$

$s_1^{2} = 10.0$ $\qquad$ $s_2^{2} = 14.2$

$$\hat{s}_{12}^{2} = \frac{45(10) + 43.0(14.2)}{86.0} = 12.3$$

$$s_{12}^{2} = (12.3)\left(\frac{88}{(45)(43)}\right) = .5$$

$$C = \frac{(6.9)^2}{(5)(.5)} = 19.0 > 4.38$$

There is a significant difference between sections.

Section 14 Versus Section 33

$n_1 = 43.0$ $n_2 = 43.0$

$\bar{x}_1 = 41.7$ $\bar{x}_2 = 30.3$

$s_1^2 = 24.8$ $s_2^2 = 14.2$

$$\hat{s}_{12}^2 = 43 \left[\frac{24.8 + 14.2}{84.0}\right] = 19.9$$

$$s_{12}^2 = 19.9 \cdot \left(\frac{86}{43^2}\right) = .9$$

$$C = \frac{(11.4)^2}{(5)(.9)} = 28.8 > 4.38, \text{ sections different.}$$

Section 14 Versus Section 21

$$(\bar{x}_1 - \bar{x}_2) = 0$$

There is no significant difference between sections.

TABLE A2. DATA FOR TEST OF SIGNIFICANCE FOR SLAB SETS WITHIN THE SAME SECTION USING "t" TEST

	n	Average PI	s^2, Variance	α = .05
Section 2 Slabs 3,4	5	24.4	2.7	1.86
Section 2 Slabs 8,9	5	21.0	3.3	1.86
Section 14 Slabs 4,5	5	36.4	16.9	1.86
Section 14 Slabs 14,15	5	41.5	11.5	1.86
Section 33 Slabs 3,4	5	30.1	18.8	1.86
Section 33 Slabs 13,14,15	5	33.9	29.3	1.86

Section 2, Slabs 3, 4 Versus Slabs 8,9

$$\hat{s} = \sqrt{\frac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2}} = \sqrt{\frac{5(2.7 + 3.3)}{8.0}} = 1.97$$

$$s = \hat{s}\sqrt{\frac{n_1 + n_2}{n_1 n_2}} = 1.97\sqrt{\frac{10}{25}} = 1.21$$

$$t = \frac{24.4 - 21.0}{1.21} = \frac{3.4}{1.21} = 2.81 > 1.86$$

The soils are different (for $\alpha = .05$).

Section 14, Slabs 4,5 Versus Slabs 14, 15

$n_1 = 5.0$ $\quad$ $n_2^2 = 5.0$

$\overline{x}_1 = 36.4$ $\quad$ $\overline{x}_2 = 41.5$

$s_1^2 = 16.9$ $\quad$ $s_2^2 = 11.5$

$$\hat{s} = \sqrt{\frac{5(16.9 + 11.5)}{8.0}} = 4.21$$

$$s_d = 4.23(.63) = 2.7$$

$$t = \frac{41.5 - 36.4}{2.7} = 1.92$$

The soils are different (for $\alpha = .05$).

Section 33, Slabs 3,4 Versus Slabs 13,14,15

$n_1 = 5.0$ $n_2 = 5.0$

$\bar{x}_1 = 30.1$ $\bar{x}_2 = 33.9$

$s_1^2 = 18.8$ $s_2^2 = 11.5$

$$\hat{s} = \sqrt{\frac{5.0}{8.0}\left(18.8 + 29.3\right)} = 5.48$$

$$s_D = .63(5.48) = 3.5$$

$$t = \frac{33.9 - 30.1}{3.5} = 1.1$$

For $\alpha = .15$ $t_{15} = 1.1$

The soils are different for $\alpha = .15$

APPENDIX 3

COMPUTER PROGRAM TO CALCULATE AVERAGE SLOPE VARIANCE

APPENDIX 3. COMPUTER PROGRAM TO CALCULATE AVERAGE SLOPE VARIANCE

This program was written to convert a series of vertical profile readings into an average slope variance. For the Guadalupe County Project, three different vertical profiles were recorded for each test section. The profiles were taken along each outside edge of the pavement and near the center line of the roadway. The purpose of the program was to compute the slope variance for each of the three profiles and then use the average of the three values as the slope variance of the section.

In order to get the desired results, the following information needed to be input:

(1) M = number of various time periods used for profile readings,
(2) NN = number of horizontal distances along north profile,
(3) NC = number of horizontal distances along center profile,
(4) NS = number of horizontal distances along south profile,
(5) NP = larger number between NN, NC and NS,
(6) TIME(I) = number of days after pouring that the profile reading was taken,
(7) XN(J) = coordinate of horizontal distance along north profile = FEET,
(8) XC(J) = coordinate of horizontal distance along center profile = FEET,
(9) XS(J) = coordinate of horizontal distance along south profile =
(10) AN(K) = coordinate of vertical distance along north profile = FEET,
(11) C(K) = coordinate of vertical distances along center profile = FEET,
(12) S(K) = coordinate of vertical distances along south profile = FEET.

