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16. Abstract

Presently there are no overlay design procedures or criteria for determining the structural value of existing pavement and its remaining life and for evaluating how the layers will function in an overlaid pavement. Furthermore, none considers fatigue, a primary failure mode or mechanism. Recently, Austin Research Engineers, Inc., under a Federal Highway Administration contract, developed a design procedure using elastic layered theory in an analytical model for overlays of rigid pavements which takes these factors into account. The procedure includes a computer program, RPOD1, which performs various aspects of the analysis required for the design. Depending on the type of existing surface conditions, void, bond, and materials used in the overlays, 22 combinations of pavements and overlays are possible. RPOD1 involves nearly 17 independent variables and the final response is the overlay thickness suitable for the projected traffic.

This report describes a sensitivity analysis to establish the relative importance of the independent variables to the response, i.e., the required thickness. For the analysis, the standard deviation is selected as a basis of sensitivity to facilitate interpretation of the final results.

Based on the study of the sensitivity, it is recommended that the method be adapted for use in the Texas State Department of Highways and Public Transportation.

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by

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W. Ronald Hudson
B. Frank McCullough

Research Report Number 177-11

Development and Implementation of the Design, Construction and Rehabilitation of Rigid Pavements

Research Project 3-8-75-177

conducted for

Texas State Department of Highways and Public Transportation

in cooperation with the
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by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

June 1977

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

PREFACE

This report presents a sensitivity analysis performed to establish the reasonableness of solutions and relative importance of some of the input variables in the rigid pavement overlay design procedure. The report will help the pavement engineers use the computerized design procedure RPOD1 more efficiently and understand the effects of different variables.

This is the eleventh in a series of reports which describe work done on Project 3-8-75-177, Development and Implementation of the Design, Construction and Rehabilitation of Rigid Pavements.

The cooperation of the entire staff of the Center for Highway Research of The University of Texas at Austin is appreciated. Special thanks are due to Mrs. Patty Wilson and Mrs. Patricia Henninger for typing the drafts of the report.

B. C. Nayak

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July 1977

LIST OF REPORTS

Report No. 177-1, "Drying Shrinkage and Temperature Drop Stresses in Jointed Reinforced Concrete Pavement," by Felipe R. Vallejo, B. Frank McCullough, and W. Ronald Hudson, describes the development of a computerized system capable of analysis and design of a concrete pavement slab for drying shrinkage and temperature drop. August 1975

Report No. 177-2, "A Sensitivity Analysis of Continuously Reinforced Concrete Pavement Model CRCP-1 for Highways," by Chypin Chiang, B. Frank McCullough, and W. Ronald Hudson, describes the overall importance of this model, the relative importance of the input variables of the model and recommendations for efficient use of the computer program. August 1975

Report No. 177-3, "A Study of the Performance of the Mays Ride Meter," by Yi Chin Hu, Hugh J. Williamson, B. Frank McCullough, and W. Ronald Hudson, discusses the accuracy of measurements made by the Mays Ride Meter and their relationship to roughness measurements made with the Surface Dynamics Profilometer. January 1977

Report No. 177-4, "Laboratory Study of the Effect of Non-Uniform Foundation Support on CRC Pavements," by Enrique Jimenez, W. Ronald Hudson, and B. Frank McCullough, describes the laboratory tests of CRC slab models with voids beneath them. Deflection, crack width, load transfer, spalling, and cracking are considered. Also used is the SLAB 49 computer program that models the CRC laboratory slab as a theoretical approach. The physical laboratory results and the theoretical solutions are compared and analyzed and the accuracy is determined. (being prepared for submission)

Report No. 177-5, "A Comparison of Two Inertial Reference Profilometers Used to Evaluate Airfield and Highway Pavements," by Chris Edward Doepke, B. Frank McCullough, and W. Ronald Hudson, describes a United States Air Force owned profilometer developed for measuring airfield runway roughness and compares it with the Surface Dynamics Profilometer using plotted profiles and mean roughness amplitude data from each profilometer. Preliminary March 1976

Report No. 177-6, "Sixteenth Year Progress Report on Experimental Continuously Reinforced Concrete Pavement in Walker County," by Thomas P. Chesney, and B. Frank McCullough, presents a summary of data collection and analysis over a 16 year period. During that period, numerous findings resulted in changes in specifications and design standards. These data will be valuable for shaping guidelines for future construction. April 1976

Report No. 177-7, "Continuously Reinforced Concrete Pavement: Structural Performance and Design/Construction Variables," by Pieter J. Strauss, B. Frank McCullough, and W. Ronald Hudson, describes a detailed analysis of design, construction, and environmental variables that may have an effect on the structural performance of a CRCP is presented. May 1977

Report No. 177-8, "Continuously Reinforced Concrete Pavement: Prediction of Distress Quantities," by John P. Machado, B. Frank McCullough, and Hugh J. Williamson, presents a general analysis of environmental, design, construction and historic pavement behavior conditions and their effects on future performance. (being prepared for submission)

Report No. 177-9, "CRCP-2, An Improved Computer Program for the Analysis of Continuously Reinforced Concrete Pavements," by James Ma and B. Frank McCullough, describes the modification of a computerized system capable of analysis of a continuously reinforced concrete pavement based on drying shrinkage and temperature drop. (being prepared for submission)

Report No. 177-10, "Development of Photographic Techniques for Performance Condition Surveys," by Pieter Strauss, James Long, and B. Frank McCullough, discusses the development of a technique for surveying heavily trafficked highways without interrupting the flow of traffic. Preliminary May 1977

Report No. 177-11, "A Sensitivity Analysis of Rigid Pavement-Overlay Design Procedure," by B. C. Nayak, W. Ronald Hudson, and B. Frank McCullough, gives a sensitivity analysis of input variables of Federal Highway Administration computer-based overlay design procedure RPOD1.

ABSTRACT

At the present time there are no overlay design procedures or criteria for determining the structural value of existing pavement and its remaining life and for evaluating how the layers will function in an overlaid pavement. Furthermore, they do not consider fatigue, which is a primary failure mode or mechanism. Recently Austin Research Engineers, Inc. under a Federal Highway Administration contract, developed a design procedure using elastic layered theory in an analytical model for overlays of rigid pavements which takes into account these factors. The design procedure includes a computer program called RPOD1 which performs various aspects of the analysis required for the design. Depending on the type of existing surface conditions, void, bond, and materials used in the overlays, 22 combinations of pavements and overlays are possible. RPOD1 involves nearly 17 independent variables and the final response is the overlay thickness suitable for the projected traffic.

This report describes a sensitivity analysis to establish the relative importance of the independent variables to the response, i.e., the required thickness. For the analysis, the standard deviation is selected as a basis of sensitivity to facilitate interpretation of the final results. Four types of overlays were selected for the sensitivity analysis, and single factorial experiments at the medium level were performed to select the independent variables for fractional factorial design. A quarter-fraction factorial of 2^8 (eight variables at two levels), a one-half fraction factorial of 2^7, and two one-half fraction factorials of 2^6 were run. The mean effects have been calculated directly from the response values by statistical methods. The independent variables considered in four types of overlays have been ranked according to their relative effects.

Based on the study of the sensitivity, the following recommendations are made.

The design method is relatively simple and straightforward to use. It would be highly desirable to adapt the method for use in the Texas State Department of Highways and Public Transportation.

KEY WORDS: rigid pavement, sensitivity analysis, standard deviation, single factorial design, factorial design, fractional factorial design, alias, confounding in factorial design, effect of a factor, rank of a factor

SUMMARY

A sensitivity analysis to investigate the effect of changes in input variables on the overlay thickness has been performed on the computerized rigid pavement overlay design procedure RPOD1, developed by Austin Research Engineers, Inc., for the Federal Highway Administration. The procedure has as many as 17 input variables and the relative importance of some of these was determined in the sensitivity analysis. About four hundred and seventy problems were solved using the RPOD1 program and the data obtained were analyzed quantitatively as well as qualitatively.

The sensitivity analysis reported here has given the program users more information about the effects of the variables, and this information provides the design engineer with greater insight into the decision-making process for use in deciding the relative amount of time and effort he should spend estimating the numerical values of the various inputs to the system.

IMPLEMENTATION STATEMENT

The findings of the sensitivity analysis presented in this report will aid in the application and implementation of the rigid pavement overlay design procedure model RPOD1 and will help the SDHPT evaluate the method for possible use. The sensitivity analysis has given considerable feedback for use in improving the program for suitable use by the State of Texas. The findings described here may be applied to improve understanding of the input variables, of the program, to judge the relative importance of each variable, and to aid in using the program more efficiently. The results of this report could be implemented to help program users decide the relative level of effort which is needed for estimating the numerical values of the various inputs to the system.

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CHAPTER 1. INTRODUCTION

BACKGROUND

This report describes a sensitivity analysis performed to establish the reasonableness of the solutions and the relative importance of the input variables in a design procedure for rigid pavement overlays, called RPOD1. RPOD1 (Ref 2) is a design method using a computer program to evaluate the required thicknesses of overlays on rigid pavements, based on the structural values of the existing pavement and on its remaining life. An evaluation of the layers as they will function in the overlaid pavement is made, based on the fatigue criteria of failure.

At the present time, a large portion of the Interstate Highway System, which was built just after the Second World War, requires major rehabilitation. Laying a new layer, or "overlay", over the existing pavement, is the most common rehabilitation practice for restoring the riding quality and/or skid properties and prolonging the useful life of the pavement structure. At present ther is no uniform overlay design procedure used by all or a majority of the states.

Among the states there are significant differences in the methods used for evaluating the conditions of highway surfaces and in the design procedures used to establish overlay thicknesses. In 1970 the Comptroller General, in a report to Congress, called for adoption of uniform overlay design standards by the Federal Highway Administration to insure that all states would establish proper overlay design methods.

The RPOD1 method for design of overlays for rigid pavements, was developed by Austin Research Engineers, Inc., as a part of the Federal Highway Administration federally coordinated research program. Most other procedures (Ref 2) for resurfacing concrete pavements are modifications of existing new design procedures and determine the thickness of the portland cement concrete (PCC) overlay as if a new single slab were being used. Existing procedures do not give much weight to the existing pavement structure and do not consider the structural value of the existing pavement, its remaining life, and possible fatigue failure. RPOD1, the newly developed overlay design procedure, however, considers these factors. The program, written in Fortran computer language, is available for use at The University of Texas at Austin. Appendices 1 and 2 of this report contain an operational guide for data input and sample output data, respectively.

The overlay design procedure for which the sensitivity analysis is being made is discussed in detail in the report "Flexible and Rigid Overlays of Rigid Pavements" (Ref 2). It is not necessary for the pavement designer to have a complete knowledge of the computational techniques used in the model RPOD1, but a basic understanding of the overall process is indispensable for effective use of the computer program.

The user of RPOD1 must specify the modulus of elasticity, the thickness, and the Poisson's ratio of all layers of the existing pavement, the bond breaker, and the overlay. The design deflection and the traffic to be carried by the existing pavement until overlay, also, must be specified. The number of variables in the program depend on the type of existing pavement, bond, and materials used in overlay, but the maximum is 17. The output of the program is the thickness of the overlay in inches required for the projected traffic load.

PURPOSE OF THE STUDY

The computerized design procedure for rigid pavement overlays called RPOD1 is a unique and fairly complete tool for determining the thickness of an overlay of rigid pavement. A designer has limited resources and time to use in determining the values of the large number of input variables needed in the method and it is important to know what the sensitivity or effect of each variable is. To warrant confidence in a program as well as to evaluate the reasonableness of its solutions, it is also important to check the system by analyzing a number of problems over a wide range of variables. To accomplish these two objectives, a comprehensive sensitivity analysis has been performed.

The objectives of this sensitivity study were

(1) to establish confidence in the reliability of the model,

(2) to establish the relative significance of the input variables,

(3) to obtain a better understanding of the effects of the variable interactions, and

(4) to assist the pavement designer in deciding the relative amount of time and effort he should spend determining the numerical values of the various inputs to the system.

CHAPTER 2. BACKGROUND OF OVERLAY DESIGN PROCEDURE AND THE METHOD OF APPROACH TO THE SENSITIVITY ANALYSIS

This chapter describes the procedure followed for the sensitivity analysis of the rigid pavement overlay design procedure RPOD1. A basic understanding of the overall process is indispensable for effective use of the computerized overlay design procedure.

TYPES OF OVERLAYS

An overlay is designated, mainly, by the material used in the overlay, the type of existing pavement, the type of cracks present in the surface layer, the type of bond breaker, the void beneath the pavement, and the mechanical treatment to the surface layer. Each type of overlay is analyzed differently by the computerized design procedure RPOD1 to determine the thickness of the overlay.

The surface of a rigid pavement is either jointed concrete pavement (JCP) or continuously reinforced concrete pavement (CRCP). Before a pavement is overlaid, the existing pavement must be classified into one of two categories on the basis of the condition of the surface layer, that is, (1) uncracked or Class 1 and 2 cracking or (2) Class 3 and 4 cracking (Ref 2). The classes of cracking are defined according to the AASHO Road Test method, in which cracks are divided into four classes, depending upon their appearance. Class 1 includes fine cracks not visible under dry surface conditions to a man with good vision standing at a distance 15 feet (4.5 m). Class 2 cracks can be seen at a distance of 15 feet (4.5 m) but exhibit only minor spalling, such that the opening at the surface is less than 1/4 inch (6.35 mm). A Class 3 crack is defined as a crack opened or spalled at the surface to a width of 1/4 inch (6.35 mm) or more over a distance equal to at least one-half the crack length; any portion of the crack opened less than 1/4 inch (6.35 mm) at the surface for a distance of 3 feet (900 mm) or more is classified separately. A Class 4 crack is defined as any crack which has been sealed. There is essentially no difference in the deflections between the uncracked and the Class 1 and 2 cracked conditions (Ref 2), and these two conditions were considered to be structurally the same. However there is a significant difference between deflections for the uncracked condition and for the Class 3 and 4 cracked conditions. The deflections for the Class 3 and Class 4 cracked conditions are the same (Ref 2) and these two conditions are considered to be structurally the same.

Pavements in Category 1 are subdivided into two types, with void and without void, depending on the presence of voids beneath the surface layer. The pavements in Category 2 are always treated as being without voids because there is no void beneath pavement in a badly cracked condition. After knowing the condition of the existing pavement, an engineering decision is made as to whether or not to break up the existing pavement mechanically before the overlay. Since the pavements in Category 1 are structurally sound, they can be bonded to the overlay layer if desired. The pavements in Category 2 are never bonded to the overlay layers because they are badly cracked. In the case of unbonded overlays a bond breaker layer is provided between the overlay and the existing pavement. The overlay layers are generally of JCP, CRCP, or ACP. These combinations yield 22 possible types of overlays, as shown in Table 2.1.

RIGID PAVEMENT OVERLAY DESIGN PROCEDURE

The overlay design procedure consists of three steps:

(1) evaluation of the existing pavement,

(2) determination of the design inputs, and

(3) analysis of the overlay thickness.

The procedure is illustrated in Fig 2.1.

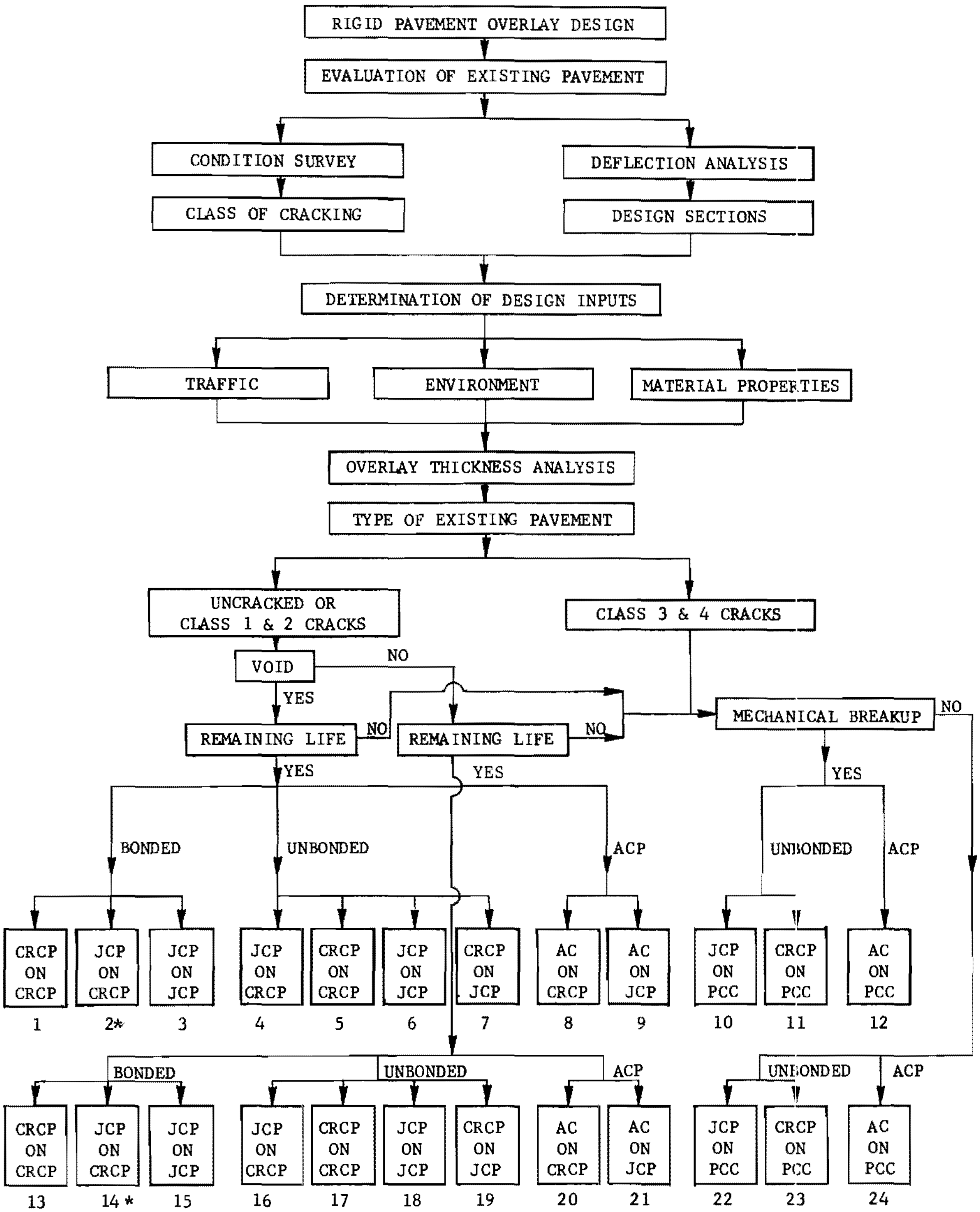
Evaluation of Existing Pavement

Evaluation of the existing pavement is accomplished by a condition survey and deflection measurements. The main purpose of the condition survey is to determine the type and amount of cracking present. The deflection measurements provide data necessary for dividing the pavement into segments that

TABLE 2.1 POSSIBLE OVERLAY TYPES

Engineering Decision										
Mechanical Treatment			Not Mechanically Broken Up					Mechanically Broken Up		
Bond			Bonded		Unbonded			Unbonded		
Overlay			JCP	CRCP	JCP	CRCP	ACP	JCP	CRCP	ACP
Physical Realities										
Surface Condition	Void Condition	Existing Pavement								
No Cracks and Class 1 and Class 2 Cracks	Without Void	JCP	X	-	X	X	X	-	-	-
		CRCP	-	X	X	X	X	-	-	-
	With Void	JCP	X	-	X	X	X	-	-	-
		CRCP	-	X	X	X	X	-	-	-
Class 3 and Class 4 Cracks	Without Void	JCP, CRCP } PCC	-	-	X	X	X	X	X	X

X - Overlays which are possible in practice.



* The overlay types are not generally recommended in practice.

Fig 2.1. Flow chart of overlay design procedure of rigid pavements.

behave differently under load. These are termed "design sections' and each is analyzed separately to determine the overlay thickness. The deflection measurements also aid in characterizing the subgrade material because the subgrade can be characterized more thoroughly by using deflections along the entire roadway in conjunction with laboratory tests than it can by using laboratory test values alone.

Determination of Design Inputs

The primary design inputs are traffic, environment, and material properties. An 18-kip (80-kN) equivalent single-axle design load is used in the procedure. Thus mixed traffic must be converted to 18 kip (80-kN) equivalent axle load applications using AASHTO equivalence factors. The traffic load prior to the overlay should be determined for use in computing the remaining life, and the projected future traffic load should be determined for the overlay thickness analysis.

It is desirable to consider the rainfall and drainage for the highway being overlaid, since moisture can have a significant effect on pavement material properties. In some cases the material strength estimates should be reduced because of excessive rainfall or poor drainage.

Material properties in the form of elastic moduli must be established for each layer in the pavement system as inputs to the linear elastic layer theory analysis. The modulus values for the overlay material, the intact existing pavement, and the base or subbase material are determined directly from laboratroy tests. The modulus for the subgrade is based on deflection measurements in conjunction with laboratory tests. The process is shown in Fig 2.2. Linear elastic layer theory is used to develop a relationship between subgrade modulus and surface deflection, as shown in Fig 2.3. The deflection measured in the field is entered into this relationship and a corresponding modulus is selected. If the deflection measurement load is different from the design load, the modulus must be adjusted for stress sensitivity (Ref 2). An uncracked pavement is assigned an effective modulus based on the strength of the concrete at the time of construction. This is usually in the range of two to five million psi (13.80 to 34.50 million kPa). The effective modulus for Class 3 and 4 cracked pavement is determined from the measured deflection. The increased deflection in the case of the Class

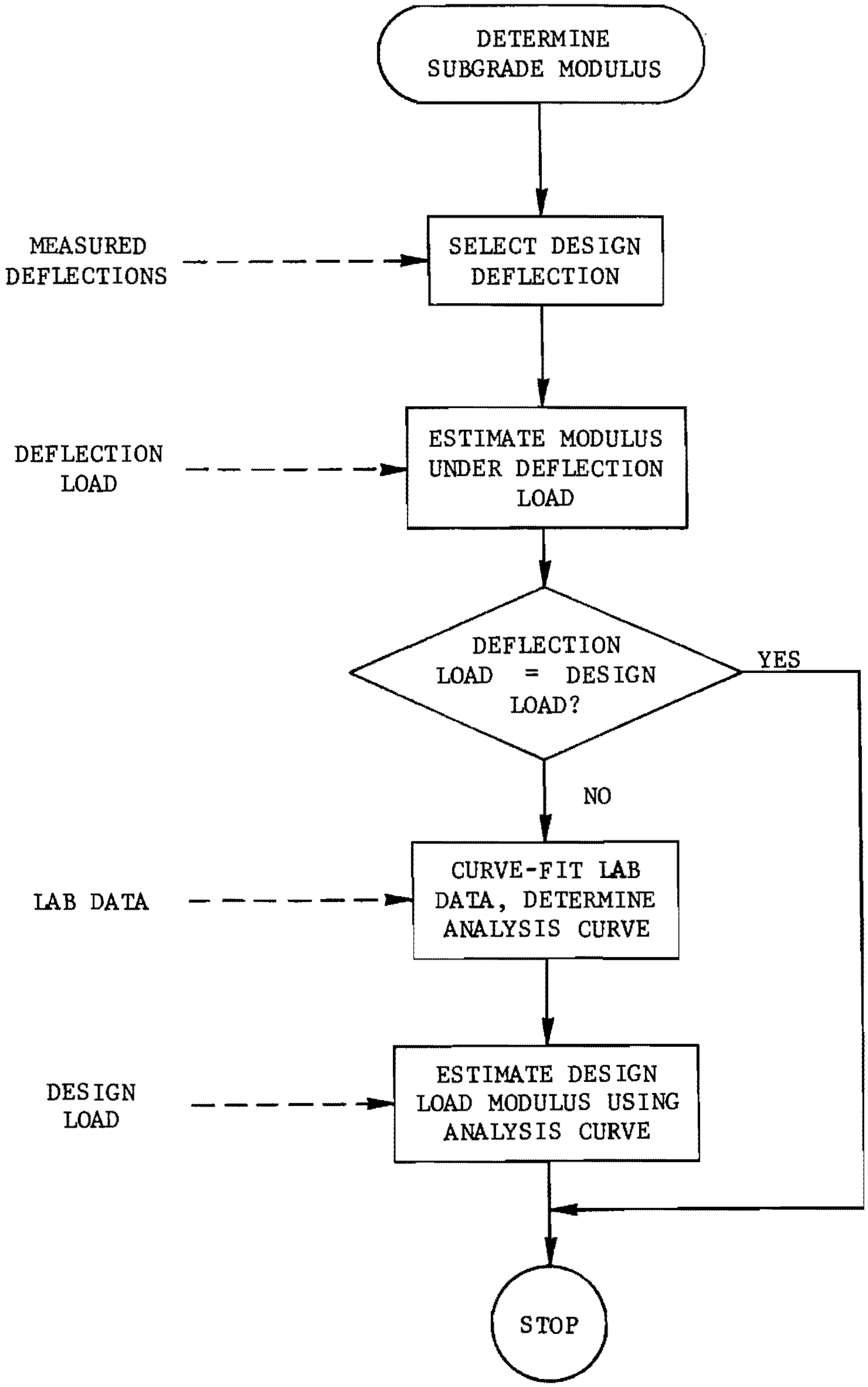


Fig 2.2. Determination of subgrade modulus.

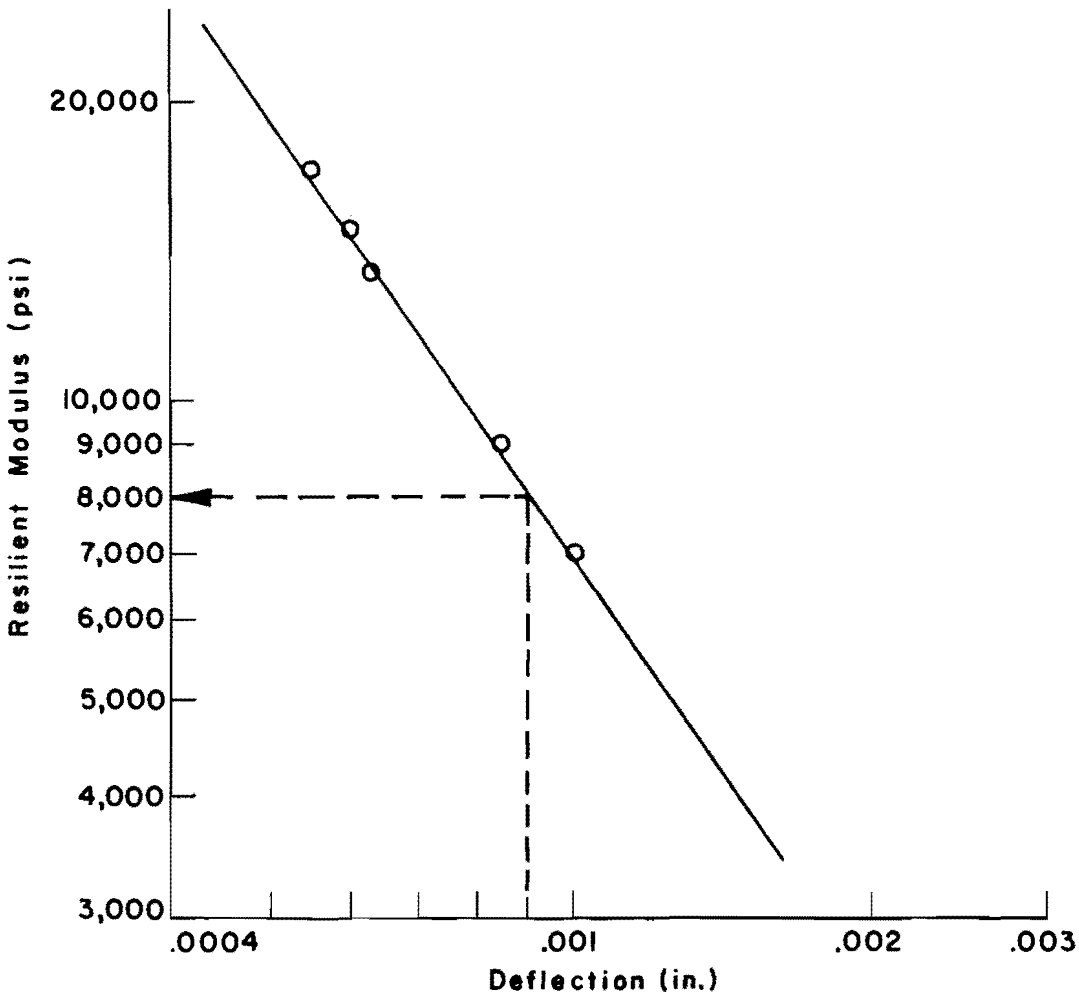


Fig 2.3. Relationship of computed deflection and subgrade modulus.

3 and 4 cracked condition is due to reduced stiffness, i.e., lower effective concrete modulus, and there is a relationship between the deflection and the modulus of the concrete pavement. From the measured deflection values, a modulus value of 500,000 psi (3.6×10^6 kPa) has been fixed for Class 3 and 4 cracked pavements (Ref 2). For the case of the mechanically broken-up condition, the cracked segments lose integrity between blocks and move under traffic. Therefore the modulus value of mechanically broken-up pavements is much less than that of the Class 3 and 4 cracked condition. A modulus value of 70.000 psi (4.8×10^5 kPa) was fixed for mechanically broken-up pavements (Ref 2).

Analysis of the Overlay Thickness

After the evaluation of the existing pavement, including designation of "design sections," and determination of design inputs, the analysis to determine overlay thickness is performed. This includes designation of the existing pavement and overlay types, stress computations, and a fatigue analysis and/or reflection cracking analysis. Figure 2.1 indicates 24 different analyses depending on the type of existing pavement, void, bond and overlay. A distinction is made between jointed and continuous pavement because the stress computations differ in each case. A jointed pavement should be designed for a corner load condition whereas a continuous pavement should be designed for an edge load condition. The fatigue analysis is performed for all 24 cases but the reflection cracking analysis is performed only in cases where the existing pavement is jointed or badly cracked. The RPOD1 program performs the fatigue cracking analysis. The reflection cracking analysis is performed by a separate program, RFLCR1.

The stresses needed for the fatigue analysis are computed by the linear elastic layered theory program ELSYM5 (Ref 4), which is the primary subroutine in the overlay design computer program. The horizontal tensile stress due to design load, an 18-kip (80-kN) single-axle, is computed at either the bottom of the overlay or the bottom of the existing pavement, depending on which the analysis is being performed on. If the existing pavement has remaining life, the critical stress is at the bottom of this layer, whereas, if the existing pavement has no remaining life, the critical stress is at the bottom of the overlay. The stress is automatically computed at the proper location in the pavement system, depending on which analysis has been designated in the program input data.

The stress computed by ELSYM5 is adjusted so that it is equivalent to the stress resulting from the design load position, that is, an edge for continuous pavements and a corner for jointed pavements. When the designer makes deflection measurements on jointed pavements, he makes them at the interior and the corner of the same panel. The ratio of these deflections is calculated and used in selecting the stress adjustment factor (Ref 2).

The fatigue analysis consists of the development of a relationship between axle applications of failure and overlay thickness. The number of axle loads to failure is computed using the following fatigue equation:

$$N = 23{,}440\ (f/\sigma)^{3.21}$$

where

N = number of axle loads until failure,

f = flexural strength of concrete, psi, and

σ = computed stress due to design load, psi.

The fatigue life is computed for a range of overlay thicknesses and a plot is made of thickness versus fatigue life, as shown in Fig 2.4. The projected traffic for the desired life of the overlay is entered on the abscissa and followed to the curve and then to the ordinate to determine the overlay thickness.

