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16. Abstract

The continuously reinforced concrete pavement model-1, designated as CRCP-1, is a mathematical model derived from field observations and laboratory observations that may be used as a design and research tool by the Highway Engineer. The theoretical model is formulated into a computer program which analyzes the behavior of continuously reinforced concrete pavements due to drying shrinkage and changes in temperature as a function of time. The program uses 15 different kinds of inputs in the broad categories of steel properties, concrete properties, slab-base frictional relationships, and temperature data.

This report describes a sensitivity analysis performed to determine the relative effects of various design parameters in pavement behavior. In addition, an effort was also made to debug the computer program to find the problem areas and list the common user errors.

It is concluded that CRCP-1 gives generally reasonable solutions although several revisions should be made in the future. The design variables are sensitive to various degrees with respect to crack spacing, crack width, maximum stress in the steel, and maximum stress in the concrete. The analysis indicates that percentage of longitudinal reinforcement and concrete strength are the most important design variables.

17. Key Words

sensitivity analysis, analysis, rigid pavements, pavement design, system analysis, performance, computer program.

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by

Chypin Chiang
B. Frank McCullough
W. Ronald Hudson

Research Report Number 177-2

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
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH

THE UNIVERSITY OF TEXAS AT AUSTIN

August 1975

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 continuously reinforced concrete pavement model CRCP-1. The variables are analyzed with respect to their effects on the pavement behavior. The report will help the designers use the CRCP-1 computer program more efficiently and understand the effects of different variables.

The analysis presented in this report is the first attempt to determine the sensitivity of various variables involved in the CRCP-1. Therefore, the analysis is designed to be simple and accurate and the level of effort is kept to the minimum.

This is the second in a series of reports that describes the work done in the project entitled "Development and Implementation of the Design, Construction, and Rehabilitation of Rigid Pavements." The project put forth a long-range comprehensive research program to develop a system analysis of pavement design and management information system. The project is conducted through a National Cooperative Highway Research Program with the State Department of Highways and Public Transportation and the Federal Highway Administration.

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. Marie Fisher, Mrs. Patricia Henninger, and Miss Judy Howard for typing the drafts of the report and to Mr. Arthur Frakes for his assistance with the manuscript.

Chypin Chiang
B. Frank McCullough
W. Ronald Hudson

August 1975

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 based on 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 and makes recommendations for efficient use of the computer program. August 1975.

ABSTRACT

The continuously reinforced concrete pavement model-1, designated as CRCP-1, is a mathematical model derived from field observations and laboratory observations that may be used as a design and research tool by the Highway Engineer. The theoretical model is formulated into a computer program which analyzes the behavior of continuously reinforced concrete pavements due to drying shrinkage and changes in temperature as a function of time. The program uses 15 different kinds of inputs in the broad categories of steel properties, concrete properties, slab-base frictional relationships, and temperature data.

This report describes a sensitivity analysis performed to determine the relative effects of various design parameters in pavement behavior. In addition, an effort was also made to debug the computer program to find the problem areas and list the common user errors.

The analysis phase of this investigation consists of a single factorial design and a $3 \times 3 \times 3$ factorial design for interaction study. In the former experiment, 87 solutions were obtained at three levels of the variables; low, medium, and high. The sensitivity of each variable was studied at each of these three basic levels by changing the value of the specific variable to the other two levels. An evaluation of the influences on pavement behavior was accomplished by the basic concepts of weighting factors and importance rating. In the succeeding study of a $3 \times 3 \times 3$ factorial experiment, an analysis of variance was made to determine what interactions among the three most important design variables are significant. The results show a greater consistency in the importance of these design variables and indicate significant interactions among the variables.

It is concluded that CRCP-1 gives generally reasonable solutions although several revisions should be made in the future. The design variables are sensitive to various degrees with respect to crack spacing, crack width, maximum stress in the steel, and maximum stress in the concrete. The analysis indicates that percentage of longitudinal reinforcement and concrete strength are the most important design variables.

KEY WORDS: Sensitivity analysis, analysis, rigid pavements, pavement design, system analysis, performance, computer program.

SUMMARY

A sensitivity analysis has been performed on the continuously reinforced concrete pavement model CRCP-1, which was developed as a computer program to analyze and rationally design continuously reinforced concrete pavements, using about fifteen input variables. The relative importance of these variables was determined in the sensitivity analysis that was made to investigate the impact of changes in input values on the CRCP structure. About two hundred different problems were solved using the CRCP-1 program and the data obtained were reasonably analyzed quantitatively as well as qualitatively.

This study is a part of an overall systematic pavement design and research program. The sensitivity analysis reported here has given the program users more information about the effects of the variables. This information provides the design engineer with greater insight into the decision-making process of accomplishing the design of CRC pavements.

IMPLEMENTATION STATEMENT

The findings of the sensitivity analysis presented in this report will aid in the application and implementation of the continuously reinforced concrete pavement model CRCP-1. The sensitivity analysis has given considerable feedback for use in improving the program. 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 solving the real problems more efficiently. The results of this report could be implemented to help program users decide the level of effort which is needed for closer attention and study, and to indicate those areas where design information is exceedingly definite.

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CHAPTER 5. ANALYSIS OF RESULTS

CHAPTER 1. INTRODUCTION

Background

This report presents a sensitivity analysis performed to establish the reasonableness of solutions and relative importance of all the input variables in a continuously reinforced concrete pavement model for highways, CRCP-1. CRCP-1 (Ref 1) is a design concept utilizing a computer program to analyze the behavior of continuously reinforced concrete pavements due to drying shrinkage and changes in temperature as a function of time.

The widespread uses of continuously reinforced concrete pavement (CRCP) led to the development of design procedures by several state highway departments, including Texas and Illinois, and by various research agencies, such as AASHO (Ref 2) and United States Steel (Ref 3). The continued observations of problems with CRCP led to the need for more fundamental studies, and a computer program designated CRCP-1 was developed at the Center for Highway Research at The University of Texas at Austin under a National Cooperative Highway Research Program.

In utilizing the program, the user must specify a number of input constraints, depending on his interests. The system involves about 15 input variables in such categories as steel properties, concrete properties, slab-base frictional relationship, and temperature history. A problem is solved through simultaneous solution of basic stress equations for shrinkage and temperature, slab-base friction, and movement.

Purpose of This Study

The mathematical model CRCP-1 developed by Adnan Abou-Ayyash provided a unique and useful tool for analyzing the design of continuously reinforced concrete pavements for highways. It must be recognized that a designer has only limited resources and time to use in estimating the large number of input variables needed in the proposed method. To warrant confidence in such a program as well as to evaluate the reasonableness of its solutions, it is imperative to check the system by analyzing a number of problems over a wide range of variables. To accomplish this, a comprehensive sensitivity analysis has been performed.

The objectives of this study are:

(1) to adapt the computer program CRCP-1 for use by the Texas Highway Department,

(2) to establish confidence in the reliability of the model;

(3) to obtain a more complete understanding of the variable interacting effects,

(4) to debug the computer program as much as possible by solving a large number of possible kinds of problems,

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

(6) to assist the pavement designer in deciding the relative amount of time and effort he should spend estimating the numerical values of the various inputs to the system,

(7) to simplify the program inputs by making some of the variables constants, and

(8) to establish design guidelines for the use of this computer model.

CHAPTER 2. THE COMPUTER PROGRAM

It is not necessary for the pavement designer to have a complete knowledge of the computational techniques used in the model CRCP-1, but a basic understanding of the overall process is indispensable for effective use of the computer program.

Model CRCP-1 is the most complete program developed to date to study the mechanistic behavior of highly complex continuous pavements. The program is written in FORTRAN computer language for the CDC6600 digital computer. Appendices 1 and 2 of this report contain an operational guide for data input and sample output data, respectively.

Theoretical Models

In order to develop a method to predict the crack spacing, crack width, stress in steel, and stress in concrete due to drying shrinkage and temperature change as a function of time, an incremental approach was adopted. The basic concept is shown in Fig 2.1. The approach can be summarized as follows:

(1) At any time t_1 , determine the tensile strength of concrete from the strength-time relationship (Fig 2.1(a)).

(2) Compute the drying shrinkage Z_1 and the temperature drop ΔT_1 corresponding to time t_1 (Fig 2.1(b)).

(3) With the mathematical models, calculate the maximum concrete tensile stress (Fig 2.1(c)).

(4) Compare the concrete strength with concrete stress (Fig 2.1(d)). If the strength is higher than the stress, cracking does not occur.

(5) Increment the time to t_2 , and repeat steps one through four. If the stress is higher than the strength, as shown in Fig 2.1(d), a crack occurs between t_1 and t_2 .

(6) Solve for the time (somewhere between t_1 and t_2) and the corresponding state of stress at which cracking occurred.

(7) Increment time and search for additional cracks as they develop.

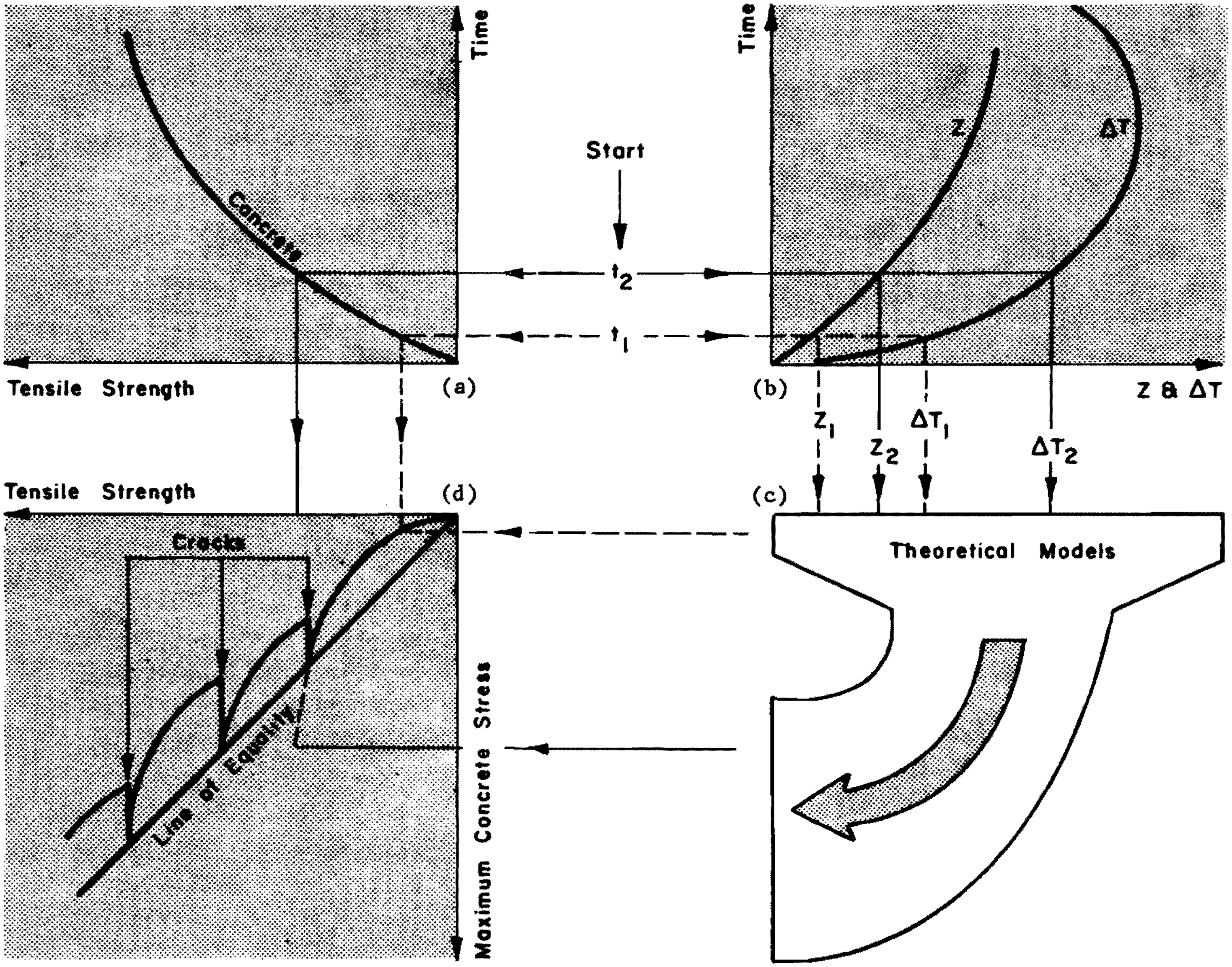


Fig 2.1. Incremental approach as applied to the continuous pavement system.

By its nature, the analysis of continuously reinforced concrete pavement is a highly complex problem. A significant number of variables influence the behavior and, hence, the performance of this pavement type. In this respect, a typical slab segment is used to analyze the pavement system. This segment is based on the behavior of continuous pavement and its response to internal and external stresses. Figure 2.2 illustrates the typical layout of a continuously reinforced concrete pavement and Fig 2.3 shows the typical slab segment.

Assumptions

In the analysis of the problem, the following assumptions have been made:

(1) A crack occurs when the concrete stress exceeds the concrete strength, and, after cracking, the concrete stress at the location of the crack is zero.

(2) Concrete and steel properties are linearly elastic.

(3) In the fully bonded sections of the concrete slab, there is no relative movement between the steel and the concrete.

(4) The force displacement curve which characterizes the frictional resistance between the concrete slab and the underlying base is elastic.

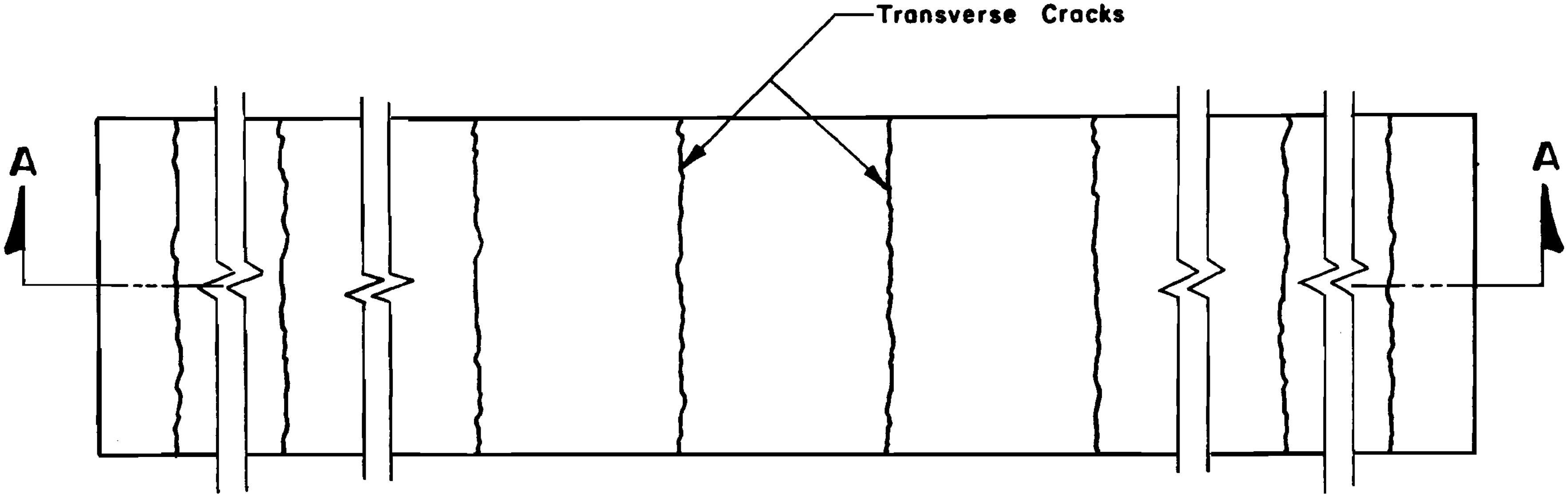
(5) Temperature variations and shrinkage due to drying are uniformily distributed throughout the slab, and, hence, a one-dimensional and axial structural model is adopted for the analysis of the problem.

(6) Material properties are independent of space.

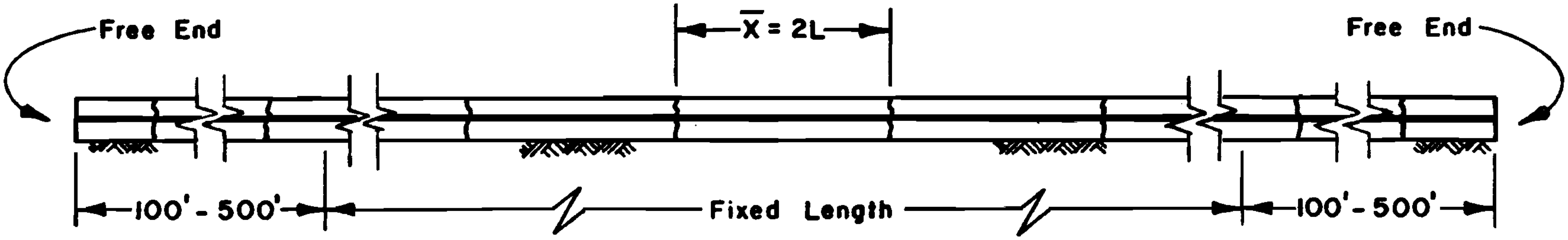
(7) Effect of creep of concrete and slab warping are neglected.

The FORTRAN Program

A Summary Flow Chart. A summary flow chart for the CRCP-1 program is given in Fig 2.4. The time required to run problems varies, of course, with the complexity of the system, the nature of the friction-movement relationship, the variation of the concrete strength with time, increment length, and the number of iterations required to obtain the desired accuracy. In general, the computer operating time for a relative closure tolerance of one percent and problem similar to the sample problems herein is usually in the range of 15 to 20 seconds.



(a) Plan



(b) Section AA

Fig 2.2. Typical layout of a continuously reinforced concrete pavement.