In reading in the input data, it was assumed that after one year no more cracks would develop in the pavement. For the test sections used, the above statement is true. With the above information the slope variance can now be computed. An example of how the north profile is handled is given below. First the slope (SLOPN(I)), the sum of the slopes SUMN, and the sum of the squares of the slopes are computed as follows:

DO 60 I = 1, NX

where

NX = NN - 1

SLOPN(I) = (AN(I + 1) - AN(I)/(XN(I + 1) - XN(I))

SUMN = SUMN + SLOPN(I)

SQSUMS = SQSUMS + SLOPN(I)^2

60 CONTINUE

After this process is repeated for the center and south profiles, the north slope variance is computed by using the following equation:

SVN = SQSUMN/YN - (SUMN/YN)^2

where

YN = NX

The center and south slope variances are handled in the same way. The average slope variance for the section is computed from the following:

SV = (SVN + SVC + SVS)/3.0

The desired information is printed out, and the entire process is repeated until all the time periods have been completed.

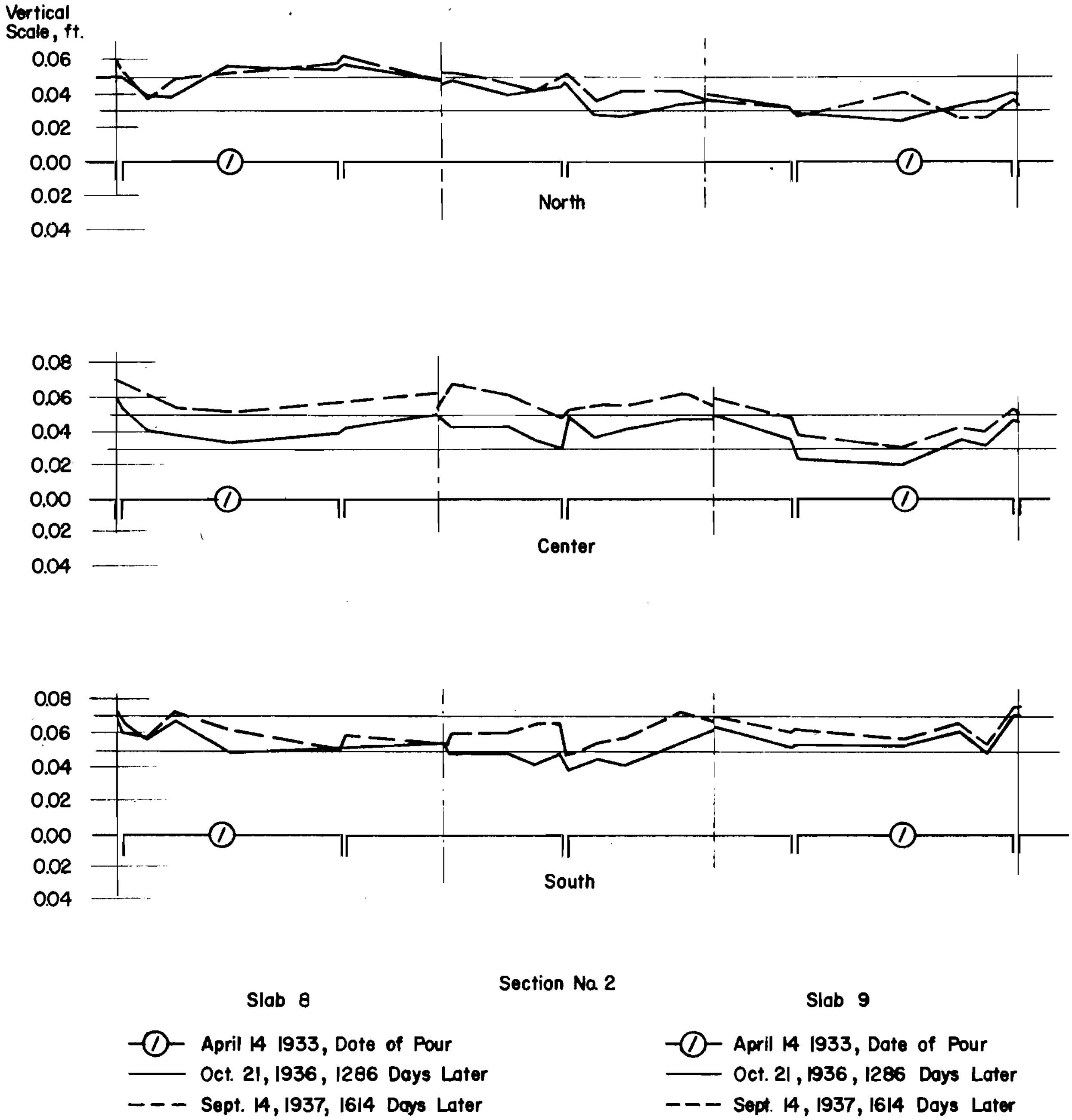

Fig A1. Typical vertical profile.