Reflection cracking analysis consists of evaluating overlay thickness using the following conceptual expression:

$$RF = f\ (E,\ t,\ \Delta T,\ \alpha,\ F)$$

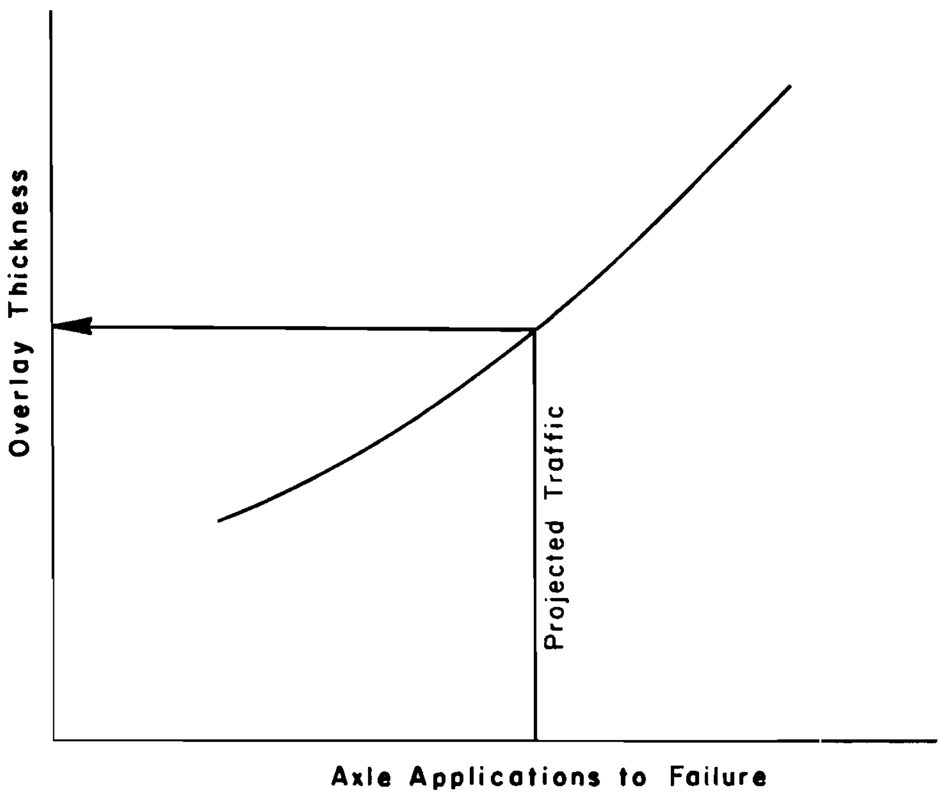


Fig 2.4. Relation of thickness and fatigue life used in selecting required overlay thickness for rigid pavements.

where

RF = reflection cracking,
E = modulus of elasticity of asphalt,
t = thickness of existing pavement or overlay
ΔT = temperature change,
α = coefficient of volume change for pavement materials, and
F = friction between pavement layers.

The overlay thcikness necessary to minimize or prevent reflection crakcing is selected based on these factors.

The final overlay thickness selected should satisfy both fatigue and reflection cracking criteria.

DEVELOPING THE SENSITIVITY ANALYSIS PROCEDURE

There are several bases for sensitivity analysis including "unit change", range, and standard deviation, but unit change and range do not give satisfactory results. The rationale for developing the procedure to be followed for sensitivity analysis of RPOD1 is as follows.

"Unit Change"

A "unit change" in each of the variables can be used for sensitivity analysis but does not result in meaningful conclusions. For example, assume that

the thickness of a concrete slab is given in inches,
the flexural strength in psi, and
the modulus of elasticity of concrete in psi.

If unit change is used as a basis for the analysis of sensitivity on the overlay thickness, the following statements could be made, but are not meaningful

(1) change in overlay thickness per inch of concrete,

(2) change in overlay thickness per psi of flexural strngth, and

(3) change in overlay thickness per psi of concrete modulus.

With the units as given for the independent parameters thickness of the concrete slab is the most important parameter from the overlay thickness point of view: addition of an inch of concrete will have a highly significant effect on the required overlay thickness, but a change of one psi in modulus will have no effect. On the other hand, if the units of the thickness are changed from inch to millimeter and those of flexural strength and modulus of of elasticity from psi to tsi (tons per square inch), the relative importance of the thickness will change. The change in overlay thickness per millimeter change of concrete slab thickness will not produce as great a change in overlay thickness as an inch, but a change in flexural strength of one tsi will be substantial. Thus change in the choice of units will alter the ranking of the independent variables and a sensitivity analysis based on "unit change" is therefore not valid.

"Range"

Range is defined as the absolute difference between the smallest and the largest values of an independent variable. For sensitivity analysis, low and high level values of an independent variable can be estimated to establish a range or span of values.

The problem of chosing a range is complicated because the choice is arbitrary and the results are not independent of the choices. In the example of the overlay in which unit change is used for the sensitivity analysis, the relative rankings of the thickness and flexural strength will change if the ranges for thickness and flexural strength of concrete are changed.

"Standard Deviation" - A Meaningful Basis for Sensitivity Analysis

A pavement designer is faced with many uncertainities in his design predictions. He has inexact knowledge about many of the inputs in his design and he has little or no quantitative information about the magnitude of these uncertainities, which create problems. The large random variability about the mean values of many parameters associated with pavement design, construction, and performance results in a large amount of uncertainity in the final response.

For many reasons, it is meaningful to select standard deviation, which is a measure of the variation of the individual observations about their arithmatic mean, as the basis for the sensitivity study. The standard deviation represents the smallest change in a variable which can be confidently controlled in practice. To compute the standard deviation, the deviations of the individual observations from their arithmatic mean are squared and the arithmatic average of the squared deviations is comptued. The square root of this average is the standard deviation, σ, which is expressed as follows:

$$\sigma = \sqrt{\frac{\Sigma(X_i - \bar{X})^2}{n}}$$

where

$\bar{X}$ = arithmatic mean of observations,

X_i = individual observation value, and

n = number of observations.

Total Variability

Generally, two types of variability are associated with pavement design inputs (Ref 3):

(1) within-project variability which is associated with variations about the means of input parameters within the same pavement section due to lack of tight quality control restrictions; is found along most highway inservice pavements; is referred to hereafter as wihtin-project standard deviation; and

(2) between-project variability the variability between assumed design average values and those actually constructed pavement; also, variation between specified design average values and the values of conditions to which pavement will be subjected during its lifetime, such as traffic loading and environment.

The total variation, both the within-project value and the between-project value, is required for sensitivity analysis. This can be calculated form the following relationship:

$$(\text{total standard deviation})^2 = (\text{within-project standard deviation})^2 + (\text{between-project standard deviation})^2$$

Input for Sensitivity Analysis

The functional relationship between the input and the output variables is often nonlinear. Because a linear effect model is considered in the sensitivity analysis, a change of two standard deviations on the positive and negative sides of the mean values of the independent variables is considered adequate for the analysis. The input data for the sensitivity analysis are the low level and high level values of the independent variables. The low and high level values are calculated as explained below.

Assuming that $X_1, X_2, X_3 \ldots X_i$ are independent variables; $\overline{X}_1, \overline{X}_2, \overline{X}_3, \ldots \overline{X}_i$ are their average values; and $\sigma_{X_1}, \sigma_{X_2}, \sigma_{X_3}, \ldots \sigma_{X_i}$ are their total standard deviations, the low level values are given by $X_{iL} = \overline{X}_i - 2\sigma_{X_i}$ and the high level values by $X_{iH} = \overline{X}_i + 2\sigma_{X_i}$.

"Full or Fractional Factorial Design" as a Meaningful Experimental Design

In order to determine the mean effects (main effects plus interactions) of independent variables, statistical methods, i.e., one-factor-at-a-time (single factorial) design and multiple factorial design are used. In one-factor-at-a-time design all design variables except one are kept constant at a certain level (medium, low, or high) and response values for several levels of the selected variable are taken. Another variable is then chosen and this process is continued until all variables have been considered. In this method the effect of an independent variable is determined from the difference of responses corresponding to different levels of that factor. The one-factor-at-a-time design could miss the most favorable treatment combinations and could lead to the following wrong conclusions.

(1) When interactions exist a factorial design is necessary to avoid misleading conclusions.

(2) In the factorial design the effect of a design variable is estimated at several levels of the other factors and the conclusions hold over a wide range of conditions.

(3) The relative rankings of design variables in one-factor-at-a-time design are not absolute rankings.

Therefore, we feel it necessary to use the multiple factorial design. A full multiple factorial design is one in which all levels of each factor or variable are combined with all levels of every other factor. A full factorial experiment is not practical here because the overlay design system involves as many as 17 variables. If there are eight variables, for example, and each variable has two levels, 2^8 i.e., 256 solutions, are required for a full factorial design. The great number of solutions required would be prohibitive from a cost and time standpoint. Recently statisticians have devoted attention to factorial designs requiring only a part of the full factorial observations. Designs of this type are called fractional designs. If the fractional factorial designs are properly analyzed nearly as much information can be obtained as is available from the full factorial design. Therefore, depending on the number of design variables, a full or fractional design can be selected for a sensitivity analysis. The technique for designing and analyzing fractional factorial desings is discussed in Appendix 4.

Estimation of Main Effects and Interactions

The sensitivity of the response is judged from the main effects and interactions of the independent variables. Thus the accurate determination of the main effects and interactions is important in the sensitivity analysis. The main effect of a variable is the average change in the responses produced by changes in levels of the factor. The interaction effect between two factors is the difference in the effects of one factor at different levels of another.

The main effects and interactions are calculated directly from the response values obtained by the solution of RPOD1, corresponding to a full or fractional factorial, as the case may be. The procedure for calculating the main effects and interactions of independent variables is presented in Appendix 3. The main effects and interactions calculated by this method must be divided by four to get the change in the response due to one standard deviation because the two levels of the independent variables used in obtaining the response value differ by four standard deviations.

The independent variables are ranked according to the relative magnitudes of their effects.

SEQUENCE OF STUDY FOR SENSITIVITY ANALYSIS

Based on the rationale discussed above the sensitivity analysis of RPOD1 followed this procedure.

(1) Define the problem for sensitivity analysis.

(2) List the response and independent variables to be studied.

(3) Estimate within-project and between-project standard deviations for all independent variables to be studied, based on available data. Calculate the total standard deviation from these two values.

(4) Assign two standard deviations change, $2\sigma_i$, to the mean values $\bar{X}_i$ of the independent variables on the high and low sides:

$$X_{iL} = \bar{X}_i - 2\sigma_i$$

$$X_{iH} = \bar{X}_i + 2\sigma_i$$

where X_{iL} represents the lower level and X_{iH} represents the higher level values of independent variable X_i .

(5) Decide which of the 22 possible overlay types shown in Table 1 are to be considered for the sensitivity analysis, based on the knowledge of common overlay types found in the State of Texas.

(6) Choose the independent variables to be considered for the multiple factorial design using single factorial design, which can provide rankings, though not absolute ones, of the independent variables.

(7) Decide whether a full factorial is feasible based on the number of independent variables selected. If it is not, carry out suitable (half or quarter) fractional factorial design and sort out the principal block.

(8) Run RPOD1 computer solutions for all the treatment combinations of the full factorial or fractional-factorial design, as the case may be, to obtain the corresponding response values.

(9) Tabulate from the computer output the thickness of the overlay corresponding to the desired future traffic.

(10) Calculate the main effects and interactions.

(11) Rank independent variables.

(12) Draw conclusions and make recommendations.

CHAPTER 3. SENSITIVITY ANALYSIS

In this chapter the medium values and standard deviations of the input variables are discussed and selected and the factorial experiments for four types of overlays are presented and discussed.

OVERLAY CONSIDERED FOR SENSITIVITY ANALYSIS

Altogether 22 types of overlays are possible, as shown in Table 2.1, depending on the type of existing pavement, void, bond, and overlay. It was not possible to make a sensitivity analysis for all 22 types of overlay because of the large amounts of time and effort required. The following four types of overlays, which are commonly used in the State of Texas, were chosen for the sensitivity analysis:

(1) bonded CRCP on CRCP without void;

(2) unbonded JCP on JCP without void for no cracks and Class 1 and Class 2 cracking condition;

(3) ACP over CRCP without void for no cracks and Class 1 and Class 2 cracking condition; and

(4) unbonded CRCP on CRCP without void for mechanically broken-up conditions.

In addition to these, single factorial experiments at the medium level were performed for some other overlays to see the effects of the input variables, and a summary of these results is presented in Appendix 5.

INDEPENDENT VARIABLES AND RESPONSE

In the solution of the RPOD1 program, the final output is the thickness of the overlay in inches. The independent variables are primarily material properties of different layers of the pavement, design deflection, laboratory data of the subgrade, and traffic. From the input guide for the computer program RPOD1 shown in Appendix 1, it can be seen that there is a maximum of 17 independent variables, the inputs for which are supplied in the form of directives to the program; there are nine main directives in the input guide of the program to describe the variables

(1) bond breaker directive,

(2) corner directive,
(3) deflection directive,
(4) laboratory data directive,
(5) layer directive,
(6) loads directive,
(7) overlay directive,
(8) pavement directive, and
(9) traffic directive.

In order to perform a one-factor-at-a-time design at the medium level for the purpose of chosing the number of variables for full or fractional factorial experiments, it is essential to estimate the medium values and the standard deviations of all the independent variables.

ESTIMATE OF MEDIUM VALUES AND STANDARD DEVIATIONS OF INPUT VARIABLES

In factorial design and in one-factor-at-a-time design, the medium, low, and high level values of the independent variables are used. The low level values are determined by subtracting two standard deviations from medium values and high level values are determined by adding two standard deviations to medium values. The sensitivity of the response of the system depends on these values, and it is important to determine the medium values and standard deviations of the input variables from field test conditions, as far as possible, to account for the actual variability of the inputs.

Flexural Strength of Concrete

In order to select values for the flexural strength of concrete, data from several sources should be considered. A summary of test results of concrete from AASHO Road Test (Ref 9) is shown in Table 3.1. An analysis of these test results gives the following information:

Mean flexural strength = 636 psi (4385 kPa)

Within-project standard deviation, σ_W, = 40.60 psi (280 kPa)

Between-project standard deviation, σ_B, = 9.78 psi (67.5 kPa)

Total standard deviation, σ, $= \sqrt{(\sigma_W)^2 + (\sigma_B)^2}$ = 41.76 psi (290 kPa)

Treybig has determined the following values for flexural strength of concrete, in "Sensitivity Analysis of the Extended AASHO Rigid Pavement Design Equation" (Ref 11):

High value = 800 psi (5500 kPa)

Standard deviation = 60 psi (410 kPa)

Low value = 400 psi (2750 kPa)

Standard deviation = 45 psi (310 kPa)

From the above values it can be determined that the mean flexural strength is 600 psi (4137 kPa) and the mean standard deviation is 52.5 psi (367 kPa).

Based on the results from these two sources, the following values were selected.

Mean flexural strength of concrete = 600 psi (4137 kPa)

Total standard deviation, σ = 50 psi (345 kPa)

Modulus of Elasticity of Concrete

The modulus of elasticity and flexural strength of concrete are approximately related by the following relationships (Ref 5)

$$E = 57400\sqrt{f_c'} \tag{3.1}$$

$$f_c = 7.5\sqrt{f_c'} \tag{3.2}$$

where

E = modulus of elasticity of concrete, in psi,

f_c' = compressive strength of concrete, in psi, and

f_c = flexural strength of concrete in psi.

The mean value and standard deviation of the modulus of elasticity of concrete are determined by Eqs 3.1 and 3.2 using the flexural strength value estimated earlier:

TABLE 3.1 SUMMARY OF TEST RESULTS OF CONCRETE FROM AASHO ROAD TEST (Ref 9)

Loop	FLEXURAL STRENGTH		
	No. of Tests	Mean (psi)	CV (%)
1	16	637	7.2
2	20	648	5.7
3	71	630	7.0
4	96	651	5.8
5	96	629	4.4
6	99	628	8.1

1 psi = 6.8948 kPa

Mean modulus value = 4.60×10^6 psi (31.7×10^6 kPa)

Total standard deviation = 0.40×10^6 psi (2.75×10^6 kPa)

Values for the modulus of elasticity from test results for concrete from ten projects in the State of Texas are shown in Table 3.2 (Ref 9). The weighted average modulus value is 3.99×10^6 psi (27.5×10^6 kPa) and the standard deviation is 1.36×10^6 psi (9.4×10^6 kPa). This standard deviation is higher than would be possible for a truly normal distribution.

The flexural strength and the modulus of elasticity are interrelated by the fundamental properties of concrete. The mean and standard deviation of the modulus of concrete determined using Eqs 3.1 and 3.2 from the flexural strength determined earlier seem reasonable and hence, those values are used for the sensitivity analysis.

Thickness of Surface Layer

Data for the thicknesses of some rigid pavements in the State of Texas are shown in Table 3.3 (Ref 9). From the data the following regression equation was developed to calculate the coefficient of variation within-project, CV_W, for any thickness:

$$CV_W = 2.398 + 0.85\,\bar{X}_i \tag{3.3}$$

From the data in Table 3.3, the mean thickness was determined to be 8.4 inches (213 mm). The value of CV_W for that thickness is 3.112 percent and σ_W is 0.25 inch (6.3 mm).

Individual project coefficients of variation of thickness for eight projects shown in Table 3.3 are used to calculate an overall weighted average mean thickness and an overall weighted between-project coefficient of variation from the following equations:

TABLE 3.2 SUMMARY OF TEST RESULTS FOR INDIVIDUAL ALONG-THE-ROAD SPECIMENS, PCC PAVEMENT PROJECTS (Ref 9)

District	Project Identification	Aggregate Type	Number of Specimens	Distance Covered (miles)	Tensile Strength		Modulus of Elasticity[2]		Density	
					Mean (psi)	CV (%)	Mean (10^6 psi)	CV (%)	Mean (pcf)	CV (%)
2	2-A	Limestone	104	17.0	459	19	4.14	40	140.6	1.1
	2-E	Limestone	134	27.3	490	20	3.70	35	140.1	1.6
12	12-Sp	Gravel	46	-	466	29	3.66	36	138.5	4.7
13	13-Sp	Gravel	28	-	584	19	4.38	22	140.7	1.7
17	17-B	Gravel	141	23.3	498	19	5.02	26	142.4	2.0
	17-M	Gravel	122	22.0	428	20	3.62	37	141.3	1.4
18	18-N	Limestone	25	4.6	424	19	3.74	24	142.0	1.8
	18-O	Limestone	72	4.2	566	19	4.24	26	146.2	1.2
19	19-A	Gravel	72	16.1	427	21	3.36	42	140.9	1.5
	19-B	Iron ore, slag, gravel	63	12.9	391	20	3.40	42	133.1	1.9
			Weighted Average		471	20	3.99	34	-	1.7
			Range		193	10	1.66	20	-	3.6
			CV of Means (%)		13		13		-	

[1] Top, center, and bottom slices from each core.

[2] Assumed Poisson's ratio = 0.20.

TABLE 3.3 THICKNESS OF PORTLAND CEMENT CONCRETE PAVEMENTS[1] (Ref 9)

District	Project Identification	Sample Plan	Number of Cores	Pavement Thickness Mean (Inches)	CV (%)	Design (Inches)
2	2-A	ATR[2]	38	8.3	2.6	8.0
	2-E	ATR	50	8.3	2.5	8.0
17	17-B	ATR	50	8.2	2.6	8.0
		Cluster[3]	10	7.8	1.2	8.0
	17-M	ATR	47	8.2	2.6	8.0
		Cluster 1	7	7.7	1.0	8.0
		Cluster 2	8	7.6	1.1	8.0
18	18-N	ATR	9	8.8	3.7	8.0
	18-O	ATR	24	9.5	4.7	9.0
19	19-A	ATR	34	8.2	2.9	8.0
	19-B	ATR	31	8.2	3.4	8.0
		Cluster 1	10	7.6	0.6	8.0
		Cluster 2	9	7.6	1.4	8.0

[1]Thickness determined by measuring depth of core in laboratory.

[2]Along-the-road.

[3]Cluster samples from thin section where thickness is less than design value.

1 inch = 25.4 mm

$$\bar{\bar{X}} = \Sigma f \bar{X}_i / \Sigma f \tag{3.4}$$

$$\sigma_B = \sqrt{\Sigma f (\bar{X}_i - \bar{\bar{X}})^2 / \Sigma f} \tag{3.5}$$

where

f = frequency of occurrence in each project,

$\bar{X}_i$ = mean value of each project, and

$\bar{\bar{X}}$ = weighted average mean.

Using the values of Table 3.3

σ_B = 0.38 inch (9.6 mm)

Total standard deviation, σ, $= \sqrt{(\sigma_w)^2 + (\sigma_B)^2}$ = 0.45 inch (11.4 mm).

Based on above results, the following reasonable values for the thickness of the surface layers were chosen for the sensitivity analysis:

Mean thickness, $\bar{X}$, = 8.0 in. (20.3 mm)

Total standard deviation, σ, = 0.50 in. (12.7 mm).

<u>Poisson's Ratio of the Surface Layer</u>

Since no test data were available for the determination of the Poisson's ratio of portland cement concrete, it was necessary to assume a value of Poisson's ratio by engineering judgement. For the sensitivity analysis the following values were assumed:

Mean value of Poisson's ratio, $\bar{X}$ = 0.20

Total standard deviation, σ = 0.05

Modulus of Bond Breaker

A bond breaker layer of asphalt concrete was considered for the sensitivity analysis. Test data for the mdoulus of ACP of a project in the State of Texas are shown in Table 3.4 (Ref 9). From these data:

Mean modulus of elasticity = 4.2×10^4 psi (29×10^4 kPa)

Coefficient of variation, CV_W, = 29 percent

As the data shown in Table 3.4 are based on the test results of one project, the above values are not reliable. The mean modulus value of that project is lower than the average value generally experienced in practice. Therefore the following reasonable values were selected for the sensitivity analysis based on engineering judgement:

Mean modulus value, $\bar{X}$ = 10×10^4 psi (69.0×10^4 kPa)

Total standard deviation, σ, = 2.5×10^4 psi (17.25×10^4 kPa)

Thickness of Bond Breaker

The following test data were obtained from the experimental records of Austin Research Engineers, Inc.:

Mean thickness of bond breaker, $\bar{X}$, = 2.05 in. (52 mm)

Total standard deviation, σ, = 0.87 in. (22 mm)

Based on these data the following values were selected for the sensitivity analysis:

Mean thickness, $\bar{X}$, = 2.00 in. (50.8 mm)

Total standard deviation, σ, = 0.80 in. (20.3 mm).

Poisson's Ratio of Bond Breaker

The test data for Poisson's ratio of ACP from a project in the State of Texas are shown in Table 3.4 (Ref 9). From Table 3.4,

TABLE 3.4 SUMMARY OF ALONG-THE-ROAD TEST RESULTS, ASPHALTIC CONCRETE (Ref 9)

District	Project Identi-fication	Number of Specimens	Distance Covered (miles)	Tensile Strength		Modulus of Elasticity		Poisson's Ratio		Density	
				Mean (psi)	CV (%)	Mean (10^3 psi)	CV (%)	Mean	CV (%)	Mean (pcf)	CV (%)
15	15-A	15	10.9	77	16	42.0	29	0.40	27	133.5	3.7

[1] Results for all individual specimens or lifts.

1 psi = 6.8948 kPa

Mean Poisson's ratio, $\bar{X}$, = 0.40

Coefficient of variation, CV_W, = 27 percent.

The test data shown in Table 3.4 are based on results obtained from only one project and therefore may not be reliable. Mean value of the Poisson's ratio seems to be reasonable but the coefficient of variation is higher. Hence by engineering judgement the following values were selected for the sensitivity analysis:

Mean Poisson's ratio, $\bar{X}$ = 0.40

Total standard deviation, σ = 0.05.

<u>Modulus of Base Course</u>

Mainly cement-treated or asphalt-treated base course is used in rigid pavements. For the sensitivity analysis a cement-treated base course was considered. The test results from four projects in the State of Texas (Ref 9) for modulus of elasticity of cement-treated base course are shown in Table 3.5. From the data the regression equation for the coefficient of variation within project is

$$CV_W(\text{percent}) = 48.72 + 18.62\,\bar{X}_i \qquad (3.6)$$

Mean modulus value, $\bar{X}_i$, from the data of Table 3.5 is 1.10×10^6 psi (7.58×10^6 kPa). Therefore, CV_W = 69.20 percent and $\sigma_W = 0.76 \times 10^6$ psi (5.23×10^6 kPa). The between-project coefficient of variation, σ_B, was estimated to be 0.46×10^6 psi (3.17×10^6 kPa).

$$\text{Total standard deviation, } \sigma, = \sqrt{\sigma_W^2 + \sigma_B^2} = 0.89 \times 10^6 \text{ psi}$$
$$(6.13 \times 10^6 \text{ kPa})$$

The total standard deviation value seems to be quite high for normal distribution and the mean value and standard deviations as determined above may not be representative ones. So the following reasonable values were selected from engineering judgement for the sensitivity analysis:

TABLE 3.5 SUMMARY OF ALONG-THE-ROAD TEST RESULTS, CEMENT-TREATED BASE PROJECTS (Ref 9)

District	Project Identi-fication	Type of Material	Number of Specimens	Distance Covered (miles)	Tensile Strength		Modulus of Elasticity[2]		Density	
					Mean (psi)	CV (%)	Mean (10^6 psi)	CV (%)	Mean (pcf)	CV (%)
12	12-A	Sand shell	32	-	210	31	1.76	72	128.4	3.9
19	19-A	Soil cement	20	1.4	90	23	1.05	83	122.0	1.9
	19-B	Soil cement	19	1.2	83	37	0.73	57	121.3	2.8
20	20-A	Burned clay	29	1.5	120	49	0.60	60	113.8	3.7
			Weighted Average		136	36	1.09	68	-	3.2
			Range		127	26	1.16	26	-	2.0
			CV of Means (%)		46	-	50	-	-	-

[1] Results for all individual specimens or lifts.

[2] Assumed Poisson's ratio = 0.22. 1 psi = 6.8948 kPa

Mean modulus value, $\bar{X}$, = 5×10^5 psi (3.45×10^6 kPa)

Total standard deviation, σ = 1×10^5 psi (6.89×10^5 kPa)

Thickness of Base Course

No test data were analyzed to estimate the mean value and standard deviations of the base course. The following values were assumed for use in the sensitivity analysis based on practical experience:

Mean thickness, $\bar{X}$, = 8.0 inches (203.2 mm)

Total standard deviation, σ, = 0.80 inch (20.3 mm)

Poisson's Ratio of Base Course

No test data were available for the determination of the Poisson's ratio of base course, but, in order to calculate the modulus of cement treated base, a Poisson's ratio of 0.22 was assumed (Ref 9). For the sensitivity analysis the following values were assumed to be reasonable:

Mean Poisson's ratio, $\bar{X}$ = 0.20

Total standard deviation, σ = 0.05.

Resilient Moduli of Subgrade

Subgrade moduli are determined with the help of triaxial test apparatus at different deviator stresses. The test results of subgrade modulus for four airports are shown in Table 3.6 (Ref 3). The moduli values were determined at three different deviator stresses, i. e., 2, 5, and 8 psi (13.78, 34.47, and 55.16 kPa). The mean values and standard deviations of subgrade moduli at three different deviator stresses are determined as follows.

Deviator stress of 2 psi (13.78 kPa). From the summary of resilient moduli of Table 3.6 the mean modulus value is 19×10^3 psi (131×10^3 kPa) and the within-project coefficient of variation, CV_W , is 22 percent.

TABLE 3.6 SUMMARY OF RESILIENT MODULI FOR SUBGRADE SOILS FOR AIRPORTS (Ref 3)

Airport	Project Identification	Reference	Number of Tests	Deviator Stress (psi)					
				8		5		2	
				Mean (10^3 psi)	CV (%)	Mean (10^3 psi)	CV (%)	Mean (10^3 psi)	CV (%)
Palmdale	Runway 7-25	18	4	10	52	10	47	8.4	26
		20	10	24	26	30	29	38	34
O'Hare	Runway 9R-27L	17	8	7.9	48	-	-	-	-
		18	3	6.3	21	8.7	12	10	13
	Runway 4R-22L	18	4	5.7	17	7.0	5.3	8.4	16
Richmond	Taxiway S-4 Runway 2 Taxiway D	18	3	8.6	8.3	12	20	11	18
Midway	Runway 4R-22L 13R-31L	18	4	2.4	10	4.0	7.9	5.4	6.6
	Weighted Average			12	29	16	22	19	22
	Variation	Limits		2.4-24	8.3-52	4-30	5.3-47	5.4-3.8	6.6-34
		Range		21.6	43.7	26	41.7	32.6	27.4

1 psi = 6.8948 kPa

The within-project standard deviation is 4.18×10^3 psi (28.82×10^3 kPa). It was observed that the subgrade modulus values between projects were not normally distributed. To find the between-project standard deviation, the logs of the moduli were considered to be normal. Between-project standard deviation was calculated by the method described and found to be 6.60×10^3 psi (45.5×10^3 kPa). Therefore,

$$\text{Total standard deviation, } \sigma = \sqrt{\sigma_W^{\,2} + \sigma_B^{\,2}} = 7.80 \times 10^3 \text{ psi } (53.77 \times 10^3 \text{ kPa}).$$

<u>Deviator Stress of 5 psi (34.47 kPa)</u>. In the way stated in the previous case, the following values were obtained:

Mean modulus, $\bar{X} = 16 \times 10^3$ psi (110.3×10^3 kPa)

Within-project standard deviation, $\sigma_W = 3.68 \times 10^3$ psi (25.37×10^3 kPa)

Between-project standard deviation, $\sigma_B = 6.00 \times 10^3$ psi (41.37×10^E kPa)

Total standard deviation, $\sigma = 7.00 \times 10^3$ psi (48.26×10^3 kPa).

<u>Deviator stress of 8 psi (55.16 kPa)</u>. Using the procedure discussed for the case of a deviator stress of 2 psi (13.78 kPa), the following values are obtained:

Mean modulus, $\bar{X} = 12 \times 10^3$ psi (82.73×10^3 kPa)

Within-project standard deviation, $\sigma_W = 3.30 \times 10^3$ psi (22.75×10^3 kPa)

Between-project standard deviation, $\sigma_B = 4.74 \times 10^3$ psi (32.68×10^3 kPa)

Total standard deviation, $\sigma = 5.62 \times 10^3$ psi (38.75×10^3 kPa).

Based on the above results, the following reasonable values were selected for the sensitivity analysis:

Deviator Stress	Mean Modulus, $\overline{X}_i$	Total Standard Deviation, σ
2 psi (13.78 kPa)	19×10^3 psi (131×10^3 kPa)	7.5×10^3 psi (51.7×10^3 kPa)
5 psi (34.47 kPa)	16×10^3 psi (110.31×10^3 kPa)	7.0×10^3 psi (48.2×10^3 kPa)
8 psi (55.16 kPa)	12×10^3 psi (82.73×10^3 kPa)	5.5×10^3 psi (37.9×10^3 kPa)

Poisson's Ratio of Subgrade

No experimental data were available for the determination of Poisson's ratio of subgrade material. The following reasonable values were selected for the sensitive analysis :

Mean Poisson's ratio, $\overline{X}$, = 0.40

Total standard deviation, σ, = 0.10

Ratio of Corner to Interior Deflection

The input data are required only for jointed concrete pavements (JCP) to convert the stresses for interior condition to corner condition. In order to find out the mean value and the standard deviation, a theoretical curve, shown in Fig 3.1 was used. The percentage of load transfer at the joint in the case of JCP varies from 0 to 100. The corresponding corner to interior deflection ratios lie within the range of 2.31 to 3.14. From these two extreme values of corner to interior deflection ratios, the mean and standard deviations are calculated as per the following:

$$\text{Mean value} = (2.31 + 3.14)/2 = 2.725$$

Assuming 95 percent confidence level, $Z = 1.96$ (from statistical table)

$$\sigma = \frac{\overline{X} - X_L}{Z} \tag{3.7}$$

$$= \frac{2.725 - 2.31}{1.96}$$

$$= 0.211 .$$

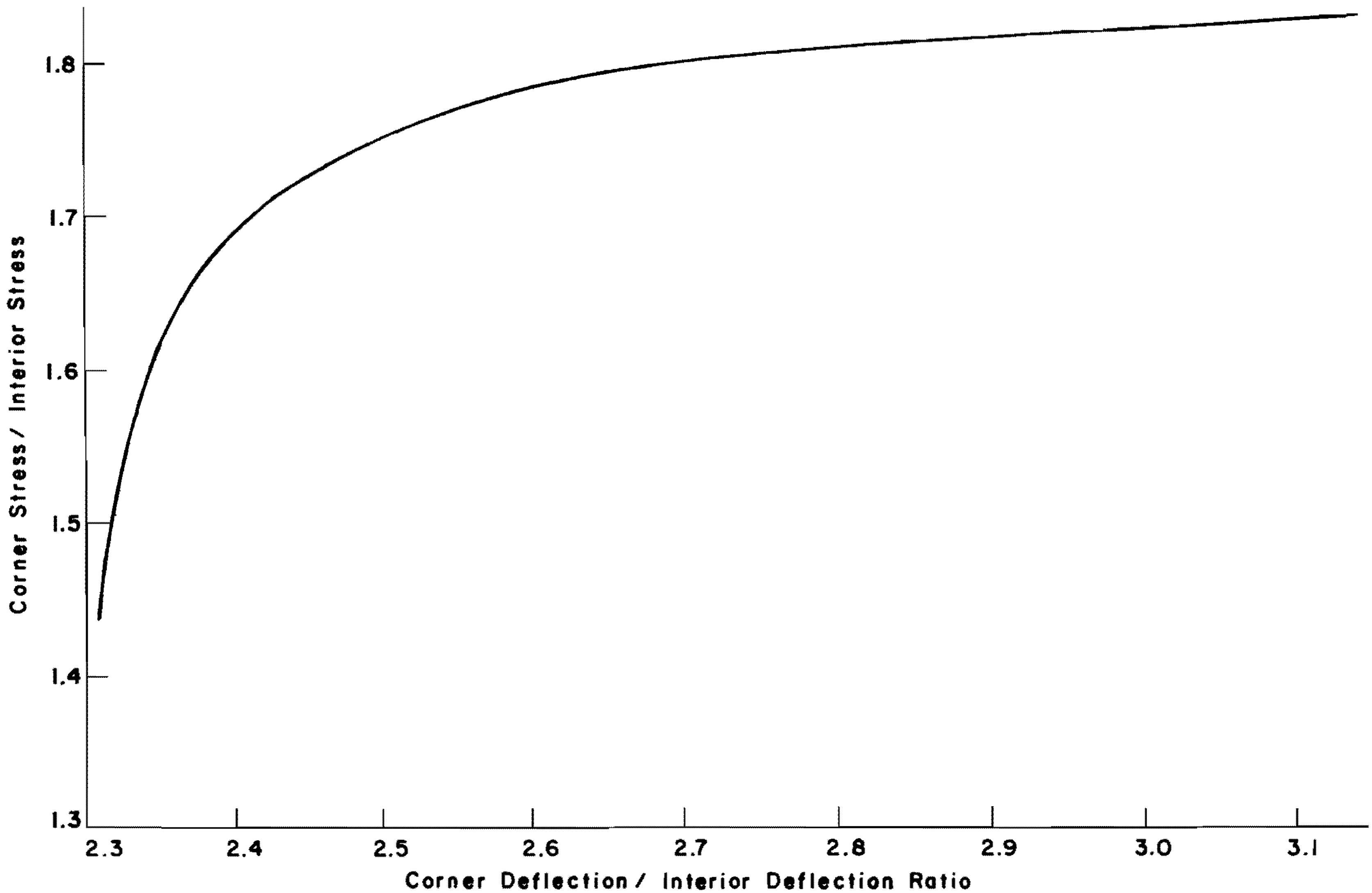


Fig 3.1. Stress ratio curve for design.