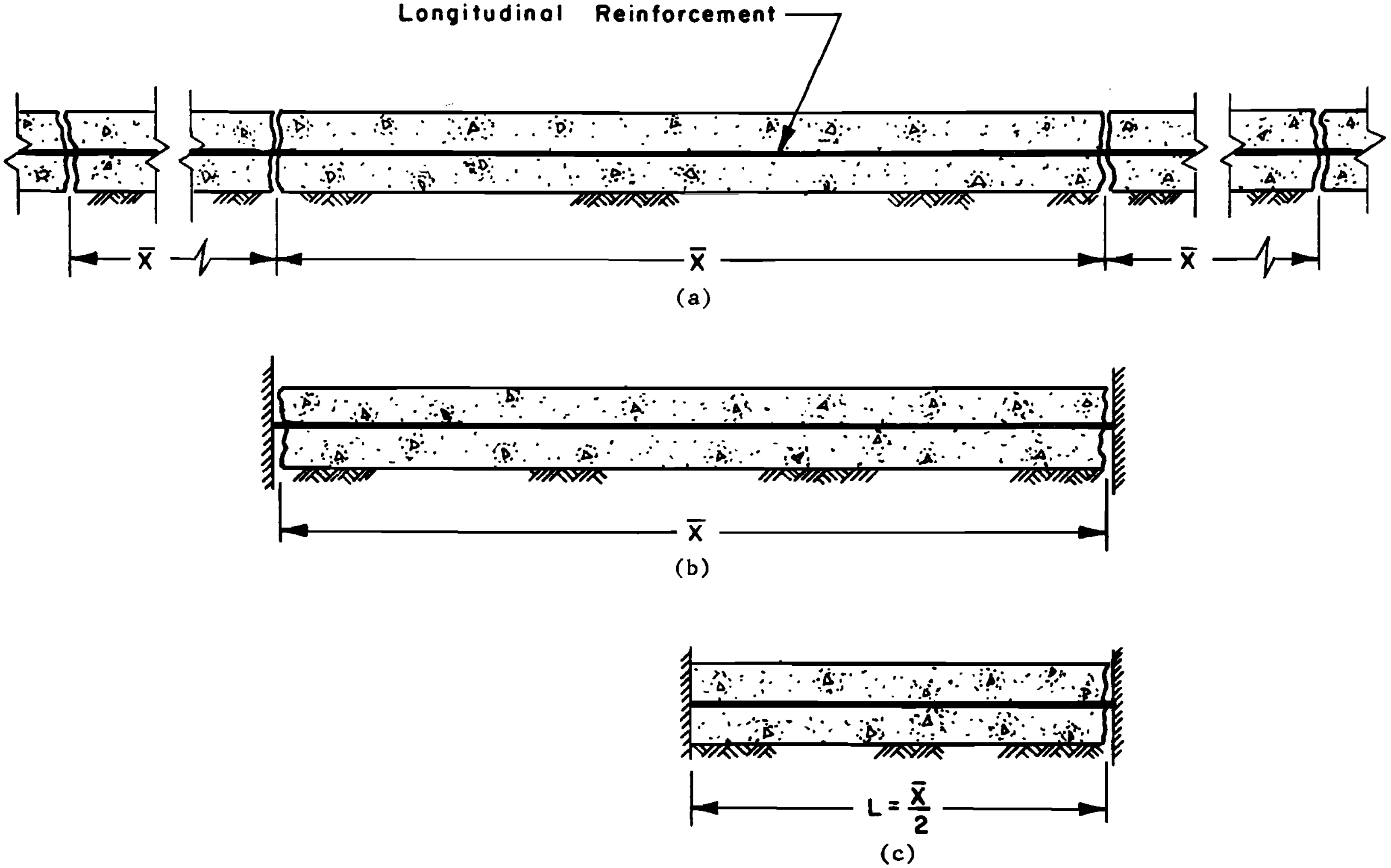


Fig 2.3. Typical slab segment in continuously reinforced concrete pavement.

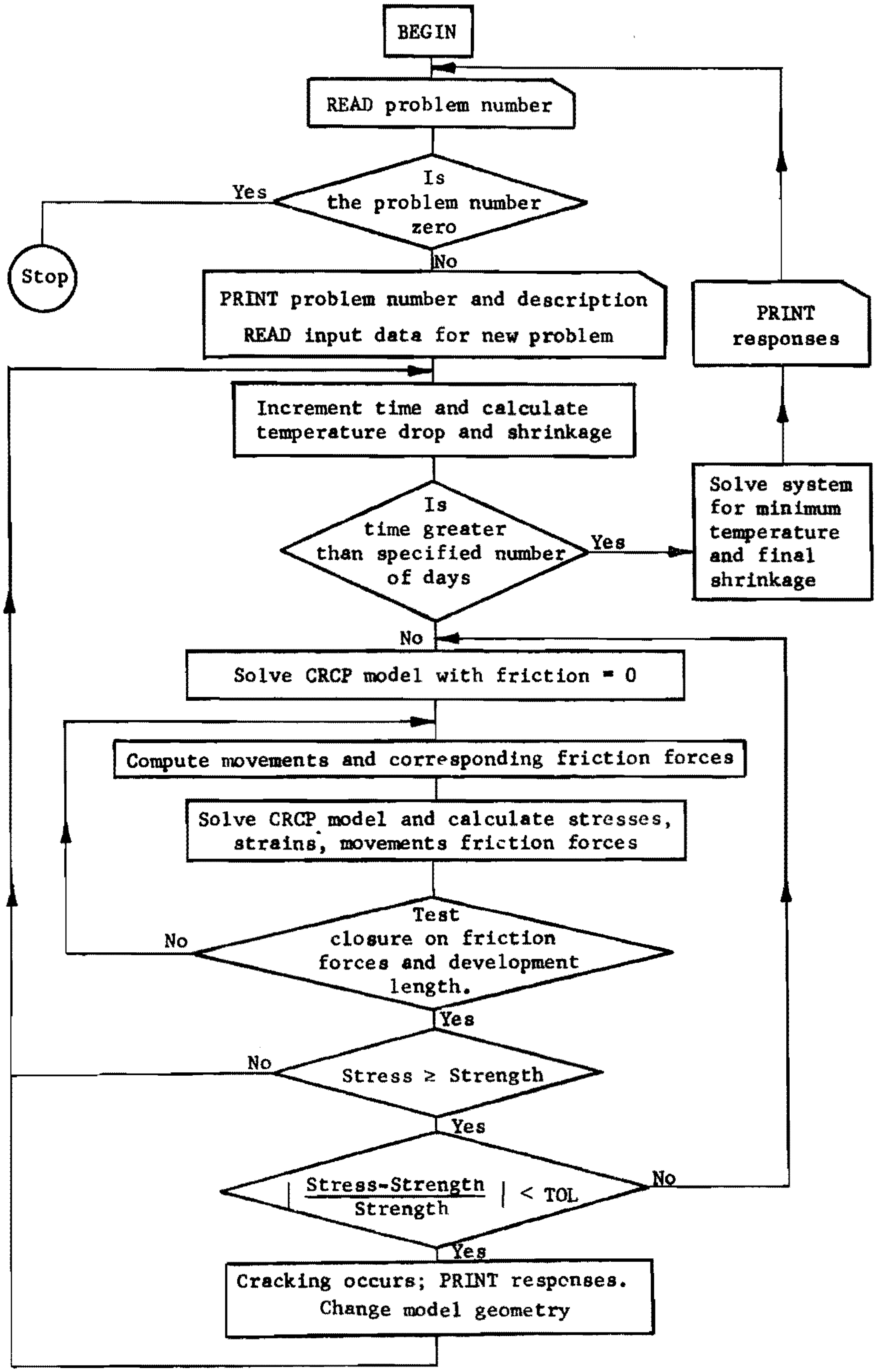


Fig 2.4. Summary flow chart of CRCP-1 program.

Output Information. The outputs of the computer program are crack spacing and crack width as a function of time, and also include drying shrinkage, concrete tensile strength, maximum concrete stress, and maximum steel stress. Figure 2.5 shows the variation in concrete strength and the predicted maximum concrete tensile stress as a function of time for the case of 0.6 percent reinforcement. The vertical arrows indicate the time at which cracking occurred.

After cracking on day 2, the stresses are reduced, but slowly build up and cracking again occurs twice on day 3. This pattern is repeated on the eighth day and would continue on if the entire stress history were presented. The implication of these occurences on crack pattern is illustrated in Fig 2.6. The first crack on day 2 occurs at the mid-point of the slab resulting in a crack spacing X_2. Each of the slab segments then crack at the mid-point on the respective days resulting in the crack spacings X_3, $X_{3.2}$, and X_8 as shown. The actual computation models are extremely complex although the concept is simple.

Grouping of Input Variables

There are four broad categories of input variables in the CRCP-1 computer program: (1) steel variables, (2) concrete variables, (3) slab-base frictional characteristics, and (4) environmental variables.

Steel Variables. Information on this input includes the type of longitudinal reinforcement, percentage of reinforcement, bar diameter, yielding stress, modulus of elasticity, thermal coefficient, and spacing of transverse wires in the case of design type specified as deformed wire fabric. The format used to input the required information is shown in the Operational Guide for Data Input, in Appendix 1.

Concrete Variables. Since transverse cracking on pavements is formed when the induced concrete-tensile stress exceeds its tensile strength, the physical and mechanical properties of the concrete also influence the crack-spacing pattern. Some of these concrete properties included in the CRCP-1 program are (1) thermal coefficient, (2) final or total drying shrinkage, (3) unit weight, (4) 28-day compressive strength, and (5) 28-day tensile strength. Also included as a concrete variable is the slab thickness.

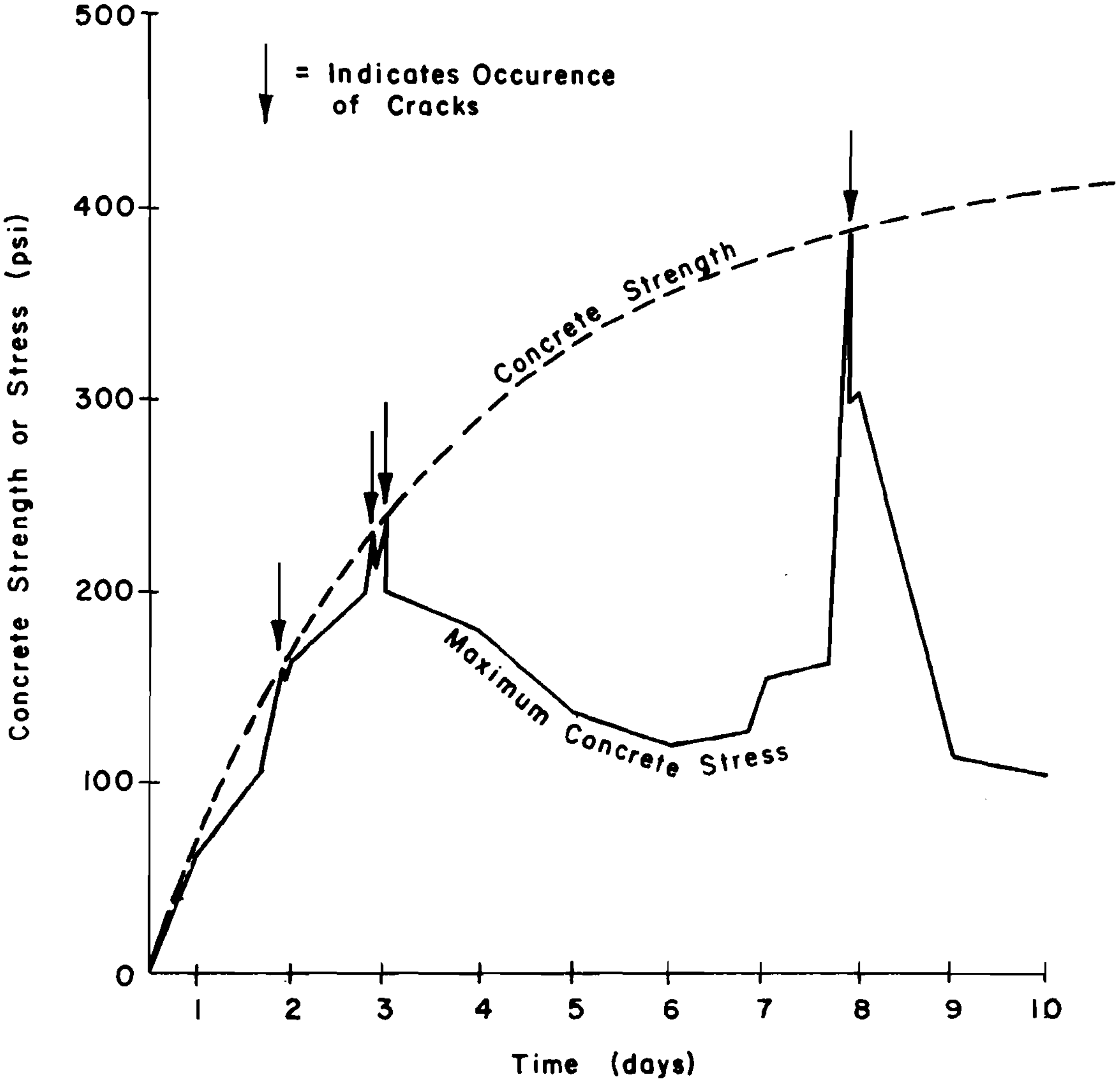


Fig 2.5. Variation of concrete strength and maximum concrete stress with time for 0.6 percent reinforcement.

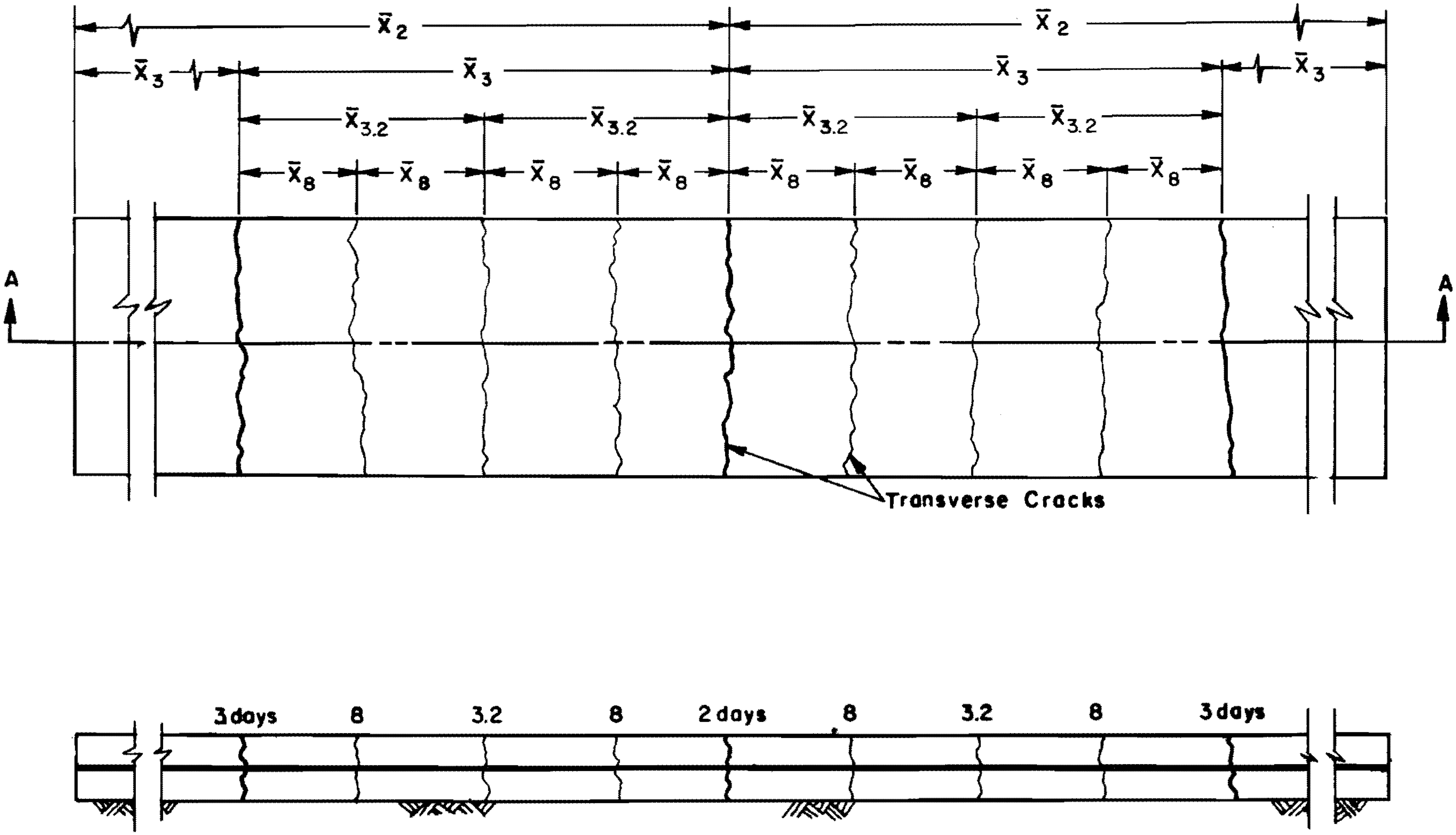


Fig 2.6. Typical occurence of transverse cracks related to Fig 2.5, on a daily basis.

If the age-tensile-strength relationship is not available, the data will be generated by using the recommendations suggested by the United States Bureau of Reclamation. The 28-day compressive strength should be provided in the input whether or not the age-tensile strength data are given by the user.