PROGRAM LISTING

```
      DIMENSION TIME(8),AN(200),C(200), S(200),SLOPN(200), SLOPC(200),
     1SLOPS(200),XN(200),XC(200),XS(200) ,TITLE(16)
C     80 COLUMNS AVAILABLE FOR IDENTIFICATION OF SECTION
C     M = NUMBER OF VARIOUS TIME PERIODS USED FOR PROFILE READINGS
C     NN = NUMBER OF HORIZONTAL DISTANCES ALONG NORTH PROFILE
C     NC = NUMBER OF HORIZONTAL DISTANCES ALONG CENTER PROFILE
C     NS = NUMBER OF HORIZONTAL DISTANCES ALONG SOUTH PROFILE
C     NP = LARGER NUMBER BETWEEN NN , NS , AND NC
C     TIME(I) = NUMBER OF DAYS AFTER POURING THE PROFILE READING WAS TAKEN
C     XN(J) = COORDINATE OF HORIZONTAL DISTANCE ALONG NORTH PROFILE--FEET
C     XC(J) = COORDINATE OF HORIZONTAL DISTANCE ALONG CENTER PROFILE--FEET
C     XS(J) = COORDINATE OF HORIZONTAL DISTANCE ALONG SOUTH PROFILE--FEET
C     AN(K) = COORDINATE OF VERTICAL DISTANCE ALONG NORTH PROFILE--FEET
C      C(K) = COORDINATE OF VERTICAL DISTANCE ALONG CENTER PROFILE--FEET
C      S(K) = COORDINATE OF VERTICAL DISTANCE ALONG SOUTH PROFILE--FEET
      READ 303,TITLE
  303 FORMAT (16A5)
      READ 1, M,NN,NC,NS,NP
    1 FORMAT  (5I6)
      READ 2, (TIME(I),I=1,M)
    2 FORMAT (8F10.0)
      READ 3, (XN(J),J=1,NN)
      READ 3, (XC(J),J=1,NC)
      READ 3, (XS(J),J=1,NS)
    3 FORMAT (8F10.2)
          DO 50 L=1,M
      READ  4,(AN(K),K=1,NN)
      READ  4,( C(K),K=1,NC)
      READ  4,( S(K),K=1,NS)
    4 FORMAT (8F10.4)
               SUMN =0.
               SUMC =0.
```

(Continued)

PROGRAM LISTING (CONTINUED)

```
      PRINT 250,TITLE
  250 FORMAT (1H1,16A5)
      PRINT 196
  196 FORMAT (1H0,4X,*XN        AN    SLOPE N        XC         C     *
     1*SLOPE C            XS       S        SLOPE S * )
          DO 200 I=1,NP
      PRINT 195
          IF (I.LE.NN) PRINT 197, XN(I),AN(I),SLOPN(I)
          IF (I.LE.NC) PRINT 198, XC(I),C(I),SLOPC(I)
          IF (I.LE.NS) PRINT 199, XS(I),S(I),SLOPS(I)
  200     CONTINUE
  195 FORMAT (1H )
  197 FORMAT (1H+,F10.4,F8.3,E11.3)
  198 FORMAT(1H+,29X,F10.4,F8.3,3X,E11.3 )
  199 FORMAT(1H+,64X,F10.4,F8.3,3X,E11.3 )
      PRINT 12, (TIME(L),SUMN,SQSUMN,SVN,SUMC,SQSUMC,SVC,SUMS,SQSUMS,SVS
     1,SV)
   12 FORMAT(1H0,4X,17HDAYS AFTER POUR =  F10.0    ,/,
     1*         SUM OF SLOPE CHANGES NORTH PROFILE =* E12.3   ,/,
     1*    SUM OF THE SQUARES OF THE SLOPE CHANGES NORTH PROFILE =*  E12
     1.3  ,/,
     1*     SLOPE VARIANCE OF NORTH PROFILE = * E12.3 ,/,
     1*         SUM OF SLOPE CHANGES CENTER PROFILE =*  E12.3 ,/,
     1*    SUM OF THE SQUARES OF THE SLOPE CHANGES CENTER PROFILE =* E12
     1.3  ,/,
     1*     SLOPE VARIANCE OF CENTER PROFILE = * E12.3,/,
     1*         SUM OF SLOPE CHANGE SOUTH PROFILE =*  E12.3   ,/,
     1*    SUM OF THE SQUARES OF THE SLOPE CHANGES SOUTH PROFILE =*  E12
     1.3  ,/,
     1*     SLOPE VARIANCE OF SOUTH PROFILE = * E12.3 ,/,
     1*     AVERAGE SLOPE VARIANCE = * E12.3  )
   50 CONTINUE
      END
```

GUIDE FOR DATA INPUT

INPUT FORMS

Card No. 1

80 Columns for Identification of Section

On Identification Card put section number, slab numbers, and programmer name.