The following values were selected for the sensitivity analysis after rounding:

Mean value, $\bar{X}$, = 2.80

Total standard deviation, σ, = 0.20.

Design Deflection

The deflections are generally measured either by Benkleman beam or by Dynaflect. The different parameters in connection with deflection measurement which are fed as input data into program RPOD1 are (1) the design deflection, (2) the magnitude and positions of loads used to measure deflection, and (3) the location of the point where deflection is measured. Table 3.7 shows a summary of a deflection survey on CRCP in the State of Texas (Ref 8). From these test data the following values are determined for CRCP:

Mean deflection, $\bar{X}$, = 0.00865 in. (.22 mm)
Total standard deviation, σ, = 0.00309 in. (.078 mm).

The deflection values for JCP are taken from the test data of 49 AASHO sections (Ref 2) and are

Mean deflection for uncracked/or Class 1 and 2 cracks
$\bar{X}$ = 0.0107 in. (.27 mm)
Total standard deviation, σ, = 0.0036 in. (.09 mm)
Mean deflection for class 3 and 4 cracks, $\bar{X}$, = 0.014 in. (.35 mm)
Total standard deviation, σ, = 0.0044 in. (0.11 mm).

After rounding off the figures, the following values were selected for the sensitivity analysis.

(1) Mean value of deflection for CRCP, $\bar{X}$, = 0.009 in. (0.22 mm)
Total standard deviation, σ, = 0.003 in. (0,08 mm)

TABLE 3.7 SUMMARY OF DEFLECTION SURVEY DATA OF CRCP IN STATE OF TEXAS (Ref 8)

Serial No.	Project Type	Number of Observations	Individual Project Deflection (in thousands of an inch)
1	Fine grain subbase + poor subgrade	4	13.64
2	Crushed stone subbase + poor subgrade	4	13.56
3	Cement stab subbase + poor subgrade	3	5.61
4	Asphalt stab subbase + poor subgrade	3	9.45
5	Lime stab subbase + poor subgrade	4	4.12
6	Fine grained subbase + fair subgrade	4	6.67
7	Crushed stone subbase + fair subgrade	4	9.73
8	Asphalt stab subbase + fair subgrade	4	7.52
9	Lime stab subbase + fair subgrade	4	5.95
10	Fine grained subbase + good subgrade	4	11.95
11	Crushed stone subbase + good subgrade	4	9.14
12	Cement stabilized subbase + good subgrade	3	5.37
13	Asphalt stab subbase + good subgrade	4	7.93
14	Lime stab subbase + good subgrade	4	9.16

1 in = 25.4 mm

(2) Mean value of deflection for JCP for uncracked or class 1 and 2 cracks, $\overline{X}$ = 0.01 in (0.25 mm).

Total standard deviation, σ = 0.0036 in. (.09 mm)

(3) Mean value of deflection for JCP for class 3 and 4 cracks, $\overline{X}$ = 0.014 in (0.35 mm)

Total standard deviation, σ = 0.0044 in (0.11 mm).

All the above deflections were measured by the Benkleman beam method. The load used to measure the deflections in Benkleman beam method is 18-kip (80-kN) single-axle with dual tires. The positions of wheels and locations of deflection measurement are shown in Fig 3.2.

Traffic Prior to Overlay

The traffic terms of 18-kip (80-kN) equivalent single-axle wheel loads that has used the existing pavement system prior to the overlay, is required for estimating the percentage of the remaining life of the pavement. Mainly an overlay is used on a rigid pavement after 15 to 20 years of service. Of course, the overlay is decided on considering the existing pavement condition and the future anticipated traffic. Traffic study data of Interstate Highways in three counties of the State of Texas are shown in Table 3.8. From these data it is found that total numbers of equivalent 18-kip (80-kN) single load applications in one direction lie between 1.5 and to 3.5 million for a period of 10 to 15 years of service. The following reasonable traffic values were assumed for the sensitivity analysis:

Mean traffic = 4×10^6 applications

Total standard deviation = 0.5×10^6 million.

INPUTS FOR FACTORIAL DESIGN

To estimate the effects of the input variables in one-factor-at-a-time (single factorial) design and multiple factorial design, the lower and higher level values of input variables are determined in the following way.

(1) Lower-level values are found by subtracting two standard deviations from mean values, i.e.,

$$X_{iL} = \overline{X}_i - 2\sigma_i \tag{3.8}$$

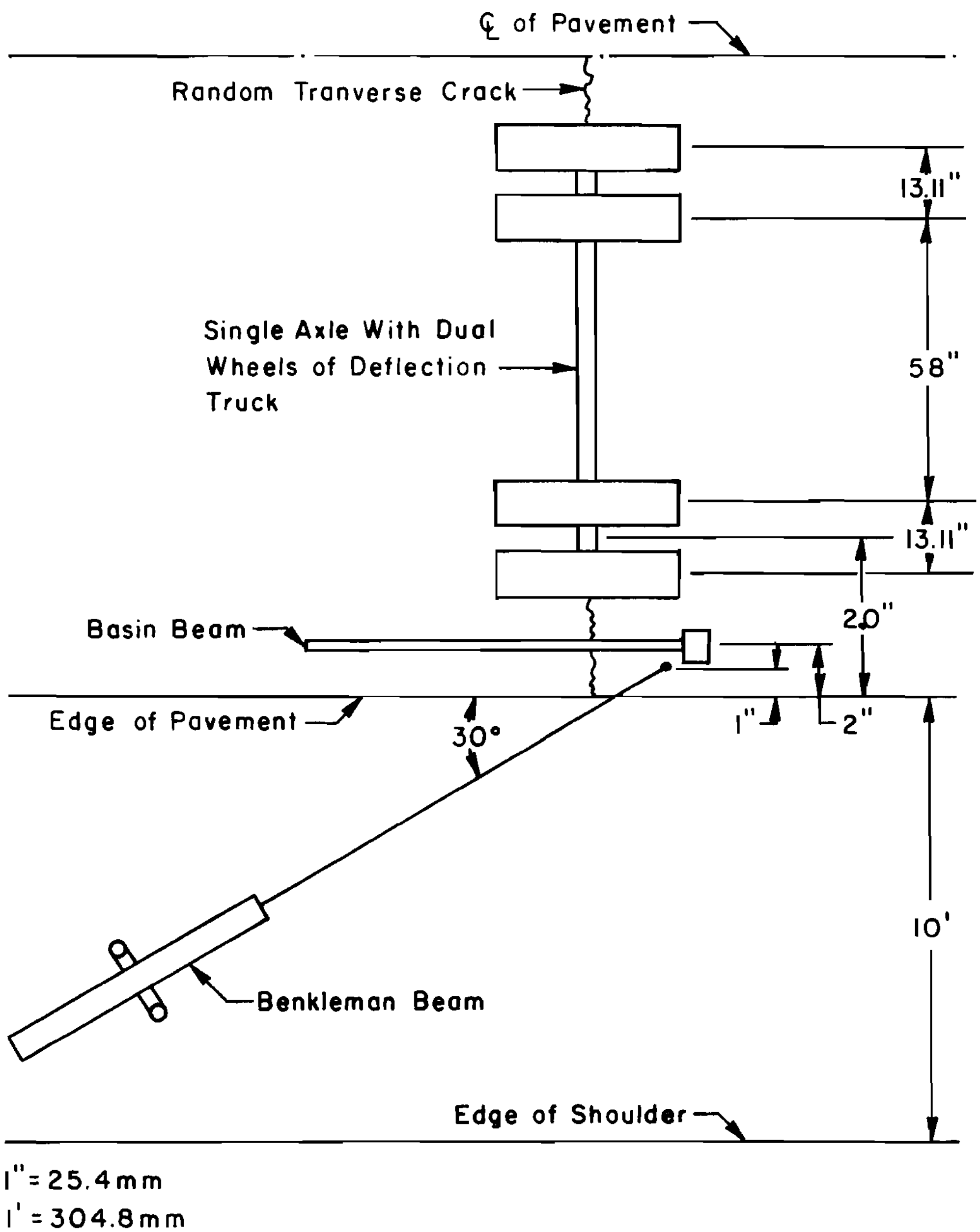


Fig 3.2. Plan view of equipment arrangement for Benkleman Beam.

TABLE 3.8 TRAFFIC ANALYSIS FOR HIGHWAY DESIGN

Description of Location	Average Daily Traffic 1965	Average Daily Traffic 1975	Percent Directional Distribution Factor	Percent Design Hourly Volume	Percent Trucks ADT	Percent Trucks DHV	Percent Anticipated Annual Rate of Growth	ATHWLD	Percent Tandem Axlea in ATHWLD	Total Number of Equivalent 18X Single Axle Load Applications One Direction Expected for a Year Design Period (19 to 19) Flexible Pavement	Rigid Pavement
Guadalupe County IH 35: From Bexar County Line to Comal County Line	1965 10,490	1975 22,500	65-35	11.5	15.3	5.1	11.4	11,400	50	-	8" Slab Thickness 10 Years (1965-1975) 3,142,000
Johnson County IH 35W: From Burleson (jct. SH 174) to 2.5 Miles North of Alvarado	1965 5,730	1975 13,400	60-40	12.8	14.4	9.8	13.4	11,000	50	-	10 Years (1965-1975) 1,505,000
McLennan County IH 35: From Falls County Line to 2.0 Miles North of Bruceville	1960 5,350	1975 17,350	60-40	12.8	16.1	9.0	14.9	11,100	50	-	15 years (1960-1975) 3,437,000

where

X_{iL} = lower-limit value of the i^{th} independent variable,

$\overline{X}_i$ = mean value of i^{th} independent variable, and

σ_i = total standard deviation of i^{th} independent variable.

(2) Higher-level values are found by adding two standard deviations to mean values, i.e.,

$$X_{iH} = \overline{X}_i + 2\sigma_i \tag{3.9}$$

where

X_{iH} = high-level value of the i^{th} indpendent variable.

All these input values are summarized in table 3.9. The variables for the overlay as shown in Fig 3.9 are applicable when the overlay layer is made of portland cement concrete. In the case of asphalt concrete overlays there will be no bond breaker and the values of the bond breaker will be considered as the values for the overlay.

SINGLE FACTOR EXPERIMENT

In the one-factor-at-a-time design (single factor design), a basic problem was run using the medium values of all input variables. Then two problems were solved for each variable, one in which the variable was moved at the low level and the other where the variable was moved to the high level, keeping all other variables at their medium levels. The responses corresponding to 30-million load applications were recorded in each solution. These load applications were selected arbitrarily to study the effects of input variables on the response. In some cases the response values, i.e., thicknesses of the overlay, are higher, which seem unreasonable from a practical construction point of view. However, the determined response values are quite significant in estimating the effects of the variables for the sensitivity analysis.

The summary of the solutions for four types of overlays, i.e., (1) bonded CRCP over CRCP, (2) unbonded JCP over CJP, (3) ACP over CRCP, and (4) unbonded CRCP over CRCP, mechanically broken up, are shown in Tables 3.10 through 3.13.

TABLE 3.9. INPUTS FOR FACTORIAL DESIGN

SL Number	Layer	Variable	Mean Value $\overline{X}_i$	Standard Deviation, σ_i (Total)	Lower Value of Variable, $\overline{X}_{iL}$ $(\overline{X}_i - 2\sigma)$	Higher Value of Variable, $\overline{X}_{iH}$ $(X_i + 2\sigma)$
1	Overlay	Modulus of elasticity (psi)	4.60×10^6	0.40×10^6	3.80×10^6	5.40×10^6
2		Poisson's ratio	0.20	0.05	0.10	0.30
3	Bond Breaker	Modulus of elasticity (psi)	10×10^4	2.5×10^4	5×10^4	15×10^4
4		Thickness (inch)	2.00	0.80	0.40	3.60
5		Poisson's ratio	0.40	0.05	0.30	0.50
6	Surface Course	*Modulus of elasticity (psi)	4.60×10^6	0.40×10^6	3.80×10^6	5.40×10^6
7		Thickness (inch)	8.00	0.50	7.00	9.00
8		Poisson's ratio	0.20	0.05	0.10	0.30
9	Base Course	Modulus of elasticity (psi)	5×10^5	1.00×10^5	3.00×10^5	7.00×10^5
10		Thickness (inch)	8.00	0.80	6.40	9.60
11		Poisson's ratio	0.20	0.05	0.10	0.30
12	Subgrade	Resilient Moduli (psi) Deviator Stress				
		2 psi	19×10^3	7.50×10^3	4.00×10^3	34.00×10^3
		5 psi	16×10^3	7.00×10^3	2.00×10^3	30.00×10^3
		8 psi	12×10^3	5.50×10^3	1.00×10^3	23.00×10^3
13		Poisson's ratio	0.40	0.10	0.20	0.60
14		Deflection (inch)				
		CRCP	0.0090	0.0030	0.0030	0.0150
		JCP-Class 1 and 2	0.0100	0.0036	0.0028	0.0172
		JCP-Class 3 and 4	0.0140	0.0044	0.0052	0.0228
15		Ratio of corner to interior deflection (JCP)	2.800	0.20	2.40	3.20
16		Flexural strength of concrete (psi)	600	50.0	500.00	700.00
17		Traffic prior to overlay	4×10^6	0.5×10^6	3.0×10^6	5.0×10^6

*Concrete elastic modulus and flexural strength are varied simultaneously (see p. 22, 23).

1 psi = 6.8948 kPa

1 inch = 25.4 mm

TABLE 3.10 SUMMARY OF SINGLE FACTORIAL EXPERIMENT OF BONDED CRCP OVERLAY ON CRCP, WITHOUT VOID

Sl. No. 1	Independent Variables 2	Thickness of overlay at lower level of variable (inch) 3	Thickness of overlay at higher level of variable (inch) 4	Effect (inch) 5	Rank of Variables 6
1	Modulus of overlay	6.90	6.40	-0.50	8
2	Poisson's ratio of overlay	6.60	6.50	-0.10	11
*3	Modulus of surface layer	8.10	5.30	-2.80	6
4	Thickness of surface layers	9.50	4.80	-4.70	3
5	Poisson's ratio of surface layer	4.80	9.40	4.60	4
6	Modulus of base course	11.30	3.90	-7.40	2
7	Thickness of base course	9.40	5.00	-4.40	5
8	Poisson's ratio of base course	6.30	6.70	0.40	9
9	Modulus of subgrade	6.60	6.60	0.00	12
10	Poisson's ratio of subgrade	6.30	7.30	1.00	7
11	Design deflection	1.00	9.60	8.60	1
12	Traffic	5.70	6.00	0.30	10

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

Thickness of overlay when all variables at medium level = 6.6 in.

1 inch = 25.4 mm

TABLE 3.11 SUMMARY OF SINGLE FACTORIAL EXPERIMENT FOR UNBONDED JCP OVERLAY ON JCP WITHOUT VOID

Sl. No. 1	Independent Variables 2	Thickness of overlay at lower level of variable (inch) 3	Thickness of overlay at higher level of variable (inch) 4	Effect (inch) 5	Rank of Variables 6
1	Modulus of overlay	15.5	13.9	-1.60	4
2	Poisson's ratio of overlay	14.0	15.4	1.40	5
3	Modulus of bond breaker	15.4	13.6	-1.80	3
4	Thickness of bond breaker	13.9	14.9	1.00	6
5	Poisson's ratio of bond breaker	14.6	14.7	0.10	12
*6	Modulus of surface layer	16.3	13.3	-3.00	1
7	Thickness of surface layer	14.9	14.5	-0.40	10
8	Poisson's ratio of surface layer	14.6	14.7	0.10	12
9	Modulus of base course	15.2	14.3	-0.90	7
10	Thickness of base course	15.0	14.4	-0.60	9
11	Poisson's ratio of base course	14.7	14.6	-0.10	12
12	Modulus of subgrade	14.7	14.7	0.00	13
13	Poisson's ratio of subgrade	14.6	14.9	0.30	11
16	Design deflection	13.3	15.2	1.90	2
15	Ratio of corner to interior deflection	14.0	14.7	0.70	8
16	Traffic	14.7	14.7	0.00	13

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

Thickness of overlay when all variables are at medium levels = 14.7 in.

1 inch = 25.4 mm

Note: The thicknesses shown here are large because relatively high levels of variables were chosen to compare variables.

TABLE 3.12 SUMMARY OF SINGLE FACTORIAL EXPERIMENT OF AC OVERLAY ON CRCP, WITHOUT VOID

Sl. No. 1	Independent Variables 2	Thickness of overlay at lower level of variable (inch) 3	Thickness of overlay at higher level of variable (inch) 4	Effect (inch) 5	Rank of Variables 6
1	Modulus of overlay	15.10	12.20	-2.90	6
2	Poisson's ratio of overlay	14.60	13.90	-0.70	11
*3	Modulus of surface layer	16.20	11.90	-4.30	5
4	Thickness of surface layer	18.60	10.00	-8.60	4
5	Poisson's ratio of surface layer	13.30	15.10	1.80	8
6	Modulus of base course	20.00	7.30	-12.70	2
7	Thickness of base course	21.00	9.70	-11.30	3
8	Poisson's ratio of base course	14.40	13.50	-0.90	9
9	Modulus of subgrade	14.10	14.10	0.00	12
10	Poisson's ratio of subgrade	14.00	14.80	0.80	10
11	Design deflection	5.30	21.30	16.00	1
12	Traffic	15.40	13.30	2.10	7

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

Thickness of overlay when all variables at medium levels = 14.10 in.

1 inch = 25.4 mm

Note: The thicknesses shown here are large because relatively high levels of variables were chosen to compare variables.

TABLE 3.13 SUMMARY OF SINGLE FACTORIAL EXPERIMENT FOR UNBONDED CRCP OVERLAY ON CRCP WITHOUT VOID, MECHANICALLY BROKEN UP

Sl. No. 1	Independent Variables 2	Thickness of overlay at lower level of variable (inch) 3	Thickness of overlay at higher level of variable (inch) 4	Effect (inch) 5	Rank of Variables 6
1	Modulus of overlay	13.80	12.00	-1.80	1
2	Poisson's ratio of overlay	12.30	13.50	1.20	3
3	Modulus of bond breaker	13.10	12.50	-0.60	4
4	Thickness of bond breaker	12.70	13.00	-0.30	6
5	Poisson's ratio of bond breaker	12.80	12.90	0.10	7
*6	Modulus of surface course	12.90	12.80	-0.10	7
7	Thickness of surface course	12.90	12.80	-0.10	7
8	Poisson's ratio of surface course	12.80	12.90	0.10	7
9	Modulus of base course	13.10	12.70	-0.40	5
10	Thickness of base course	13.00	12.70	-0.30	6
11	Poisson's ratio of base course	12.80	12.90	0.10	7
12	Modulus of subgrade	12.80	12.80	0.00	8
13	Poisson's ratio of subgrade	12.80	12.80	0.00	8
16	Design deflection	11.90	13.30	1.40	2

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

Thickness of overlay when all variables at medium levels = 12.8 in.

1 inch = 25.4 mm

Note: The thicknesses shown here are large because relatively high levels of variables were chosen to compare variables.

The values in column five in Tables 3.10 through 3.13 are the difference between columns four and three. The independent variables were ranked according to the magnitude of their responses shown in column five.

The number of independent variables for further full factorial or fractional experiments for each four types of overlays were selected on the basis of the relative ranking of independent variables.

The reader will note that the average overlay thicknesses seem excessively large. This results from the combination of levels chosen for medium levels in the study. Please ignore the thicknesses themselves and consider primarily the changes and rankings.

Bonded CRCP Overlay on CRCP Without Void

In the single factorial experiment for this type of overlay, there were 12 independent variables. It can be seen from Table 3.10 that the effect for an individual variable ranges from 0.0 to 8.60 in. (0 to 218.4 mm). The variables whose effects are equal to or more than 0.5 in. (12.7 mm) were considered for study in the larger factorial experiment. The variables so considered are shown below and are identified by A, B, C, D, E, F, G, and H for convenience.

(1) modulus of overlay = A,
*(2) modulus of surface layer = B,
(3) thickness of surface layer = C,
(4) Poisson's ratio of surface layer = D,
(5) modulus of base course = E,
(6) thickness of base course = F,
(7) Poisson's ratio of subgrade = G, and
(8) design deflection = H.

Unbonded JCP Overlay on JCP Without Void

In the single factorial experiment for this type of overlay, there were 16 independent variables. Seven variables whose individual effects are 0.9 (22.8 mm) or more were considered for further full or fractional factorial experiments. These variables are also identified as A, B, C. D, E, F, and G for convenience and are shown below.

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23)

(1) modulus of overlay = A,

(2) Poisson's ratio of overlay = B,

(3) Modulus of bond breaker = C,

(4) thickness of bond breaker = D,

*(5) modulus of surface layer = E,

(6) modulus of base course = F, and

(7) design deflection = G.

AC Overlay on CRCP, Without Void

Asphalt concrete (AC) overlay on CRCP without void for uncracked condition had 12 variables in the single factorial experiment. The effects of variables are shown in Table 3.12. Six variables out of 12 which had effects equal to or more than 2.5 in. (63.5 mm) were selected for full factorial or fractional factorial experiment and are shown below.

(1) modulus of overlay = A,

(2) modulus of surface layer = B,

(3) thickness of surface layer = C,

*(4) modulus of base course = D,

(5) thickness of base course = E, and

(6) design deflection = F.

Unbonded CRCP Overlay on CRCP Without Void Mechanically Broken Up

This type of overlay has 14 variables in single factorial experiments. The effects of variables are shown in Table 3.13. The following six variables were selected for full or fractional factorial design.

(1) modulus of overlay = A,

(2) Poisson's ratio of overlay = B,

(3) modulus of bond breakers = C,

*(4) modulus of surface layers = D,

(5) modulus of base course = E, and

(6) design deflection = F.

*See footnote on page 51.

MULTIPLE FACTORIAL DESIGN

As discussed above there are eight variables for bonded CRCP overlay CRCP, seven variables for unbonded JCP overlay on JCP, six variables for ACP overlay on CRCP, and six variables for unbonded CRCP overlay on CRCP to be considered in factorial experiments. A factorial design for each type of overlay is considered separatelv below.

Bonded CRCP Overlay on CRCP

There are eight independent variables in the present sensitivity analysis. The other nine independent variables are fixed at their medium levels. For these eight factors in a two-level full factorial, it will not be economical to run a whole factorial of 256 solutions (a two-level factorial of eight variables = 2^8 = 256). However, nearly as much information can be obtained from a half or quarter factorial design (fractional factorial) as from a full factorial, and it was decided to use one-fourth of the observations of a 2^8 factorial. In this design of a quarter-fraction factorial, three degrees of freedom are confounded with blocks. If two fourth-order interactions are confounded withblocks, one fifth-order interaction is automatically confounded, as given by the following defining contrast:

$$I = ABCDEF = DEFGH = ABCGH \tag{3.10}$$

which confounds 3df with the four blocks. In this design, if only one of the four blocks of 64 observations is run each effect will have three aliases (refer to Table A4.1). There are 63df within each block. In this design, all three factors and the higher order interactions must be neglected. The main effects are clear of two-factor interactions, and two-factor interactions are not confounded with one another. This is a very practical design. Table A4.2 gives the treatment combinations in all four blocks. It also shows the principal block.

Sixty-four solutions of RPOD1, corresponding to the treatment combinations of the selected quarter-fractional factorial design were obtained. The response values, i.e., the thickness of overlays in inches corresponding to 30-million applications of equivalent 18-kip (80-kN) single-axle loads, of 64 solutions are given in Table 3.14.

TABLE 3.14. THICKNESS OF BONDED CRCP OVERLAY ON CRCP CORRESPONDING TO A QUARTER FRACTION FACTORIAL DESIGN OF 2^8 (all values in inches)

H	G	F	E	D	A_0 B_0 C_0	A_0 B_0 C_1	A_0 B_1 C_0	A_0 B_1 C_1	A_1 B_0 C_0	A_1 B_0 C_1	A_1 B_1 C_0	A_1 B_1 C_1
H_0	G_0	F_0	E_0	D_0	11.10			0.50		3.40	4.70	
				D_1								
			E_1	D_0								
				D_1	5.20			0.50		0.50	3.50	
		F_1	E_0	D_0								
				D_1	11.00			3.00		4.80	6.50	
			E_1	D_0	0.50			0.50		0.60	0.50	
				D_1								
	G_1	F_0	E_0	D_0								
				D_1		10.20	9.0		12.70			4.40
			E_1	D_0		0.50	0.60		3.40			0.50
				D_1								
		F_1	E_0	D_0		3.40	4.70		8.10			0.50
				D_1								
			E_1	D_0								
				D_1		0.50	0.5		1.70			0.50
H_1	G_0	F_0	E_0	D_0								
				D_1		12.70	10.0		14.50			11.10
			E_1	D_0		5.60	7.0		9.10			3.20
				D_1								
		F_1	E_0	D_0		9.80	9.2		13.9			5.0
				D_1								
			E_1	D_0								
				D_1		4.90	6.10		7.10			3.60
	G_1	F_0	E_0	D_0	13.40			9.50		14.30	11.70	
				D_1								
			E_1	D_0								
				D_1	12.30			8.1		12.30	10.70	
		F_1	E_0	D_0								
				D_1	12.80			13.20		13.80	11.10	
			E_1	D_0	4.40			0.50		1.20	3.10	
				D_1								

1 inch = 25.4 mm

A = Modulus of overlay
*B = Modulus of surface layer
C = Thickness of surface layer
D = Poisson's ratio of surface layer
E = Modulus of base course
F = Thickness of base course
G = Poisson's ratio of subgrade
H = Design deflection

*Concrete modulus and flexural strength are varied simultaneously (See p. 22, 23).

Unbonded JCP Overlay on JCP

Seven independent variables are considered for a two-level factorial experiment. The other independent variables are kept constant at their medium levels. Since it may not be economical to run a full factorial of 128 solutions (two-level factorial of seven variables = 2^7 = 128), it was decided to use a one-half replicate of a 2^7, thus requiring 64 solutions to complete the factorial experiment. The decision to confound the highest-order interaction with blocks, gave

$$I = ABCDEFG \tag{3.11}$$

Two blocks were found by placing (1) and all pairs quadruples, and sextuples of seven letters in one block and single letters, triples, quintuples, and one septuple of seven letters in the other block (Refer to Table A4.3). This is a very practical design as there are good tests on all main effects and first-order interactions, assuming all higher-order interactions are zero. Table A4.5 gives the treatment combinations in the two blocks. The response values in terms of the thickness of the overlay in inches are shown in Table 3.15.

AC Overlay on CRCP

There are six independent variables for consideration of a two-level factorial experiment. The other independent variables are kept constant at their medium levels. It was thought to be economical to run one-half replicate of 2^6 thus requireing 32 solutions. Deciding to confound the highest-order interaciton with blocks, we have

$$I = ABCDEF \tag{3.12}$$

Table A4.6 gives the aliases of effects for a one-half fraction of a 2^6 factorial design. Table A4.7 gives the treatment combination of the principle block. The response values of 32 solutions are shown in Table 3.16.

Unbonded CRCP Overlay on CRCP (Mechanically Broken Up)

As mentioned earlier, in this type of overlay, six variables are considered for a two-level factorial design and all other variables are kept constant at

TABLE 3.15 THICKNESS OF UNBONDED JCP OVERLAY ON JCP CORRESPONDING TO ONE-HALF FRACTION FACTORIAL DESIGN OF 2^7 (all values are in inches)

A				A_0				A_1			
B				B_0		B_1		B_0		B_1	
G	F	E	D \ C	C_0	C_1	C_0	C_1	C_0	C_1	C_0	C_1
G_0	F_0	E_0	D_0	13.2			13.7		13.9	15.7	
			D_1		13.6	15.9		15.5			15.8
		E_1	D_0		9.3	11.6		11.7		12.4	
			D_1	12.4			12.1		12.1	14.2	
	F_1	E_0	D_0		8.8	8.4		7.8			8.0
			D_1	5.4			6.3		5.9	4.8	
		E_1	D_0	7.1			6.9		6.5	6.4	
			D_1		5.0	4.2		4.0			4.4
G_1	F_0	E_0	D_0		15.2	17.6		17.4			19.0
			D_1	16.7			17.2		17.0	19.1	
		E_1	D_0	12.5			13.4		13.6	15.8	
			D_1		12.4	15.3		15.0			15.5
	F_1	E_0	D_0	14.3			15.2		15.5	17.8	
			D_1		14.4	17.4		17.1			17.5
		E_1	D_0		9.5	12.5		12.8			13.8
			D_1	13.2			12.7		12.9	15.6	

1 inch = 25.4 mm

A = Modulus of overlay
B = Poisson's ratio of overlay
C = Modulus of bond breaker
D = Thickness of bond breaker
*E = Modulus of surface layer
F = Modulus of base course
G = Design deflection

*Concrete modulus and flexural strength are varied simultaneously (See p. 22, 23).

TABLE 3.16 THICKNESS OF AC OVERLAY ON CRCP CORRESPONDING TO ONE-HALF FRACTION FACTORIAL DESIGN OF 2^6 (all values in inches)

F	E	D	A_0				A_1			
			B_0		B_1		B_0		B_1	
			C_0	C_1	C_0	C_1	C_0	C_1	C_0	C_1
F_0	E_0	D_0	24.0			6.2		1.7	16.0	
		D_1		1.8	4.9		6.9			0.5
	E_1	D_0		7.5	9.8		13.1			3.6
		D_1	0.4			0.5		0.5	0.4	
F_1	E_0	D_0		25.1	26.3		18.3			21.2
		D_1	22.0			12.8		14.1	15.9	
	E_1	D_0	22.2			17.8		21.4	26.6	
		D_1		4.6	6.3		6.4			2.6

1 inch = 25.4 mm

A = Modulus of overlay
*B = Modulus of surface layer
C = Thickness of surface layer
D = Modulus of base course
E = Thickness of base course
F = Design deflection

*Concrete modulus and flexural strength are varied simultaneously (See p. 22, 23).

their medium levels. A full factorial design of six variables each at two levels require 64 solutions. From a time and economic point of view it was decided to go for a one-half fraction factorial design which requires 32 solutions. Table A4.6 gives the aliases of effects for a one-half fraction 2^6 factorial design. Table A4.7 gives the treatment combination of the principle block. The response values of 32 solutions are shown in Table 3.17.

SENSITIVITY OF RESPONSE

The changes occurring in the responses corresponding to changes made in input variables for four types of overlays considered are estimated in this section.

The mean effects (Main effects and interactions) were calculated from RPOD1 solution response values of Table 3.14, 3.15, 3.16, and 3.17 according to the procedure described in Appendix 3. Since two levels of the input variables spanned a total of four standard deviations, 4σ, or two standard deviations on either side of their mean values, the calculated mean effects corresponded to a change of 4σ in the independent variables. Tables 3.18, 3.19, 3.20, and 3.21 show the values of mean effects calculated in this manner for (1) bonded CRCP overlay on CRCP, (2) unbonded JCP overlay on JCP, (3) ACP overlay on CRCP, and (4) unbonded CRCP overlay on CRCP, mechanically broken up, respectively. For the sensitivity analysis, however, mean effects corresponding to one standard deviation change in the input variables were required. These values can be obtained simply by dividing the above calculated mean effects by four.

RANKINGS OF VARIABLES

Based on the relative values of the main effects, the independent variables which were considered for fractional factorial designs were given appropriate rankings. Figures 4.1, 4.10, 4.19, and 4.30 indicate the rankings of variables of bonded CRCP overlay on CRCP, unbonded JCP overlay on JCP, ACP overlay on CRCP and unbonded CRCP overlay on CRCP, respectively. All these results are discussed in detail in Chapter 4.