Slab-Base Frictional Variables. Research by the Bureau of Public Roads and New Jersey State Highway Department (Refs 4 and 5) has established that frictional resistance to movement is not constant but increases with movement, rapidly at first and at a decreasing rate with further increase in movement. Since the frictional resistance is not constant with movement, its effect should be characterized by the complete curve defining the resistance-movement relationship. There are three types of frictional resistance relationship prepared on the computer program, straight line, parabola, and multilinear. Various relationships can be input to define the F-y curve (i.e., F-resistance and y-movement) used in the program computations; for it the number of input cards is variable, depending on the number of points defining the F-y relationship. It is worth noting that F is expressed as the force per unit length and per unit width.

The desired frictional relationship should be specified by the user. It is also worth realizing that according to the sign convention adopted in the CRCP-1 model, the input movements at sliding should be negative and the friction forces should be positive.

Environmental Variables. The formation of transverse cracks in continuously reinforced concrete pavement is also influenced by the atmospheric conditions prevalent during the curing period, including any severe drop in daily temperature the pavement is subjected to during its service life. These selected variables are included in the program: average curing temperature of concrete, minimum daily temperature, and minimum temperature expected after the concrete gains its full strength.

This part of the input data consists of two components. The first deals with the analysis period (28 days) directly after the concrete placement; the average curing temperautre and minimum daily temperature for the desired number of days are input. The number of cards required is variable and depends on the number of datapoints. The second component of the temperature data deals with the analysis period after the concrete achieves, for all practical purposes, its maximum strength.

CHAPTER 3. COMPUTATIONAL EXPERIMENTAL DESIGN AND ANALYSIS

The basic objective of a sensitivity analysis is to relate variations in inputs to variations in outputs. A complete sensitivity study of a complex model like CRCP-1 would require an analysis of program output at various levels of the possible range of all the design variables involved. Such an analysis would need a very large experiment to cover the effects of individual variations of the variables as well as the variations in groups. For instance, for three levels of each variable, the total number of runs required to determine the main effects and interactions for 15 design variables is 3^{15} (over 14 million). It is obvious that such a large-scale study is not practical because of cost and time involved.

What is actually required in the beginning is a preliminary design which can be done with a reasonable amount of time and effort and provide maximum information for effective use of the program. Thus, the confidence required for conducting a full scale factorial experiment will be achieved.

Figure 3.1 presents the general sequence for designing and conducting the sensitivity analysis. The initial step was to fix several of the primary inputs. Next, magnitudes for each of the variables were defined. A traditional sensitivity analysis was performed to establish the three most important variables. A full factorial analysis is then performed on these variables to study the interactions.

Fixed Variables

In each of the primary input categories, variables were fixed that would permit subsequent analyses to be added to this study. For example in the steel category, deformed bars were selected for study. Thus, a future study could be made of welded wire fabric which would supplement this study.

Table A3.1 present the fixed input values for concrete age-tensile strength relationships, frictional characteristics, and the temperature history.

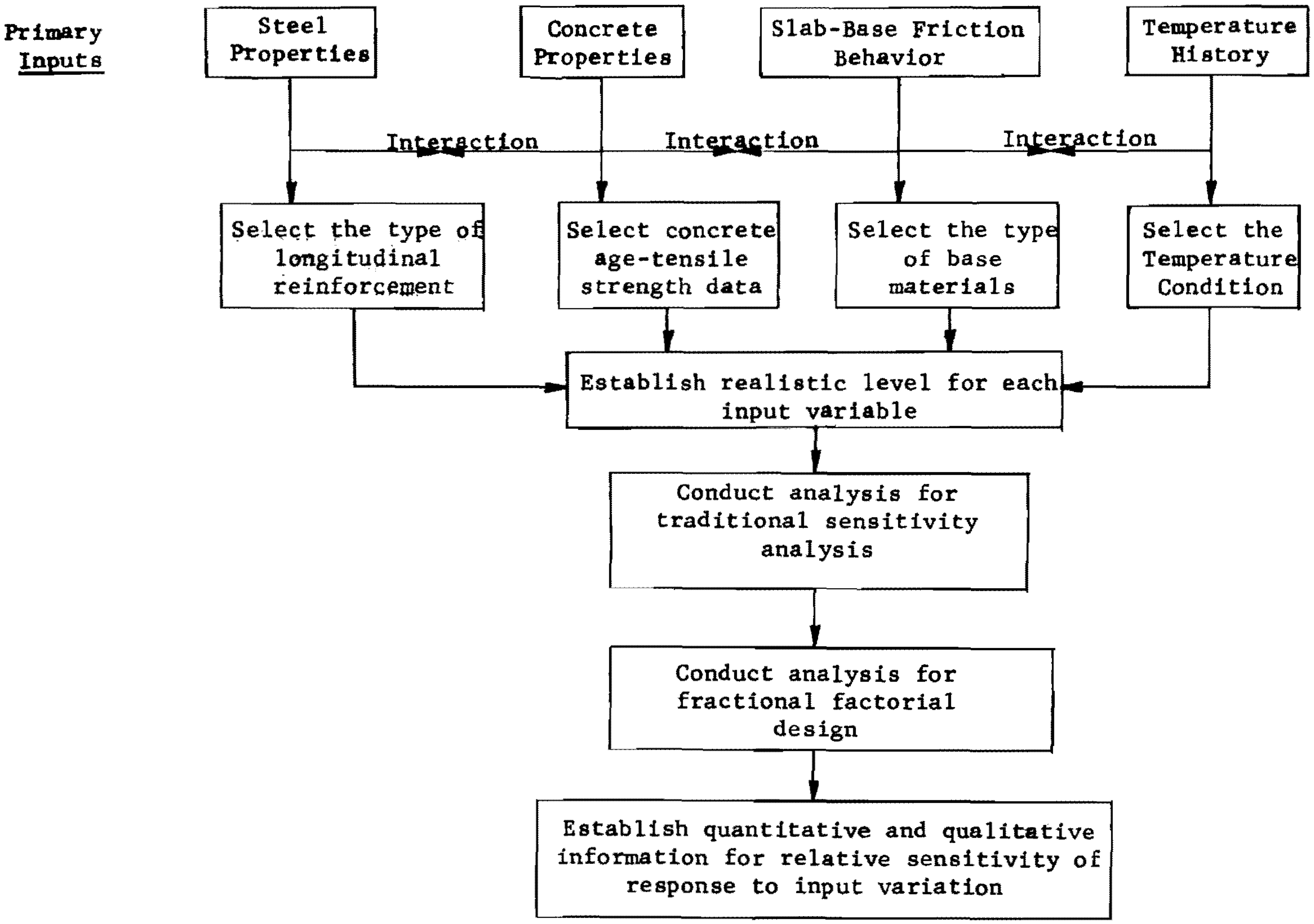


Fig 3.1. General sequence for conducting the sensitivity analysis.

In addition, a small study was performed to establish reasonable values of the closure tolerance and the initial length input into the program. Since both of these factors influence the computational time, a reasonable level for each would not affect accuracy was established.

To establish the proper level of the relative closure tolerance required for a reasonable number of iterations, the variations of steel stress, crack width and crack spacing with different levels of closure tolerance were studied. The results are presented in Figs 3.2, 3.3, and 3.4 for a percent reinforcement of 0.6 and for median values of the other input variables. Relative closure tolerances of one to six percent gave the desired accuracy in computing the steel stress, crack width and crack spacing values. Since the computation time increases with smaller closure tolerances, a value of five percent is recommended.

In addition, a small study was conducted to establish the optimum initial length of the slab in terms of crack spacing variations. The theory, in essence, makes the computations assuming an infinite length of slab, but must start from a finite length as shown in Fig 2.2. Fig 3.5 presents the influence of slab length on the crack spacing. Note that the initial length does not affect the end result, but it does have a significant effect on computational time. For this study, the initial length was fixed at 100 feet.

Selection of Levels

The choice of levels of factors to be used in an experiment depends upon the nature of the experimental yields and upon the objectives of the experiment. If the experimenter knows the range in levels of interest and if he desires to investigate the form of the response curve he should select as many levels as are practical. A three level experiment was established here; each input variable was given low, medium, and high values, based on engineering judgement and the following research resources:

(1) "AASHO Interim Guide for the Design of Rigid Pavement Structures," 1972 (Ref 2),

(2) "Design and Construction - Continuously Reinforced Concrete Pavement," Continuously Reinforced Pavement Group, 1968 (Ref 6),

(3) "Design and Control of Concrete Mixtures," Portland Concrete Association 1968 (Ref 7),

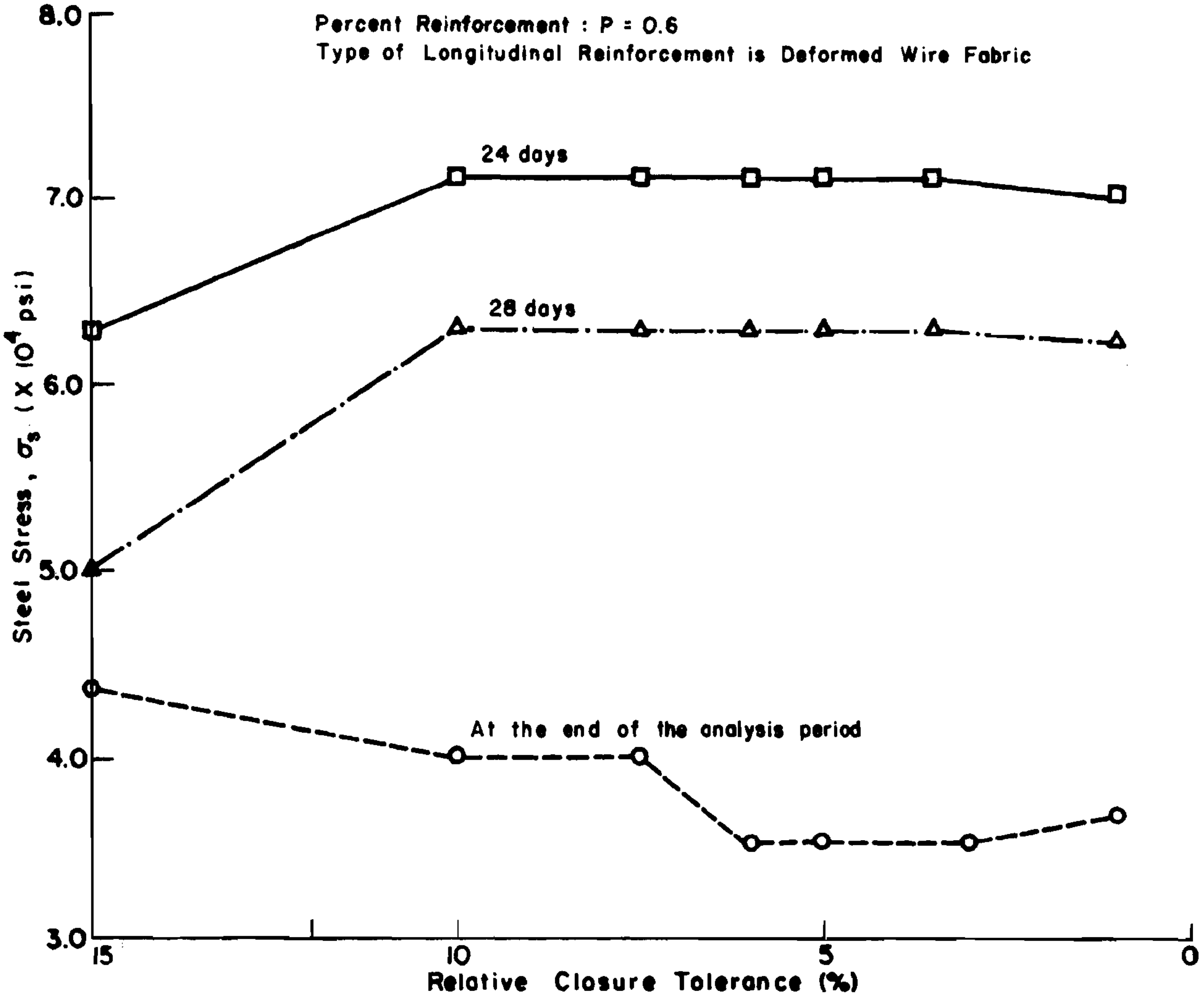


Fig 3.2. The accuracy in computing the steel stress for different closure tolerance levels.

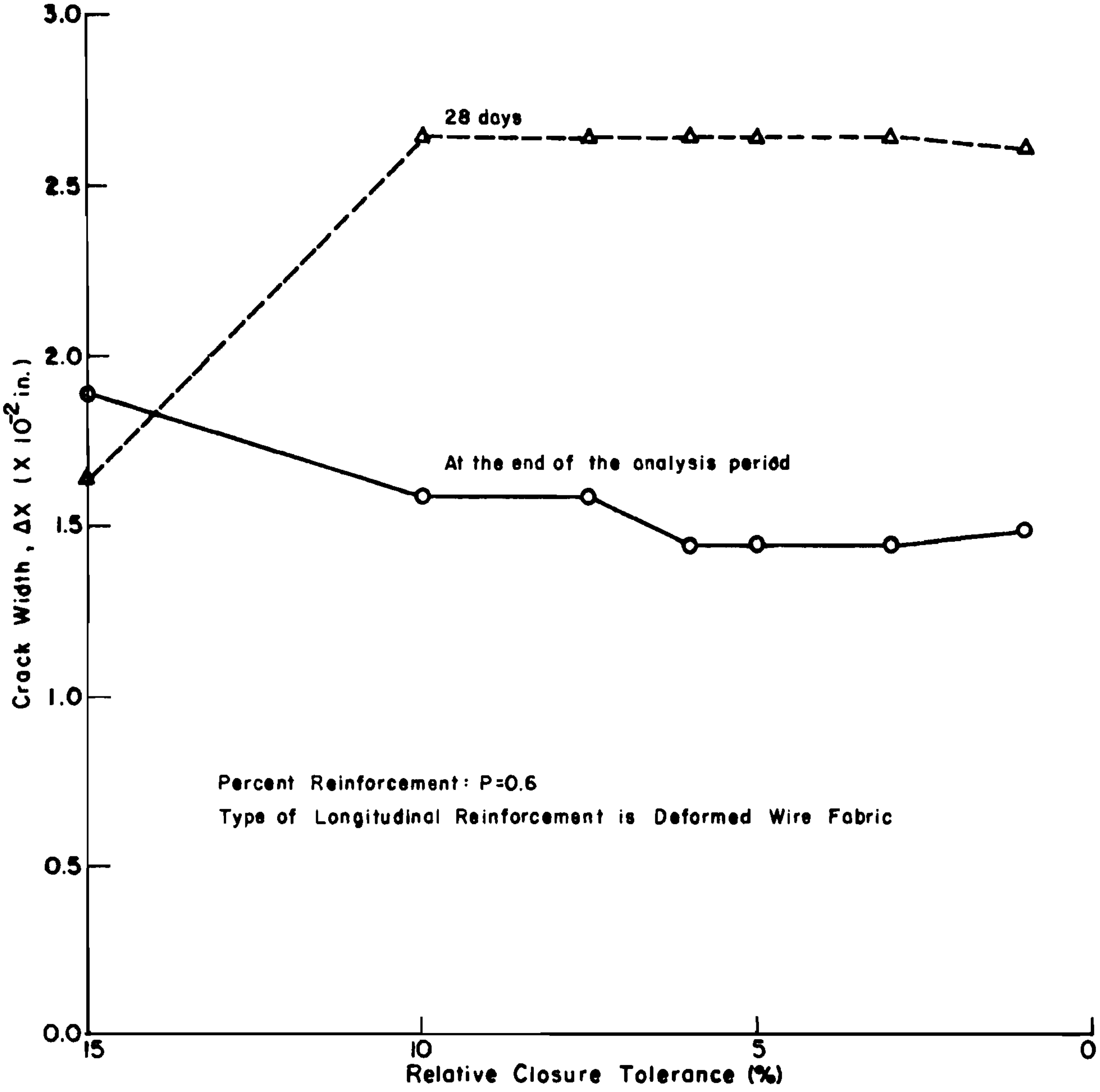


Fig 3.3. The accuracy in computing crack width for different closure tolerance levels.

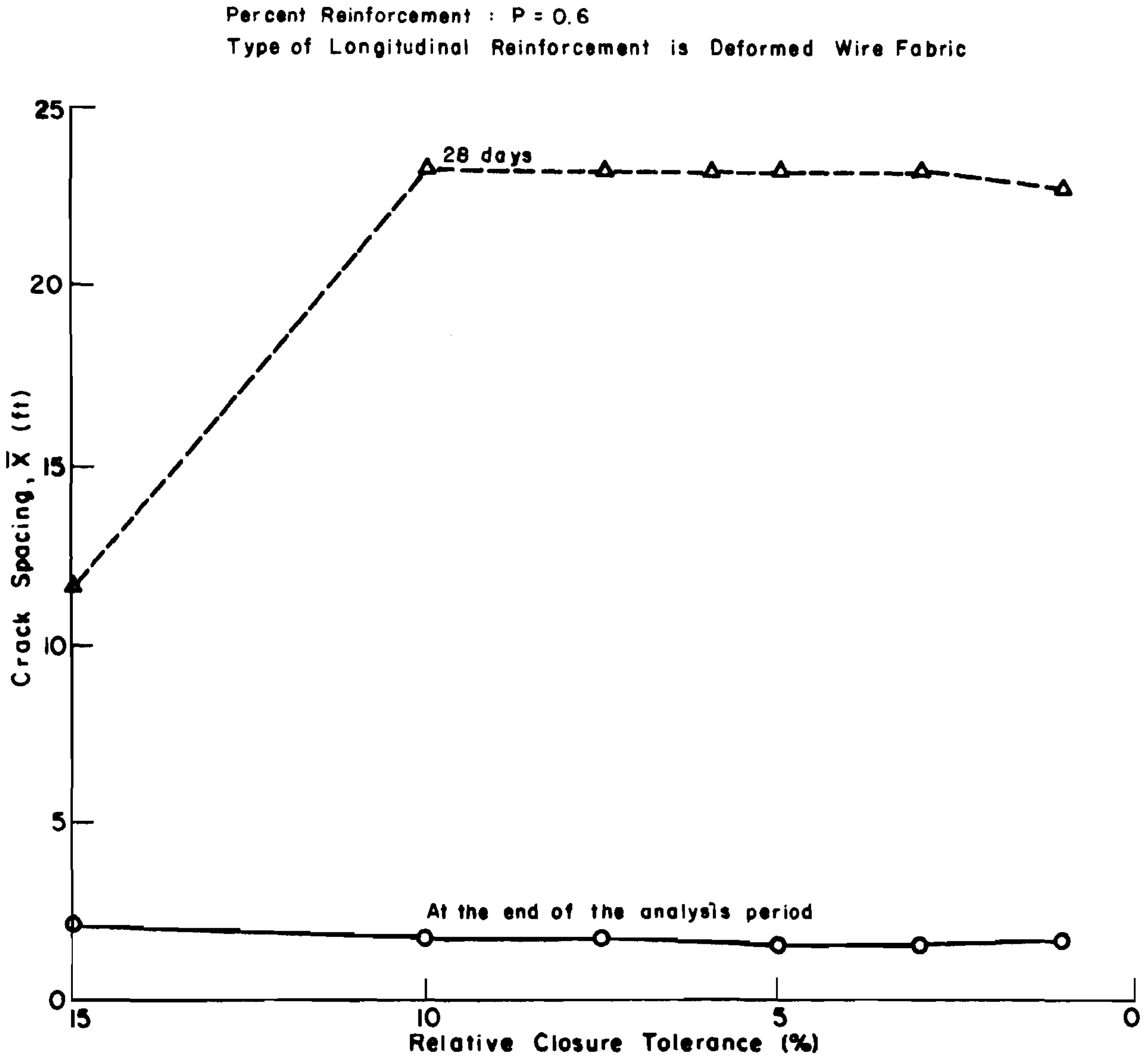


Fig 3.4. The accuracy in computing crack spacing for different closure tolerance levels.