Card No. 2

M	NN	NC	NS	NP	
I6	I6	I6	I6	I6	

M = Number of various time periods used for profile readings

NN = Number of horizontal distances along north profile

NC = Number of horizontal distances along center profile

NS = Number of horizontal distances along south profile

NP = Larger number between NN, NS, and NC

Card No. 3

TIME (I)	TIME (I+1)	Etc.	
F10.0			

FORMAT = (6F10.0)

TIME (I) = Number of days after pouring profile reading was taken

GUIDE FOR DATA INPUT

INPUT FORMS

Card No. 4

XN(J)	XN(J+1)				Etc.

FORMAT = (8F10.2)

XN(J) = Coordinate of horizontal distance along north profile

Card No. 5

XC(J)	XC(J+1)			Etc.	

FORMAT = (8F10.2)

XC(J) = Coordinate of horizontal distance along center profile

Card No. 6

XS(J)	XS(J+1)			Etc.	

FORMAT = (8F10.2)

XS(J) = Coordinate of horizontal distance along south profile

GUIDE FOR DATA INPUT

INPUT FORMS

Card No. 7

AN(J)	AN(J+1)			Etc.	

FORMAT = (8F10.4)

AN(J) = Coordinate of vertical distance along north profile

Card No. 8

XC(J)	XC(J+1)			Etc.	

FORMAT = (8F10.4)

XC(J) = Coordinate of vertical distance along center profile

Card No. 9

XS(J)	XS(J+1)			Etc.	

FORMAT = (8F10.4)