TABLE 3.17 THICKNESS OF UNBONDED CRCP OVERLAY ON CRCP, MECHANICALLY BROKEN UP, ONE-HALF FRACTION FACTORIAL DESIGN (all values in inches)

F	E	D \ A	A_0				A_1			
		B	B_0		B_1		B_0		B_1	
		C	C_0	C_1	C_0	C_1	C_0	C_1	C_0	C_1
F_0	E_0	D_0	12.6			13.7		10.4	11.8	
		D_1		12.2	13.6		10.8			11.5
	E_1	D_0		12.0	13.4		10.7			11.30
		D_1	12.4			13.1		10.3	11.70	
F_1	E_0	D_0		13.8	15.4		12.3			13.3
		D_1	14.2			15.2		12.1	13.6	
	E_1	D_0	13.6			14.4		11.4	13.0	
		D_1		13.1	14.8		11.8			12.7

1 inch = 25.4 mm

A = Modulus of overlay
B = Poisson's ratio of overlay
C = Modulsu of bond breaker
D = Modulus of surface layer
E = Modulus of base course
F = Design deflection

TABLE 3.18 AVERAGE EFFECTS ON THE BONDED CRCP OVERLAY ON CRCP (OVERALL MEAN VALUE OF OVERLAY = 6.6 IN.)

Number	Factor	Average effect on factor, (inches)	Effect as a percent of overall mean	Rank
1	A	-0.04	- 0.6	30
2	B	-2.67	-40.5	4
3	C	-2.69	-40.8	3
4	D	+2.09	+31.6	6
5	E	-5.32	-80.6	1
6	F	-2.16	-32.7	5
7	G	+0.75	+11.3	11
8	H	+4.93	+74.7	2
9	AB	-0.168	- 2.5	25
10	AC	-0.256	- 3.8	21
11	BC	+0.262	+ 4.0	20
12	AD	-0.100	- 1.5	28
13	BD	+0.181	+ 2.7	24
14	CD	+0.493	+ 7.5	14
15	AE	+0.212	+ 3.2	22
16	BE	+1.106	+16.7	8
17	CE	+0.393	+ 6.0	16
18	DE	-0.025	- 0.3	32
19	AF	-0.212	- 3.2	22
20	BF	+0.506	+ 7.5	14
21	CF	+0.187	+ 2.8	23
22	DF	-0.125	- 1.9	26
23	EF	-0.762	-11.5	10
24	AG	+0.375	+ 5.7	17
25	BG	+0.106	+ 1.6	27
26	CG	+0.731	+11.0	12
27	DG	+1.059	+16.0	9

(Continued)

TABLE 3.18. (Continued)

28	EG	-0.600	- 9.1	13
29	FG	-1.187	-18.0	7
30	AH	+0.362	+ 5.5	18
31	BH	-0.056	- 0.8	29
32	CH	+0.681	+10.3	13
33	DH	-0.381	- 5.7	17
34	EH	-0.275	- 4.2	19
35	FH	-0.037	- 0.5	31
36	GH	+0.475	+ 7.2	15

1 in. = 25.4 mm

A = Modulus of overlay
*B = Modulus of surface layer
C = Thickness of surface layer
D = Poisson's ratio of surface layer
E = Modulus of base course
F = Thickness of base course
G = Poisson's ratio of subgrade
H = Design deflection

*Concrete modulus and flexural strength are varied simultaneously (See p. 22, 23).

TABLE 3.19 SUMMARY OF AVERAGE EFFECTS ON UNBONDED JCP OVERLAY ON JCP
(OVERALL MEAN VALUE OF OVERLAY = 14.70 IN.)

Factors	Average Effect of Factor (inches)	Effect of Percent of Overall Mean	Rank
A	-0.90	- 6.12	6
B	+1.08	+ 7.34	5
C	-0.60	- 4.08	12
D	+0.10	+ 0.68	24
E	-2.64	-17.95	4
F	-4.18	-28.43	2
G	+5.38	+36.60	1
AB	+0.012	+ 0.08	27
AC	+0.156	+ 1.06	21
AD	-0.212	- 1.44	20
AE	+0.062	+ 0.42	25
AF	-0.375	- 2.55	14
AG	+0.643	+ 4.37	10
BC	-0.875	- 5.95	7
BD	-0.118	- 0.80	23
BE	-0.031	- 0.21	26
BF	-0.350	- 2.38	16
BG	+0.537	+ 3.65	13
CD	-0.10	- 0.68	24
CE	-0.15	- 1.02	22
CF	+0.243	+ 1.65	18
CG	-0.368	- 2.50	15
DE	+0.218	+ 1.48	19
DF	-0.762	- 5.18	8
DG	+0.712	+ 4.84	9
EF	+0.312	+ 2.12	17

(Continued)

TABLE 3.19. (Continued)

EG	-0.612	- 4.16	11
FG	+2.893	+19.72	3

1 inch = 25.4 mm

A = Modulus of elasticity of the overlay
B = Poisson's ratio of the overlay
C = Modulus of elasticity of the bond breaker
D = Thickness of the bond breaker
*E = Modulus of elasticity of the surface layer
F = Modulus of elasticity of the base course
G = Design deflection of the existing pavement

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

TABLE 3.20 SUMMARY OF AVERAGE EFFECTS ON ACP OVERLAY ON CRCP (OVERALL MEAN VALUE OF OVERLAY = 14.10 IN.)

Number	Factor	Average effect on factor, (inches)	Effect as a percent of overall mean	Rank
1	A	- 1.58	-11.20	12
2	B	- 1.33	- 9.40	14
3	C	- 4.85	-34.40	3
4	D	-10.02	-71.00	2
5	E	- 4.63	-32.80	4
6	F	+10.19	+72.25	1
7	AB	+ 1.70	+12.00	10
8	AC	+ 0.09	+ 0.63	20
9	AD	+ 0.68	+ 4.82	15
10	AE	+ 2.11	+15.00	7
11	AF	+ 0.10	+ 0.70	19
12	BC	- 0.28	- 2.00	18
13	BD	- 0.44	- 3.12	17
14	BE	+ 3.01	+21.34	5
15	BF	+ 0.51	+ 3.61	16
16	CD	+ 1.61	+11.41	11
17	CE	+ 1.50	+10.70	13
18	CF	+ 1.79	+12.70	8
19	DE	- 2.53	-17.96	6
20	DF	- 1.76	-12.48	9
21	EF	- 1.51	-10.70	13

1 in. = 25.4 mm

A = Modulus of overlay
*B = Modulus of surface layer
C = Thickness of surface layer
D = Modulus of base
E = Thickness of base
F = Design deflection

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

TABLE 3.21 SUMMARY OF AVERAGE EFFECTS ON UNBONDED CRCP OVERLAY ON CRCP, MECHANICALLY BROKEN UP (OVERALL MEAN VALUE OF OVERLAY = 12.8 IN.)

Number	Factor	Average effect of the factor, (inches)	Effect as a percent of overall mean	Rank
1	A	-1.76	-11.97	1
2	B	+1.14	+ 7.75	3
3	C	-0.35	- 2.38	5
4	D	+0.03	+ 0.20	11
5	E	-0.38	- 2.58	4
6	F	+1.48	+10.06	2
7	AF	+0.062	+ 0.42	10
8	AC	-0.168	- 1.14	8
9	AD	+0.062	+ 0.42	10
10	AE	+0.031	+ 0.21	11
11	AF	-0.018	- 0.12	12
12	BC	+0.031	+ 0.21	11
13	BD	+0.018	+ 0.12	12
14	BE	+0.062	+ 0.42	10
15	BF	+0.118	+ 0.80	9
16	CD	+0.018	+ 0.12	12
17	CE	-0.031	- 0.21	11
18	CF	+0.018	+ 0.12	12
19	DE	-0.018	- 0.12	12
20	DF	-0.218	- 1.48	7
21	EF	-0.250	- 1.70	6

1 in. = 25.4 mm

A = Modulus of overlay
B = Poisson's ratio of overlay
C = Modulus of bond breaker
*D = Modulus of surface layer
E = Modulus of base course
F = Design deflection

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

CHAPTER 4. DISCUSSION AND ANALYSIS OF RESULTS

The principal objective of this study was to evaluate the relative sensitivity of input variables to the response of the overlay design system RPOD1. The following is a discussion of the results of the statistical analysis.

BONDED CRCP OVERLAY ON CRCP

The mean effects (main effects and interactions) of eight variables which were considered for the sensitivity analysis were calculated by the methods described in Appendix 3 and are presented in Table 3.18. The main effects of eight variables along with their relative ranking and the main effects with significant two-factor interactions are presented as bar graphs in Figs 4.1 and 4.2, respectively. Both the bar graphs are self-explanatory. It can be said from Table 3.18 and Figs 4.1 and 4.2 that

(1) the modulus of the base course (E), which is of cement stabilized material, is the most significant parameter.

(2) The design deflection (H) is the second most significant parameter.

(3) The modulus of the overlay layer has little effect in determination of the thickness of the overlay.

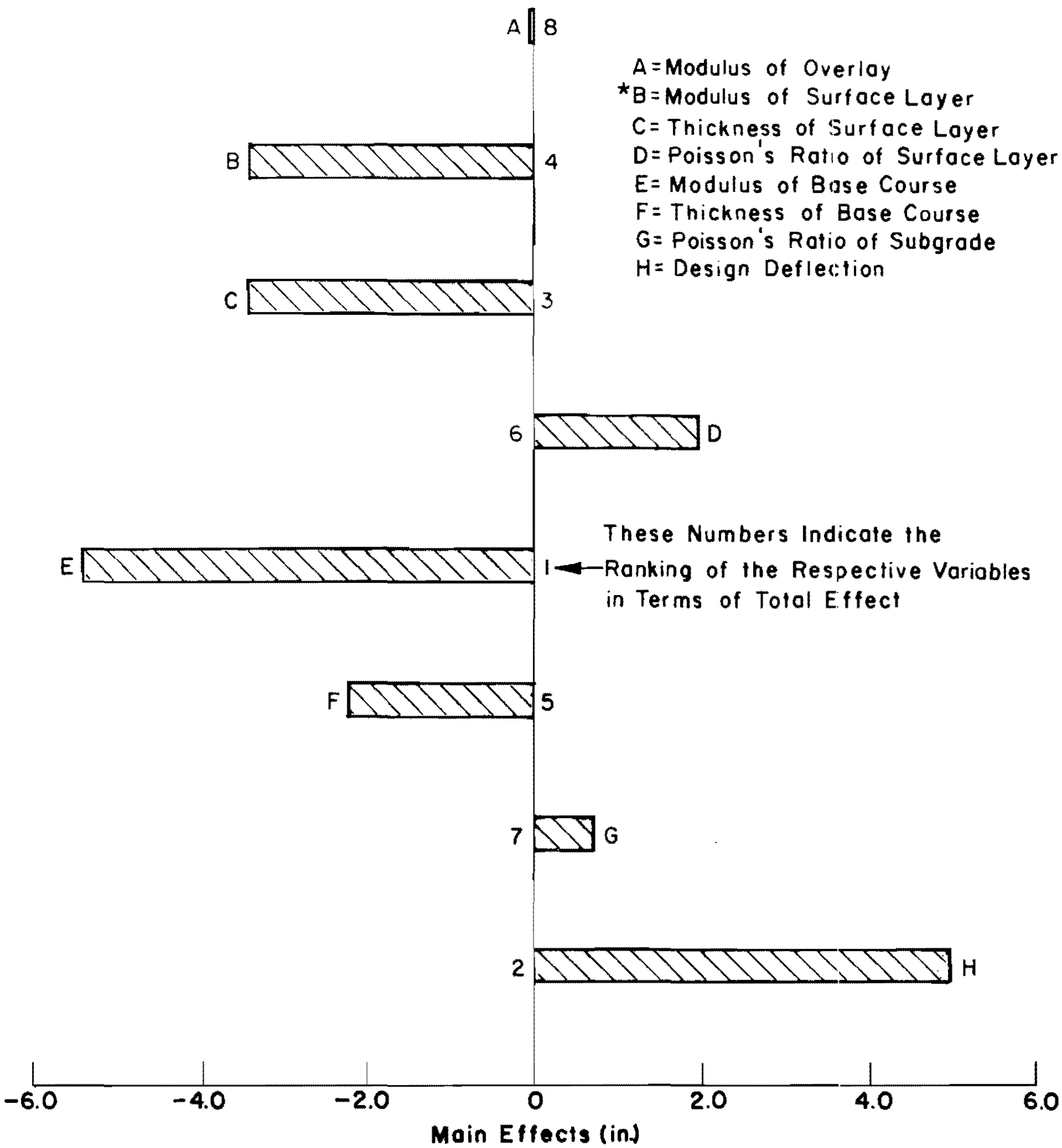
(4) The interaction between the thickness of the base course and Poisson's ratio of subgrade is the most important interaction effect.

(5) The Poisson's ratio of the surface layer, the Poisson's ratio of the subgrade, and the design deflection have positive effects on the thickness of overlay, which means when the values of these variables increase the thickness of the overlay increases.

(6) The modulus* of the surface layer, the thickness of the surface layer, the modulus of the base course and the thickness of the base course have negative effects, which means when the values of these variables increases the thickness of overlay decreases.

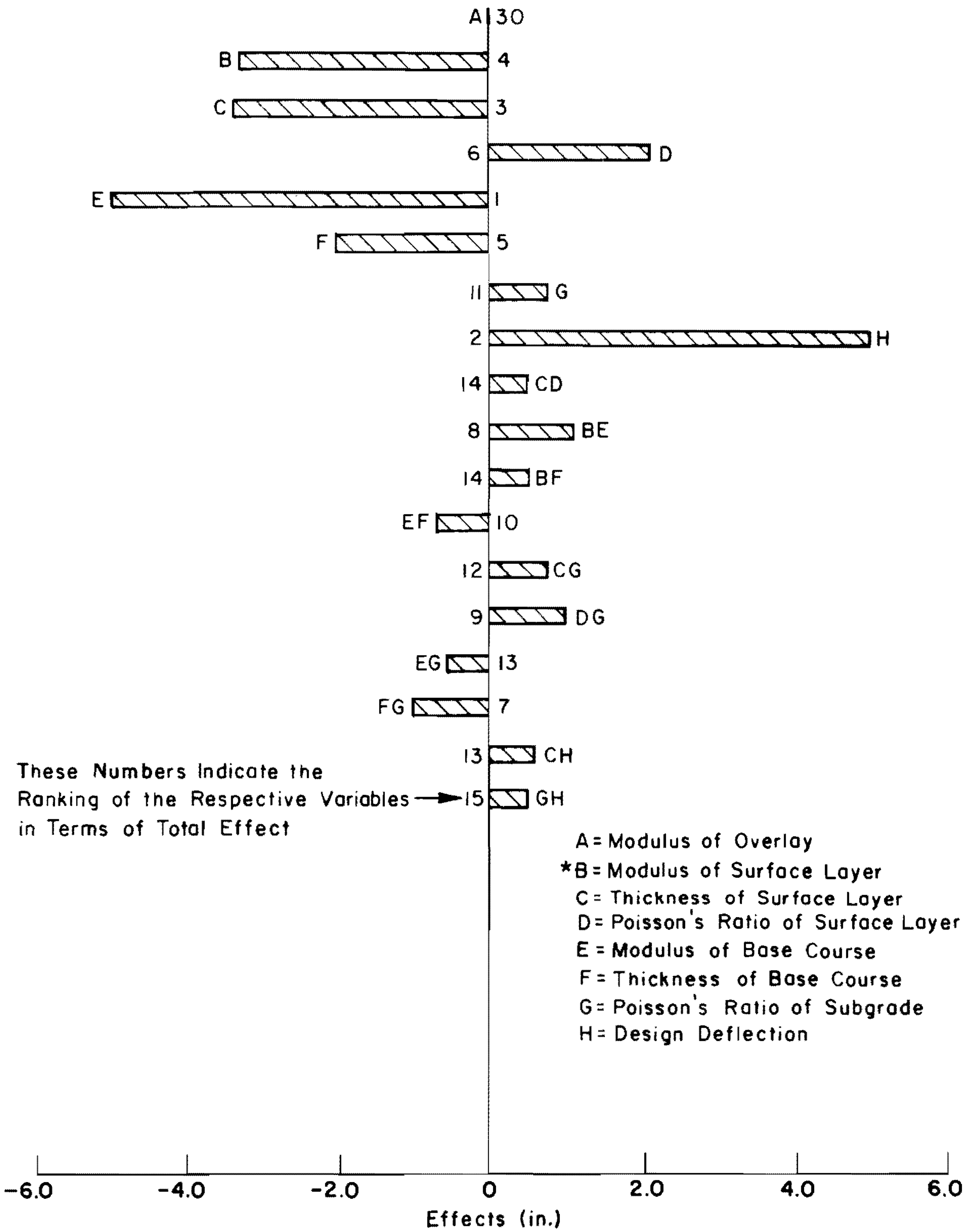
The effects of the significant main factors and their two-factor interactions with dependent variable, overlay thickness, are presented in Figs

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).



*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

Fig 4.1. Sensitivity of the bonded CRCP overlay on CRCP.



*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

Fig 4.2. Main effects and interactions for bonded CRCP overlay on CRCP.

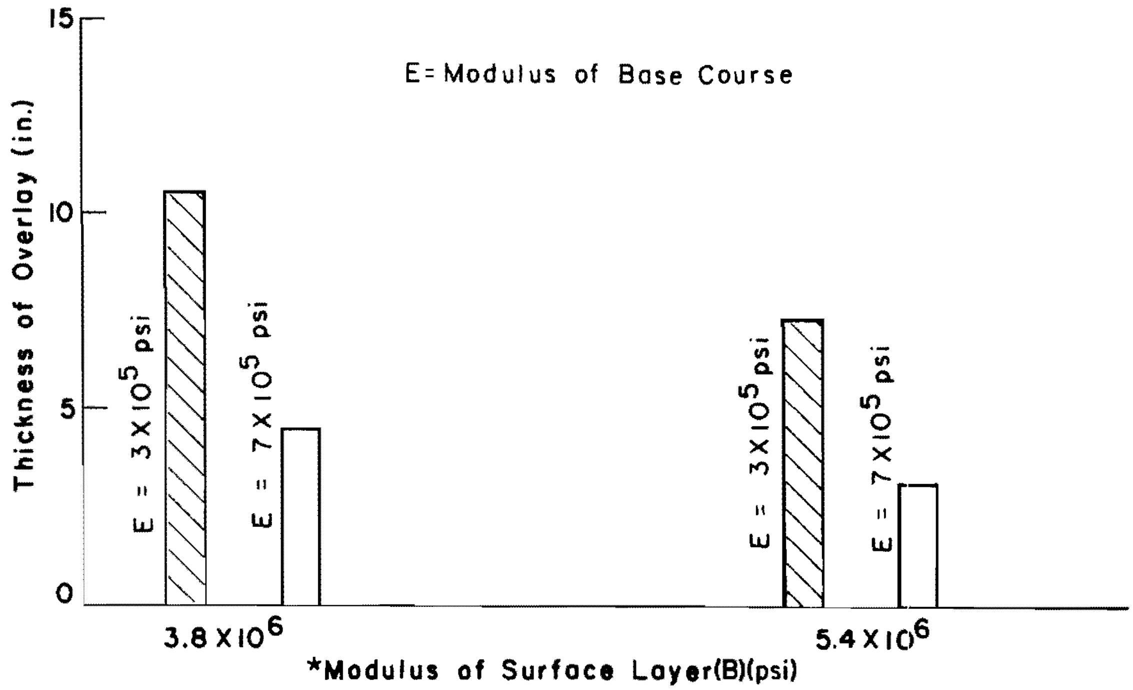
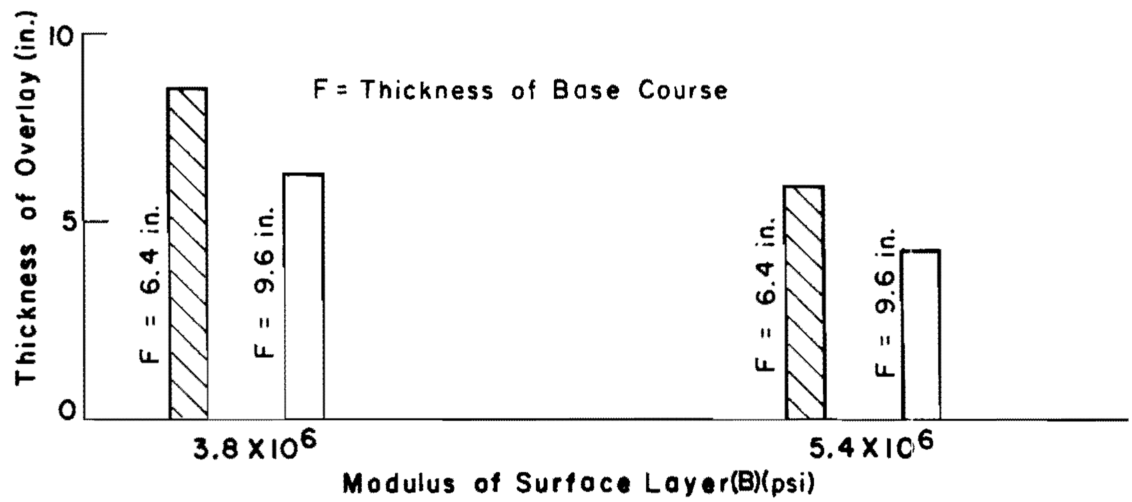


Fig 4.3. Interaction between modulus of surface layer (B) and modulus of base course (E).



*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

Fig 4.4. Interaction between modulus of surface layer (B) and thickness of base (F).

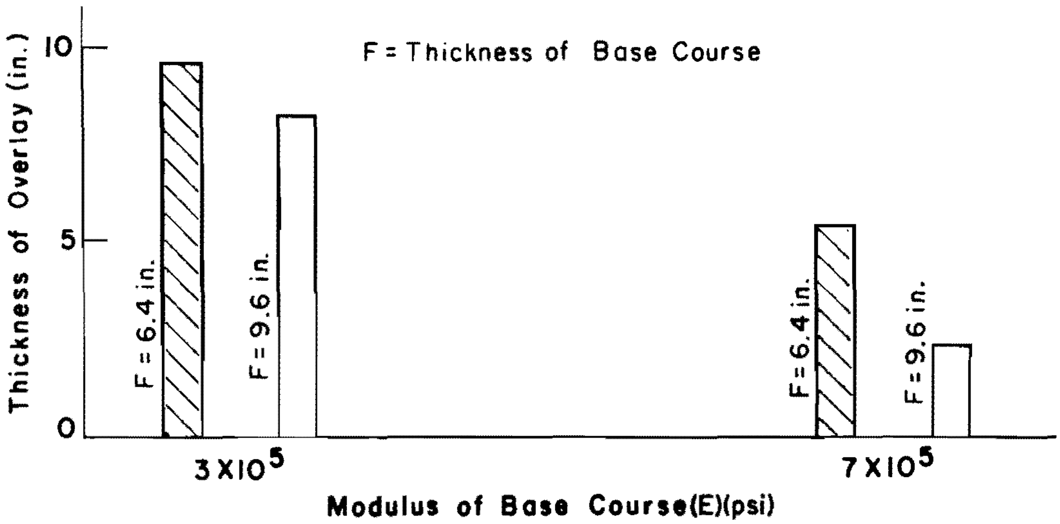


Fig 4.5. Interaction between modulus of base course (E) and thickness of base course (F).

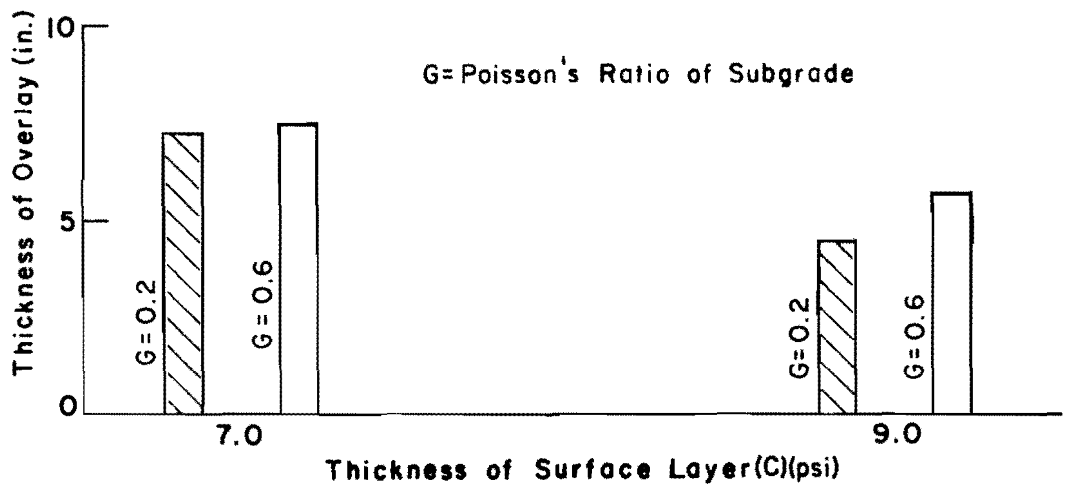


Fig 4.6. Interaction between thickness of surface layer (C) and Poisson's ration of subgrade (G).

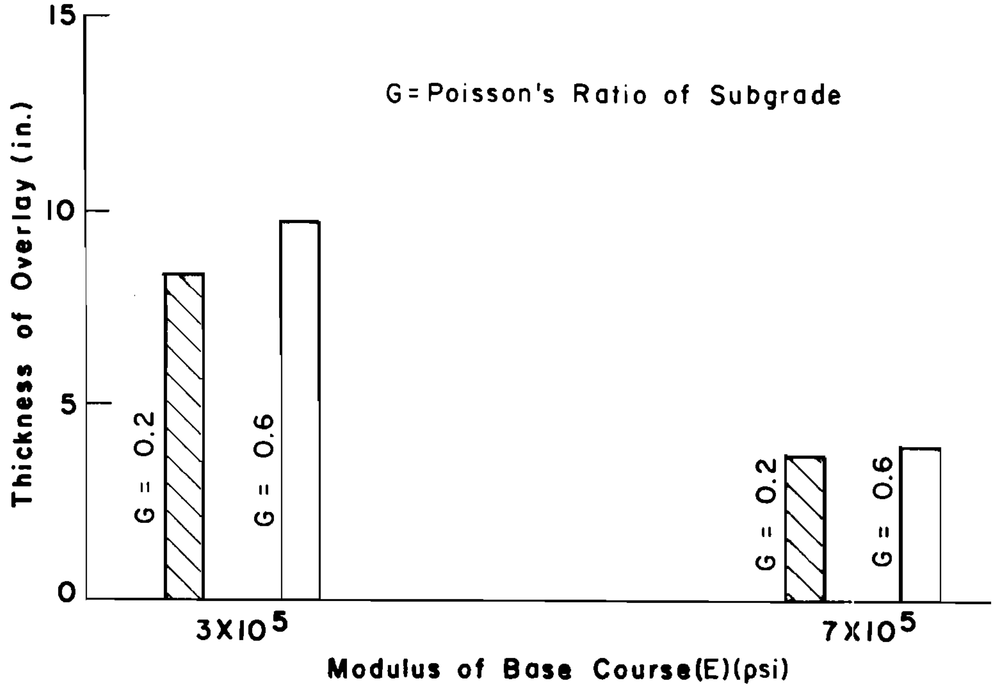


Fig 4.7. Interaction between modulus of base course (E) and Poisson's ration of subgrade (G).

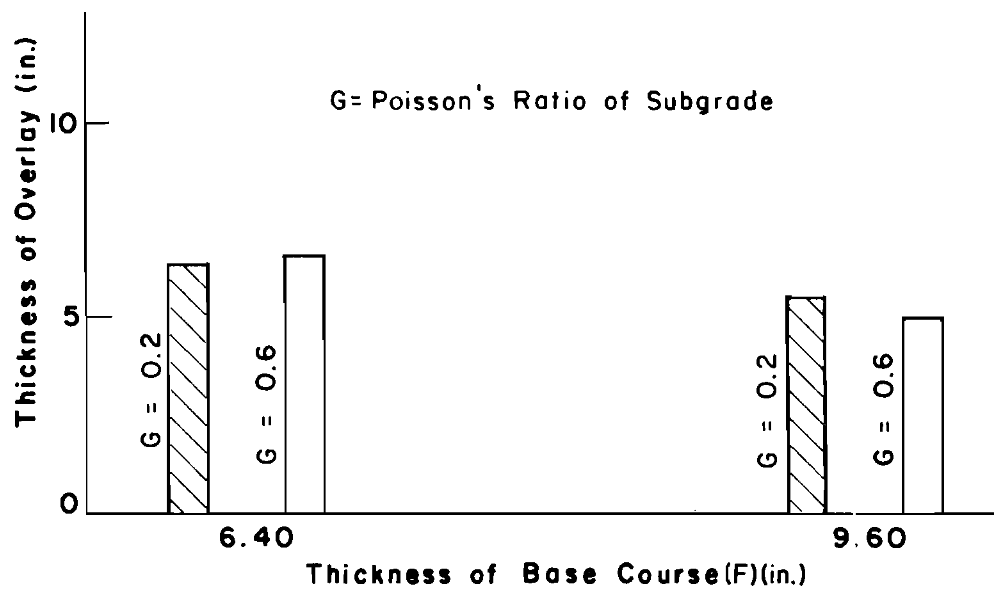


Fig 4.8. Interaction between thickness of base course (F) and Poisson's ratio of subgrade (G).

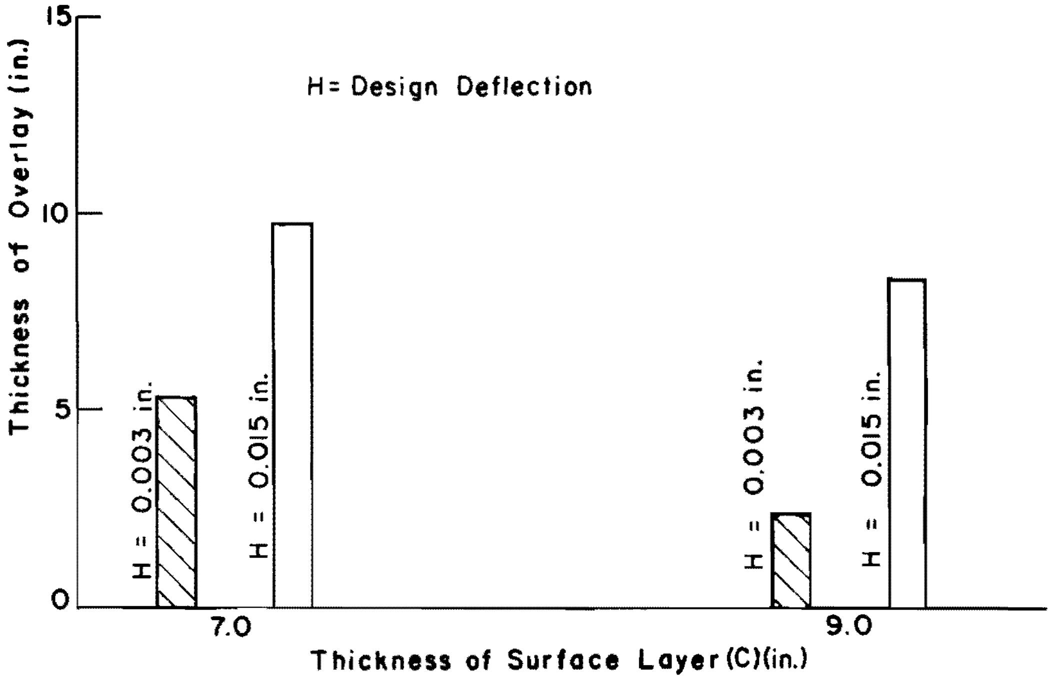


Fig 4.9. Interaction between thickness of surface layer (C) and design deflection (H).

4.3 through to 4.9. The data points presented in these figures are the average values of the dependent variable for the system containing a given level of the main factor. For instance, there are four possible combinations of factor levels for a two-way interaction; therefore, each value plotted is the mean for the data from sixteen different combinations in a quarter fraction factorial design of 2^8.

UNBONDED JCP OVERLAY ON JCP

Seven variables were considered for the factorial experiment. The main effects and interactions of the seven variables were calculated by the method described in Appendix 3 from the one-half fraction factorial experiment of 2^7, and are presented in Table 3.19. The main effects of seven variables are presented in the form of a bar graph in Fig 4.10. Figure 4.11 shows the interactions along with the main effects. Both the bar graphs are self-explanatory. The following information is from the table and figures.

(1) Amongst the seven variables, the design deflection (G) is the most important parameter (Fig 4.10).

(2) The modulus of the base course is the second most important parameter (Fig 4.10).