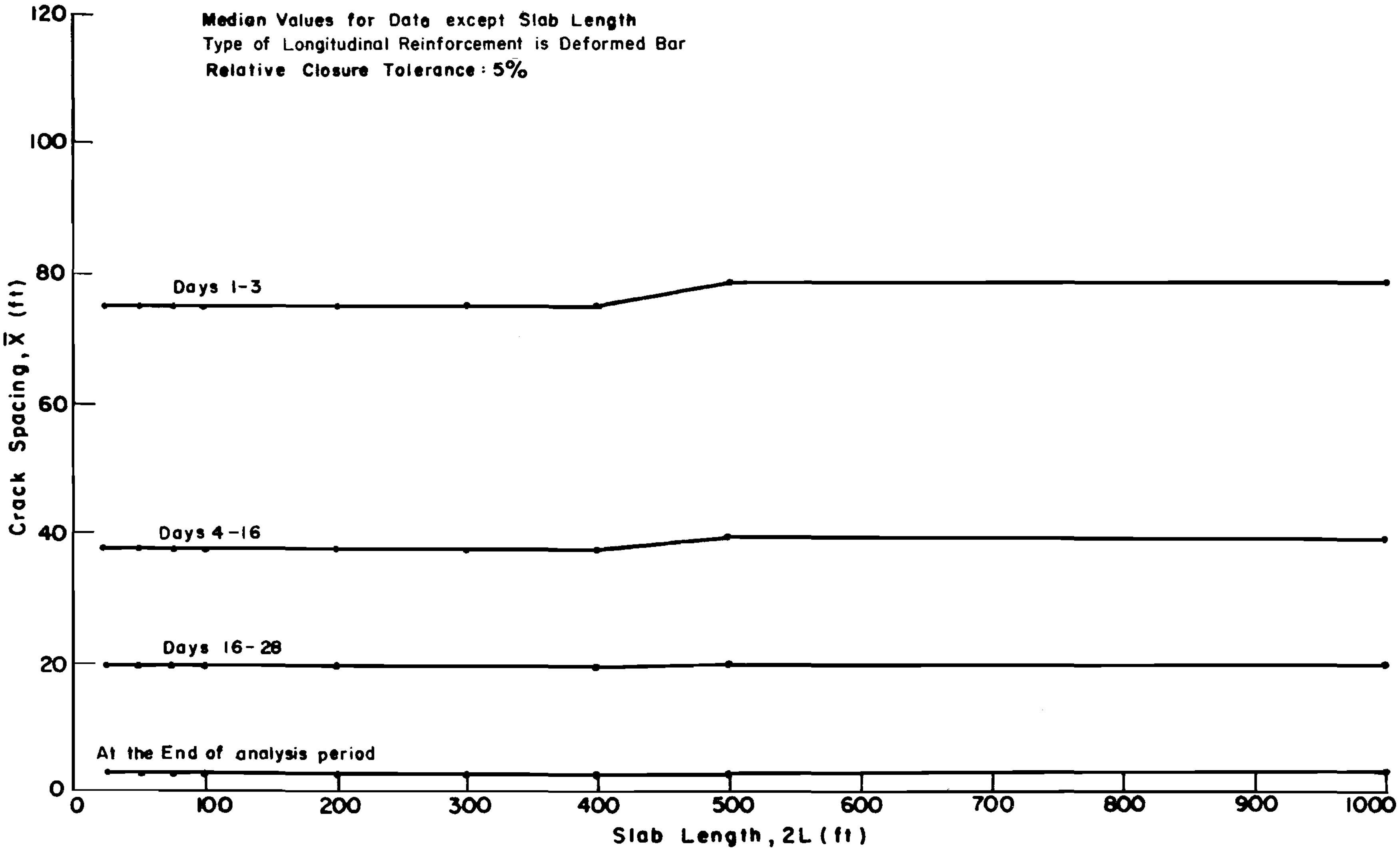


Fig 3.5. The computed crack spacing for different slab length.

(4) "Friction Tests of Concrete on Various Subbases" Public Roads, 1924 (Ref 4), and

(5) "Subgrade Friction Tests" New Jersey State Highway Department, 1953 (Ref 5).

Medium levels are those which might be met in practice under average design conditions. A low level is a practical value at the lower extreme with respect to the medium level, while a high level is a practical value at the upper extreme. There is an advantage in using three levels of factors because with three levels information is supplied on both the linear and the quadratic components of the effects. A quadratic component may imply a maximum or minimum response at some intermediate factor combination or at a point outside the range examined for some or all of the factors, indicating a need for further experimental work at a different set of levels. Thus, there is special interest in designs with factors at three levels when quantitative factors are involved, and they have received considerable study for this reason.

Traditional Experiment Design

The proposed initial experiment is designed to hold all design variables except one constant at a certain level (medium, low or high) and to take response readings for several levels of this variable; then another variable is chosen to vary and this process is continued until all variables of interest have been considered.

First, a basic problem was solved by using the medium values of all the design variables; i.e., in a medium basic solution, all the input variables were at their medium levels. With respect to the medium level, two problems were also solved for each variable, one in which the variable was held at its low value and the other where the variable was held at its high value. For each of these problems, all other variables were held at their medium levels. A similar procedure was studied for the low basic level, in which each variable was varied individually to its medium and high values, and for the high basic level, where each variable was studied at its low and medium values. The process required about 90 separate solutions, which could be accomplished with a reasonable work effort, to obtain the desired information.

In order to complete the analysis of single factorial experiments at the medium level, some revisions were made on the initially selected numerical values, for the reasons listed below:

(1) to successfully obtain the solution output, since some problem could not be solved at their initially decided values due to diagonastic errors or infeasibility of the solution;

(2) to obtain the best usable information from the solution output and to avoid unnecessary work; and

(3) to obtain the solution output within reasonable computation time.

Table A3.1 shows the revised numerical values for the three levels of all the input variables.

Factorial Experiment Design

The above traditional one-factor-at-a-time design would miss the most favorable treatment combinations. In addition, the one-factor-at-a-time design can lead to the following wrong conclusions:

(1) When interactions exist, the nature being unknown, a factorial design is necessary to avoid misleading conclusions.

(2) When there are no interactions, the factorial design will give the maximum efficiency in the estimation of the effects.

(3) 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.

It can be shown that if the result of changing two or more design variables is to be studied, then, in general, the most reliable way is to use a factorial design, By this efficient approach, the required information can be obtained with the required degree of precision and a minimum expenditure of effort.

As has been noted a complete factorial design in which all possible treatment combinations of all the levels of the design variables are investigated involves a large number of tests when the system includes as many as 15 variables. A great number of solutions is needed, which may be impractical from the standpoint of cost and time. It has been shown that it is possible to investigate the main effects of the design variables and the more important interactions in a 3^3 factorial design. In this study, the three most important design variableswere obtained from the results of the traditional sensitivity study.

CHAPTER 4. PRESENTATION OF RESULTS

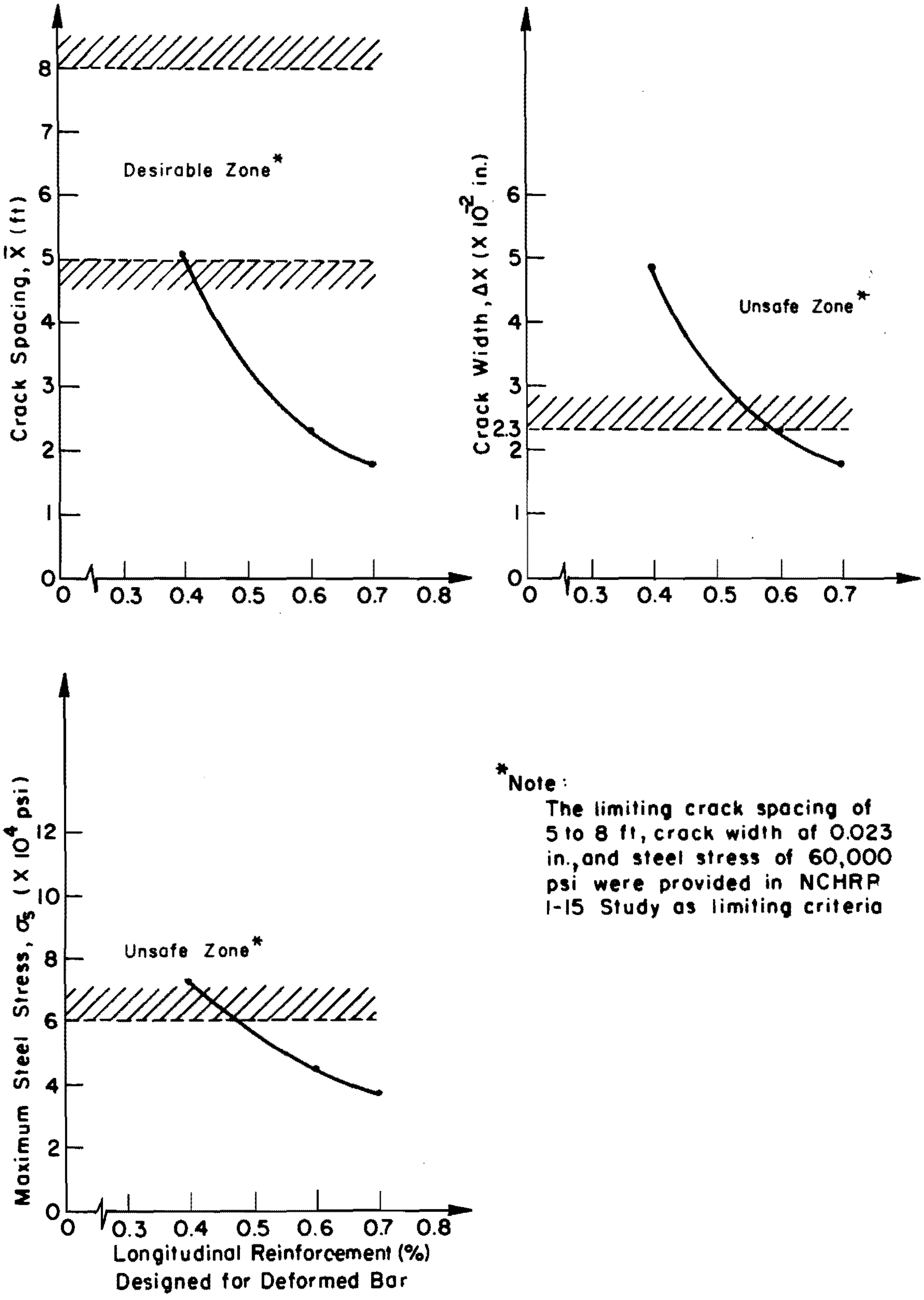
The data outputs for medium level, low level, and high level solutions are presented in Tables A3.2, A3.3 and A3.4, respectively. The effects of input variable variation on pavement behavior for medium level solutions are also plotted and are presented in Figs 4.1 through 4.11. Since, the variation of transverse wire spacing (in which the design type of longitudinal reinforcement is deformed wire fabric) for medium level solutions was not studied, for the reason explained in the text, the effect of transverse wire spacing on pavement response is shown only for the low level solutions in Fig 4.11.

Output Parameters

Several methods of rating the variables importance were investigated. Based on the nature of the output data to be analyzed, the method best suited for such an analysis was a study of the effect of variation in the system parameters on the pavement response or on some performance criteria. For medium level solutions, figures (Figs 4.1 through 4.11) were plotted to show the output data in terms of crack spacing, crack width, and maximum steel stress against the levels of each input variable.

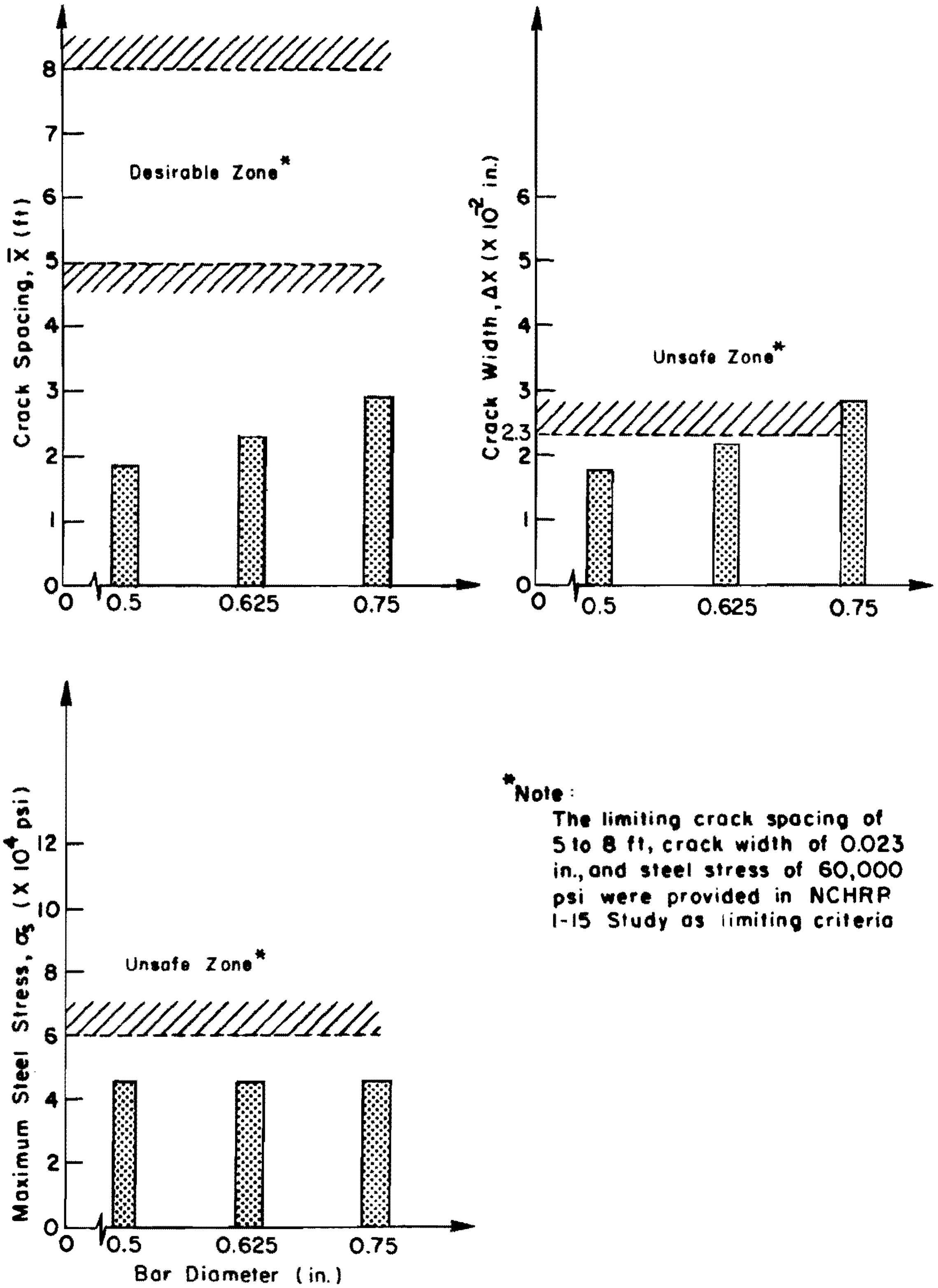
Each of these output parameters are instrumental factors in the pavement performance under traffic and environmental conditions. The NCHRP 1-15 Study provided limiting criteria of 5 to 8 feet for the crack spacing and a value less than 0.023 in for the crack width.

Thus, the output for these two parameters should be evaluated in terms of these criteria shown on the graphs. The concrete and steel strength provides the limiting criteria for the respective stress values. Of course, the concrete strength is changing with age. For cases where concrete stress exceeds the strength, cracking occurs, hence the average crack spacing values reflect this condition. The program does not recognize the condition where the steel stress exceeds the strength so the user must make this evaluation.