XS(J) = Coordinate of vertical distance along south profile

```
                SECTION 2  SLABS 8 AND 9          DATA OUTPUT

   XN          AN    SLOPE N        AC        C      SLOPE C            XS        S       SLOPE S
 -.2500      .062 -1.200E-02    -.2500     .069   -4.000E-03        -.2500     .073   -1.400E-02
  .2500      .056 -3.789E-03     .2500     .067   -1.474E-03         .2500     .066   -2.526E-03
 5.0000      .038  2.400E-03    5.0000     .060   -1.400E-03        5.0000     .054    3.600E-03
10.0000      .050  2.000E-04   10.0000     .053   -1.000E-04       10.0000     .072   -1.200E-03
20.0000      .052  3.684E-04   20.0000     .052    2.632E-04       20.0000     .060   -5.263E-04
39.0000      .059  6.000E-03   39.0000     .057    2.000E-03       39.0000     .050    1.600E-02
39.5000      .062 -6.957E-04   39.5000     .058    3.030E-04       39.5000     .058   -2.319E-04
56.7500      .050  4.000E-03   56.0000     .063   -2.200E-02       56.7500     .054    0.
57.2500      .052  1.600E-03   56.5000     .052    6.500E-03       57.2500     .054    3.200E-03
58.5000      .054 -6.000E-04   58.5000     .065   -5.000E-04       58.5000     .058    2.000E-04
68.5000      .048 -1.400E-03   68.5000     .060   -1.000E-03       68.5000     .060    8.000E-04
73.5000      .041  1.895E-03   73.5000     .055   -1.474E-03       73.5000     .064    0.
78.2500      .050  4.000E-03   78.2500     .048    8.000E-03       78.2500     .064   -3.200E-02
78.7500      .052 -3.158E-03   78.7500     .052    6.316E-04       78.7500     .048    1.263E-03
83.5000      .037  1.000E-03   83.5000     .055   -4.000E-04       83.5000     .054    4.000E-04
88.5000      .042  0.          88.5000     .053    8.000E-04       88.5000     .056    1.600E-03
98.5000      .042 -1.263E-03   98.5000     .061   -9.600E-04       98.5000     .072   -6.400E-04
103.2500     .036  0.         104.7500     .055    6.000E-03      104.7500     .068    4.000E-03
103.7500     .036 -2.909E-04  105.2500     .058   -9.163E-04      105.2500     .070   -7.347E-04
117.5000     .032 -1.200E-02  117.5000     .048   -2.200E-02      117.5000     .061    4.000E-03
118.0000     .026  7.368E-04  118.0000     .037   -2.632E-04      118.0000     .063   -3.684E-04
137.0000     .040 -1.500E-03  137.0000     .032    1.000E-03      137.0000     .056    8.000E-04
147.0000     .025  0.         147.0000     .042   -4.000E-04      147.0000     .064   -2.000E-03
152.0000     .025  2.105E-03  152.0000     .040    2.316E-03      152.0000     .054    4.421E-03
156.7500     .035 -4.000E-03  156.7500     .051   -2.000E-03      156.7500     .075    2.000E-03
157.2500     .033  0.         157.2500     .050    0.             157.2500     .076    0.

 DAYS AFTER POUR =        1514
      SUM OF SLOPE CHANGES NORTH PROFILE =  -1.639E-02
SUM OF THE SQUARES OF THE SLOPE CHANGES NORTH PROFILE =   4.211E-04
 SLOPE VARIANCE OF NORTH PROFILE =    1.642E-05
      SUM OF SLOPE CHANGES CENTER PROFILE =  -3.097E-02
SUM OF THE SQUARES OF THE SLOPE CHANGES CENTER PROFILE =   1.151E-03
 SLOPE VARIANCE OF CENTER PROFILE =    4.452E-05
      SUM OF SLOPE CHANGE SOUTH PROFILE =  -1.194E-02
SUM OF THE SQUARES OF THE SLOPE CHANGES SOUTH PROFILE =   1.574E-03
 SLOPE VARIANCE OF SOUTH PROFILE =    6.272E-05
 AVERAGE SLOPE VARIANCE =    4.122E-05
```

```
                 SECTION 2  SLABS 8 AND 9  DATA OUTPUT (CONTINUED)

   XN            AN     SLOPE N         XC          C       SLOPE C              XS         S        SLOPE S
  -.2500        .050 -2.000E-03      -.2500       .060    -1.200E-02          -.2500      .069    -1.800E-02
   .2500        .049 -2.105E-03       .2500       .054    -2.947E-03           .2500      .060    -8.421E-04
  5.0000        .039  0.             5.0000       .040    -4.000E-04          5.0000      .056     1.600E-03
 10.0000        .039  1.900E-03     10.0000       .038    -6.000E-04         10.0000      .064    -1.800E-03
 20.0000        .058 -2.105E-04     20.0000       .032     3.684E-04         20.0000      .046     2.632E-04
 39.0000        .054  4.000E-03     39.0000       .039     6.000E-03         39.0000      .051     2.000E-03
 39.5000        .056 -4.638E-04     39.5000       .042     4.848E-04         39.5000      .052     5.797E-05
 56.7500        .048 -4.000E-03     56.0000       .050     0.                56.7500      .053     4.000E-03
 57.2500        .046  1.600E-03     56.5000       .050    -4.000E-03         57.2500      .055    -7.200E-03
 58.5000        .048 -8.000E-04     58.5000       .042     0.                58.5000      .046     0.
 68.5000        .040  4.000E-04     68.5000       .042    -1.200E-03         68.5000      .046    -8.000E-04
 73.5000        .042  4.211E-04     73.5000       .036    -1.263E-03         73.5000      .042     4.211E-04
 78.2500        .044  2.000E-03     78.2500       .030     4.000E-02         78.2500      .044    -1.200E-02
 78.7500        .045 -3.789E-03     78.7500       .050    -2.737E-03         78.7500      .038     1.053E-03
 83.5000        .027 -2.000E-04     83.5000       .037     8.000E-04         83.5000      .043    -4.000E-04
 88.5000        .026  6.000E-04     88.5000       .041     5.000E-04         88.5000      .041     1.100E-03
 98.5000        .032  8.421E-04     98.5000       .046     0.                98.5000      .052     1.440E-03
103.2500        .036  8.000E-03    104.7500       .046     4.000E-03        104.7500      .061     4.000E-03
103.7500        .040 -5.818E-04    105.2500       .048    -9.796E-04        105.2500      .063    -1.061E-03
117.5000        .032 -1.200E-02    117.5000       .036    -2.600E-02        117.5000      .050     6.000E-03
118.0000        .026 -1.053E-04    118.0000       .023    -1.579E-04        118.0000      .053     5.263E-05
137.0000        .024  1.000E-03    137.0000       .020     1.400E-03        137.0000      .054     6.000E-04
147.0000        .034  2.000E-04    147.0000       .034    -4.000E-04        147.0000      .060    -2.000E-03
152.0000        .035  1.263E-03    152.0000       .032     2.526E-03        152.0000      .050     4.211E-03
156.7500        .041 -2.000E-03    156.7500       .044    -2.000E-03        156.7500      .070    -2.000E-03
157.2500        .040  0.           157.2500       .043     0.               157.2500      .069     0.
  DAYS AFTER POUR =        1286
      SUM OF SLOPE CHANGES NORTH PROFILE =  -6.030E-03
 SUM OF THE SQUARES OF THE SLOPE CHANGES NORTH PROFILE =   2.823E-04
  SLOPE VARIANCE OF NORTH PROFILE =     1.123E-05
      SUM OF SLOPE CHANGES CENTER PROFILE =   1.395E-03
 SUM OF THE SQUARES OF THE SLOPE CHANGES CENTER PROFILE =   2.522E-03
  SLOPE VARIANCE OF CENTER PROFILE =    1.009E-04
      SUM OF SLOPE CHANGE SOUTH PROFILE =  -1.931E-02
 SUM OF THE SQUARES OF THE SLOPE CHANGES SOUTH PROFILE =   6.310E-04
  SLOPE VARIANCE OF SOUTH PROFILE =     2.464E-05
  AVERAGE SLOPE VARIANCE =    4.559E-05
```