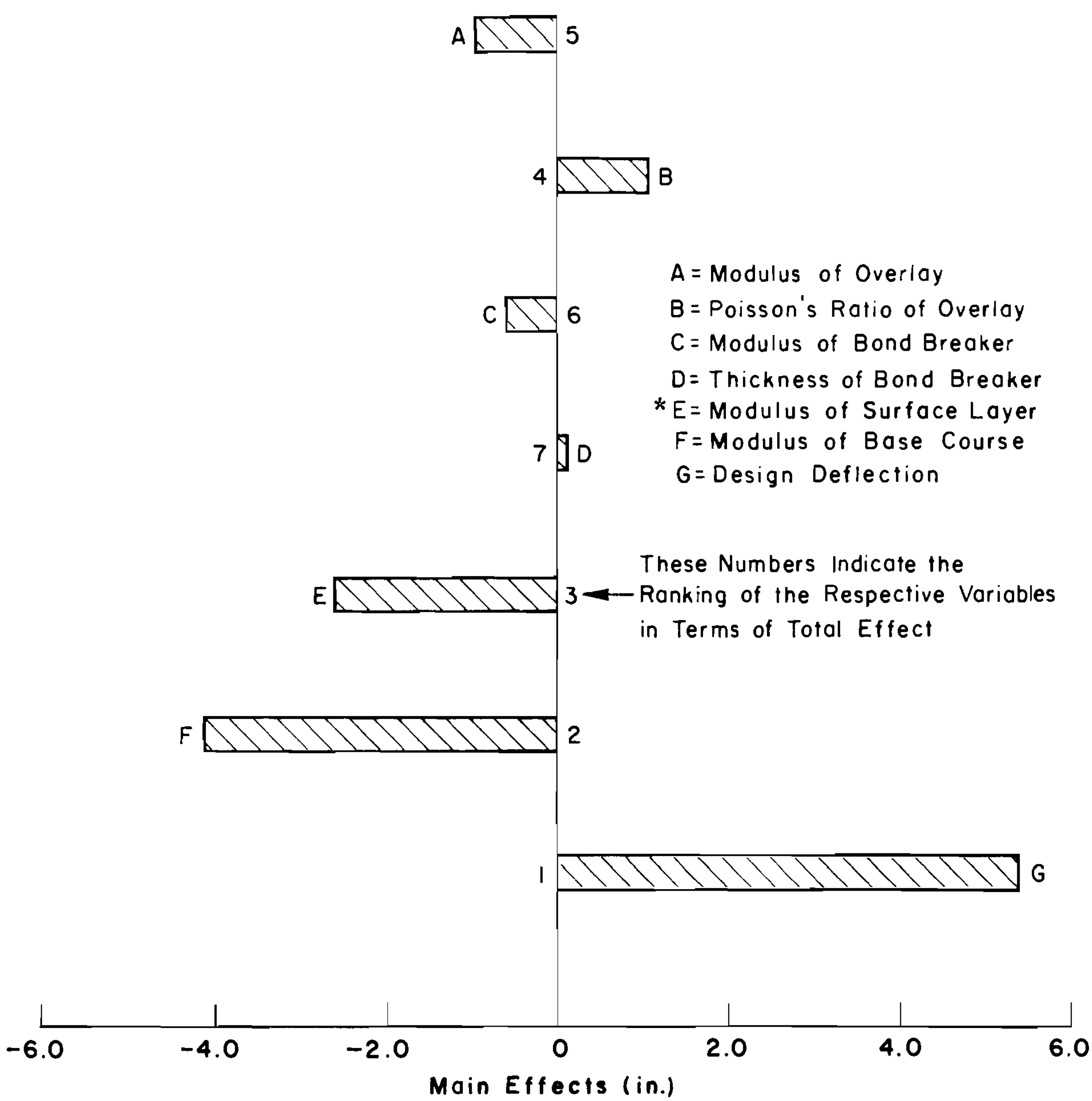
(3) The Poisson's ratio of the overlay, the thickness of the bond breaker, and the design deflection have a positive effect on the thickness of overlay, which means that when the values of these variables increase the thickness of overlay increases (Fig 4.11).

(4) The modulus of the overlay, the modulus of the bond breaker, the modulus* of the surface layer, and the modulus of base course have negative effects on the thickness of the overlay (Fig 4.11).

(5) Amongst the interactions, that between the modulus of the base course and the design deflection (FG) is the strongest (Fig 4.11).

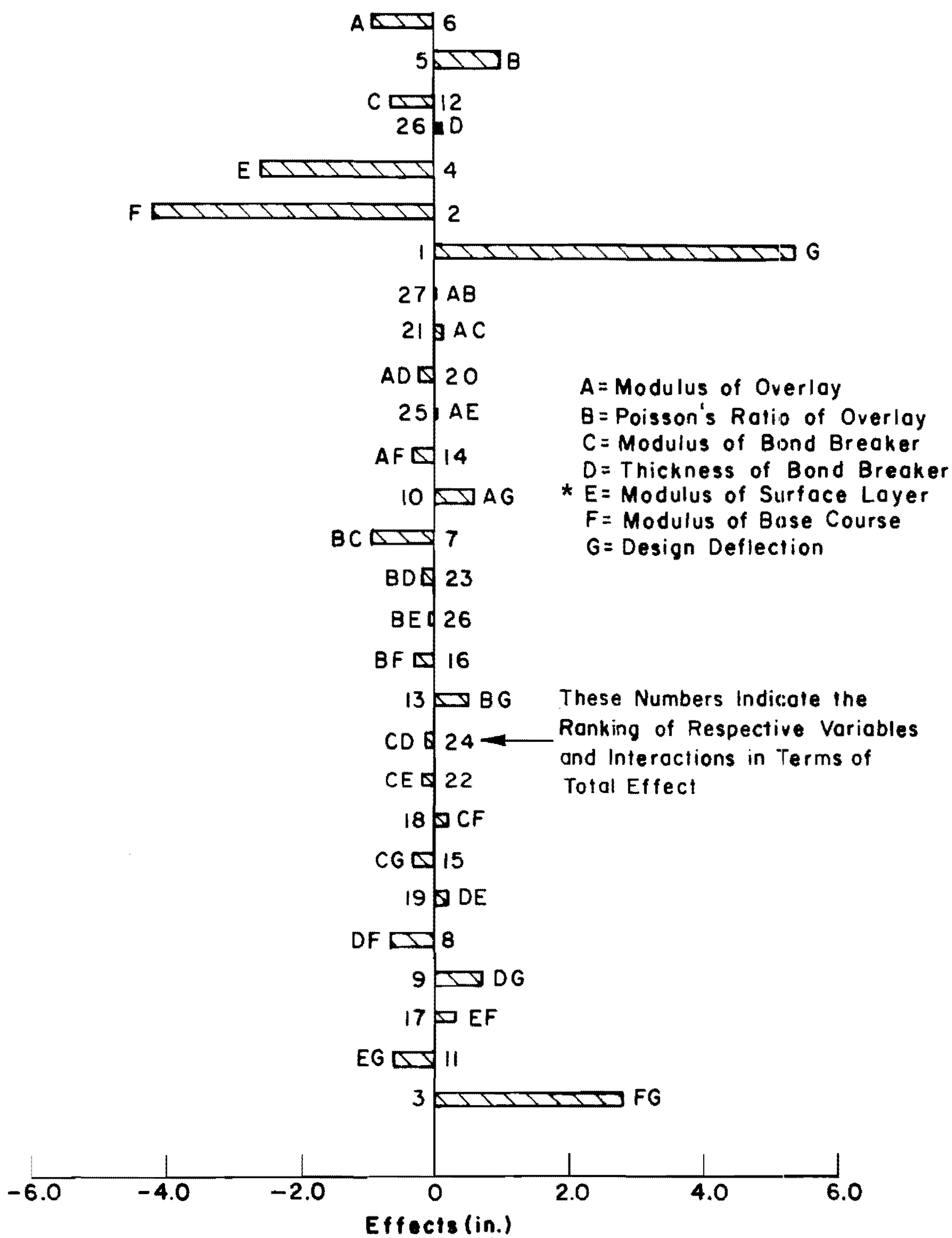
In the above, it was seen that the bond breaker thickness has a positive effect on the overlay thickness, i.e., when the bond breaker thickness increases the overlay thickness increases. From a lay point of view this does not sound reasonable, but it is feasible. When the thickness of the bond breaker increases, the critical stress at the top of bond breaker increases and, hence, reduces the fatigue life of the overlay. Therefore, in the design of the overlay, the thickness of the bond breaker should be selected carefully.

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).



*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

Fig 4.10. Sensitivity of the unbonded JCP overlay on JCP.



*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

Fig 4.11. Main effects and interactions for unbonded JCP overlay on JCP (inches).

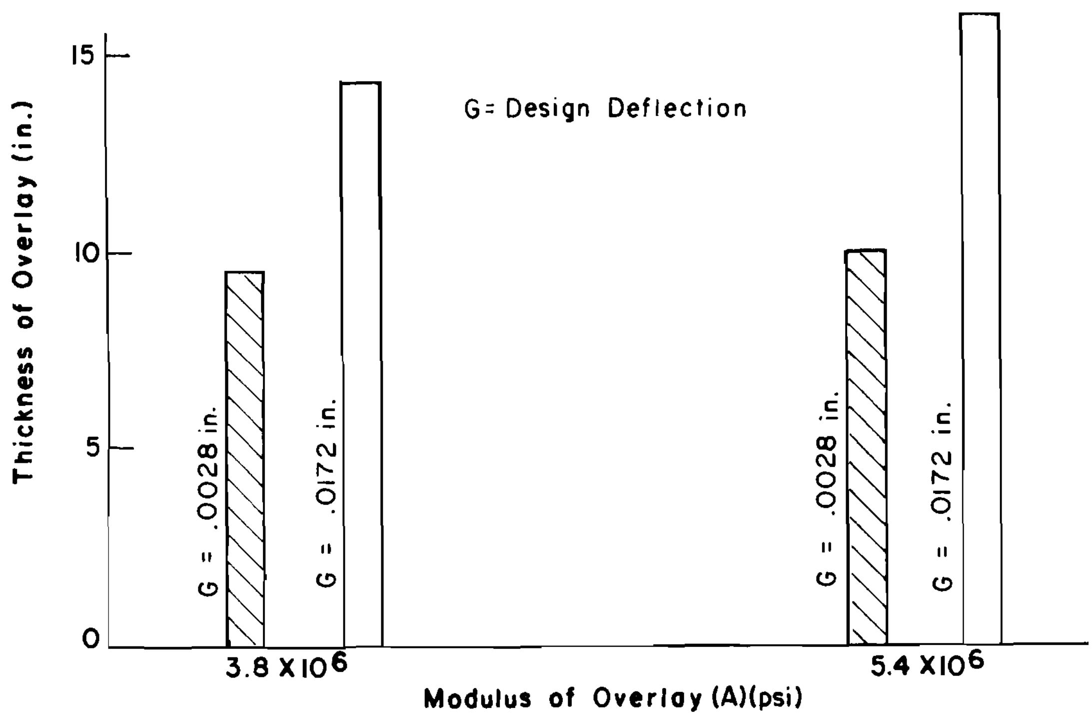


Fig 4.12. Interaction between modulus of overlay (A) and design deflection (G).

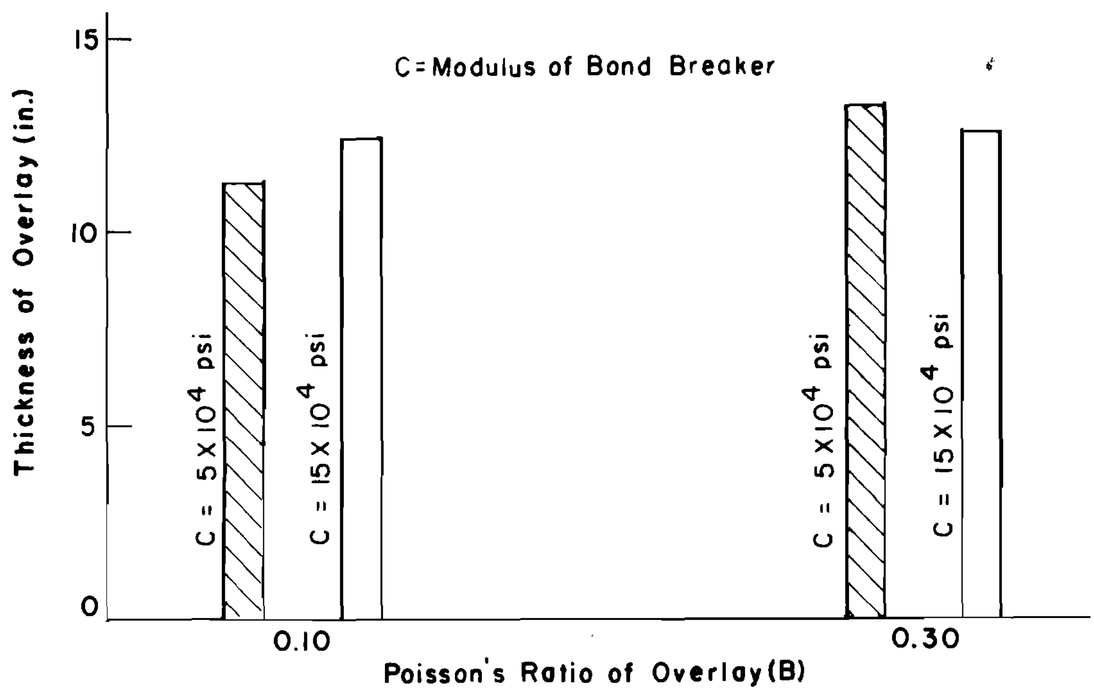


Fig 4.13. Interaction between Poisson's ratio of overlay (B) and modulus of bond breaker (C).

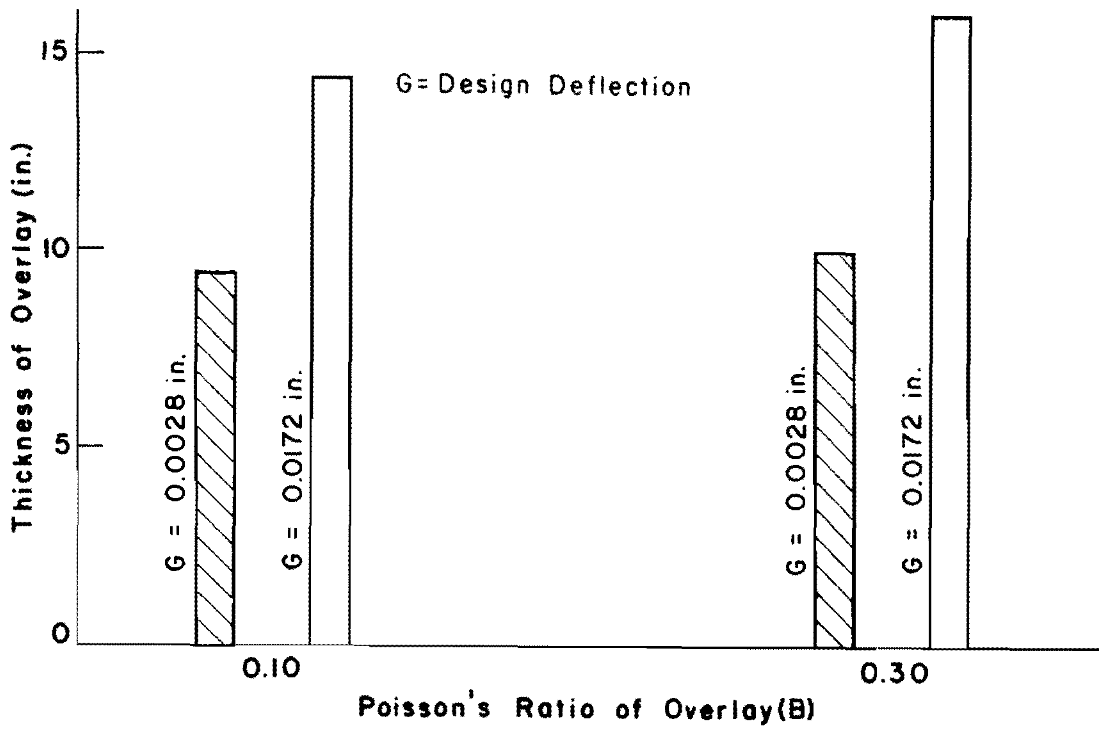


Fig 4.14. Interaction between Poisson's ratio of overlay (B) and design deflection (G).

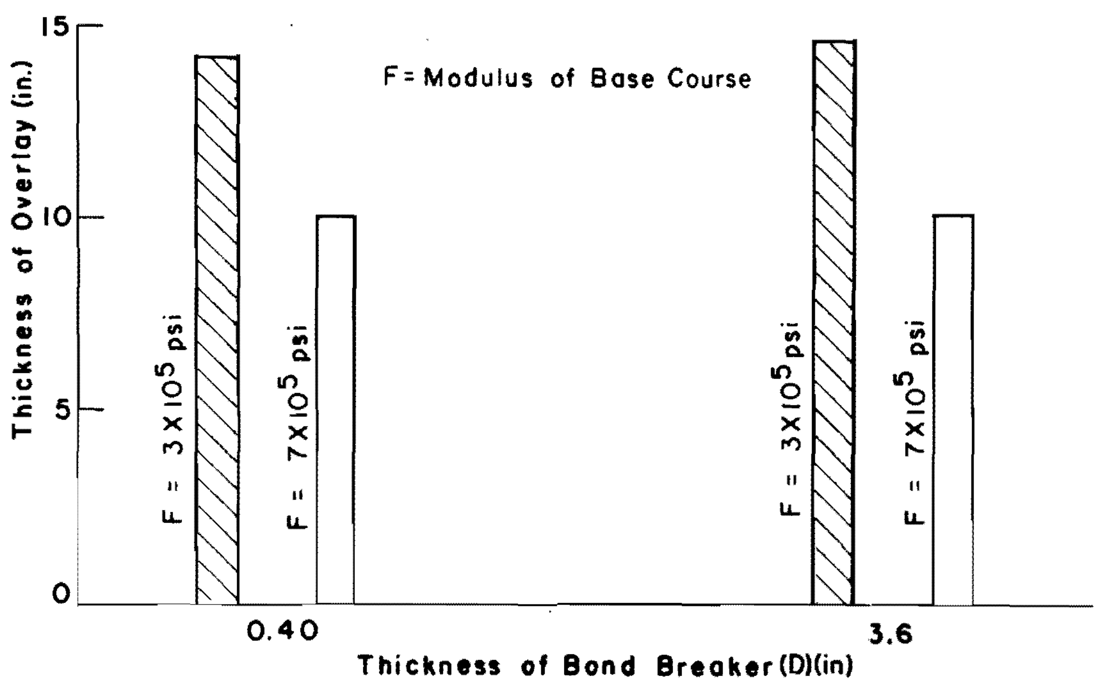


Fig 4.15. Interaction between bond breaker thickness (D) and modulus of base (F).

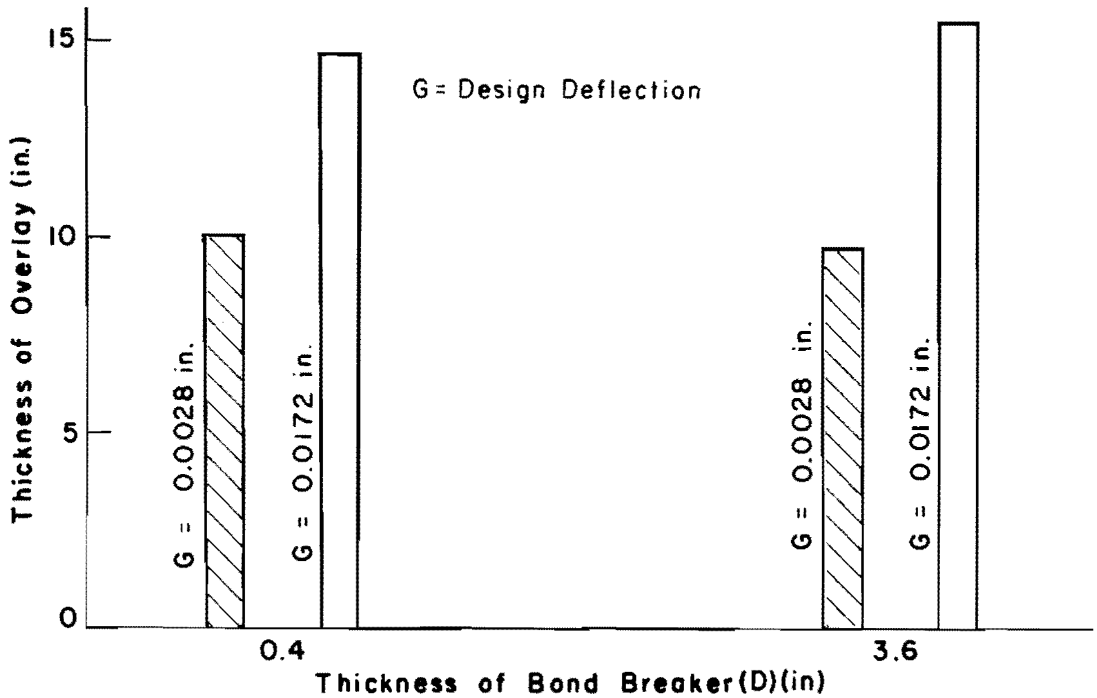
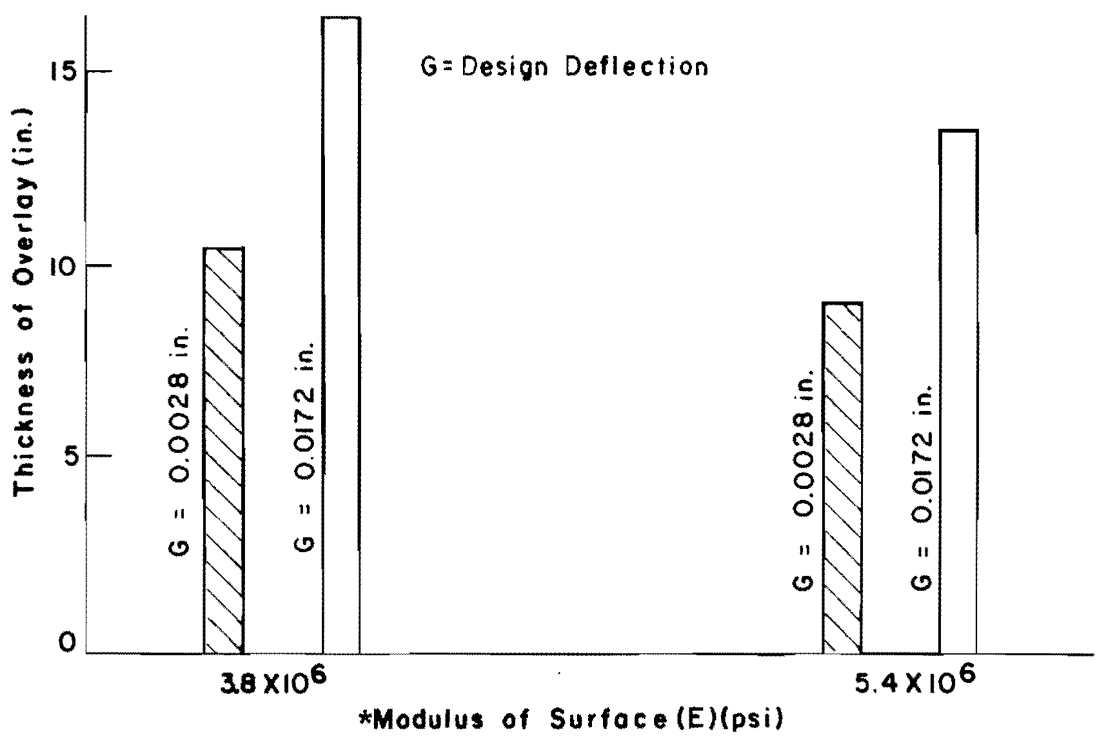


Fig 4.16. Interaction between bond breaker thickness (D) and design deflection (G).



*Concrete modulus and flexural strength are varied simultaneously (p. 22, 23).

Fig 4.17. Interaction between modulus of surface layer (E) and design deflection (G).

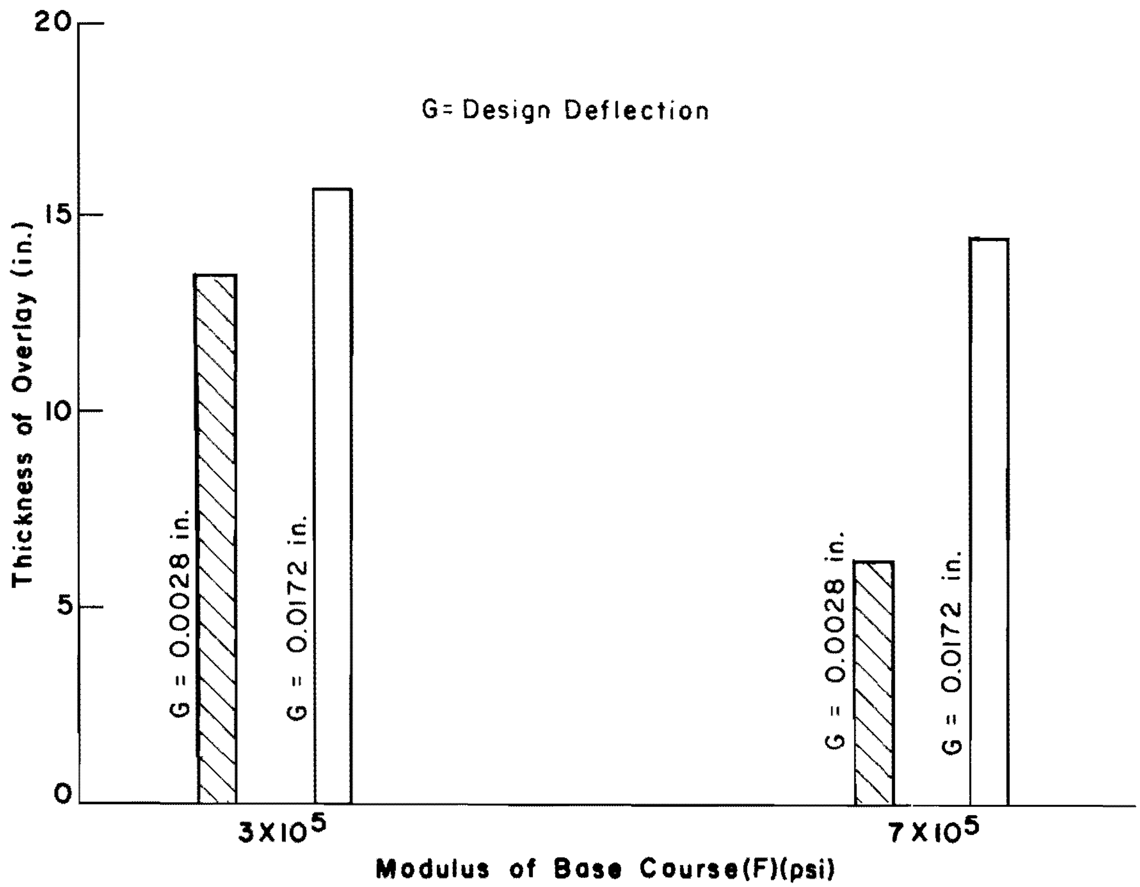


Fig 4.18. Interaction between modulus of base course (F) and design deflection (G).

The effects of the significant main factors and their two-factor interactions with the dependent variable of overlay thickness are presented in Figs 4.12 through 4.18. The data points presented in these figures are the average values of the dependent variable for the system containing a given level of the main factor.

AC OVERLAY ON CRCP

Six independent variables were considered for the factorial design. There are 32 response values from the one-half factorial experiment, as shown in Table 3.15. With these 32 response values the main effects and interactions are estimated by using the proper coefficeint (+1 or -1) on these 32 observations, as outlined in Appendix 3 and shown in Table 3.20. The main effects of six variables are shown as bar graphs in Fig 4.19. Figure 4.20 shows the interactions and the main effects. Table 3.20 and Figs 4.19 and 4.20 give the following information.

(1) Only the design deflection (F) has a positive effect on the overlay, which means that when the design deflection value increases, the required thickness of the overlay increases.

(2) The modulus values of the overlay, the surface layer, and the base course and the thickness of the surface layer and the base course have negative effects on the required overlay thickness.

(3) The design deflection is the most important of the input parameters.

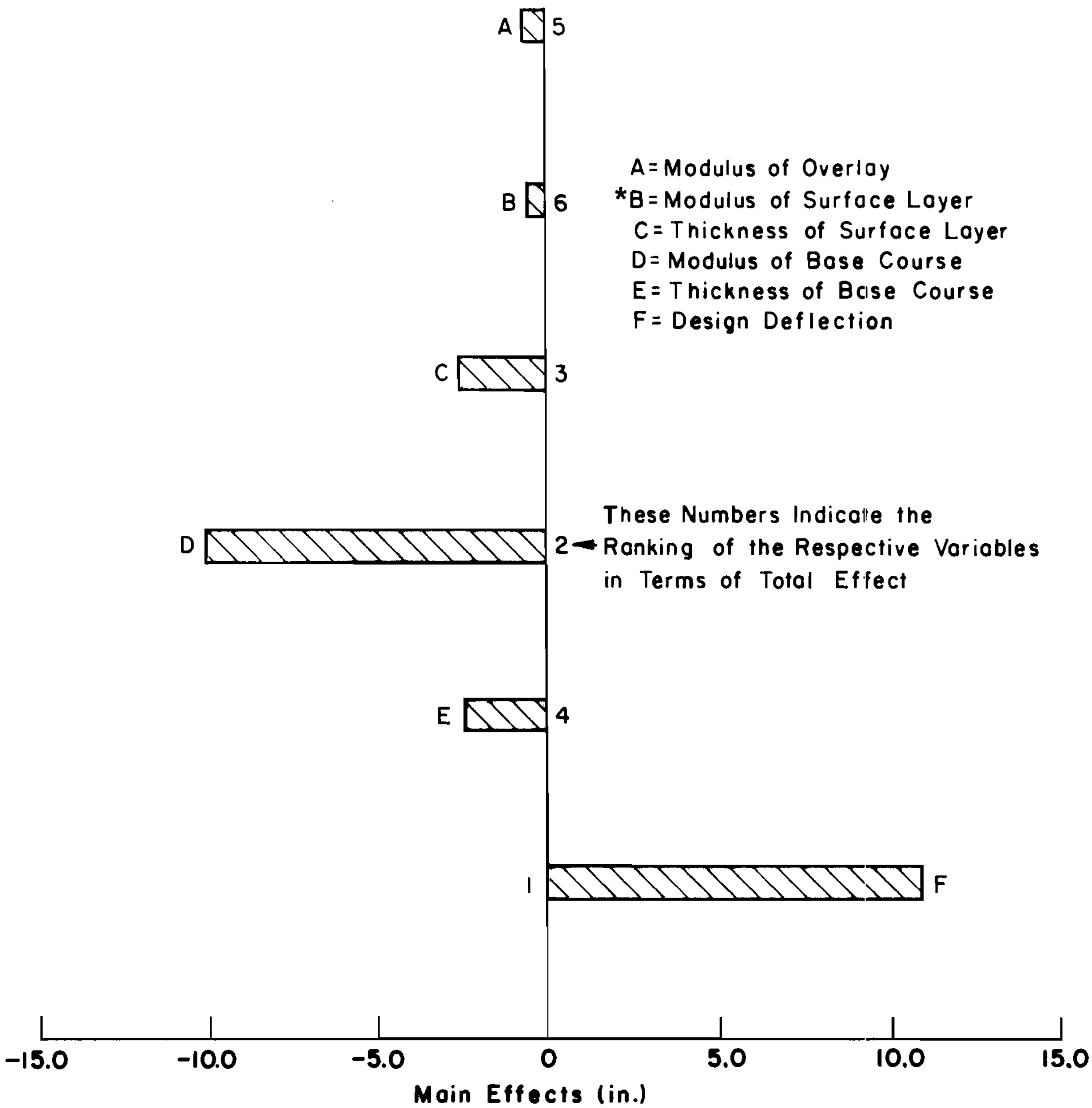
(4) The modulus of the base course is the second most important of the input parameters.

(5) Of all two-factor interactions, the interaction between the modulus of the surface layer and the thickness of the base course (BE) is the strongest.

The effects of the significant main factors and their two-factor interactions on the dependent variable, overlay thickness, are presented in Figs 4.21 through 4.29. The data points presented in these figures are the average values of the dependent variable for the system containing a given level of main factors.