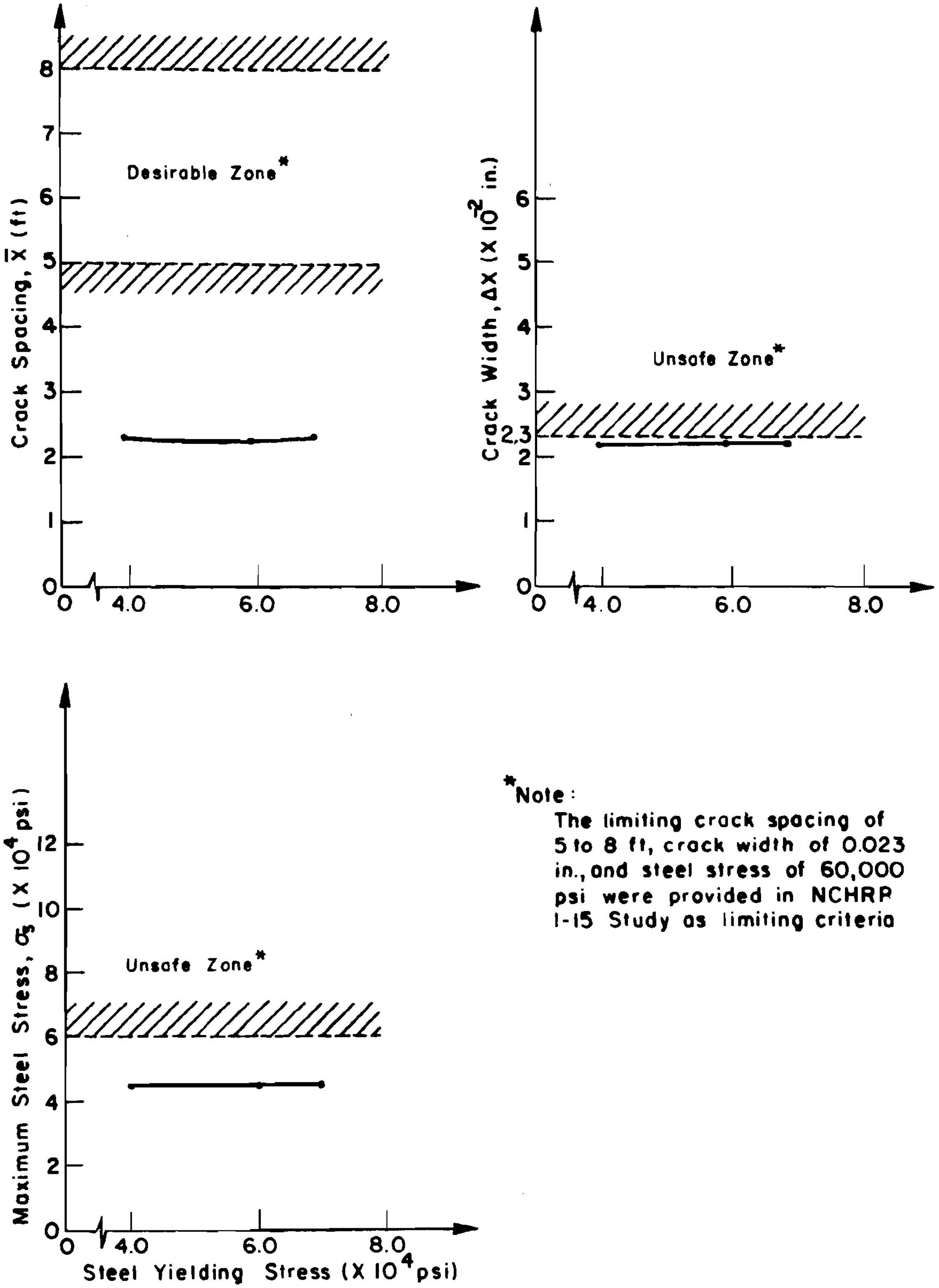
*Note:
The limiting crack spacing of 5 to 8 ft, crack width of 0.023 in., and steel stress of 60,000 psi were provided in NCHRP 1-15 Study as limiting criteria

Fig 4.1. Effect of percentage reinforcement on pavement behavior.



*Note:
The limiting crack spacing of 5 to 8 ft, crack width of 0.023 in., and steel stress of 60,000 psi were provided in NCHRP 1-15 Study as limiting criteria

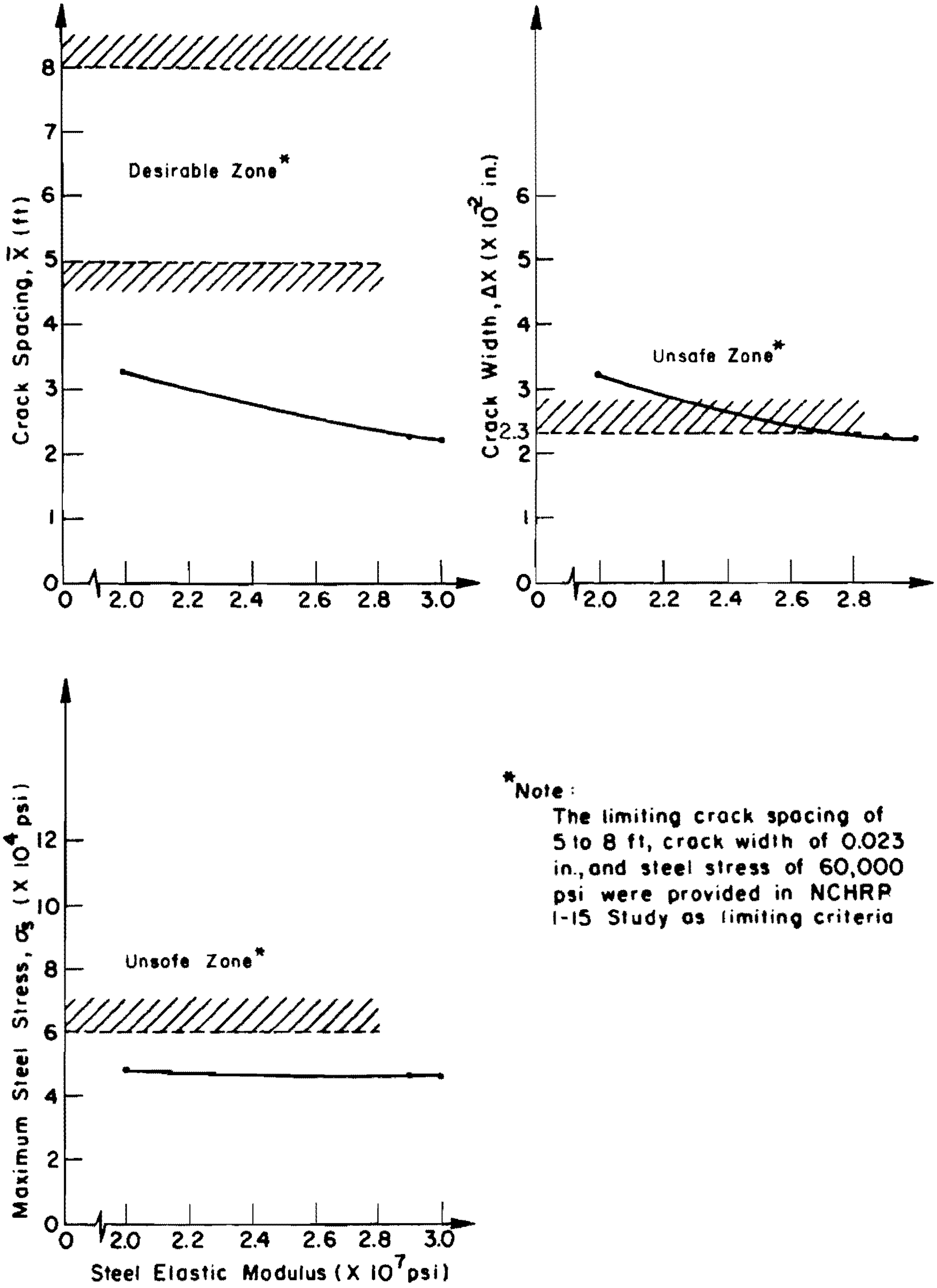
Fig 4.2. Effect of bar diameter on pavement behavior.



*Note:

The limiting crack spacing of 5 to 8 ft, crack width of 0.023 in., and steel stress of 60,000 psi were provided in NCHRP 1-15 Study as limiting criteria

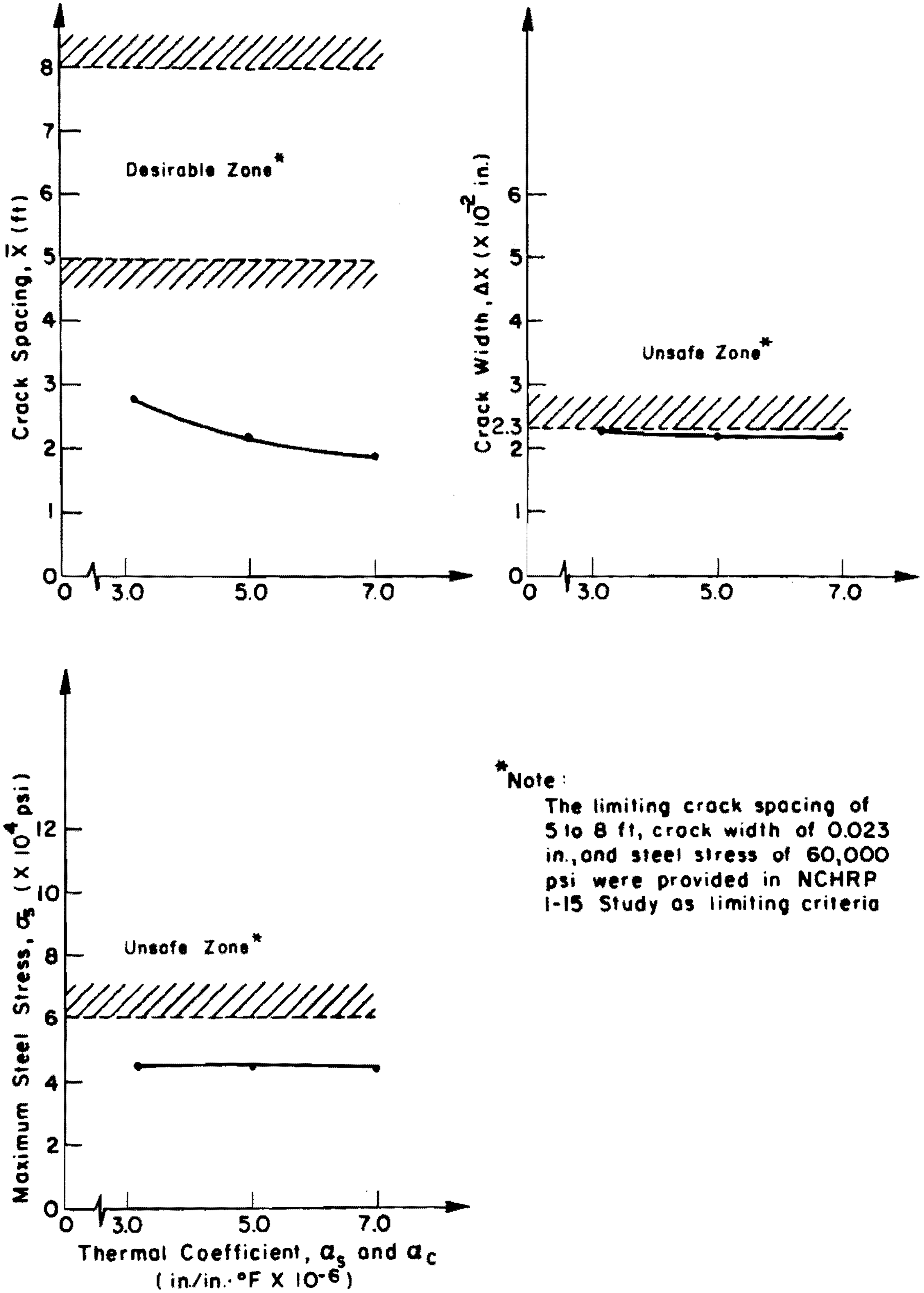
Fig 4.3. Effect of steel yielding stress on pavement behavior.



*Note:

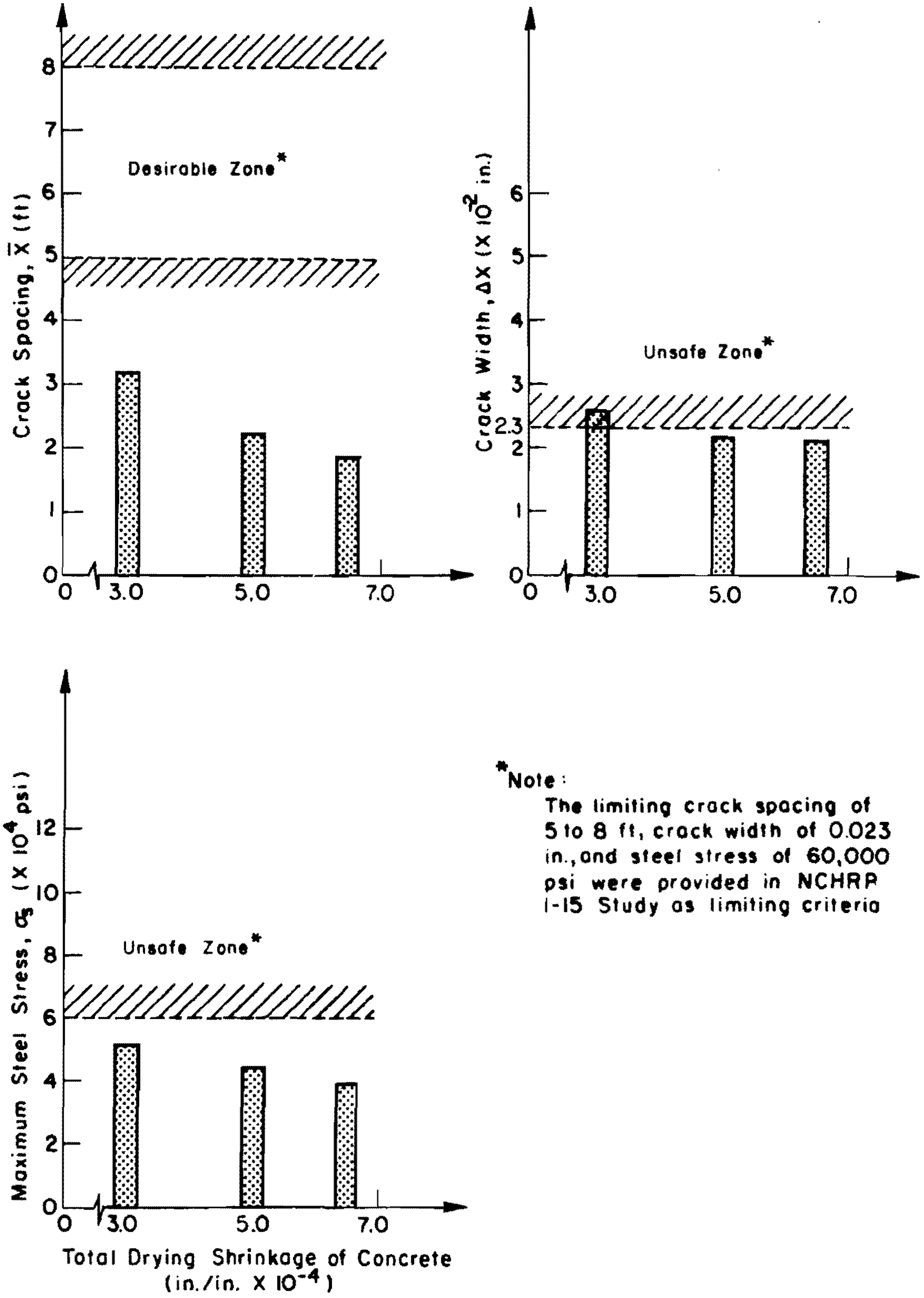
The limiting crack spacing of 5 to 8 ft, crack width of 0.023 in., and steel stress of 60,000 psi were provided in NCHRP 1-15 Study as limiting criteria

Fig 4.4. Effect of steel elastic modulus on pavement behavior.