APPENDIX 4

DERIVATION OF SERVICEABILITY LOSS FUNCTION USED IN QUANTIFICATION OF SWELLING CLAY PARAMETER

APPENDIX 4. DERIVATION OF SERVICEABILITY LOSS FUNCTION USED IN QUANTIFICATION OF SWELLING CLAY PARAMETER

Serviceability Loss Function considering only the effects of swelling clay:

$$Q = Q'_2 \left[1 - e^{-b(t_k - t_{k-1})} \right] \tag{A.1}$$

Variables are defined in Appendix 1.

$$Q'_2 = \sqrt{5 - P'_2} - \sqrt{5 - P_1}$$

$$P'_2 = 0.0$$

$$P_1 = 4.5$$

$$Q'_2 = \sqrt{5 - 0.0} - \sqrt{5 - 4.5} = 1.53$$

$$Q = \sqrt{5 - P_k} - \sqrt{5 - 4.5} = \sqrt{5 - P_k} - .71$$

$t_{k-1} = 0.0 =$ time pavement was poured

Rewriting Eq A.1

$$Q = Q'_2 \left[1 - e^{-b(t_k)} \right]$$

$$\frac{Q}{Q'_2} = \left[1 - e^{-bt_k} \right]$$

$$\frac{Q}{Q_2} - 1 = -e^{-bt_k}$$

$$1 - \frac{Q}{Q_2} = e^{-bt_k}$$

$$\ln_e 1 - \frac{Q}{Q_2} = -bt_k$$

APPENDIX 5

STEP-01

STEP-01

STEPWISE REGRESSION

1. GENERAL DESCRIPTION

a. This program computes a sequence of multiple linear regression equations in a stepwise manner. At each step one variable is added to the regression equation. The variable added is the one which makes the greatest reduction in the error sum of squares. Equivalently it is the variable which has highest partial correlation with the dependent variable partialed on the variables which have already been added; and equivalently it is the variable which, if it were added, would have the highest F value. In addition, variables can be forced into the regression equation. Non-forced variables are automatically removed when their F values become too low. Regression equations with or without the regression intercept may be selected.

b. Output from this program includes:

(1) Input data

(2) At each step:

(a) Multiple R
(b) Standard error for residuals
(c) Analysis-of-variance table
(d) For variables in the equation:

1. Regression coefficient
2. Standard error
3. F to remove

(e) For variables not in the equation:

1. Tolerance
2. Partial correlation coefficient
3. F to enter

(3) Optional output prior to performing regression:

(f) Means and standard deviations
(g) Covariance matrix
(h) Correlation matrix

(4) Optional output after performing regression:

(i) List of residuals, y-values, and y-estimates
Any residual $> 2\sigma$ is denoted by an asterisk.
(j) Plots of residuals vs. input variables
(k) Summary table

c. Limitations per problem:

(1) p, number of original variables ($2 \le p \le 80$)
(2) q, number of variables added by transgeneration ($-9 \le q \le 78$)
(3) p+q, total number of variables ($2 \le p+q \le 80$)
(4) s, number of Sub-problem Cards ($1 \le s \le 99$)
(5) k, number of Variable Format Cards ($1 \le k \le 10$)
(6) i, number of variables to be plotted ($0 \le i \le 30$)
(7) n, number of cases ($1 \le n \le 9999$)
(8) m, number of Transgeneration Cards ($0 \le m \le 99$)

d. Estimation of running time and output pages per problem:

$$\text{Number of seconds} \approx \frac{(p+q) \times n}{100} \quad \text{(for IBM 7094)}$$

$$\text{Number of pages} \approx \frac{\text{no. of steps} \left[23 + 3/4\ (p+q) \right]}{56} + 5 \text{ per sub-problem}$$

e. This program allows transgeneration of the variables. Codes 0-17 and 20-24 of the transgeneration list may be used.

2. <u>ORDER OF CARDS IN JOB DECK</u>

Cards indicated by letters enclosed in parentheses are optional. All other cards must be included in the order shown (see Fig A2).

a. System Cards

b. Title Card

c. Problem Card

(d.) Transgeneration Card (s)

(e.) Label Card (s)

f. F-type Variable Format Cards

(g.) Data Input Cards
(Place data input deck here
if data input is from cards.)