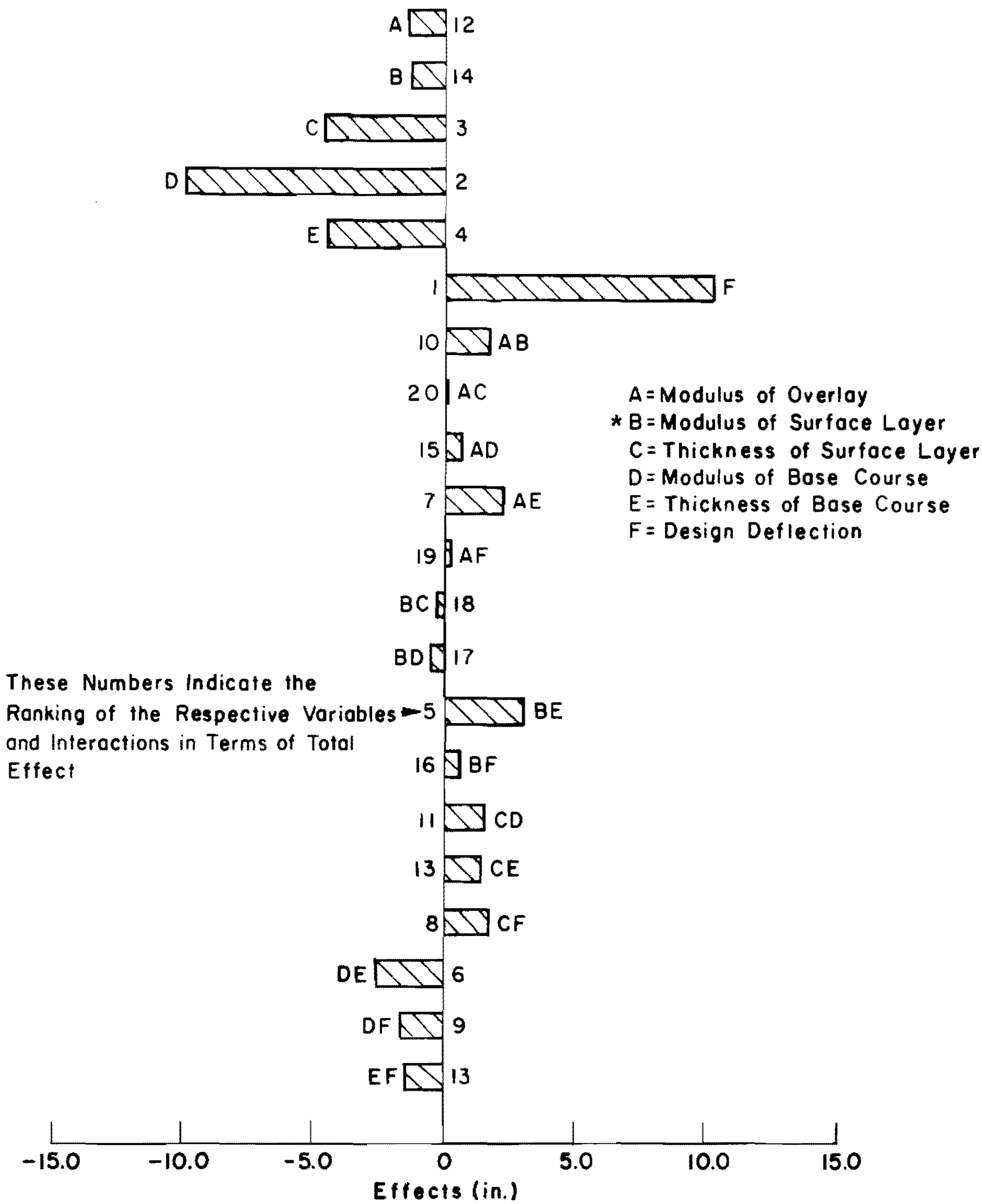
UNBONDED CRCP OVERLAY ON CRCP (MECHANICALLY BROKEN UP)

For this type of overlay six variables were considered for the factorial design. The main effects and interaction of these six variables were calculated by the method, as outlined above, and presented in Table 3.21.



*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

Fig 4.19. Sensitivity of the ACP overlay on CRCP.



*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

Fig 4.20. Main effects and interactions in inches for ACP overlays on CRCP (inches).

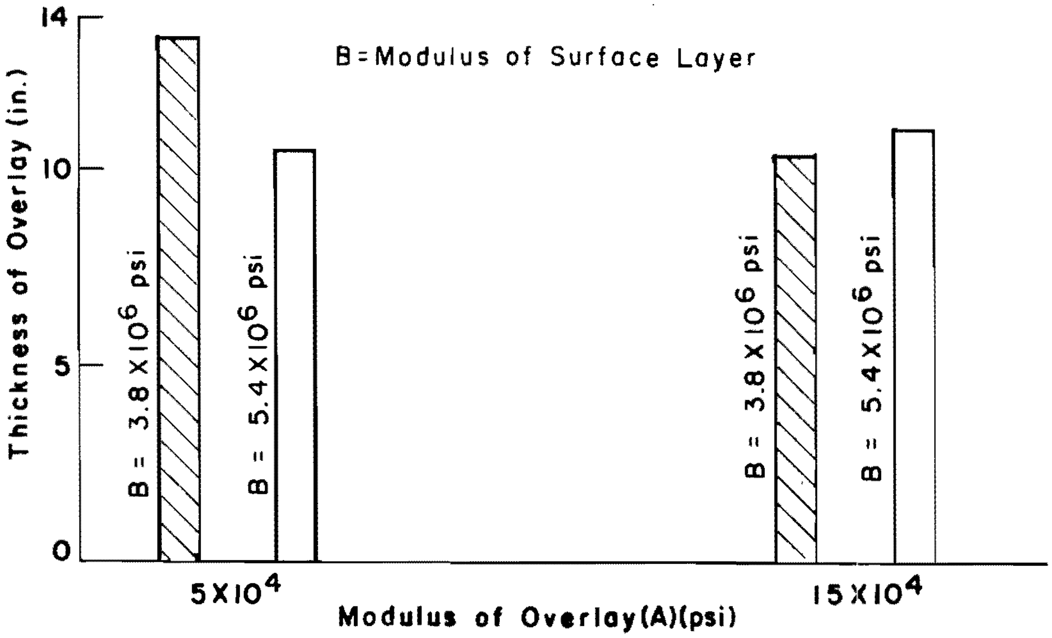


Fig 4.21. Interaction between modulus of overlay (A) and modulus of surface layer (B).

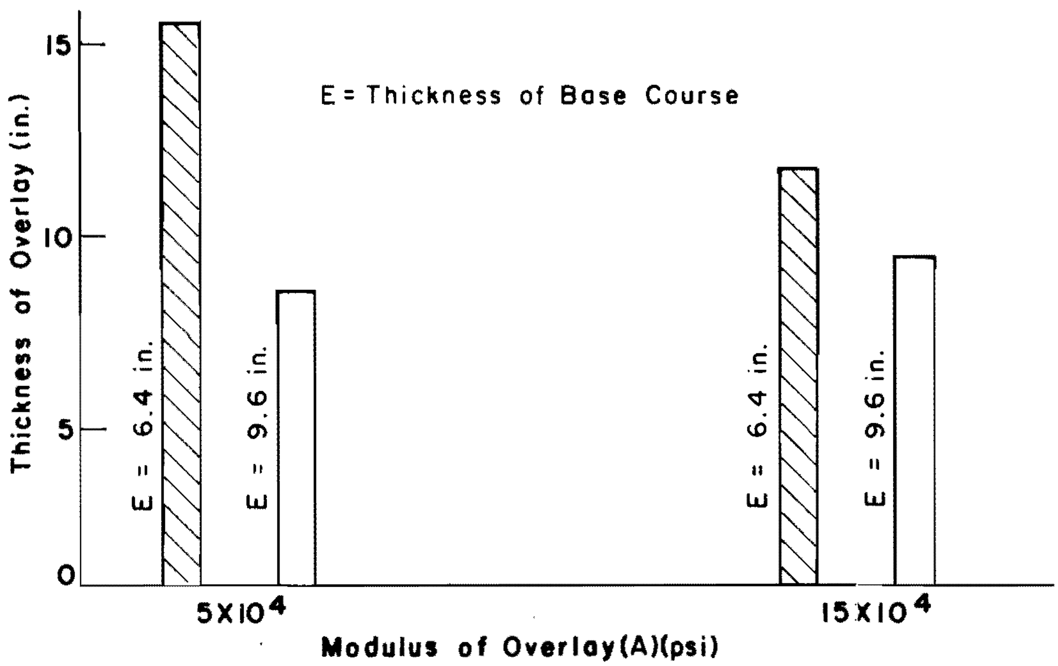


Fig 4.22. Interaction between modulus of overlay (A) and thickness of base course (E).

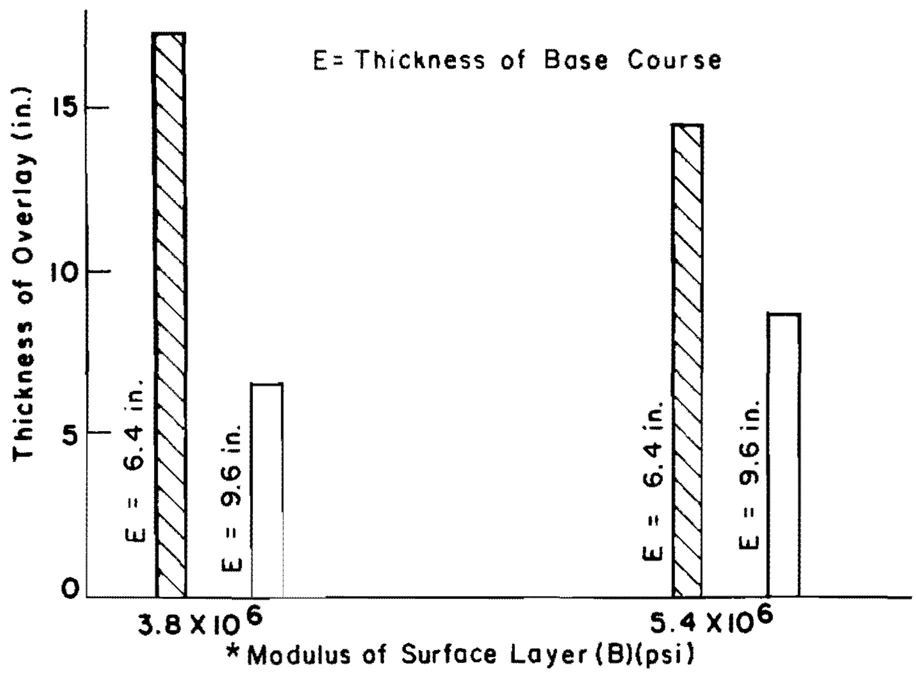
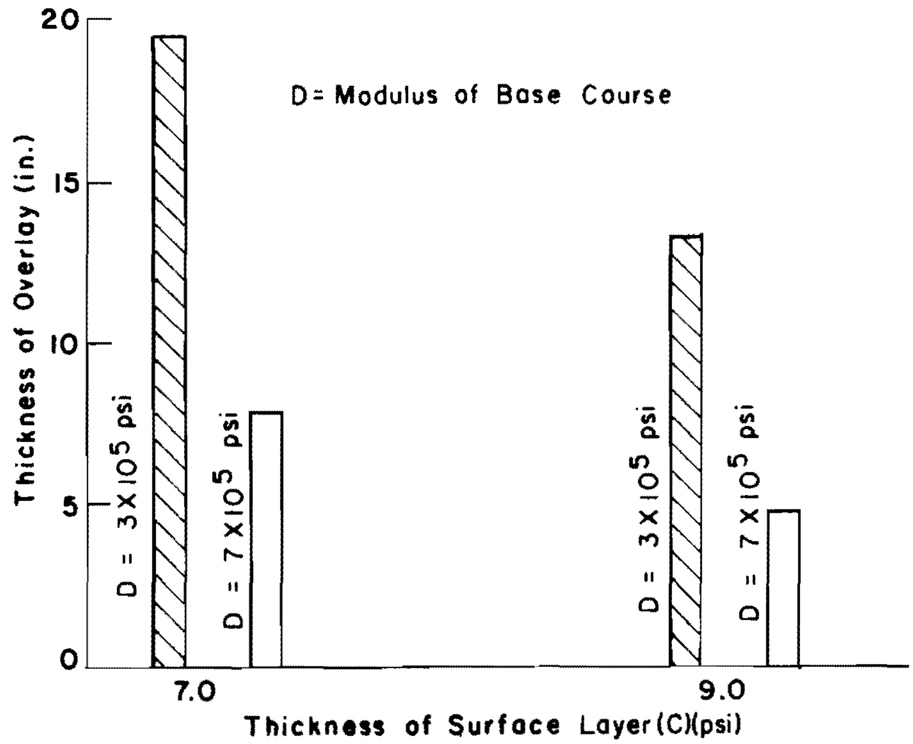


Fig 4.23. Interaction between modulus of surface layer (B) and thickness of base course (E).



*Concrete modulus and flexural strength are varied simultaneously (p. 22, 23).

Fig 4.24. Interaction between thickness of surface layer (C) and modulus of base course (D).

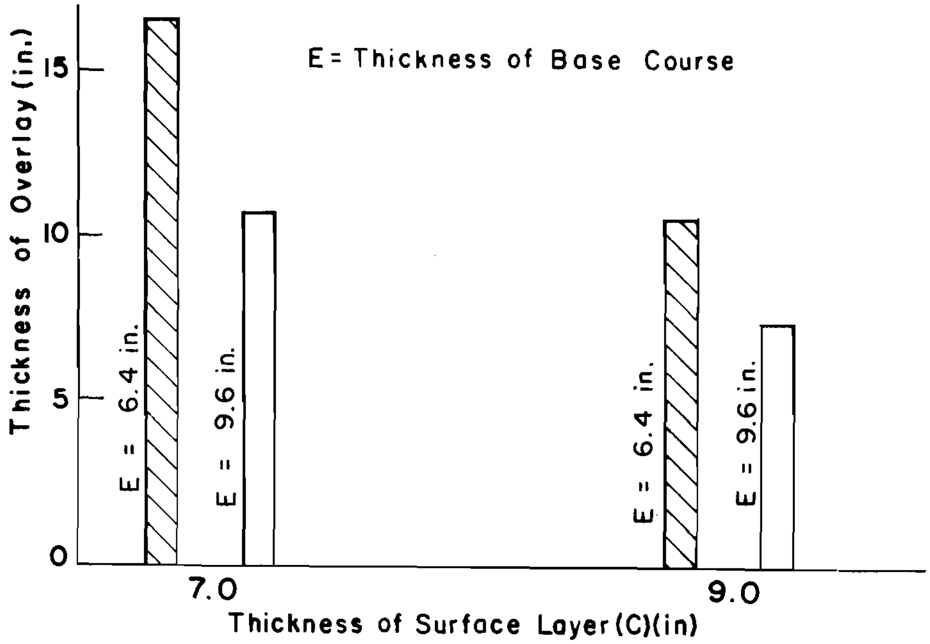


Fig 4.25. Interaction between thickness of surface layer (C) and thickness of base course (E).

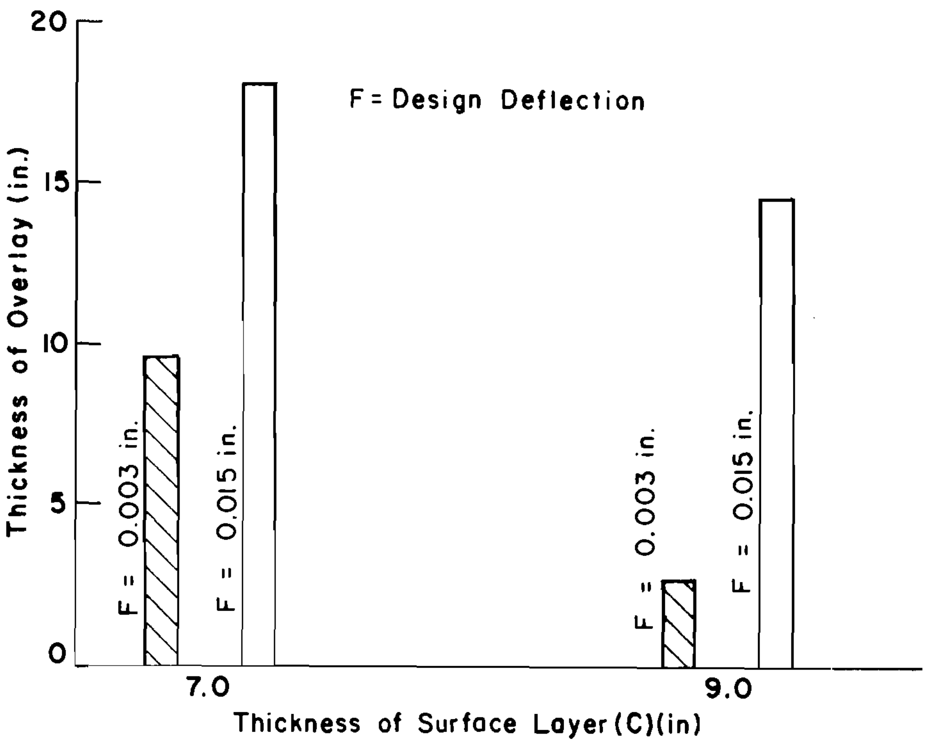


Fig 4.26. Interaction between thickness of surface layer (C) and design deflection (F).

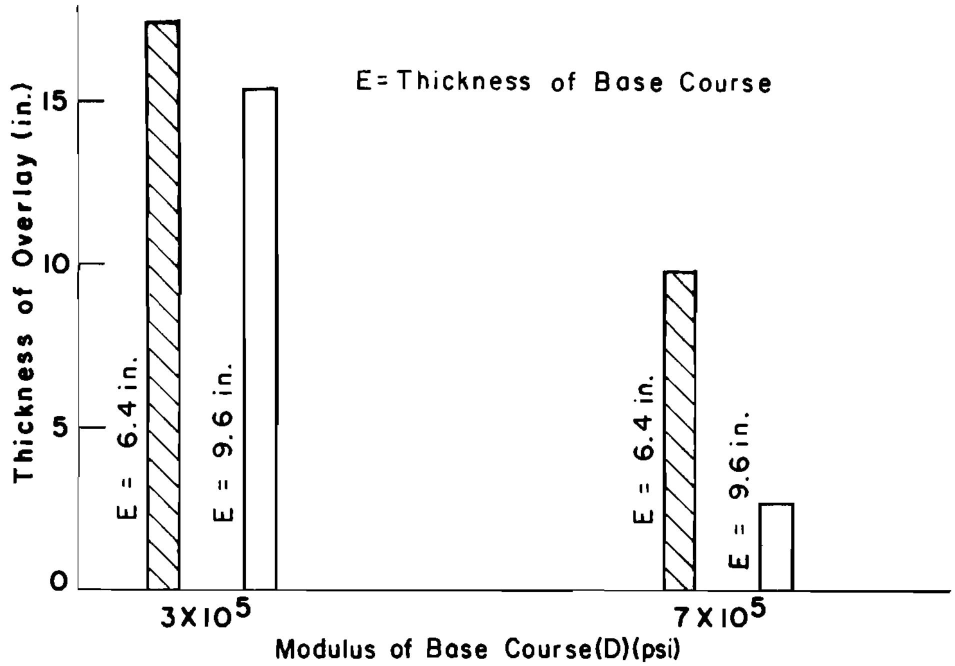


Fig 4.27. Interaction between modulus of base course (D) and thickness of base course (E).

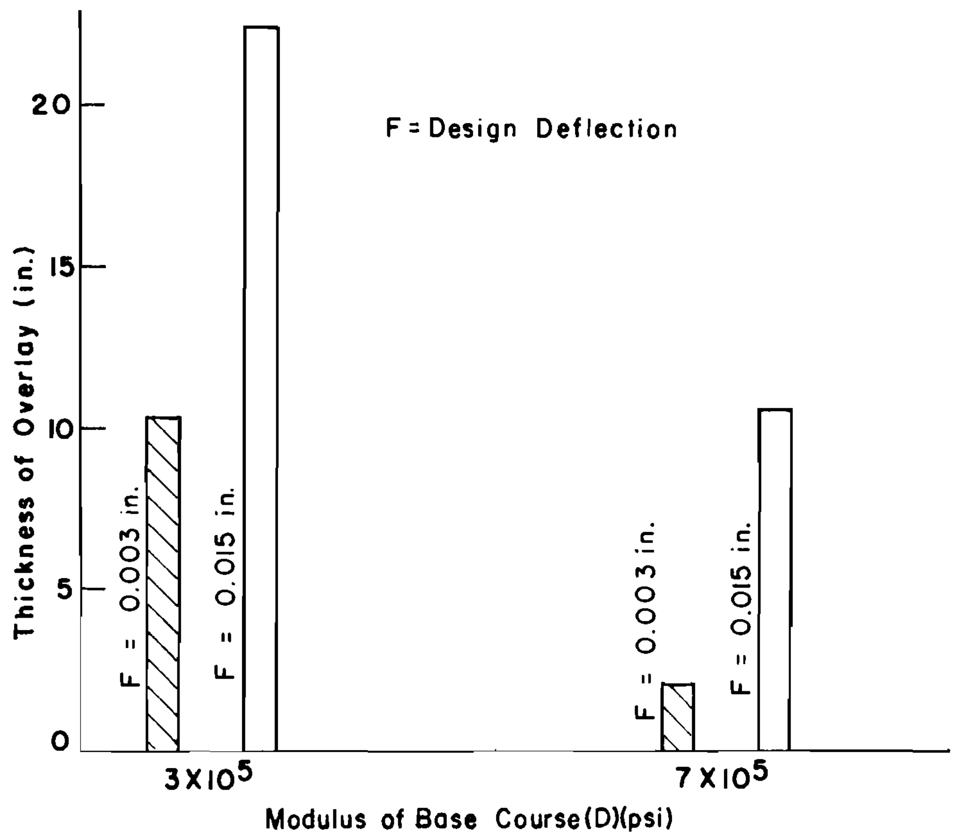


Fig 4.28. Interaction between modulus of base course (D) and design deflection (F).

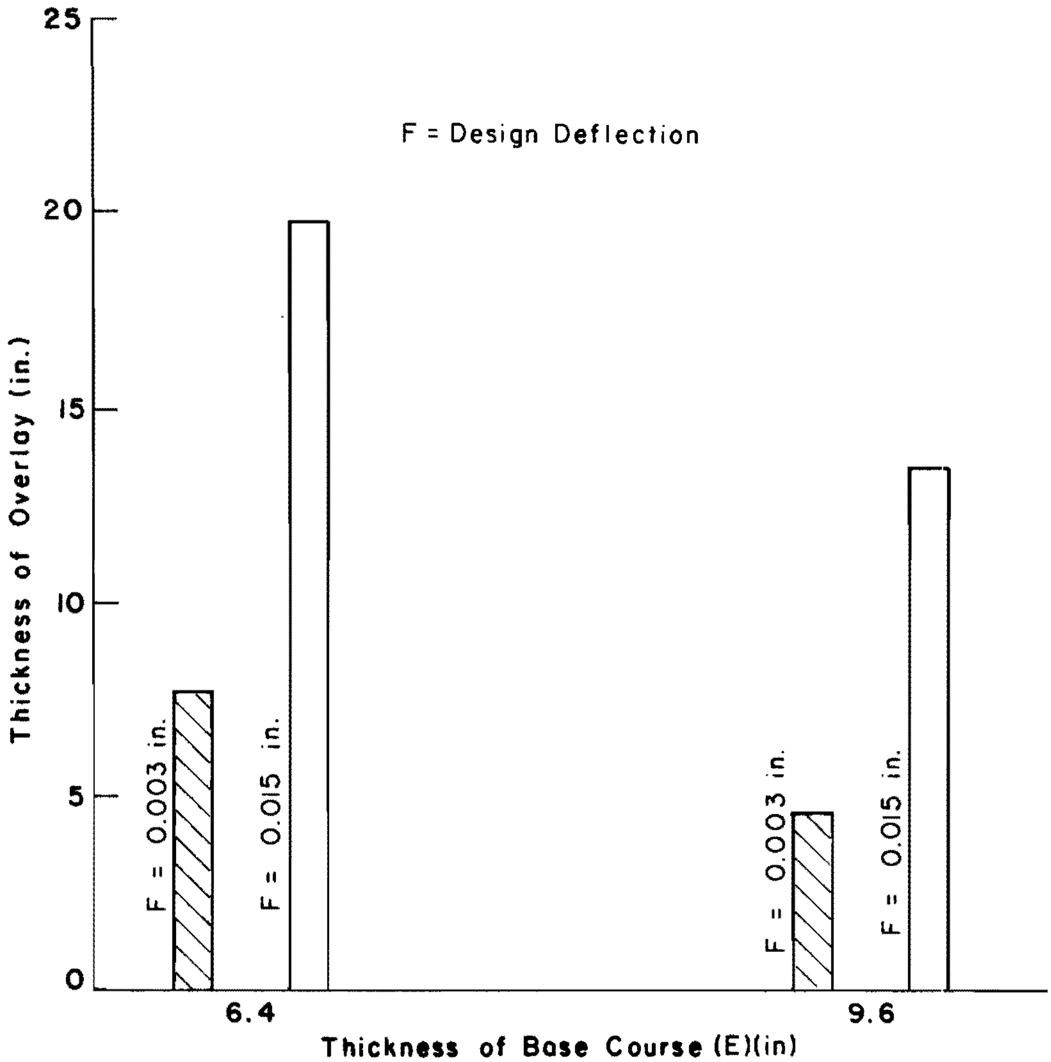
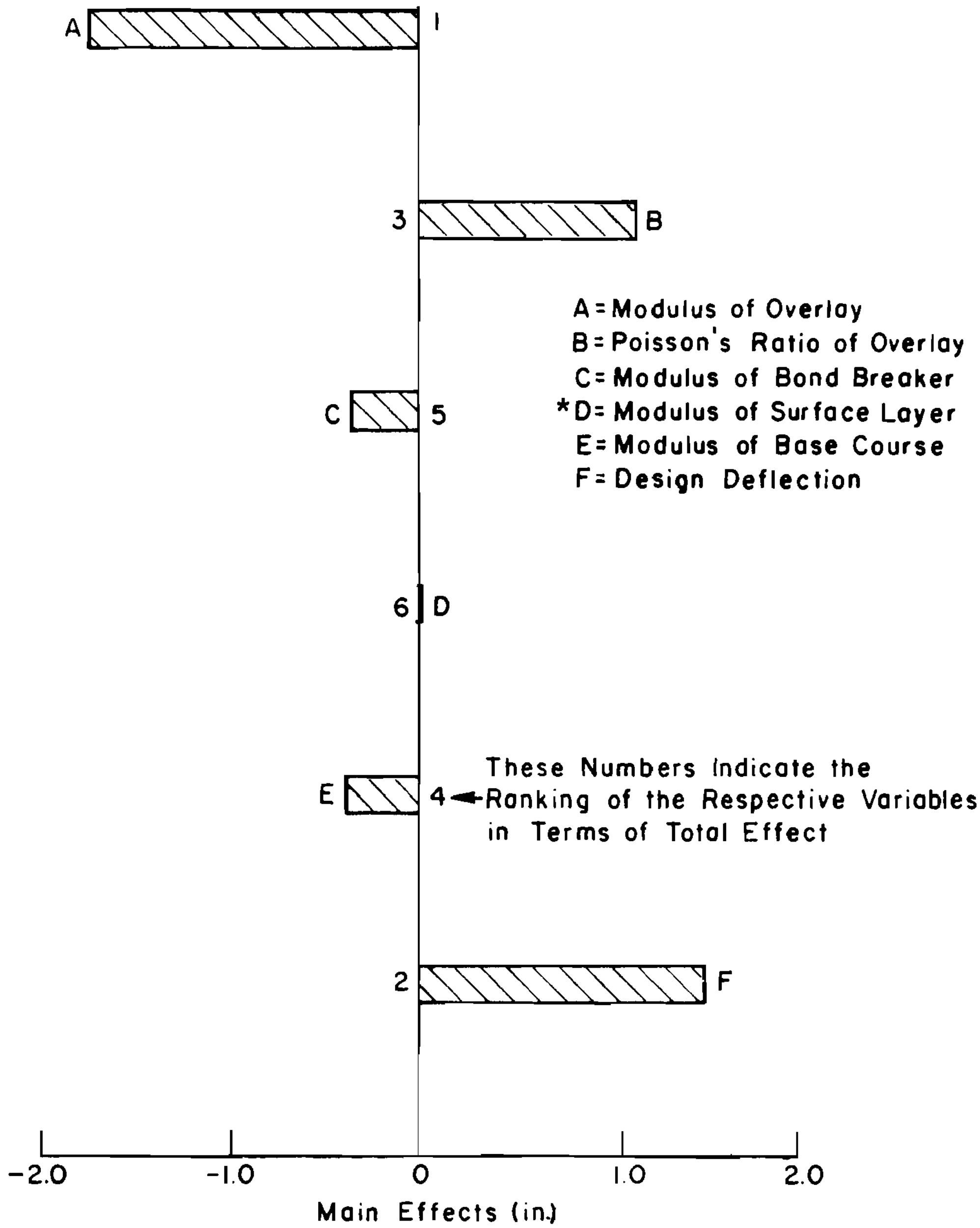
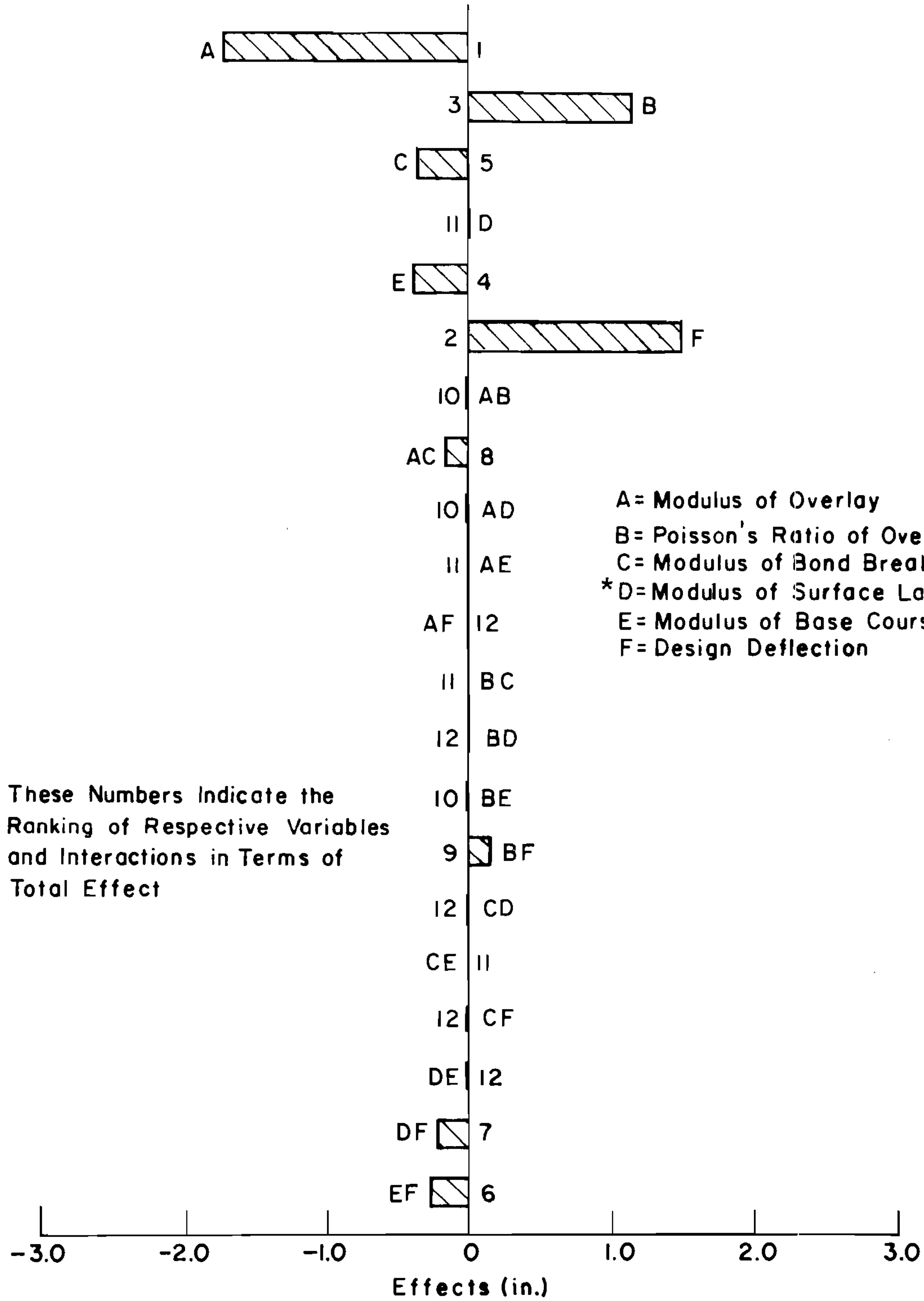


Fig 4.29. Interaction between thickness of base course (E) and design deflection (F).



*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

Fig 4.30. Sensitivity of the unbonded CRCP overlay on CRCP (mechanically broken up).



*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

Fig 4.31. Main effects and interactions in inches for unbonded CRCP overlay on CRCP (mechanically broken).

The main effects of six variables are shown in Fig 4.30. Figure 4.31 shows the interactions along with main effects. The following is the summary of information from Table 3.21 and Figs 4.30 and 4.31.

(1) The Poisson's ratio of the overlay and the design deflection have a positive effect on the thickness of the overlay, which means that when the values of these variables increase, the thickness of the overlay increases.