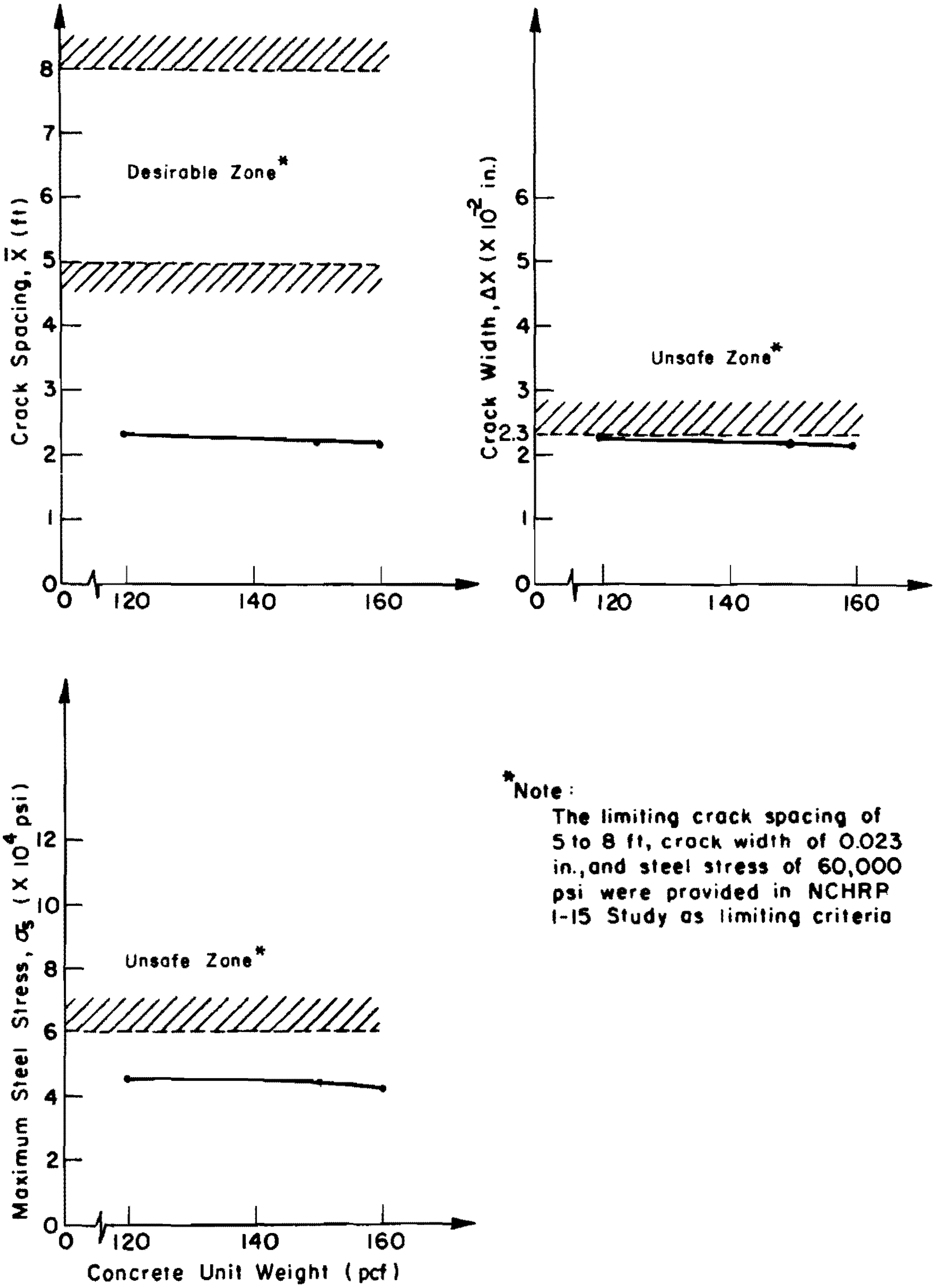
*Note :
The limiting crack spacing of 5 to 8 ft, crack width of 0.023 in., and steel stress of 60,000 psi were provided in NCHRP 1-15 Study as limiting criteria

Fig 4.5. Effect of thermal coefficient on pavement behavior.



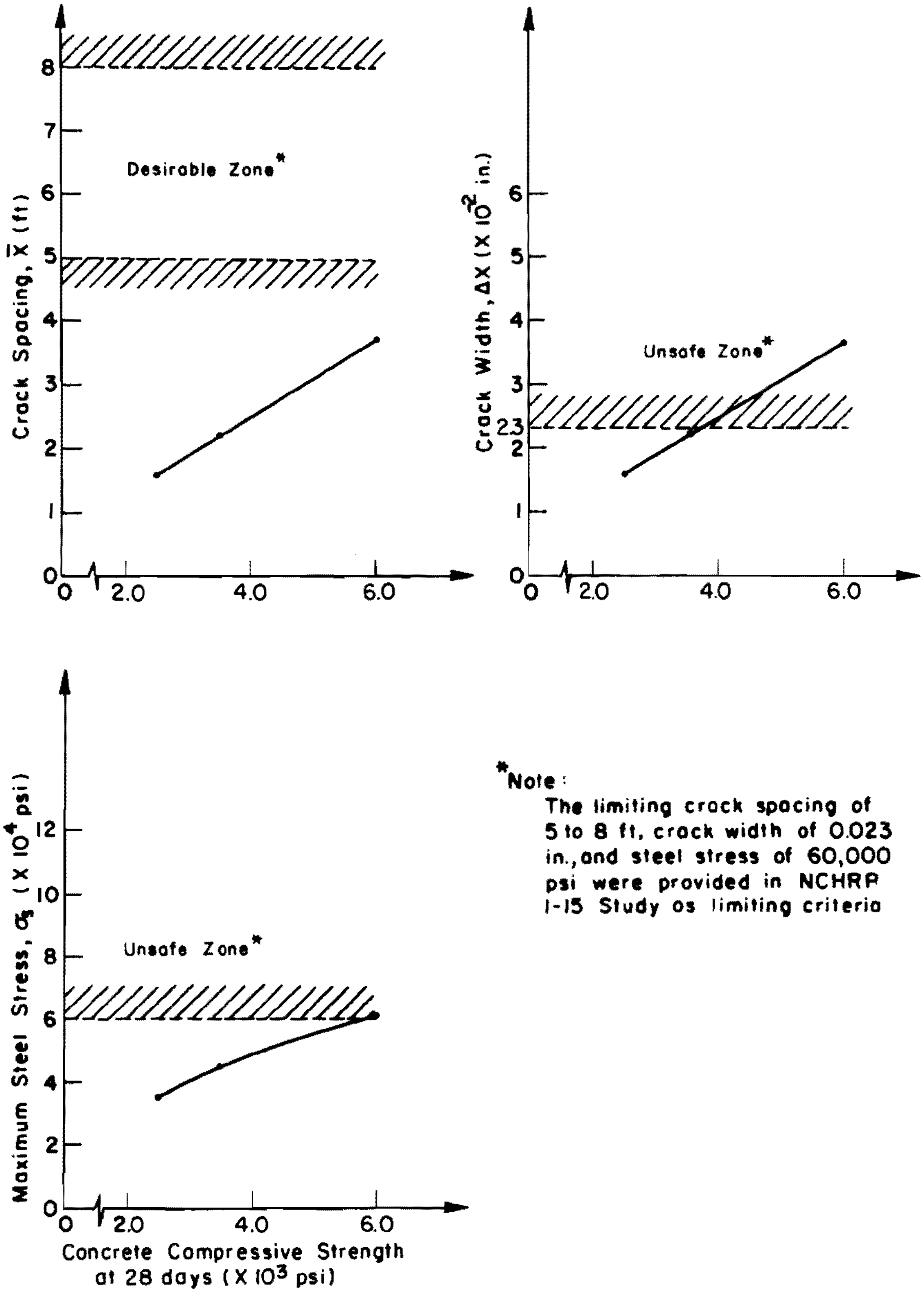
*Note:
The limiting crack spacing of 5 to 8 ft, crack width of 0.023 in., and steel stress of 60,000 psi were provided in NCHRP 1-15 Study as limiting criteria

Fig 4.6. Effect of drying shrinkage of concrete on pavement behavior.



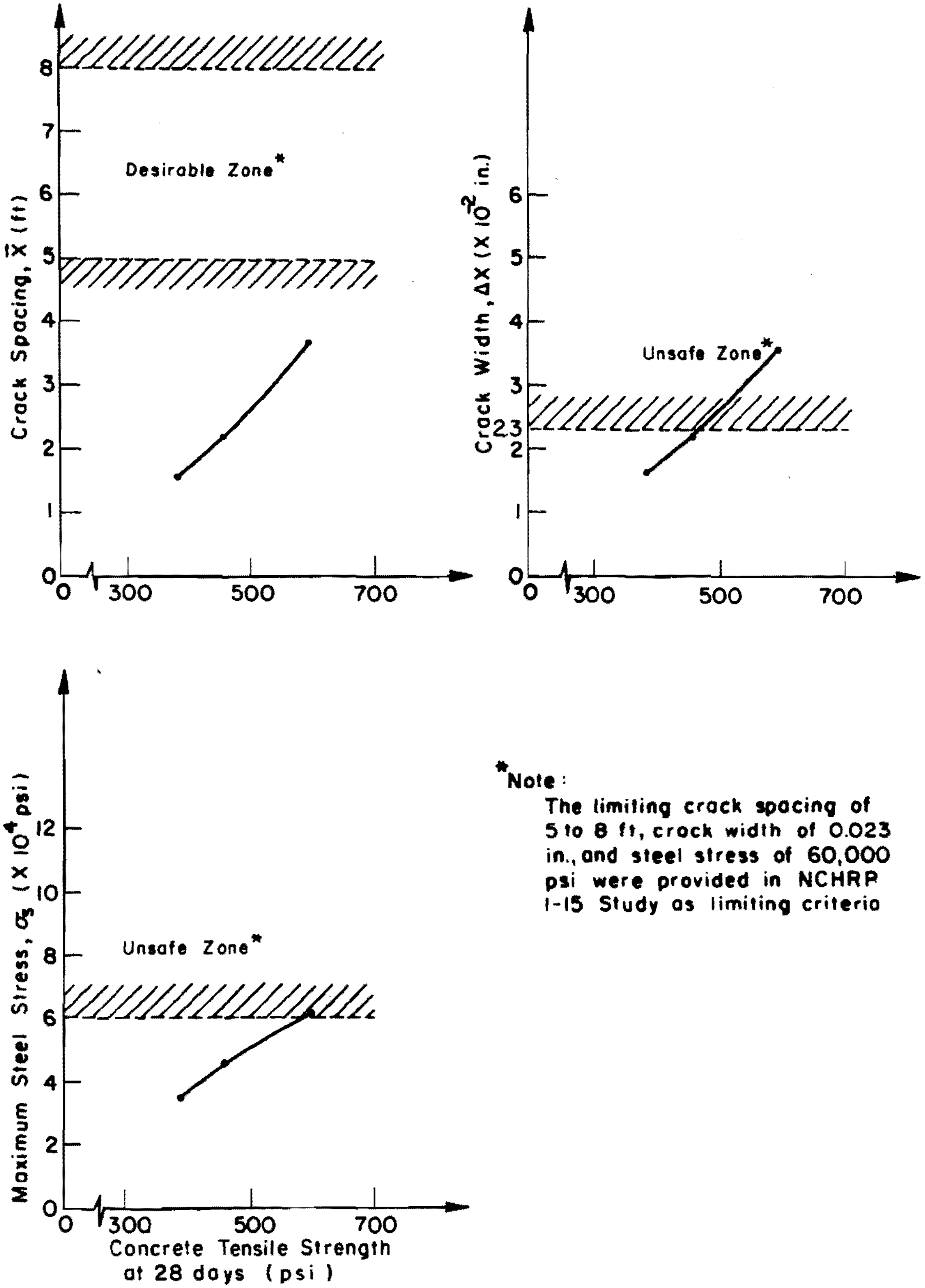
*Note:
The limiting crack spacing of 5 to 8 ft, crack width of 0.023 in., and steel stress of 60,000 psi were provided in NCHRP 1-15 Study as limiting criteria

Fig 4.7. Effect of unit weight of concrete on pavement behavior.



*Note:
The limiting crack spacing of 5 to 8 ft, crack width of 0.023 in., and steel stress of 60,000 psi were provided in NCHRP 1-15 Study as limiting criteria

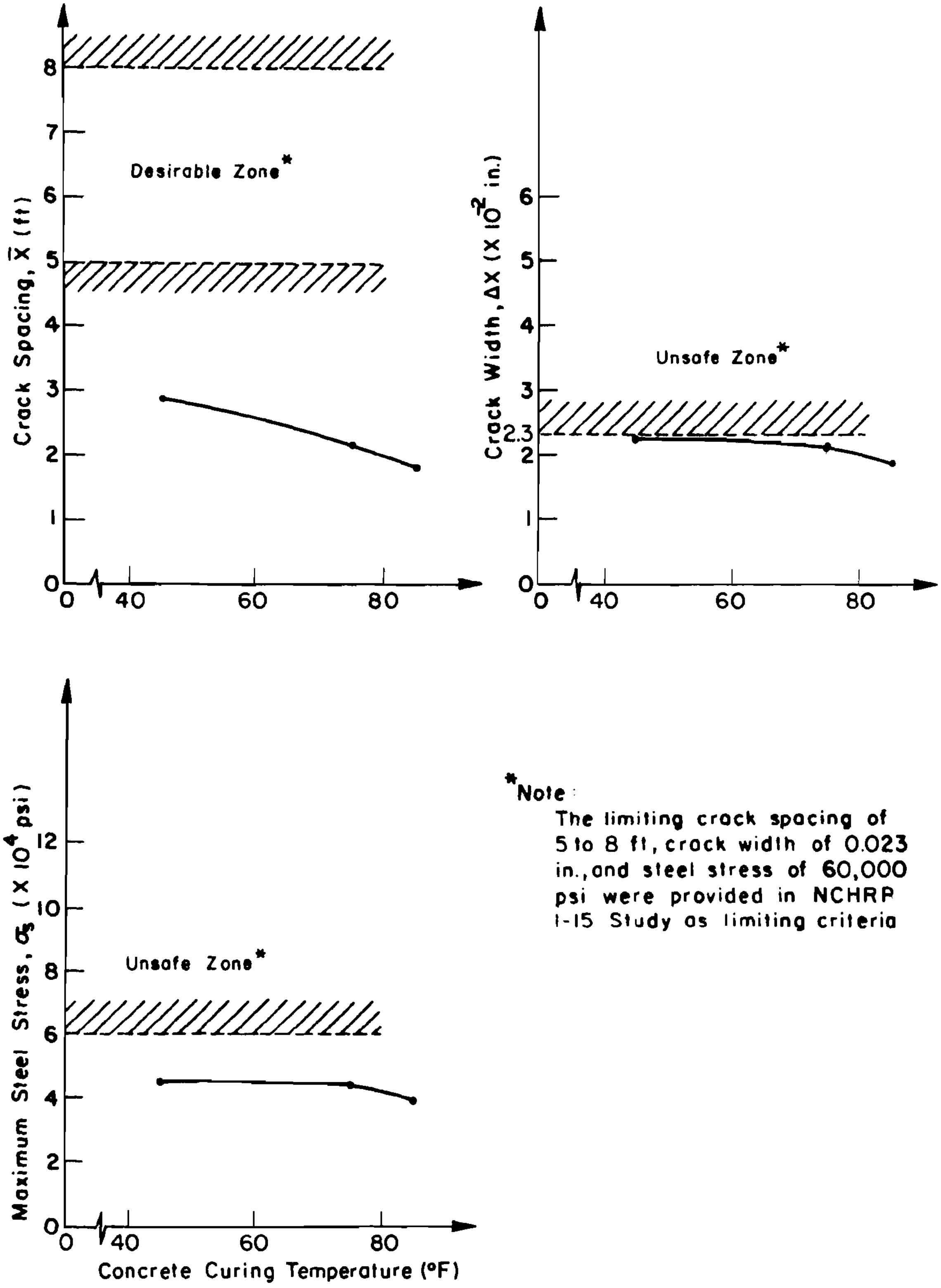
Fig 4.8. Effect of concrete compressive strength on pavement behavior.



*Note:

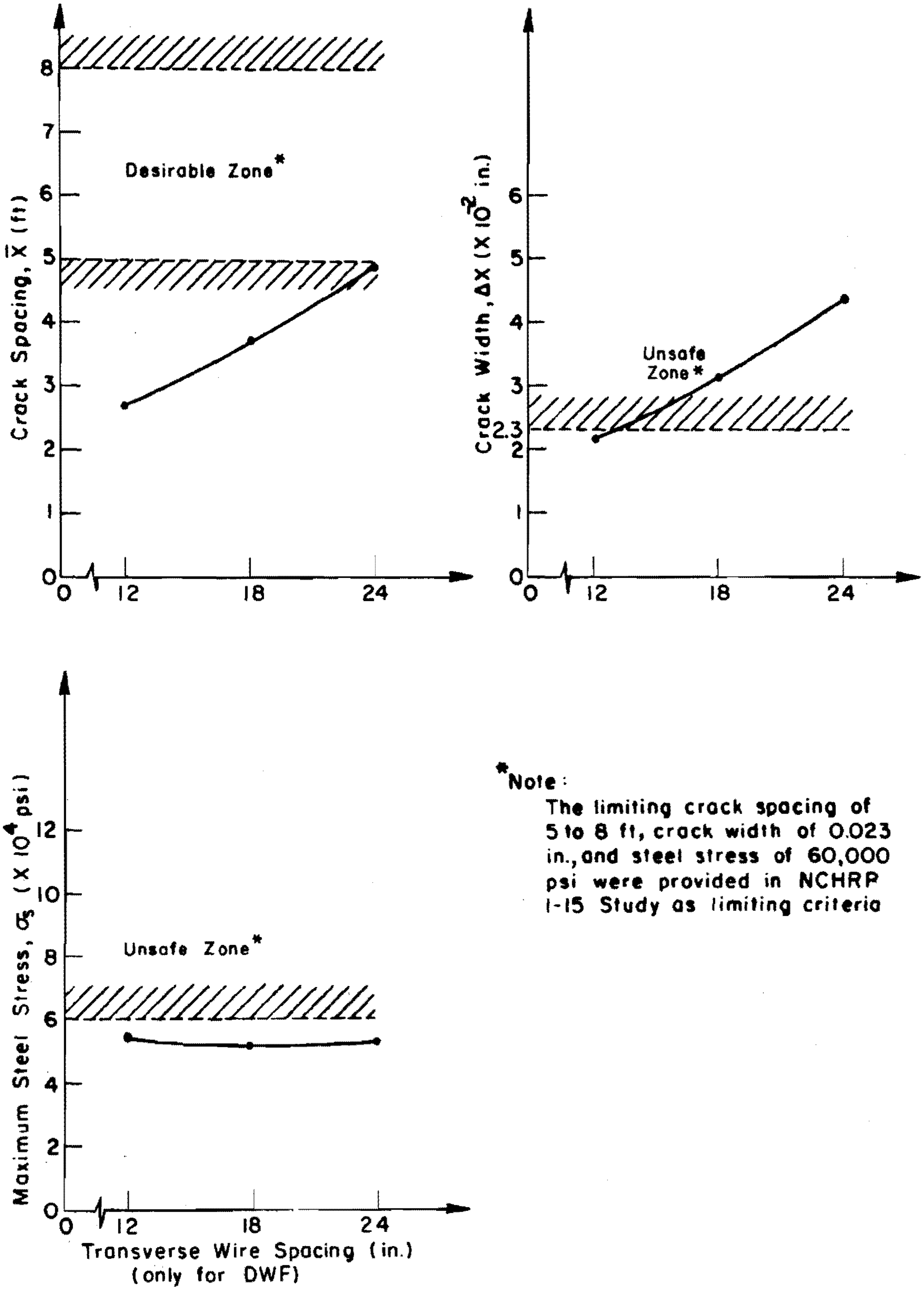
The limiting crack spacing of 5 to 8 ft, crack width of 0.023 in., and steel stress of 60,000 psi were provided in NCHRP 1-15 Study as limiting criteria

Fig 4.9. Effect of concrete tensile strength on pavement behavior.