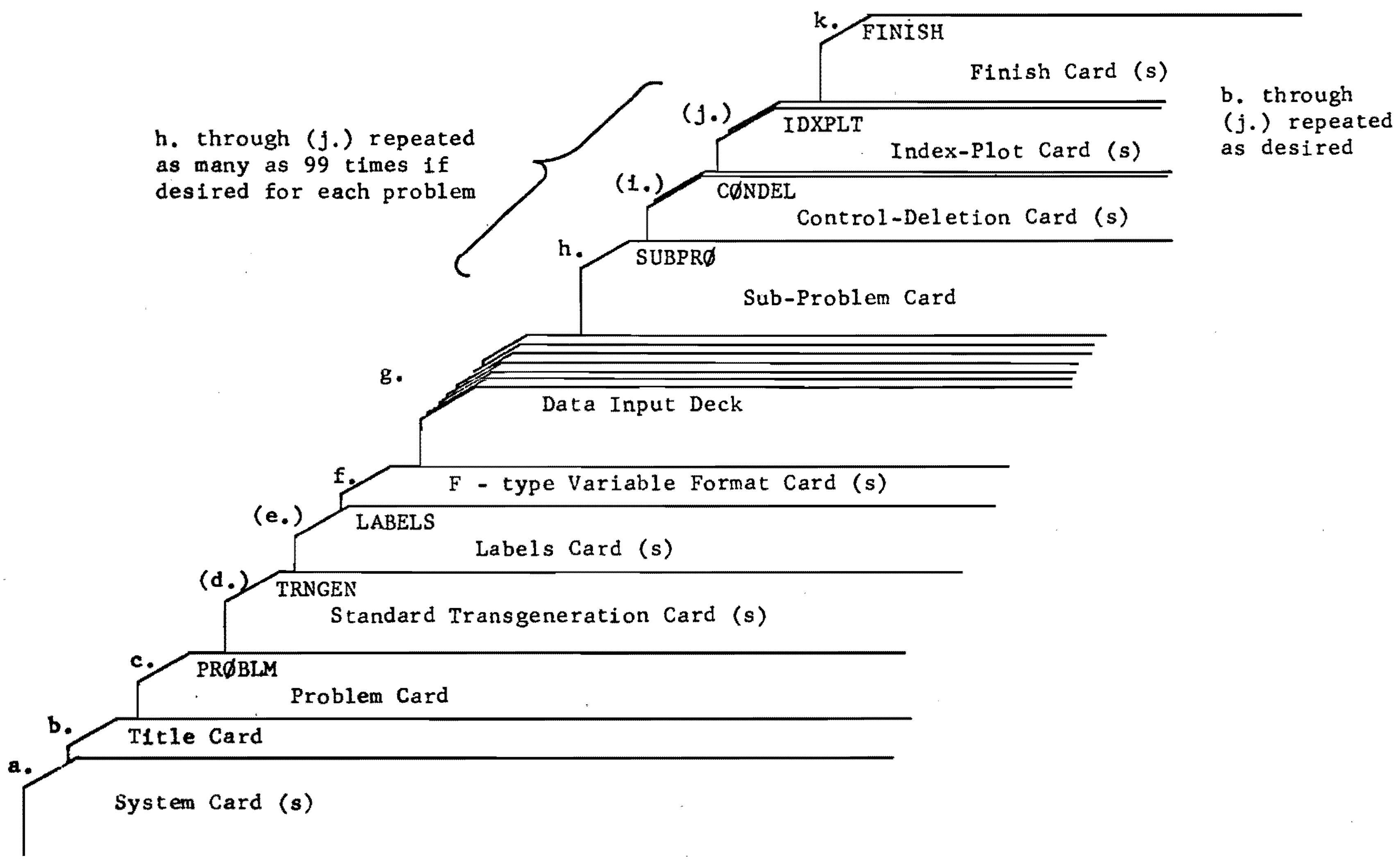

Fig A2. Order of cards in job deck.

h. Sub-problem Card (s)

(i.) Control-Delete Card (s)

(j.) Index-Plot Card (s)

h. through (j.) may be repeated as many as 99 times in each problem; b. through (j.) may be repeated as often as desired.

k. Finish Card

3. CARD PREPARATION (SPECIFIC FOR THIS PROGRAM)

Preparation of the cards listed below is specific for this program. All other cards listed in the preceding section are prepared according to instructions in the Appendix.

b. Title Card - 80 Alphanumeric characters

c. Problem Card (One Problem Card for each problem)