(2) The modulus values of the overlay, the bond breaker, and the base course have negative effect on the thickness of the overlay.

(3) The modulus of the overlay is the most important parameter and the design deflection is the second most important parameter.

(4) The modulus* of the surface layer has no effect in the determination of the overlay thickness.

(5) Of all the two-factor interactions, the interaction between the modulus of base and design deflection is the strongest. Most of the two-factor interactions are negligible.

From these points it is seen that the modulus of the existing surface layer has little effect in the determination of the overlay thickness. This is because, in the case of mechanically broken up surface layers, the existing portland cement concrete (PCC) pavement is assigned a fixed modulus value of 70,000 psi for determining overlay thickness. The original modulus value of PCC therefore has no effect.

The effects of the significant main factors and their two-factor interactions on the overlay thickness, are presented in Figs 4.32 through 4.35. The data points presented in these figures are the average values of overlay thickness for the system containing a given level of main factors.

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

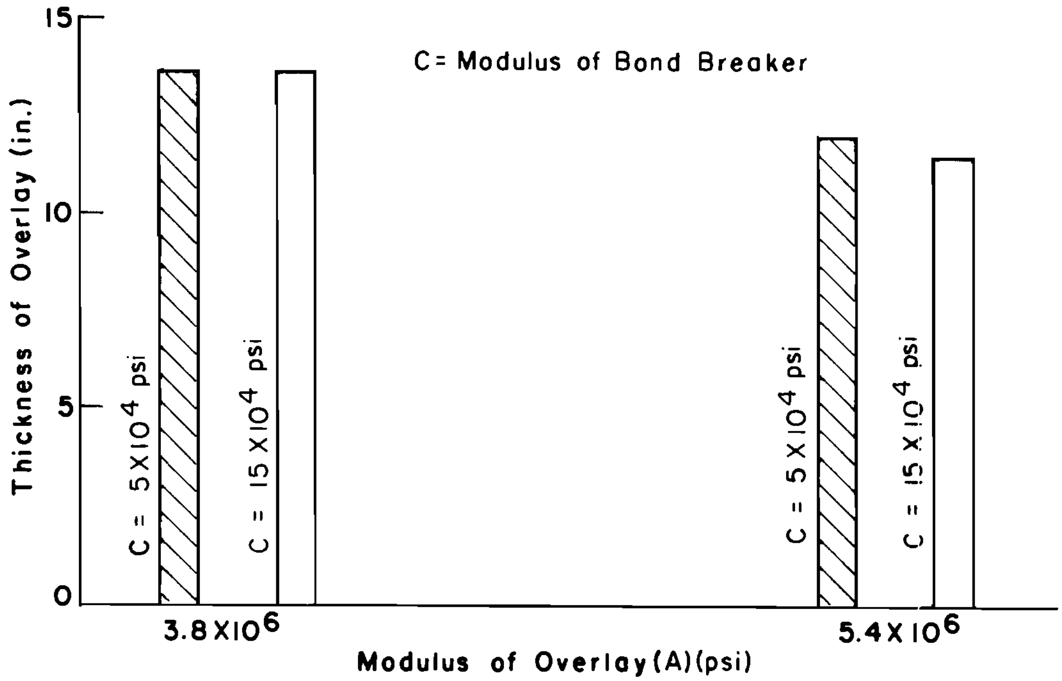


Fig 4.32. Interaction between modulus of overlay (A) and modulus of bond breaker (C).

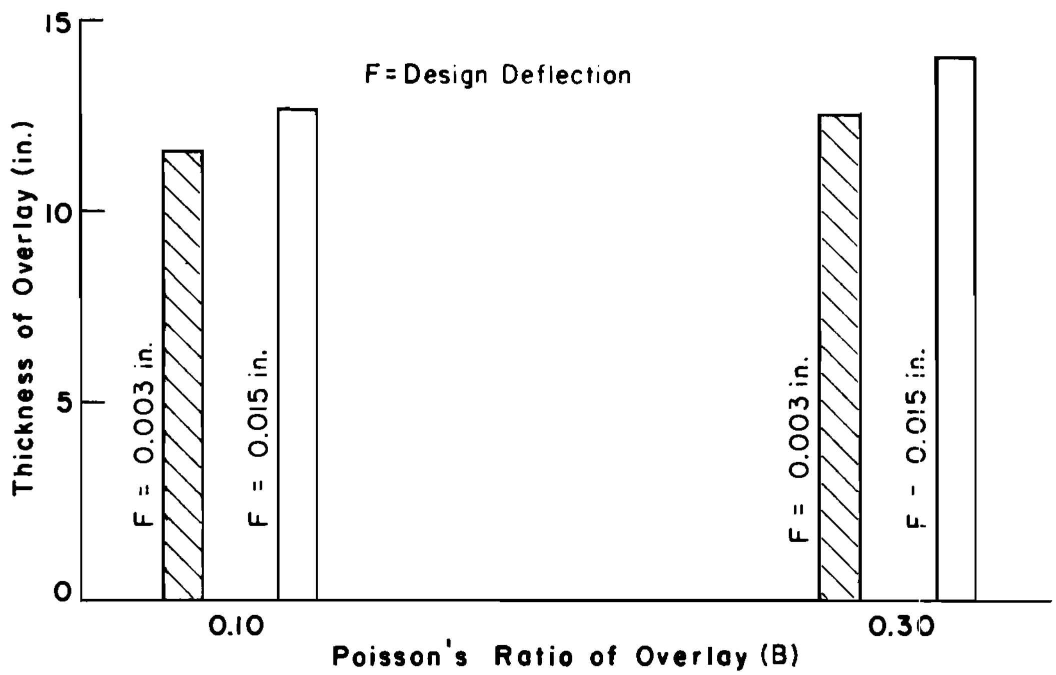


Fig 4.33. Interaction between Poisson's ratio of overlay (B) and design deflection (F).

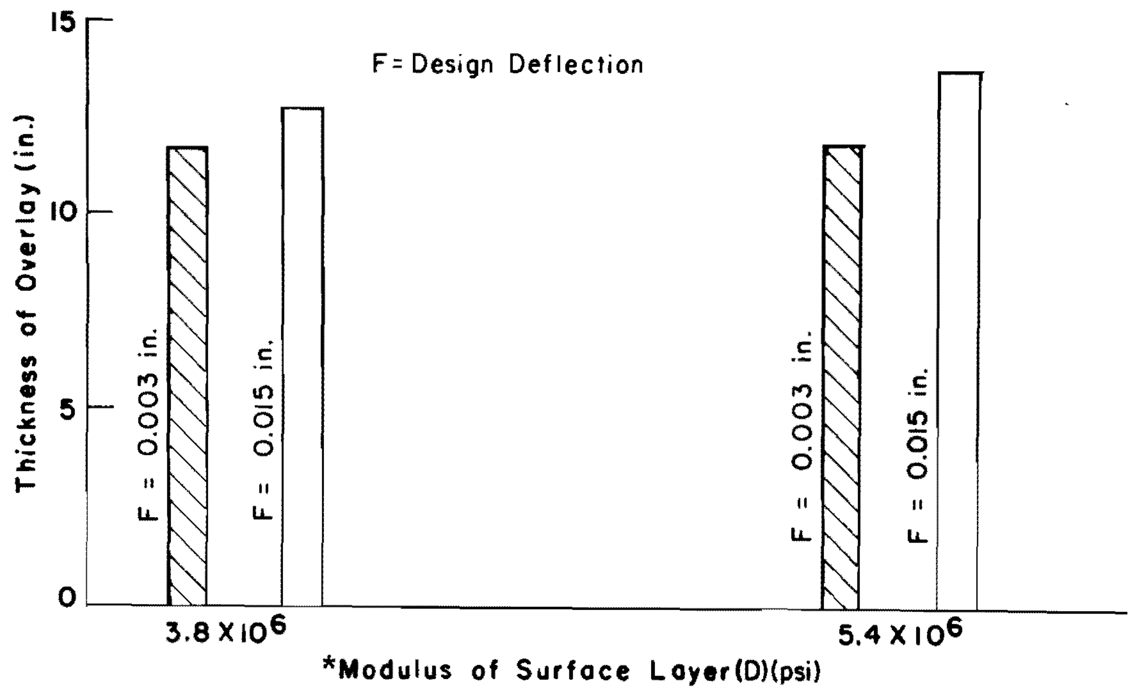
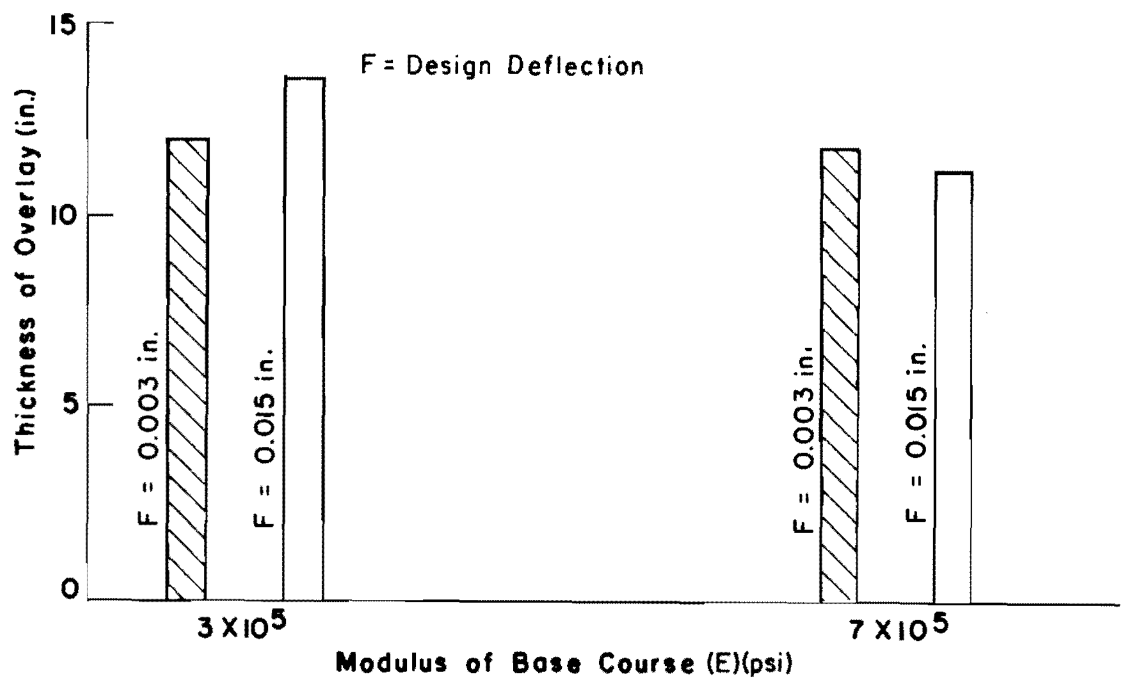


Fig 4.34. Interaction between modulus of surface layer (D) and design deflection (F).



*Concrete modulus and flexural strength are varied simultaneously (p. 22, 23).

Fig 4.35. Interaction between modulus of base course (E) and design deflection (F).

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

From this study of sensitivity, it appears that the RPOD1 computer program for overlay design of rigid pavements is a useful and effective tool worthy of additional consideration and trial use.

The method is relatively simple and straight forward and would be highly desirable to adapt it for use by the Texas State Department of Highways and Public Transportation.

Specific conclusions from this study include the following.

(1) A summary of the sensitivity of the system RPOD1 is presented in in Table 5.1. The effects presented in Table 5.1 are qualitative. Tables 3.18 through 3.21 give the quantitative values. In Table 5.1 "increase" indicates that the mean value ($\bar{X}_i$) of the independent variable (X_i) is increased and the table gives the corresponding effects on response.

(2) Based on rankings of the independent variables considered, as shown in Figs 4.1, 4.10, 4.19, and 4.30, it is concluded that

   (a) the modulus of the base course is the most important parameter in a bonded CRCP overlay on CRCP,

   (b) the design deflection is the most important parameter, in an unbonded JCP overlay on JCP,

   (c) the design deflection is the most important parameter in AC overlay on CRCP, and,

   (d) design deflection is the most important input parameter in unbonded CRCP overlay on CRCP (mechanically broken up).

(3) The rankings of the input variables established in this study can help the pavement designer to judge whether or not the time and effort he spends in measuring the input parameters are justified.

(4) The thickness required for the unbonded JCP overlay on CRCP with voids is 35 percent greater than the required thickness for the same pavement without voids (see Figs A5.1 and A5.2).

(5) The presence of voids in JCP increases the thickness of overlay required by approximately 24 percent (see Figs 3.11 and A5.3).

TABLE 5.1 SUMMARY OF SENSITIVITY ANALYSIS OF RPOD1

Independent Variable (X_i)	Change in Mean ($\overline{X}_i$) of Variable	Effects on Output Response (Thickness of Overlay)			
		Bonded CRCP Overlay on CRCP	Unbonded JCP Overlay on JCP	AC Overlay on CRCP	Unbonded CRCP Overlay on CRCP
Modulus of overlay	Increase	No Effect	Decrease	Decrease	Decrease
Poisson's ratio of overlay	Increase		Increase		Increase
Modulus of bond breaker	Increase		Decrease		Decrease
Thickness of bond breaker	Increase		Increase		
Poisson's ratio of bond breaker	Increase				
Modulus of surface layer	Increase	Decrease	Decrease	Decrease	No Effect
Thickness of surface layer	Increase	Decrease		Decrease	
Poisson's ratio of surface layer	Increase	Increase			
Modulus of base course	Increase	Decrease	Decrease	Decrease	Decrease
Thickness of base course	Increase	Decrease		Decrease	
Poisson's ratio of base course	Increase				
Poisson's ratio of subgrade	Increase	Increase			
Design deflection	Increase	Increase	Increase	Increase	Increase

(6) The random variability of the input parameters has a significant effect on the overlay thickness. This is clear from the sensitivity analysis of RPOD1. A change of only one standard deviation in the mean value of the input parameters can change the thickness of the asphalt concrete overlay required by 2.5 inches (63.5 mm), which demonstrates the need to control the variability of the most significant parameters.

RECOMMENDATIONS

This study shows the utility of RPOD1 in its present form as a study tool for overlays. Of 22 possible types of overlays, only four types were considered for the sensitivity analysis. The other types of overlays should be analyzed in the way described in this study.

The study to date warrants consideration of this methodology for use by the Texas State Department of Highways and Public Transportation. Modifications and perhaps simplifications may well be called for but the basic method seems sound.

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APPENDIX 1

INPUT GUIDE FOR COMPUTER PROGRAM RPOD1

APPENDIX 1. INPUT GUIDE FOR COMPUTER PROGRAM RPOD1

I N P U T   G U I D E

INSTRUCTIONS TO THE PROGRAM ARE SUPPLIED IN THE FORM OF DIRECTIVES. A DIRECTIVE OCCUPIES EITHER THE FIRST OR SECOND HALF OF A CARD (COLUMNS 1-40 OR 41-80). THE FIRST EIGHT CHARACTERS OF EACH DIRECTIVE CONTAIN A KEYWORD IDENTIFYING THE TYPE OF INFORMATION BEING ENTERED. ALL KEYWORDS MAY BE ABBREVIATED TO THEIR FIRST FOUR CHARACTERS, THE REST OF THE IDENTIFIER IS IGNORED. IF THE FIRST FOUR CHARACTERS OF A DIRECTIVE ARE BLANK, THEN THE WHOLE DIRECTIVE IS SKIPPED, AND READING CONTINUES WITH THE NEXT DIRECTIVE. THIS MEANS THAT ALL DIRECTIVES MAY BEGIN IN COLUMN ONE AT THE OPTION OF THE USER.

MORE THAN ONE PROBLEM MAY BE SOLVED IN A SINGLE EXECUTION OF THE PROGRAM. EACH PROBLEM IS PREFACED WITH A *PROBLEM* DIRECTIVE AND THE LAST PROBLEM OF A RUN IS TERMINATED BY AN *END* DIRECTIVE. ALL RELEVANT INFORMATION MUST BE SUPPLIED FOR THE FIRST PROBLEM OF A RUN VIA THE VARIOUS DIRECTIVES WHICH ARE EXPLAINED BELOW. SUBSEQUENT PROBLEMS IN THE SAME RUN NEED ONLY SPECIFY DIRECTIVES WHICH ARE TO BE CHANGED, ALL OTHER VALUES WILL BE RETAINED FROM THE PRECEDING PROBLEM, WITH THE EXCEPTION OF THE CORNER DIRECTIVE, WHICH APPLIES ONLY TO THE CURRENT PROBLEM. ALL DATA ON A SINGLE DIRECTIVE MUST BE SUPPLIED, HOWEVER, EVEN IF ONLY ONE NUMBER IS BEING CHANGED.

ALL DIRECTIVES SHARE A COMMON FORMAT, BUT THE MEANINGS OF THE FIELDS DIFFER DEPENDING ON THE KEYWORD IDENTIFIER. THESE SPECIFIC MEANINGS ARE DESCRIBED BELOW UNDER THE HEADINGS OF THE APPROPRIATE KEYWORDS. THE GENERAL FORMAT IS AS FOLLOWS:

FIELD NAME	COLUMN NUMBERS	TYPE OF VALUE	FORMAT USED
KEYWORD	1-8	CHARACTER	2A4
IVL	9-10	INTEGER	I2
VAL(1)	11-20	REAL	F10.0
VAL(2)	21-25	REAL	F5.0
VAL(3)	26-30	REAL	F5.0
ITYPE(1)	31-34	CHARACTER	A4
ITYPE(2)	35-38	CHARACTER	A4

ADDING 40 TO THE COLUMNS LISTED ABOVE GIVES THE CORRESPONDING COLUMN NUMBER FOR A DIRECTIVE WHICH IS PUNCHED IN THE SECOND HALF OF THE CARD.

SOME DIRECTIVES REQUIRE FURTHER VALUES FROM CARDS WHICH ARE PLACED IMMEDIATELY AFTER THE CARD ON WHICH THE DIRECTIVE APPEARS. THESE CARDS WILL BE READ IN 8F10.0 FORMAT. AS MANY CARDS AS ARE NEEDED TO HOLD THE NUMBER OF VALUES TO BE INPUT SHOULD BE SUPPLIED. IF TWO SUCH DIRECTIVES ARE PUNCHED ON A SINGLE CARD, THE EXTRA CARDS FOR THE DIRECTIVE IN COLUMNS 1 THROUGH 40 SHOULD PRECEDE THOSE REQUIRED FOR THE ONE IN COLUMNS 41 THROUGH 80.

K E Y W O R D   D I C T I O N A R Y

BOND BKR

THIS DIRECTIVE IS NEVER REQUIRED. IF IT DOES NOT APPEAR, THEN THE DEFAULT VALUES FOR THE BOND BREAKER LAYER WILL BE USED. DEFAULT VALUES WILL ALSO BE SUPPLIED FOR ANY FIELD ON THE DIRECTIVE WHICH IS LEFT BLANK.

NOTE THAT A BOND BREAKER LAYER IS ONLY USED IF THE *UNBD* OPTION IS SELECTED ON THE OVERLAY DIRECTIVE, INDICATING THAT AN UNBONDED OVERLAY IS TO BE BUILT (SEE COMMENTS FOR OVERLAY DIRECTIVE BELOW). IF THIS OPTION IS NOT SPECIFIED, THEN THE BOND BREAKER DESCRIPTION WILL BE IGNORED, ALTHOUGH THE VALUES SUPPLIED WILL STILL BE AVAILABLE TO SUBSEQUENT PROBLEMS.

FIELD DEFINITIONS:

```
VAL(1) = MODULUS OF BOND BREAKER LAYER IN PSI.
         (DEFAULT IS 100000.0)
VAL(2) = THICKNESS OF BOND BREAKER LAYER IN INCHES.
         (DEFAULT IS 1.0)
VAL(3) = POISSON/S RATIO FOR BOND BREAKER LAYER
         (DEFAULT IS 0.3)
```

CORNER

THIS DIRECTIVE IS NEVER REQUIRED. IT IS USED ONLY WITH JCP EXISTING PAVEMENT, AND PROVIDES A MEASURED RATIO OF CORNER DEFLECTION TO INTERIOR DEFLECTION FOR A GIVEN PAVEMENT SECTION. THIS RATIO IS USED TO OBTAIN THE LOAD LOCATION (STRESS ADJUSTMENT) FACTOR FOR THE DETERMINATION OF REMAINING LIFE AND, FOR JCP OVERLAYS, OF ESTIMATED OVERLAY LIFE. INTERPOLATION IS DONE IN A CURVE OF STRESS RATIO VS. DEFLECTION RATIO DEVELOPED BY CARMICHAEL (1976). THIS DIRECTIVE APPLIES ONLY TO THE PROBLEM WITH WHICH IT WAS READ. DEFAULT VALUE OF THE LOAD LOCATION FACTOR FOR JCP EXISTING PAVEMENT AND JCP/JCP OVERLAYS IS 1.5.

FIELD DEFINITIONS:

VAL(1) = RATIO OF DEFLECTION MEASURED AT A CORNER (JCP) TO THAT MEASURED AT AN INTERIOR POINT.

VAL(2), VAL(3) = NOT USED.

DEFLECT

THIS DIRECTIVE IS REQUIRED FOR THE FIRST PROBLEM OF EVERY RUN. DEFAULT VALUES WILL NOT BE SUPPLIED BY THE PROGRAM. NOTE THAT THE COORDINATE SYSTEM USED HERE IS THE SAME AS THAT USED FOR THE LOADS DIRECTIVE. IT WILL GENERALLY SAVE KEY-PUNCHING ON MULTI-PROBLEM RUNS IF THE DEFLECTION MEASUREMENTS ARE TAKEN AT THE ORIGIN.

FIELD DEFINITIONS:

VAL(1) = DESIGN DEFLECTION IN INCHES. THIS DEFLECTION SHOULD BE REPRESENTATIVE OF THE MORE DISTRESSED PORTIONS OF THE PAVEMENT, HENCE THE 90TH PERCENTILE OF THE DEFLECTION MEASUREMENT DISTRIBUTION IS RECOMMENDED. (NO DEFAULT VALUE)

VAL(2) = X-COORDINATE OF DEFLECTION MEASUREMENT IN INCHES. (NO DEFAULT VALUE)

VAL(3) = Y-COORDINATE OF DEFLECTION MEASUREMENT IN INCHES. (NO DEFAULT VALUE)

END

THIS DIRECTIVE INFORMS THE PROGRAM THAT NO MORE PROBLEMS ARE TO BE EXECUTED IN THIS RUN. EVERY INPUT DECK MUST CONTAIN AN END DIRECTIVE, EVEN IF ONLY ONE PROBLEM IS TO BE ANALYSED. THIS DIRECTIVE HAS NO PARAMETERS.

LAB DATA

THIS DIRECTIVE IS REQUIRED IF THE LOAD UNDER WHICH THE DEFLECTION MEASUREMENTS WERE TAKEN DIFFERS SIGNIFICANTLY FROM 18 KIPS (THE DESIGN LOAD). LAB TESTS MUST BE MADE TO DETERMINE ELASTIC MODULUS AS A FUNCTION OF DEVIATOR STRESS FOR THE SUB-GRADE MATERIALS. THESE DATA ARE ENTERED ON CARDS WHICH ARE PLACED IMMEDIATELY AFTER THE DIRECTIVE IN 8F10.0 FORMAT. CORRESPONDING VALUES OF MODULUS AND DEVIATOR STRESS ARE ENTERED IN PAIRS, WITH THE MODULUS VALUE FIRST. A MINIMUM OF TWO POINTS AND A MAXIMUM OF 10 MAY BE SUPPLIED. FOUR POINTS CAN BE PUNCHED ON A SINGLE CARD. NO FIELDS CAN BE SKIPPED, AS MANY CARDS AS ARE NECESSARY TO HOLD THE DATA MUST BE PROVIDED.

FIELD DEFINITIONS:

IVL = NUMBER OF PAIRS OF POINTS TO BE READ. (1 < IVL < 100)
(NO DEFAULT VALUE)

LAYER

THIS DIRECTIVE DEFINES THE PROPERTIES OF A SINGLE LAYER OF THE EXISTING PAVEMENT. A LAYER DIRECTIVE IS REQUIRED FOR EACH LAYER DOWN TO AND INCLUDING THE SUBGRADE. AFTER THE FIRST PROBLEM IT IS POSSIBLE TO CHANGE THE VALUES FOR A SINGLE LAYER WITHOUT ALTERING THE OTHERS BY INCLUDING A LAYER DIRECTIVE FOR THAT LAYER ONLY. A MAXIMUM OF FOUR LAYERS ARE PERMITTED, UNLESS A BOND BREAKER LAYER IS TO BE USED (SEE OVERLAY DIRECTIVE) IN WHICH CASE ONLY THREE EXISTING LAYERS ARE ALLOWED. IF THE THICKNESS OF THE SUBGRADE LAYER IS INPUT AS ZERO, THEN IT IS ASSUMED TO BE SEMI-INFINITE. OTHERWISE THE PROGRAM WILL SIMULATE THE PRESENCE OF BEDROCK AT THE INDICATED DEPTH BELOW THE TOP OF THE SUBGRADE WHEN PERFORMING DEFLECTION CALCULATIONS.

FIELD DEFINITIONS:

IVL = LAYER NUMBER. LAYERS ARE NUMBERED FROM THE TOP DOWN.
0 < IVL < 5
(NO DEFAULT VALUE)

VAL(1) = MODULUS OF ELASTICITY FOR LAYER MATERIAL IN PSI.
(NO DEFAULT VALUE)

VAL(2) = LAYER THICKNESS IN INCHES (ZERO IF INFINITE).
(NO DEFAULT VALUE UNLESS SUBGRADE)

VAL(3) = POISSON/S RATIO FOR LAYER MATERIAL.
(DEFAULT VALUE BASED ON MATERIAL TYPE)

ITYPE(1) = MATERIAL TYPE AS FOLLOWS:
≠AC ≠ - ASPHALTIC CONCRETE,
≠CRCP≠ - CONTINUOUSLY REINFORCED CONCRETE PAVEMENT,
≠GRAN≠ - GRANULAR BASE MATERIAL,
≠JCP ≠ - JOINTED CONCRETE PAVEMENT,
≠STAB≠ - STABALIZED BASE MATERIAL,
≠SUBG≠ - SUBGRADE LAYER.
(MUST BE JCP OR CRCP IF TOP LAYER)

LOADS

THIS DIRECTIVE DESCRIBES THE LOAD GEOMETRY OF THE DEFLECTION MEASURING DEVICE. IT IS REQUIRED FOR THE FIRST PROBLEM OF A RUN, BUT ORDINARILY NEED NOT BE INPUT AGAIN UNLESS MORE THAN ONE SUCH DEVICE IS EMPLOYED. FROM ONE TO FOUR UNIFORM CIRCULAR LOADS MAY BE MODELLED WITH THIS DIRECTIVE. A SINGLE LOAD FORCE AND PRESSURE ARE INPUT FOR ALL OF THESE LOADS. AN EXTRA CARD MUST BE PROVIDED IMMEDIATELY AFTER THIS DIRECTIVE, SPECIFYING THE POSITIONS OF THE LOADS AS PAIRS OF X AND Y COORDINATES IN

8F10.0 FORMAT. THESE ARE THE HORIZONTAL CARTESIAN COORDINATES IT WILL USUALLY BE FOUND CONVENIENT TO SELECT A COORDINATE SYSTEM WHICH PLACES THE POINT AT WHICH DEFLECTIONS ARE MEASURED AT THE ORIGIN (SEE DEFLECT DIRECTIVE ABOVE).

FIELD DEFINITIONS:

```
IVL = NUMBER OF LOADS (0 < IVL < 5).
      (NO DEFAULT VALUE)
VAL(1) = DEFLECTION LOAD FORCE IN POUNDS.
         (NO DEFAULT VALUE)
VAL(2) = DEFLECTION LOAD PRESSURE IN PSI.
         (NO DEFAULT VALUE)
```

OVERLAY

THIS DIRECTIVE DEFINES THE TYPE OF OVERLAY TO BE BUILT. WITH IT THE DESIGNER SPECIFIES THE MATERIAL TO BE USED, ITS PROPERTIES, AND THE PRESENCE OR ABSENCE OF A BOND BREAKER LAYER. IT IS IMPORTANT TO NOTE THAT THE INCLUSION OF A BOND BREAKER LAYER (VIA THE ≠UNBD≠ OPTION) REDUCES THE MAXIMUM NUMBER OF EXISTING PAVEMENT LAYERS FROM FOUR TO THREE. AN OVERLAY DIRECTIVE IS REQUIRED FOR THE FIRST PROBLEM OF EVERY RUN.

FIELD DEFINITIONS:

```
VAL(1) = MODULUS OF OVERLAY MATERIAL IN PSI.
         (NO DEFAULT VALUE)
VAL(2) = POISSON/S RATIO FOR OVERLAY MATERIAL.
         (DEFAULT VALUE BASED ON MATERIAL TYPE)
ITYPE(1) = MATERIAL TYPE AS FOLLOWS:
           ≠AC≠ - ASPHALTIC CONCRETE OVERLAY,
           ≠CRCP≠ - CONTINUOUSLY REINFORCED CONCRETE PAVEMENT,
           ≠JCP≠ - JOINTED CONCRETE PAVEMENT.
ITYPE(2) = BOND BREAKER CONDITION AS FOLLOWS:
         = BLANK IF AC OVERLAY,
         = ≠BOND≠ IF BONDED PORTLAND CEMENT OVERLAY,
         = ≠UNBD≠ IF UNBONDED PCC OVERLAY.
           (BOND BREAKER LAYER WILL BE USED)
```

PAVEMENT

THIS DIRECTIVE DESCRIBES THE CONDITION OF THE EXISTING PAVEMENT. IT IS REQUIRED FOR THE FIRST PROBLEM OF EVERY RUN. NOTE THAT LAYER DIRECTIVES ARE ALSO REQUIRED FOR EACH LAYER INCLUDING THE TOP ONE.

FIELD DEFINITIONS:

```
IVL = NUMBER OF LAYERS IN EXISTING PAVEMENT DOWN TO AND
      INCLUDING THE SUBGRADE.  AT LEAST ONE AND NOT MORE
      THAN FOUR LAYERS MAY BE SPECIFIED (THREE IF BOND
      BREAKER LAYER SPECIFIED ON OVERLAY DIRECTIVE).
      (NO DEFAULT VALUE)
VAL(1) = NUMBER OF 18 KIP EQUIVALENT SINGLE AXLE WHEEL LOADS
         APPLIED TO DATE (PUNCHED WITH DECIMAL POINT).
         (NO DEFAULT VALUE)
VAL(2) = CONCRETE FLEXURAL STRENGTH IN PSI.
          (DEFAULT IS 690.0)
ITYPE = 8-CHARACTER FIELD SPECIFYING PAVEMENT CONDITION:
        BLANK - UNCRACKED PAVEMENT, OR TYPE 1 OR 2 CRACKING.
        ≠VOIDS   ≠ - VOIDS OBSERVED.
        ≠TYPE 3,4≠ - TYPE 3 OR 4 CRACKING PRESENT,
        ≠MECH BKN≠ - PAVEMENT WILL B MECHANICALLY BROKEN UP
                     PROIR TO BUILDING OVERLAY.
```

PROBLEM

THIS DIRECTIVE SIGNALS THE BEGINNING IF A GROUP OF DIRECTIVES THAT DESCRIBE A SINGLE PROBLEM FOR WHICH SOLUTIONS OF ALLOWABLE TRAFFIC AS A FUNCTION OF OVERLAY THICKNESS ARE DESIRED. IT PERMITS THE USER TO SPECIFY A TITLE AND A PROBLEM NUMBER WHICH WILL APPEAR IN THE PRINTED OUTPUT AND CAN BE USED TO IDENTIFY THE RESULTS. IF A NON-ZERO DIGIT APPEARS ANYWHERE BETWEEN COLUMNS 11 AND 20 OF THIS DIRECTIVE, THEN AN 80-CHARACTER TITLE IS READ FROM AN EXTRA CARD WHICH IMMEDIATELY FOLLOWS THE PROBLEM DIRECTIVE. THIS TITLE WILL REMAIN IN EFFECT UNTIL ANOTHER IS PROVIDED.