*Note:
The limiting crack spacing of 5 to 8 ft, crack width of 0.023 in., and steel stress of 60,000 psi were provided in NCHRP 1-15 Study as limiting criteria

Fig 4.10. Effect of concrete curing temperature on pavement behavior.



*Note:
The limiting crack spacing of 5 to 8 ft, crack width of 0.023 in., and steel stress of 60,000 psi were provided in NCHRP 1-15 Study as limiting criteria

Fig 4.11. Effect of transverse wire spacing on pavement behavior.

Since high yield strength steel has been used extensively in Texas, a limiting value of 60,000 psi is shown for allowable working stress and yield strength, respectively.

Review of Output

A review of the crack spacing predictions for all the graphs (Fig 4.1 to 4.11) show that values are less than the lower limit of five feet with only one exception. For the low and high level solutions (Tables A3.3 and A3.4), the final crack spacings were outside the 5 to 8 foot limits in 18 of 28 cases, and 7 of 8 cases, respectively.

The limiting crack width of 0.023 inch is exceeded in 26 of 28 cases and 7 of 8 cases for the low and high levels of the input variables, respectively. The medium level had three cases in which the crack width is equal to the limiting value of 0.023 inch.

A review of the steel stress values for the medium level shows the yield strength and the allowable working stress are exceeded 3 and 6 times, respectively. Similar data summaries for the low and high level solutions indicate the allowable working stress was exceeded 26 and 5 times, respectively. For yield strength, the 60,000 psi level was exceeded 23 and 2 times for the low and high level solutions, respectively.

An evaluation of the influence of each input variable on pavement behavior is accomplished by the basic concepts of weighting factor and importance rating. The weighting factor is denoted by the numerical value of one if the observed performance variation from low to high level results in the maximum factors of the remaining input variables are then expressed as a ratio of this maximum variation. This approach is applied to the three behavior items of output data: crack spacing, crack width, and maximum steel stress. The corresponding results for the medium level basic study are presented in Table 4.1, which shows the weighting factors of each input variable computed from CRCP-1 data outputs.

The concept of importance rating for each data item of output is introduced at this point in the analysis of variable evaluation. The importance rating is the analyst's numerical appraisement of the relative importance it is that these particular performance data outputs be included in the model CRCP-1.

TABLE 4.1. WEIGHTING FACTORS OF INPUT VARIABLES ON CRCP-1 DATA OUTPUT (FOR MEDIUM LEVEL SOLUTIONS)

Variable Number	Input Variable	Crack Spacing $\bar{x}$ (feet)	Crack Width ΔX (inches)	Maximum Steel Stress σs (psi)
1	Percentage of reinforcement	1	1	1
2	Bar diameter (inches)	0.34	0.35	0.17
3	Elastic modulus of steel (psi)	0.31	0.31	0.11
4	Thermal coefficeint of steel (in/in)	0.27	0.02	0.02
5	Thermal coefficient of concrete	0.27	0.02	0.02
6	Total drying shrinkage (in/in)	0.36	0.02	0.31
7	Unit weight of concrete (pcf)	0.07	0.05	0.07
8	Compressive strength of concrete (psi)	0.63	0.63	0.73[*]
9	Tensile strength of concrete (psi)	0.63	0.63	0.73[*]
10	Curing temperature of concrete (°F)	0.32	0.12	0.15

[*] The tensile strength of concrete variable is the controlling variable, since the compressive strength of concrete variable is only recognized internally in the program.

Accordingly, the importance rating of crack spacing, crack width, and maximum steel stress are represented by numerical values of 1, 1.33, and 1.33, respectively. The relative effect of each variable was calculated as the multiplication of the weighting factor by its related importance rating and summing horizontally each column to find the total evaluation of each column to find the total evaluation of each input variable. The relative importance among design variables is obtained by numerical sequencing using the highest value as the number one rating, etc. Table 4.2 summarizes this information for the medium level analysis. Note that the percentage of reinforcement, concrete strength and bar diameter are the three most important variables.

The relative position of slab-base friction and movement may be misleading in this analysis, since inadequate data were available initially to properly chart this variable. Subsequent information indicates this range from low to high level in Table A3.1 for maximum subbase friction is much less than experienced in the field.

Interaction Study

A sensitivity analysis of the three most important variables and their interaction on pavement behavior was conducted to establish the full factorial analysis. In the process of factorial design, all the input parameters (except those considered in the interaction) were kept at their medium level, thus resulting in 27 treatment combinations from the three selected input factors, that is, percent reinforcement, tensile strength of concrete, and for diameter of steel.

The results are graphically represented in Figs 4.12, 4.13, and 4.14 for the variation of crack spacing, crack width and maximum steel stress, respectively. The limiting criteria for crack spacing, crack width and steel yield stress are not exceeded for a percent reinforcement greater than 0.6. This is in a good agreement with the performance experience with continuously reinforcement concrete pavement. Most of the agencies in northern climates recommend 0.6 to 0.7 percent reinforcement. On the other hand, the interaction study shows that the limiting criteria for crack spacing can not be achieved for the same levels of the input variables as for the crack width and steel yield stress.

TABLE 4.2. SUMMARY OF ESTIMATED EFFECTS ON EACH INPUT VARIABLE

Pavement behavior Importance rating Input Variables	Crack Spacing	Crack Width	Maximum Steel Stress	Total Evaluation	Order of Importance
	1	1.33	1.33	3.66	
Percentage of reinforcement	1.000	1.330	1.33	3.66	1
Bar diameter	0.340	0.466	0.226	1.032	3
Elastic modulus of steel	0.310	0.412	0 146	0.868	4
Thermal coefficient	0.270	0.027	0.027	0.324	7
Concrete drying shrinkage	0.360	0.027	0.412	0.799	5
Concrete unit weight	0.070	0.067	0.093	0.230	8
Concrete strength	0.630	0.838	0.971	2.439	2
Concrete curing temperature	0.320	0.160	0.200	0.680	6

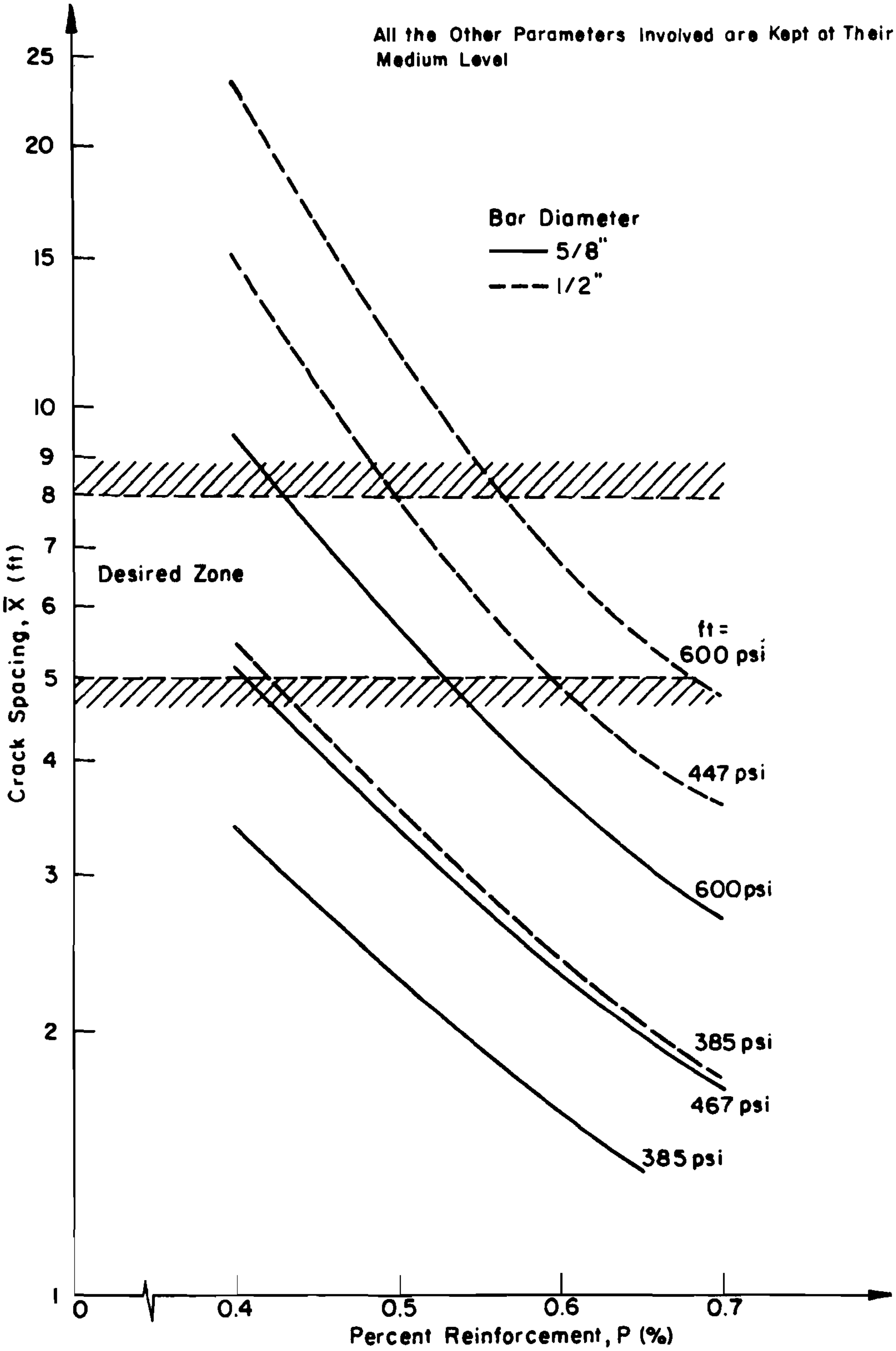


Fig 4.12. Interaction of percent reinforcement, concrete tensile strength and bar diameter of steel on the computed maximum-steel stress.

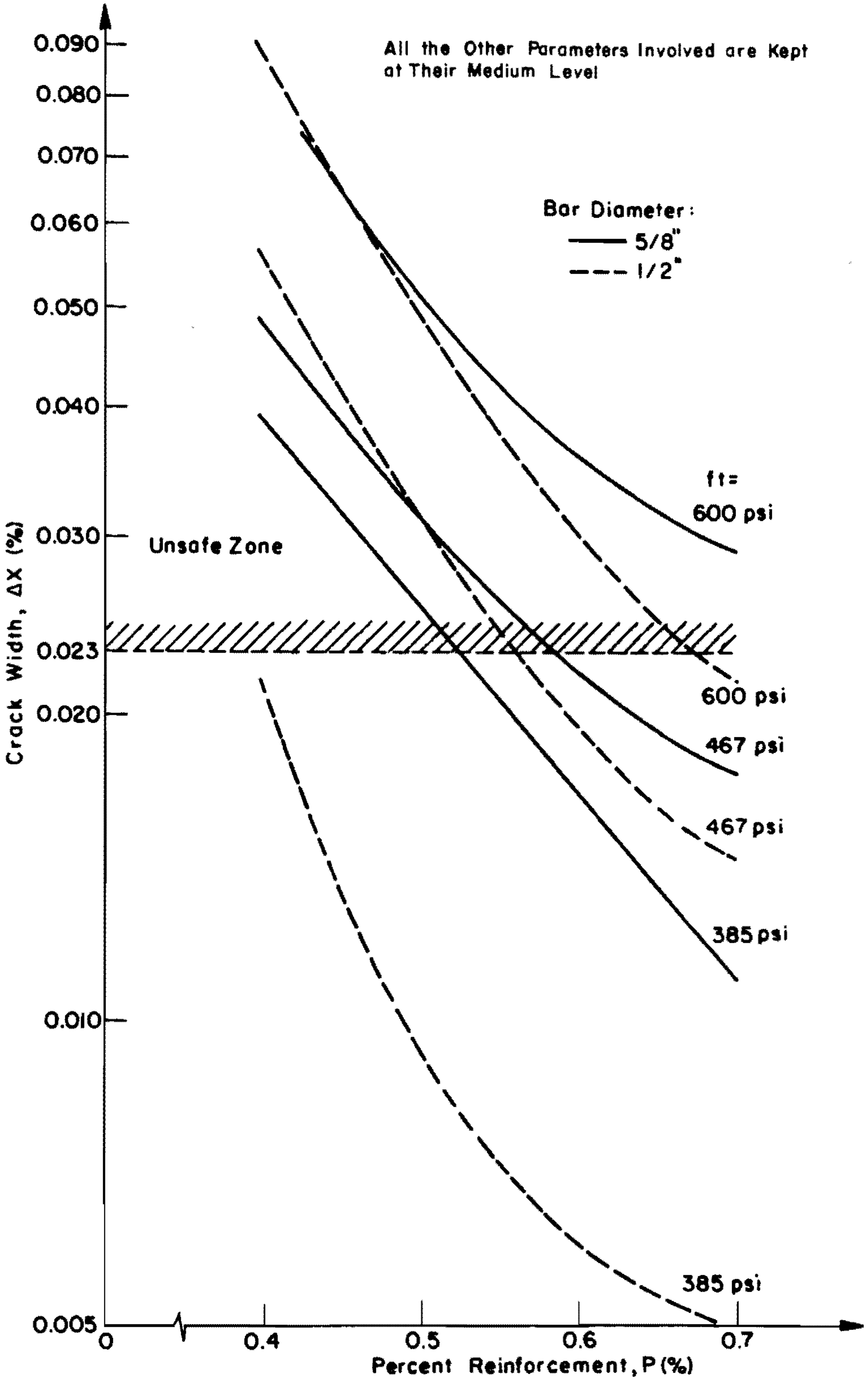


Fig 4.13. Interaction of percent reinforcement, concrete tensile strength and bar diameter of steel on the computed crack width.

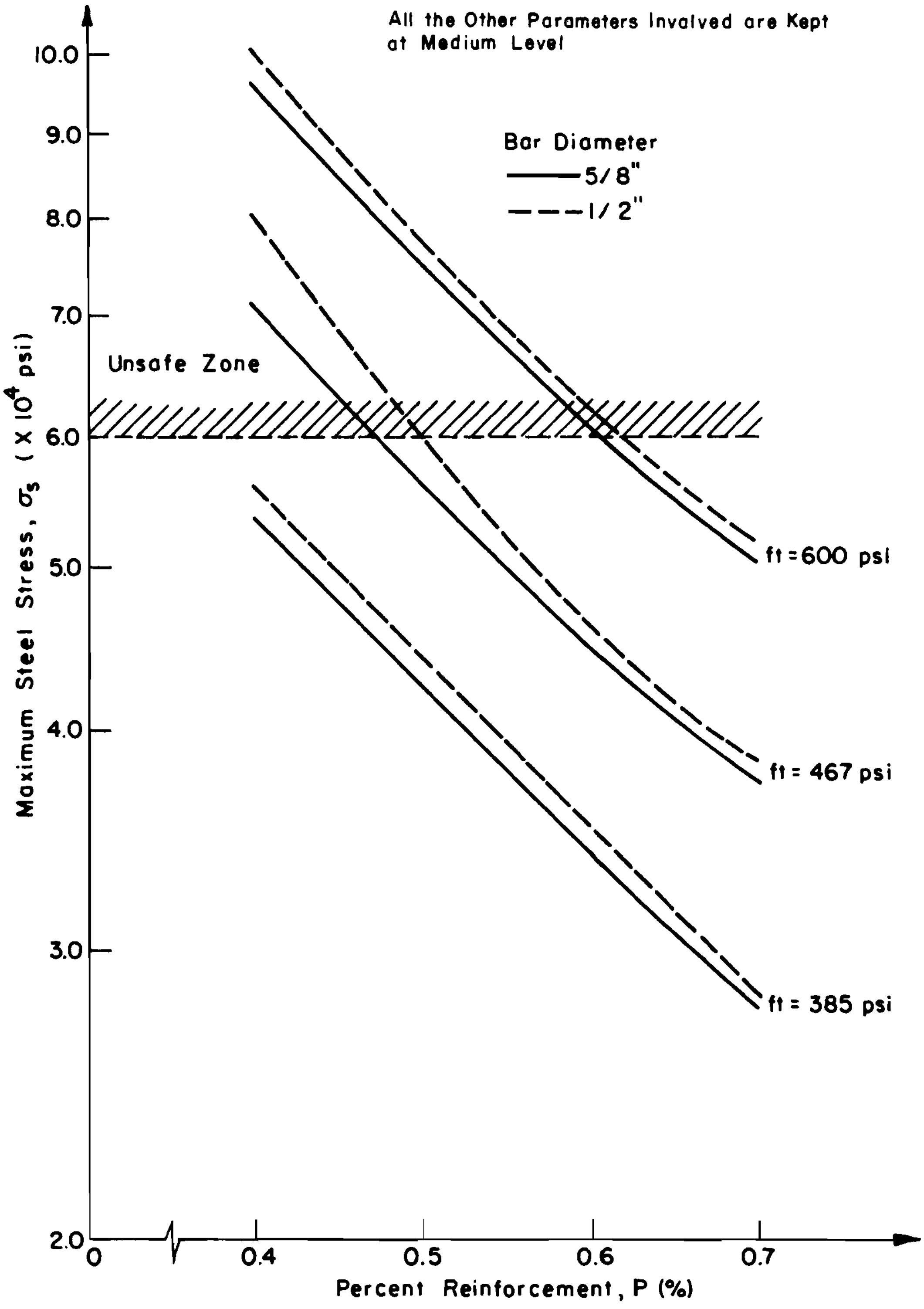


Fig 4.14. Interaction of percent reinforcement, concrete tensile strength and bar diameter of steel on the computed maximum steel stress.