Col. 1-6	PRØBLM	(Mandatory)
Col. 10-15	Alphanumeric problem name	
Col. 17-20	Sample size ($1 \leq n \leq 9999$)	
Col. 24,25	Number of original variables ($2 \leq p \leq 80$)	
Col. 29,30	Number of Transgeneration Cards ($0 \leq m \leq 99$)	
Col. 34,35	Number of variables added by transgeneration ($-9 \leq q \leq 78$)	
Col. 39,40	Tape number if data is on tape ($\neq$ logical 2); otherwise, leave blank.	
Col. 44,45	Number of Sub-problem Cards ($1 \leq s \leq 99$)	
Col. 48,49	Number of variables labeled on Labels Cards. Leave blank if Labels Cards are not used.	
Col. 51-53	YES	If means and standard deviations are to be printed; otherwise, leave blank
Col. 55-57	YES	If covariance matrix is to be printed; otherwise, leave blank.
Col. 59-61	YES	If correlation matrix is to be printed; otherwise, leave blank.

Col. 63-65 YES If zero regression intercept is desired; otherwise, leave blank.

Col. 68,69 NO If tape specified in Columns 39, 40 is not to be rewound before this problem; leave blank if Columns 39, 40 are blank, or if tape rewind is desired.

Col. 71,72 Number of F-Type Variable Format Cards ($1 \leq k \leq 10$)

(d.) Transgeneration Cards (if used)

Transgeneration includes transformation of input veriables and/or creation of new variables prior to the normal computations performed by the program. Each transgeneration card contains one instruction. The cards are prepared as follows:

Col.	1-6	TRNGEN
	7-9	variable index k (number of new variable)
	10-11	code from transgeneration list below
	12-14	variable index i
	15-20	variable index j or constant c (keypunch with decimal)

The codes available are:

Code	Transgeneration	Restriction
01	$\sqrt{X_i} \rightarrow X_k$	$X_i \geq 0$
02	$\sqrt{X_i} + \sqrt{X_i + 1} \rightarrow X_k$	$X_i \geq 0$
03	$\log_{10} X_i \rightarrow X_k$	$X_i > 0$
04	$e^{X_i} \rightarrow X_k$	———
05	$\arcsin \sqrt{X_i} \rightarrow X_k$	$0 \leq X_i \leq 1$
06	$\arcsin \sqrt{X_i/(n+1)} + \arcsin \sqrt{(X_i+1)/(n+1)} \rightarrow X_k$	$0 \leq (X_i/n) \leq 1$
07	$1/X_i \rightarrow X_k$	$X_i \neq 0$
08	$X_i + c \rightarrow X_k$	———
09	$X_i c \rightarrow X_k$	———
10	$X_i^{\,c} \rightarrow X_k$	$X_i \geq 0$
11	$X_i + X_j \rightarrow X_k$	———
12	$X_i - X_j \rightarrow X_k$	———
13	$X_i X_j \rightarrow X_k$	———

f. F-Type Variable Format Cards

A maximum of 10 format cards may be used to describe the data layout. Use Col. 1-72 to punch a regular Fortran format statement omitting the word "Format".

h. Sub-problem Card

Col. 1-6	SUBPRØ (Mandatory)
Col. 9,10	Number of the dependent variable
Col. 13-15	Maximum number of steps. This will be 2(p+q) if left blank.
Col. 20-25	F-level for inclusion. This will be 0.01 if left blank.
Col. 30-35	F-level for deletion. This will be 0.005 if left blank.
Col. 40-45	Tolerance level. This will be 0.001 if left blank.
Col. 49,50	Number of variables on the Index-Plot Card ($0 \leq i \leq 30$)
Col. 53-55	YES If Control-Delete Cards are included.
Col. 58-60	YES If list of residuals is to be printed.
Col. 63-65	YES If summary table is to be printed.

(i.) Control-Delete Card

Col. 1-6	CØNDEL (Mandatory)
Col. 7	Control value* for first variable
Col. 8	Control value* for second variable
	...
Col. 72	Control value* for 66th variable

If there are more than 66 variables, continue on another card of the same form, until p+q variables have been specified.

The variable numbers above refer to variables after transgeneration.

*CONTROL VALUES

1	Delete Variable (or dependent variable)
2	Free variable
3	Low-level forced variable
...	
9	High-level forced variable

If no Control-Delete Cards are included, or if a field is left blank on the Control-Delete Cards included in the deck, the value 2 will be assigned if the variable is not the dependent variable and the value 1 assigned if it is the dependent variable.

(j.) Index-Plot Card

Variables specified on this card are plotted against the residuals.

Col. 106	IDXPLT (Mandatory)
Col. 7,8	First variable to be plotted
Col. 9,10	Second variable to be plotted
	...
Col. 65,66	30th variable to be plotted

No more than 30 variables may be plotted per sub-problem.

Variables specified refer to the original data after transgeneration.

k. Finish Card

The finish Card indicates the end of an entire job, and must be the last card.

Col. 1-6 FINISH

THE AUTHORS

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