FIELD DEFINITIONS:

```
IVL = PROBLEM NUMBER (IVL < 100).
      (DEFAULT IS 1 IF FIRST PROBLEM, PREVIOUS PROBLEM NUMBER
       PLUS ONE OTHERWISE)
VAL(1) = 0 IF NO TITLE CARD,
       ≠ 0 IF TITLE CARD FOLLOWS.
```

TRAFFIC

```
   THIS DIRECTIVE IS NEVER REQUIRED.  IT PROVIDES UP TO 5
DESIGN TRAFFIC VALUES, FOR WHICH OVERLAY THICKNESSES ARE
OBTAINED BY INTERPOLATION IN THICKNESS AS A FUNCTION OF LOG(PRE-
DICTED APPLICATIONS TO FAILURE).  IT IS POSSIBLE TO OBTAIN
NEGATIVE THICKNESSES BECAUSE OF THE LOGARITHMIC EXTRAPOLATION.
SUCH VALUES ARE SET TO ZERO BY THE PROGRAM.
   AN EXTRA CARD MUST BE PROVIDED IMMEDIATELY AFTER THIS
DIRECTIVE, SPECIFYING THE DESIGN TRAFFIC VALUES IN 5F10.0 FORMAT.

FIELD DEFINITIONS:
   IVL = NUMBER OF DESIGN TRAFFIC VALUES (≤5)
         (DEFAULT: 0)
```

APPENDIX 2

SAMPLE OUTPUT OF COMPUTER PROGRAM RPOD1

APPENDIX 2. SAMPLE OUTPUT OF COMPUTER PROGRAM RPOD1

```
 RPOD1 - PAVEMENT REHABILITATION PROCEDURE - VERSION 1.0
LATEST REVISION - JUNE 1976 - AUSTIN RESEARCH ENGINEERS INC

PROBLEM   1   BONDED CRCP ON CRCP

          I N P U T   V A R I A B L E S

EXISTING PAVEMENT
*****************

  CONDITION                                  UNCRACKED WITH NO VOIDS
  CONCRETE FLEXURAL STRENGTH, PSI                              500.0
  EQUIVALENT 18 KIP SINGLE AXLE LOADS TO DATE                4000000.

  LAYER  THICKNESS  POISSON/S  ELASTIC       TYPE OF
   NO.     (IN.)      RATIO    MODULUS       MATERIAL
                                (PSI)
    1        9.0      .100    3800000.         CRCP
    2        6.4      .200     700002.   STABILIZED BASE
    3   SEMI-INFINITE .200      11000.       SUBGRADE


DEFLECTION DATA
***************

  INTERIOR DESIGN DEFLECTION, INCHES            .01500
  RATIO OF CORNER TO INTERIOR DEFLECTION          2.80
  LOAD MAGNITUDE, POUNDS                        4500.0
  TIRE PRESSURE, PSI                              75.0

                         X,Y COORDINATES, INCHES
  LOAD  1 LOCATION      (  12.45  ,       0  )
  LOAD  2 LOCATION      (  25.36  ,       0  )
  LOAD  3 LOCATION      (  83.56  ,       0  )
  LOAD  4 LOCATION      (  96.67  ,       0  )
  DEFLECTION LOCATION   (      0  ,       0  )
```

LABORATORY TESTS OF SUBGRADE SAMPLES
****

DATA DETERMINED FROM REPETITIVE LOAD TRIAXIAL TESTING
MEAN SUBGRADE MODULUS FOR EACH DEVIATOR STRESS.

DEVIATOR STRESS (PSI)	ELASTIC MODULUS (PSI)
2.00	19000.
5.00	16000.
8.00	12000.

OVERLAY CHARACTERISTICS
****

OVERLAY TYPE	BONDED CRCP
ELASTIC MODULUS, PSI	3800000.
POISSON/S RATIO	.20

DESIGN TRAFFIC
****

EQUIVALENT 18 KIP SINGLE AXLE LOADS ANTICIPATED ON OVERLAY.
(TO BE USED IN CALCULATING CORRESPONDING REQUIRED OVERLAY
THICKNESSES.)

1	3000000.
2	10000000.
3	30000000.

MODULUS OF SUBGRADE UNDER DEFLECTION LOAD= 5082.
TO MATCH DEFLECTION OF .015000 INCHES
STRESS AND LOCATION AND VOID FACTORS FOR
REMAINING LIFE CALCULATION 6.333E+01 1.20 1.00

OVLIFE PARAMETERS
NOVL,LAYR,FLOC,REM= 1 2 1.200 .597

PAVEMENT SYSTEM FOR WHICH
OVERLAY LIFE PREDICTIONS MADE

LAYER	MODULUS	POISSONS RATIO	THICKNESS (INCHES)
1	3800000.	.20	
2	3800000.	.10	9.0
3	700000.	.20	6.4
4	5082.	.20	0

CRITICAL STRESS AT BOTTOM OF LAYER 2 AND EXPECTED LIFETIME

OVERLAY THICKNESS	STRESS(PSI)	LOAD APPLICATIONS
12.0	2.354E+01	1.419E+08
9.0	2.926E+01	7.054E+07
6.0	3.703E+01	3.311E+07
3.0	4.776E+01	1.463E+07

RPOD1 - PAVEMENT REHABILITATION PROCEDURE - VERSION 1.0
LATEST REVISION - JUNE 1976 - AUSTIN RESEARCH ENGINEERS INC

PROBLEM 1 BONDED CRCP ON CRCP

S Y S T E M R E S U L T S

OVERLAY LIFE PREDICTIONS
****

PAVEMENT SYSTEM DESCRIPTION FOR WHICH OVERLAY LIFE PREDICTIONS WERE MADE.

LAYER NO.	THICKNESS (IN.)	POISSON/S RATIO	ELASTIC MODULUS (PSI)	TYPE OF MATERIAL
1	VARIES	.200	3800000.	CRCP
2	9.00	.100	3800000.	CRCP
3	6.40	.200	700000.	STABILIZED BASE
4	SEMI-INFINITE	.200	5082.	SUBGRADE

PREDICTED LIFE OF ORIGINAL PAVEMENT
(EQUIVALENT 18 KIP SINGLE AXLE LOADS) 9914102.
REMAINING LIFE OF ORIGINAL PAVEMENT, PERCENT 59.7

OVERLAY THICKNESS (INCHES)	CALCULATED FATIGUE LIFE (EQUIVALENT 18 KIP SINGLE AXLE LOADS)	REQUESTED DESIGN LIFE (EQUIVALENT 18 KIP SINGLE AXLE LOADS)	INTERPOLATED THICKNESS (INCHES)
3.0	14631000	3000000	0
6.0	33110000	10000000	1.7
9.0	70537000	30000000	5.6
12.0	141853000		

RPOD1 - PAVEMENT REHABILITATION PROCEDURE - VERSION 1.0
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PROBLEM 1 BONDED CRCP ON CRCP

PLOT
****

```
                      OVERLAY THICKNESS  VS.  FATIGUE LIFE

                          FATIGUE    LIFE    18K ESAWL
                 0 40000000, 80000000,120000000,160000000,200000000,
  OVERLAY                                                                FATIGUE
 THICKNESS  I---------I---------I---------I---------I---------I           LIFE
 (INCHES)   >                                                   <       18K ESAWL
            >                                                   <
            >                                                   <
   12.00    >                                   *               <  14.185E+07
            >                                                   <
            >                                                   <
            >                                                   <
    9.00    >                 *                                 <  70.537E+06
            >                                                   <
            >                                                   <
            >                                                   <
    6.00    >         *                                         <  33.110E+06
            >                                                   <
            >                                                   <
            >                                                   <
    3.00    >     *                                             <  14.631E+06
            >                                                   <
            >                                                   <
            >                                                   <
            I---------I---------I---------I---------I---------I

                0 40.00E+06 80.00E+06 12.00E+07 16.00E+07 20.00E+07
```

APPENDIX 3

PROCEDURE FOR CALCULATION OF MAIN EFFECTS AND INTERACTIONS

APPENDIX 3. PROCEDURE FOR CALCULATION OF MAIN EFFECTS AND INTERACTIONS

The procedure for calculating the main effects and interaction effects of three factors each at two levels (2^3 factorial) for a full factorial design is presented below. The main effects and interactions of n factors each considered at two levels for a full factorial or fractional factorial design can be foundout in the same way.

Consider that factors are A, B, and C and that each is to be considered at two levels. For a full factorial experiment (2^3 factorial) there are eight (2^3) treatment combinations (1), a, b, ab, c, ac, bc, and abc. The main effects and each interaction may be expressed by using the proper coefficients (-1 or +1) with these eight responses, as shown in Table A3.1 and explained below. For the response data of Table A3.1, the effects are

$$
\begin{aligned}
A &= [-(1) + a - b + ab = c + ac - bc + abc]/4 \\
B &= [-(1) - a + b + ab - c - ac + bc + abc]/4 \\
C &= [-(1) - a - b - ab + c + ac + bc + abc]/4 \\
AB &= [+(1) - a - b + ab + c - ac - bc + abc]/4 \\
ABC &= [-(1) + a + b - ab + c - ac - bc + abc]/4
\end{aligned}
$$

It should be noted that the coefficients to be multiplied with the treatment combinations in order to find the main effect of a factor are all +1 when that factor is at its high level and -1 when that factor is at its low level. In the example given above for the main effect of A , the treatment combinations a, ab, ac, and abc are multiplied with +1 as these contain higher levels of A and treatment combinations (1), b, c, and bc are multiplied with -1 as they contain lower levels of A.

The coefficients for the interaction effect can be found by multiplying the corresponding coefficients of concerned main effects.

The normal order for writing these treatment combinations in tabular form as shown in Table A3.1 is: (1). a, b, and ab in the case of two factors. Note that (1) is written first, then the high level of each factor with the low level of the other (a, b) and then the fourth term, which is the algebraic product of the second and third (ab). When a third factor is introduced, it is placed at the end of this sequence and then multiplied by all of its predecessors. For example, when three factors A, B, and C are present the sequence of writing the treatment combinations is

(1) a, b, ab, c, ac, bc, abc

The same procedure is followed when there are n factors present in the factorial experiment.

TABLE A3.1 COEFFICIENTS FOR EFFECTS IN A 2^3 FACTORIAL EXPERIMENT

	Effect						
Treatment Combination	A	B	AB	C	AC	BC	ABC
(1)	-	-	+	-	+	+	-
a	+	-	-	-	-	+	+
b	-	+	-	-	+	-	+
ab	+	+	+	-	-	-	-
c	-	-	+	+	-	-	+
ac	+	-	-	+	+	-	-
bc	-	+	-	+	-	+	-
abc	+	+	+	+	+	+	+

APPENDIX 4

FACTORIAL DESIGNS USED IN THIS REPORT

APPENDIX 4. FACTORIAL DESIGNS USED IN THIS STUDY

Important definitions applied to factorial design are given below.

(1) Factor (variable) - a factor can be independent (explanatory) or dependent (response).

(2) Effect of a factor - a change in the response produced by a change in level of the factor.

(3) Main effect - the average effect of a factor called the main effect.

(4) Interaction - two factors are said to interact if the effect of one factor is different at different levels of another.

(5) Treatment combination - the levels of all factors to be run for that set of conditions.

(6) Confounding - an arrangement in which certain effects can not be distinguished from others: one such effect is usually blocks, a process by which unimportant comparisons are purposely sacrificed for the purpose of assessing the more important comparison with greater precisions. Confounding is required in fractional factorial design.

(7) Alias - in a fractional factorial design, if two effects for which estimates are required are given by the same comparisons, they are said to be confounded and each is an alias of the other and cannot be independently determined.

(8) Defining contrast - an expression indicating which effects are confounded.

(9) Principal block - the block in a confounded design containing the treatment combination in which all factors are at their lower level.

A full factorial design is the one in which all levels of each factor or variable are combined with all levels of every other factor. An experimental design is called a single factorial design when all design variables except one are kept constant at certain level (medium, low, or high); the responses are found for several levels of this variable, then another variable is chosen to vary, and this process is continued until all variables of interest are considered. A factorial design having n factors, each at two levels, requires 2^n observations for one full replication. A fractional replication that has a subset of 2^{n-p} observations from 2^n is called $1/2^p$ replicate, because $2^n = (2^{n-p})/(1/2^p)$.

In a fractional design of 2^n , n factors are designated by the capital letters A, B, C . . . . The capital letters are also used to indicate main effects and interactions. The main effect of a factor A is denoted by A , the interaction between A and B by AB , etc. The treatments are indicated by lower-case italicized letters. The presence of a letter indicates the high level of that factor and its absence denotes the low level of that factor. Thus, for example, in a design having six factors, A, B, C, D, E, and F, the treatment combination acd indicates the high level of factors A, C, D and low level of factors B, E, and F. The symbol (1) denotes that treatment in which all factors are at low levels.

The reduction in the number of treatments using a fractional design is achieved by confounding information on main effects and interactions. In a half replicate or half factorial, every effect is aliased with another effect; that is, the effects occur in pairs. In a quarter replicate or quarter factorial, the effects occur in sets of four and each effect is aliased with three others, and so on. It is advisable that two factor and higher order interactions be confounded with three factor and higher order interactions.

TABLE A4.1 QUARTER-FRACTION OF 2^8 FACTORIAL DESIGN
ALIASES OF EFFECTS

Defining Contrast = I = ABCDEF = DEFGH = ABCGH

Each effect in block one has three aliases. The aliases of any effect in a fractional factorial is obtained by multiplying the effect by the terms in the defining contrast.

Sr. No.	Effect	Alias (1)	Alias (2)	Alias (3)
1	A	BCDEF	ADEFGH	BCGH
2	B	ACDEF	BDEFGH	ACGH
3	C	ABDEF	CDEFGH	ABGH
4	D	ABCEF	EFGH	ABCDGH
5	E	ABCDF	DFGH	ABCEGH
6	F	ABCDE	DEGH	ABCFGH
7	G	ABCDEFG	DEFH	ABCH
8	H	ABCDEFH	DEFG	ABCG
9	AB	CDEF	ABDEFGH	CGH
10	AC	BDEF	ACDEFGH	BGH
11	AD	BCEF	AEFGH	BCDGH
12	AE	BCDF	ADFGH	BCEGH
13	AF	BCDE	ADEGH	BCFGH
14	AG	BCDEFG	ADEFH	BCH
15	AH	BCDEFH	ADEFG	BCG
16	BC	ADEF	BCDEFGH	AGH
17	BD	ACEF	BEFGH	ACDGH
18	BE	ACDF	BDFGH	ACEGH

(Continued)

TABLE A4.1 (Continued)

Sr. No.	Effect	Alias (1)	Alias (2)	Alias (3)
19	BF	ACDE	BDEGH	ACFGH
20	BG	ACDEFG	BDEFH	ACH
21	BH	ACDEFH	BDEFG	ACG
22	CD	ABEF	CEFGH	ABDGH
23	CE	ABDF	CDFGH	ABEGH
24	CF	ABDE	CDEGH	ABFGH
25	CG	ABDEFG	CDEFH	ABH
26	CH	ABDEFH	CDEFG	ABG
27	DE	ABCF	FGH	ABCDEGH
28	DF	ABCE	EGH	ABCDFGH
29	DG	ABCEFG	EFH	ABCDH
30	DH	ABCEFH	EFG	ABCDG
31	EF	ABCD	DGH	ABCEFGH
32	EG	ABCDFG	DFH	ABCEH
33	EH	ABCDFH	DFG	ABCEG
34	FG	ABCDEG	DEH	ABCFH
35	FH	ABCDEH	DEG	ABCFG
36	GH	ABCDEFGH	DEF	ABC
37	ABD	CEF	ABEFGH	CDGH
38	ABE	CDF	ABDFGH	CEGH
39	ABF	CDE	ABDEGH	CFGH
40	BCD	AEF	BCEFGH	ADGH
41	BCE	ADF	BCDFGH	AEGH
42	BCF	ADE	BCDEGH	AFGH

(Continued)

TABLE A4.1 (Continued)

Sr. No.	Effect	Alias (1)	Alias (2)	Alias (3)
43	CDG	ABEFG	CEFH	ABDH
44	CDH	ABEFH	CEFG	ABDG
45	ACD	BEF	ACEFGH	BDGH
46	ACE	BDF	ACDFGH	BEGH
47	BDE	ACF	BFGH	ACDEGH
48	ADG	BCEFG	AEFH	BCDH
49	BDG	ACEFG	BEFH	ACDH
50	AEG	BCDFG	ADFH	BCEH
51	BEG	ACDFG	BDFH	ACEH
52	CEG	ABDFG	CDFH	ABEH
53	AFG	BCDEG	ADEH	BCFH
54	BFG	ACDEG	BDEH	ACFH
55	CFG	ABDEG	CDEH	ABFH
56	ADH	BCEFH	AEFG	BCDG
57	BDH	ACEFH	BEFG	ACDG
58	AEH	BCDFH	ADFG	BCEG
59	BEH	ACDFH	BDFG	ACEG
60	CEH	ABDFH	CDFG	ABEG
61	AFH	BCDEH	ADEG	BCFG
62	CFH	ABDEH	CDEG	ABFG
63	BDEG	ACFG	BFH	ACDEH

Note:

(1) All main effects are clear of two-factor interactions.

(2) All two-factor interactions are not confounded with one another.

(3) Gives main effects and two-factor interactions, as all other higher-order interactions are negligible.

TABLE A4.2 QUARTER-FRACTION OF 2^8 FACTORIAL DESIGN TREATMENT COMBINATIONS

One-Fourth Replication of Eight Factors

Sr. No.	1 (Principal) (0, 0)	2 (1, 0)	3 (0, 1)	4 (1, 1)
1	bcgh	a	adefgh	bcdef
2	acgh	b	bdefgh	acdef
3	abgh	c	cdefgh	abdef
4	efgh	abcef	abcdgh	d
5	dfgh	abcdf	abcegh	e
6	degh	abcde	abcfgh	f
7	abcdefg	defh	g	abch
8	abcdefh	defg	h	abcg
9	ab	cgh	cdef	abdefgh
10	ac	bgh	bdef	acdefgh
11	bcef	aefgh	ad	bcdgh
12	bcdf	adfgh	ae	bcegh
13	bcde	adegh	af	bcfgh
14	adefh	bcdefg	bch	ag
15	adefg	bcdefh	bcg	ah
16	bc	agh	adef	bcdefgh
17	acef	befgh	bd	acdgh
18	acdf	bdfgh	be	acegh
19	acde	bdegh	bf	acfgh

(Continued)

TABLE A4.2 (Continued)

Sr. No.	1 (Principal) (0, 0)	2 (1, 0)	3 (0, 1)	4 (1, 1)
20	bdefh	acdefg	ach	bg
21	bdefg	acdefh	acg	bh
22	abef	cefgh	cd	abdgh
23	abdf	cdfgh	ce	abegh
24	abde	cdegh	cf	abfgh
25	cdefh	abdefg	abh	cg
26	cdefg	abdefh	abg	ch
27	de	abcdegh	abcf	fgh
28	df	abcdfgh	abce	egh
29	abcdh	dg	efh	abcefg
30	abcdg	dh	efg	abcefh
31	ef	abcefgh	abcd	dgh
32	abceh	eg	dfh	abcdfg
33	abceg	eh	dfg	abcdfh
34	abcfh	fg	deh	abcdeg
35	abcfg	fh	deg	abcdeh
36	gh	abc	abcdefgh	def
37	abefgh	cef	cdgh	abd
38	abdfgh	cdf	cegh	abe
39	abdegh	cde	cfgh	abf
40	bcefgh	aef	adgh	bcd
41	bcdfgh	adf	aegh	bce
42	bcdegh	ade	afgh	bcf

(Continued)

TABLE A4.2 (Continued)

Sr. No.	1 (Principal) (0, 0)	2 (1, 0)	3 (0, 1)	4 (1, 1)
43	cdg	abdh	abefg	cefh
44	cdh	abdg	abefh	cefg
45	acefgh	bef	bdgh	acd
46	acdfgh	bdf	begh	ace
47	acdegh	bde	bfgh	acf
48	adg	bcdh	bcefg	aefh
49	bdg	acdh	acefg	bdg
50	aeg	bceh	bcdfg	adfh
51	beg	aceh	acdfg	bdfh
52	ceg	abeh	abdfg	cdfh
53	afg	bcfh	bcdeg	adeh
54	bfg	acfh	acdeg	bdeh
55	cfg	abfh	abdeg	cdeh
56	adh	bcdg	bcefh	aefg
57	bdh	acdg	acefh	befg
58	aeh	bceg	bcdfh	adfg
59	beh	aceg	acdfh	bdfg
60	ceh	abeg	abdfh	cdfg
61	afh	bcfg	bcdeh	adeg
62	cfh	abfg	abdeh	cdeg
63	bfh	acfg	acdeh	bdeg
64	(1)	abcgh	abcdef	defgh

TABLE A4.3 ONE-HALF FRACTION OF 2^7 FACTORIAL DESIGN ALIASES OF EFFECTS

Defining Contrast = I = ABCDEFG

Each effect in block one has one alias. The alias of any effect in a fractional factorial is obtained by multiplying the effect by the terms on the defining contract.

Sr. No.	Effect	Alias
1	A	BCDEFG
2	B	ACDEFG
3	C	ABDEFG
4	D	ABCEFG
5	E	ABCDFG
6	F	ABCDEG
7	G	ABCDEF
8	AB	CDEFG
9	AC	BDEFG
10	AD	BCEFG
11	AE	BCDFG
12	AF	BCDEG
13	AG	BCDEF
14	BC	ADEFG
15	BD	ACEFG
16	BE	ACDFG
17	BF	ACDEG
18	BG	ACDEF
19	CD	ABEFG
20	CE	ABDFG
21	CF	ABDEG
22	CG	ABDEF
23	DE	ABCFG

(Continued)

TABLE A4.3 (Continued)

Sr. No.	Effect	Alias
24	DF	ABCEG
25	DG	ABCEF
26	EF	ABCDG
27	EG	ABCDF
28	FG	ABCDE
29	BFG	ACDE
30	AFG	BCDE
31	ABG	CDEF
32	ABF	CDEG
33	CDE	ABFG
34	BDE	ACEG
35	BCE	ADFG
36	BCD	AEFG
37	ADE	BCFG
38	ACE	BDFG
39	ACD	BEFG
40	ABE	CDFG
41	EFG	ABCD
42	ABD	CEFG
43	DFG	ABCE
44	DEG	ABCF
45	DEF	ABCG
46	ABC	DEFG
47	CFG	ABDE
48	CEG	ABDF
49	CEF	ABDG
50	CDG	ABEF
51	CDF	ABEG
52	ACF	BDEG
53	BCG	ADEF
54	ACG	BDEF
55	BCF	ADEF
56	ADF	BCEF

(Continued)

TABLE A4.3 (Continued)

Sr. No.	Effect	Alias
57	BDG	ACEF
58	ADG	BCEF
59	BDF	ACEG
60	AEG	BCDF
61	BEF	ACDG
62	BEG	ACDF
63	AEF	BCDG

TABLE A4.4 TREATMENT OF COMBINATIONS OF ONE-HALF FRACTION FACTORIAL DESIGN OF 2^7

One-half replication of seven factors.

Sr. No.	Principal block	
1	1	a
2	ab	b
3	ac	c
4	ad	e
5	ae	e
6	af	f
7	ag	g
8	bc	bfg
9	bd	afg
10	be	abg
11	bf	abf
12	bg	cde
13	cd	bde
14	ce	bce
15	cf	bcd
16	cg	ade
17	de	ace
18	df	acd
19	dg	abe
20	ef	efg
21	eg	abd
22	fg	dfg
23	bcde	deg
24	acde	def
25	abde	abc
26	defg	cfg
27	abce	ceg

(Continued)

TABLE A4.4 (Continued)

Sr. No.	Principal block	
28	cefg	cef
29	abcd	cdg
30	cdfg	cdf
31	cdeg	acf
32	cdef	bcg
33	bcfg	acg
34	bdfg	bcf
35	befg	adf
36	acfg	bdg
37	adfg	adg
38	aefg	bdg
39	abcg	aeg
40	abcf	bef
41	abdg	beg
42	abdf	aef
43	abeg	abcfg
44	abef	abdfg
45	bdef	abefg
46	adeg	adefg
47	bdeg	acefg
48	adef	acdfg
49	bcef	bcdeg
50	aceg	acdeg
51	bceg	bcdeg
52	acef	acdef
53	bcdg	bdefg
54	acdf	bcefg
55	acdg	bcdfg
56	bcdf	abdef
57	abfg	abdeg
58	abcdef	abcef
59	bcdefg	abceg
60	cdefga	abcdf

(Continued)

TABLE A4.4 (Continued)

Sr. No.	Prinicipal block	
61	defgab	abcdg
62	efgabc	abcde
63	fgabcd	cdefg
64	gabcde	abcdefg

TABLE A4.5 ONE-HALF FRACTION OF 2^6 FACTORIAL DESIGN ALIASES OF EFFECTS

Defining contrast = I = ABCDEF

Each effect in block one has one alias. The alias of any effect in a fractional factorial is obtained by multiplying the effect by the terms in the defining contrast.

Sr. No.	Effect	Alias
1	A	BCDEF
2	B	ACDEF
3	C	ABDEF
4	D	ABCEF
5	E	ABCDF
6	F	ABCDE
7	AB	CDEF
8	AC	BDEF
9	AD	BCEF
10	AE	BCDF
11	AF	BCDE
12	BC	ADEF
13	BD	ACEF
14	BE	ACDF
15	BF	ACDE
16	CD	ABEF
17	CE	ABDF
18	CF	ABDE
19	DE	ABCF
20	DF	ABCE
21	EF	ABCD
22	ABC	DEF

(Continued)

TABLE A4.5 (Continued)

Sr. No.	Effect	Alias
23	ABD	CEF
24	ABE	CDF
25	ABF	CDE
26	ACD	BEF
27	ACE	BDF
28	ACF	BDE
29	ADE	BCF
30	ADF	BCE
31	AEF	BCD

TABLE A4.6 ONE-HALF FRACTION FACTORIAL DESIGN TREATMENT COMBINATION OF 2^6

Sr. No.	Principal block	
1	1	a
2	ab	b
3	ac	c
4	ad	d
5	ae	e
6	af	f
7	bc	abc
8	bd	abd
9	be	abe
10	bf	abf
11	cd	acd
12	ce	ace
13	cf	acf
14	de	ade
15	df	adf
16	ef	aef
17	abcd	bcd
18	bcde	abcde
19	cdef	acdef
20	adef	def
21	abef	bef
22	abcf	bcf
23	acde	cde
24	bdef	abdef
25	acef	cef
26	abdf	bdf
27	abde	bde

(Continued)

TABLE A4.6 (Continued)

Sr. No.	Principal block	
28	bcef	abcef
29	acdf	cdf
30	abce	bce
31	bcdf	abcdf
32	abcdef	bcdef

APPENDIX 5

RESULTS OF SINGLE FACTORIAL DESIGNS OF SOME OVERLAYS

TABLE A5.1 SUMMARY OF SINGLE FACTORIAL DESIGN OF UNBONDED JCP OVERLAY ON CRCP WITHOUT CRACKS AND VOIDS.

Sl. No.	Variable	Thickness of overlay at lower level of variable (inch)	Thickness of overlay at higher level of variable (inch)	Effect (inch)
1	Modulus of overlay	7.5	6.8	-0.7
2	Poisson's ratio of overlay	7.0	7.2	+0.2
3	Modulus of bond breaker	7.1	6.9	-0.2
4	Thickness of bond breaker	6.2	8.1	+1.9
5	Poisson's ratio of bond breaker	6.6	8.6	+2.0
6	*Modulus of surface layer	8.2	6.2	-2.0
7	Thickness of surface layer	9.1	5.8	-3.3
8	Poisson's ratio of surface layer	5.5	9.6	+4.1
9	Modulus of base course	12.0	4.4	-7.6
10	Thickness of base course	9.6	5.0	-4.6
11	Poisson's ratio of base course	6.9	7.2	+0.3
12	Modulus of subgrade	7.1	7.1	0.0
13	Poisson's ratio of subgrade	6.8	7.7	+0.9
14	Design deflection	3.4	9.6	+6.2
15	Traffic	6.4	7.1	+0.7

Thickness of overlay when all variables are at medium levels = 7.1 in.

1 inch = 25.4 millimeters

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

TABLE A5.2 SUMMARY OF SINGLE FACTORIAL DESIGN OF UNBONDED JCP OVERLAY ON CRCP WITHOUT CRACKS AND WITH VOIDS

Sl. No.	Variable	Thickness of overlay at lower level of variable (inch)	Thickness of overlay at higher level of variable (inch)	Effect (inch)
1	Modulus of overlay	10.1	9.2	-0.9
2	Poisson's ratio of overlay	9.7	9.4	-0.3
3	Modulus of bond breaker	9.2	9.7	+0.5
4	Thickness of bond breaker	10.8	8.6	-2.2
5	Poisson's ratio of bond breaker	9.0	11.1	+2.1
6	*Modulus of surface layer	11.9	8.2	-2.7
7	Thickness of surface layer	12.5	7.6	-4.9
8	Poisson's ratio of surface layer	7.3	12.4	+5.1
9	Modulus of base course	12.9	6.0	-6.9
10	Thickness of base course	12.7	7.3	-5.4
11	Poisson's ratio of base course	9.1	9.9	+0.8
12	Modulus of subgrade	9.6	9.6	0.0
13	Poisson's ratio of subgrade	9.2	10.8	+1.6
14	Design deflection	4.7	12.8	+8.1
15	Traffic	8.1	12.6	+4.5

Thickness of overlay when all variables are at medium levels = 7.1 in.

1 inch = 25.4 millimeters

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

TABLE A5.3 SUMMARY OF SINGLE FACTORIAL DESIGN OF UNBONDED JCP OVERLAY ON JCP WITHOUT CRACKS AND WITH VOIDS.

Sl. No.	Variable	Thickness of overlay at lower level of variable (inch)	Thickness of overlay at higher level of variable (inch)	Effect (inch)
1	Modulus of overlay	17.4	18.8	+1.4
2	Poisson's ratio of overlay	17.5	19.0	+1.5
3	Modulus of bond breaker	18.7	17.9	-0.8
4	Thickness of bond breaker	17.9	18.3	+0.4
5	Poisson's ratio of bond breaker	18.1	18.3	+0.2
6	*Modulus of surface layer	19.8	16.9	-2.9
7	Thickness of surface layer	17.0	16.7	-0.3
8	Poisson's ratio of surface layer	18.2	18.2	0
9	Modulus of base course	18.7	17.8	-0.9
10	Thickness of base course	18.5	17.9	-0.6
11	Poisson's ratio of base course	18.2	18.2	0
12	Modulus of subgrade	18.2	18.2	0
13	Poisson's ratio of subgrade	18.1	18.4	+0.4
14	Ratio of corner to internal deflection	17.6	18.2	+0.6
15	Design deflection	16.7	18.9	+2.2
16	Traffic	18.2	18.2	0

Thickness of overlay when all variables at medium levels = 18.2 in.

1 inch = 25.4 millimeters

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

TABLE A5.4 SUMMARY OF SINGLE FACTORIAL EXPERIMENT OF UNBONDED CRCP OVERLAY ON JCP WITHOUT CRACKS AND VOIDS.

Sl. No.	Variable	Thickness of overlay at lower level of variable (inch)	Thickness of overlay at higher level of variable (inch)	Effect (inch)
1	Modulus of overlay	11.5	9.9	-1.6
2	Poisson's ratio of overlay	10.1	11.6	+1.5
3	Modulus of bond breaker	11.8	10.2	-1.6
4	Thickness of bond breaker	9.5	11.2	+1.7
5	Poisson's ratio of bond breaker	10.7	10.8	+0.1
6	*Modulus of surface layer	12.5	9.4	-3.1
7	Thickness of surface layer	11.0	10.6	-0.4
8	Poisson's ratio of surface layer	10.7	10.9	+0.2
9	Modulus of base course	11.4	10.4	-1.0
10	Thickness of base course	11.2	10.5	-0.7
11	Poisson's ratio of base course	10.8	10.8	0.0
12	Modulus of subgrade	10.8	10.8	0.0
13	Poisson's ratio of subgrade	10.7	11.0	0.3
14	Ratio of corner to interior deflection	10.8	10.8	0.0
15	Design deflection	9.9	11.2	+1.3
16	Traffic	10.8	10.8	0.0

Thickness of overlay when all variables are at medium levels = 10.8 in.

1 inch = 25.4 millimeters

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

TABLE A5.5 SUMMARY OF SINGLE FACTORIAL DESIGN OF UNBONDED JCP OVERLAY ON JCP WITH CLASS 3 AND 4 CRACKS.

Sl. No.	Variable	Thickness of overlay at lower level of variable (inch)	Thickness of overlay at higher level of variable (inch)	Effect (inch)
1	Modulus of overlay	15.7	14.0	-1.7
2	Poisson's ratio of overlay	14.0	15.4	+1.4
3	Modulus of bond breaker	15.4	14.2	-1.2
4	Thickness of bond breaker	13.9	14.9	+1.0
5	Poisson's ratio of bond breaker	14.6	14.7	+0.1
6	*Modulus of surface layer	16.7	14.7	-2.0
7	Thickness of surface layer	14.9	14.5	-0.4
8	Poisson's ratio of surface layer	14.6	14.7	+0.1
9	Modulus of base course	15.2	14.3	-0.9
10	Thickness of base course	15.0	14.4	-0.6
11	Poisson's ratio of base course	14.6	14.7	+0.1
12	Modulus of subgrade	14.7	14.7	0.0
13	Poisson's ratio of subgrade	14.6	16.9	+0.3
14	Design deflection	13.2	15.3	+2.1
15	Ratio of corner to interior deflection	14.2	15.0	+0.8

Thickness of overlay when all variables are at medium levels = 14.7 in.

1 in. = 25.4 millimeters

*Concrete modulus and flexural strength are varied simultaneously (see p. 22, 23).

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