The percent reinforcement, concrete tensile strength and bar diameter of steel interaction has a very significant influence on the crack spacing, crack width and maximum steel stress variation, and, specially for percent reinforcement smaller than 0.6 (the smaller the percent reinforcement, the higher the slope of the curves). The higher the concrete tensile strength, the higher the value of crack spacing, crack width and maximum concrete stress. In terms of pavement behavior, the smaller the diameter, the smaller value of crack width, but the higher value of maximum steel stress and crack spacing. The problem is to find the optimum interaction between the variable to insure a good correlation between the crack spacing, crack width, and steel stress in order to improve the load transfer and, generally, the pavement behavior.

CHAPTER 5. ANALYSIS OF RESULTS

One of the objectives of sensitivity analysis is to establish the relative importance of each input variable and recognize the presence of variable interaction, thus give the designer advice as to the amount of time and effort to spend in quantifying or estimating the numerical values of these design variables. Moreover, this investigation will indicate possible areas of priority for future research needs.

It should be recognized that rating variables on the basis of data developed during this sensitivity study is affected by several factors involved in the data generation, including the numerical values used for the input variables, and the variation of levels. Consequently, different results of variable testing might be obtained through different methods of approach.

The analysis phase of this present investigation actually consists of a single factorial design and a 3 × 3 × 3 factorial design. The results show a greater consistency in the importance of which design variables and indicate significant interactions among the variables. In this study, the order of importance of each input variable presented below is from the findings of previous Chapter 4.

Percentage of Longitudinal Reinforcement

A review of this study indicates that the percentage of longitudinal reinforcement has major influence on the crack spacing, crack width, and stresses in the steel and concrete. The effect of this highly important design variable justifies the considerable attention it has received in the past from highway design and research engineers.

In this study, three levels were studied, corresponding to 0.4, 0.6, and 0.7 percent longitudinal reinforcement, respectively. Figures 5.1 and 5.2 show the predicted discrete values of crack width and maximum stress in the steel calculated on a daily basis for 0.6 percent reinforcement. For the analysis of 0.4 and 0.7 percent reinforcement, similar patterns are also observed.

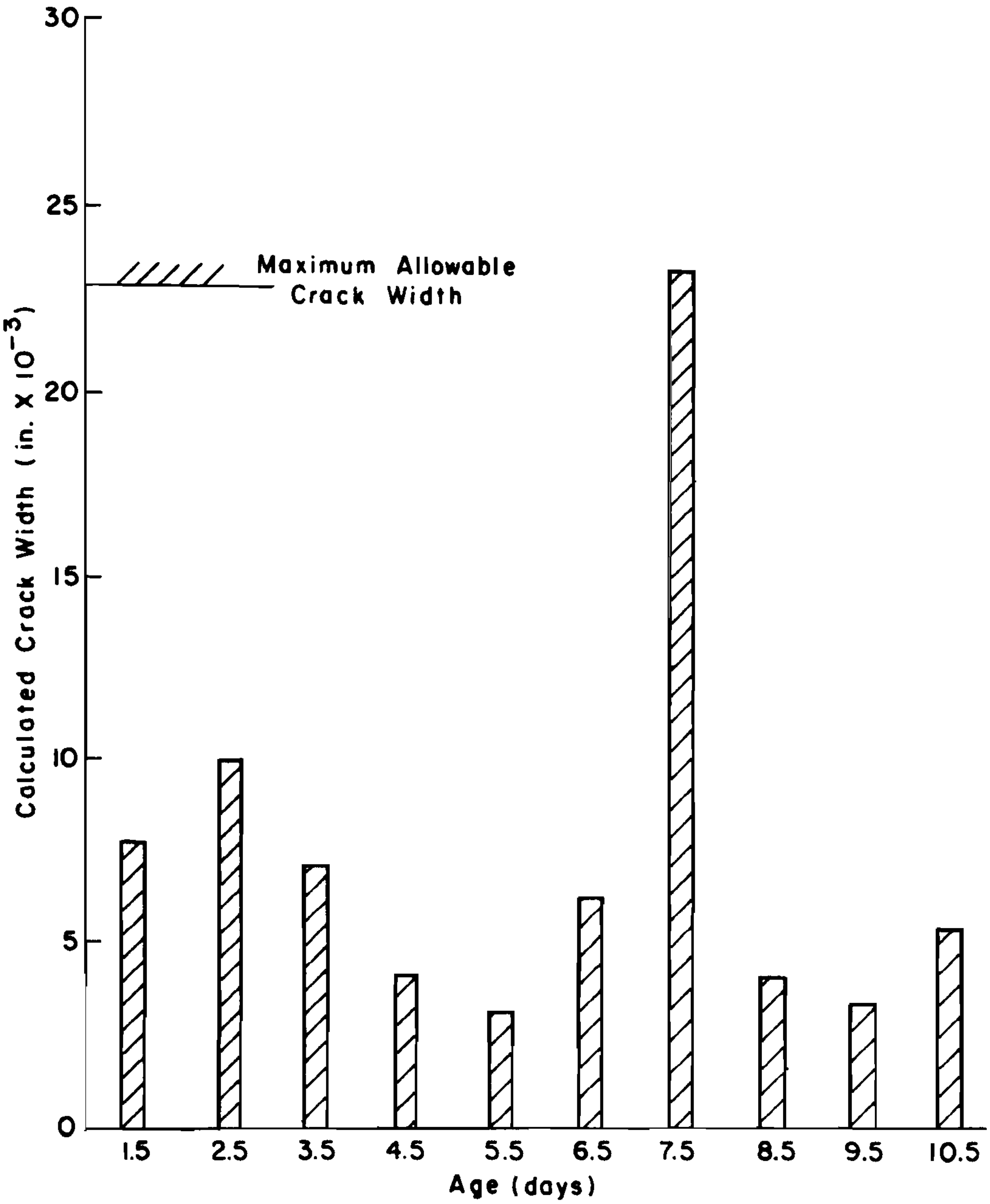


Fig 5.1. Predicted values of crack width for 0.6 percent longitudinal reinforcement.

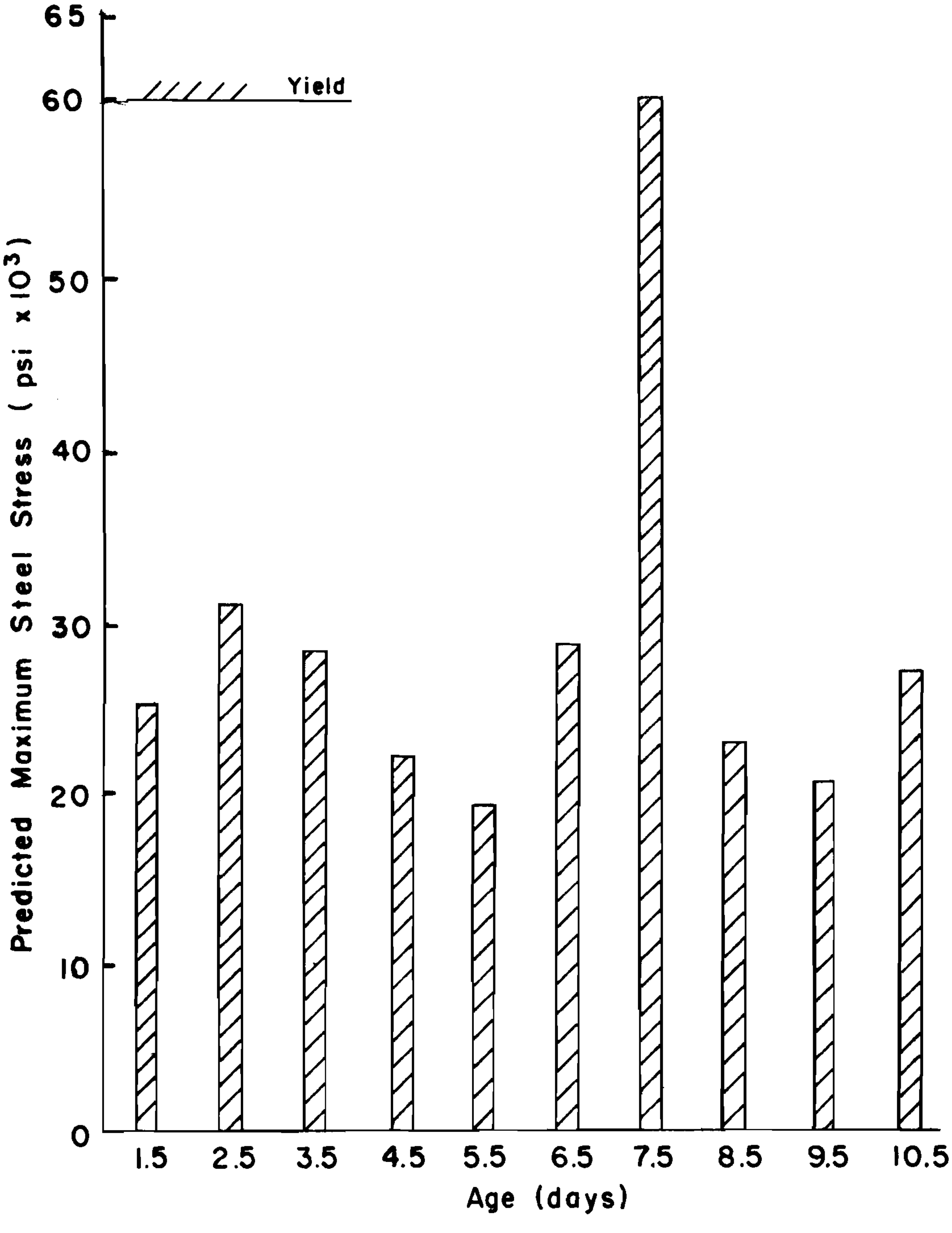


Fig 5.2. Predicted values of maximum steel stress for 0.6 percent longitudinal reinforcement.

The effect of longitudinal reinforcement at the end of the analysis period is demonstrated in Fig 4.1, which shows that the crack spacing, crack width, and the maximum stress in the steel decrease rapidly with an increase in percent reinforcement. This behavior of crack pattern agrees satisfactorily with field observations, as shown in Figs 5.3 and 5.4. It has also been demonstrated that a smaller crack spacing results from an increase in the percentage of longitudinal reinforcement. The percent reinforcement also affects the tightness of the transverse cracks, which, in turn, will influence aggregate interlock and the load transfer in the pavement slab. Very few steel stress measurements have been made successfully in the field on CRCP pavements, but the predicted values of the steel stress (Fig 4.1(c)) indicate that considerable stress is induced at the transverse cracks due to temperature drop and drying shrinkage.

For the materials variables and environmental conditions used in this study, the 0.4 percent longitudinal reinforcement revealed a fairly high stress in the steel and a large amount of crack width. Various data from both the laboratory and field studies provide the design engineer with an insight into the characteristics of crack width; a value of 0.023 inch can generally be used as a limiting amount from the standpoint of water flow or spalling. Obviously, pavement behavior varies with different conditions, but it is suggested from the study conditions that longitudinal reinforcement of less than 0.5 percent may not provide satisfactory performance. In practice, most agencies based the required percentage of longitudinal reinforcement on experience, that is, on empirical data obtained from experimental pavements. Most researchers (Refs 1, 2, 3, and 11) recommended that no less than 0.5 percent longitudinal reinforcement be used. This coincides with the results observed from this study. In addition, many observations of distressed areas in a pavement section revealed that a crack spacing of from one to two feet. In this respect, too small a crack spacing is also undesirable. In the study of 0.7 percent steel reinforcement for medium level solutions, the predicted crack spacing is obviously too small, which might adversely influence pavement behavior.(Fig 4.1(a)). Consequently, the use of more than 0.7 percent of longitudinal reinforcement may not significantly improve the pavement performance.

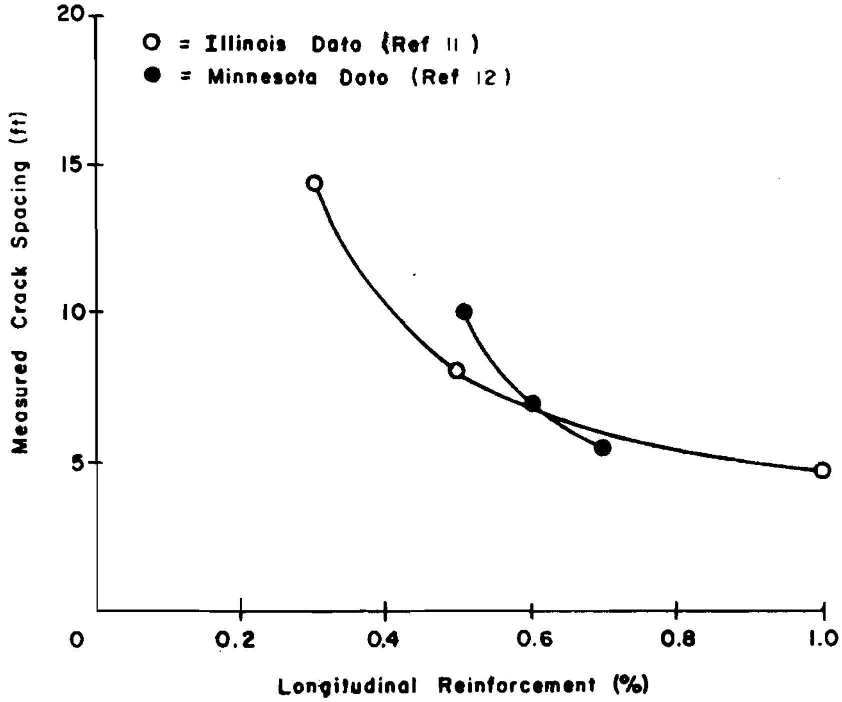


Fig 5.3. Relationship between crack spacing and percent reinforcement.

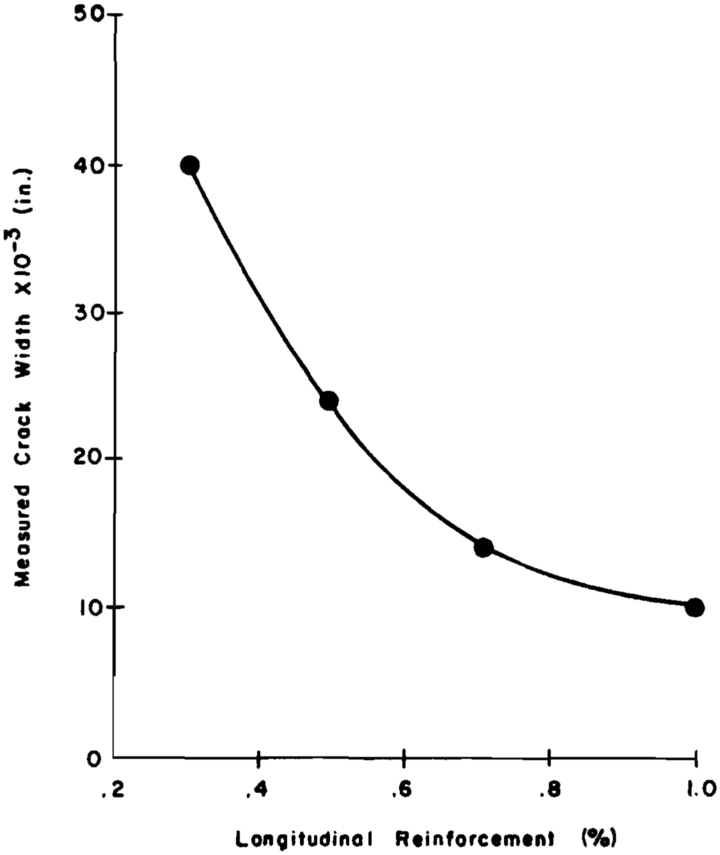


Fig 5.4. Variation of crack width at transverse cracks with percent longitudinal reinforcement (Ref 11).

To provide a more detailed look at the pavement responses at the end of the analysis period, Fig 5.5 shows the variations of concrete movement, friction resistance, concrete stress, and steel stress longitudinally along the pavement. The results are based on the study of 0.6 percent reinforcement at medium level solutions. This information is also a part of the computer program output shown in Appendix 2 of this report. It is worth noting that, due to concrete drying shrinkage, the steel stress in the vicinity of the center of a continuous pavement slab is in compression and that it changes to tension near the predicted transverse crack (Fig 5.5(e)).

Concrete Strength

The concrete strength varies considerably with the mixing properties and curing conditions. In this study, three compressive strength values (or tensile strength values) were used to investigate the influence of concrete strength on pavement behavior. These strength values are 2500, 3500, and 6000 psi (or tensile strength of 385, 467, and 600 psi), respectively. Figures 4.8 and 4.9 indicate that crack spacing and crack width are directly related to the concrete strength. Examination of these output data, Table A3.3, also points out that the CRCP-1 model makes extremely high estimates of the resulting crack spacing and crack width when combinations of design variables meet at the low level. These changes in pavement behavior due to variations in this design factor over the medium level solutions are useful in evaluating its relative importance.

The analysis of variance for these data has indicated its main effects and two-factor interactions to be significant on the program output in terms of spacing, crack width, and maximum steel stress. Subsequently, the analysis of variance yielded essentially the same ordering of significance on the concrete strength as the analysis results of single-factorial variation.

As expected and indicated by this study, the concrete strength is one of the most significant factors observed in the CRCP-1 model. Buick, in his "analysis and synthesis of Highway Pavement Design," (Ref 13) found that the AASHO rigid pavement design method, the flexural strength and/or compressive strength (or tensile strength) was one of the most important variables. McCullough et.al. (Ref 14) also indicated that the effects of concrete strength

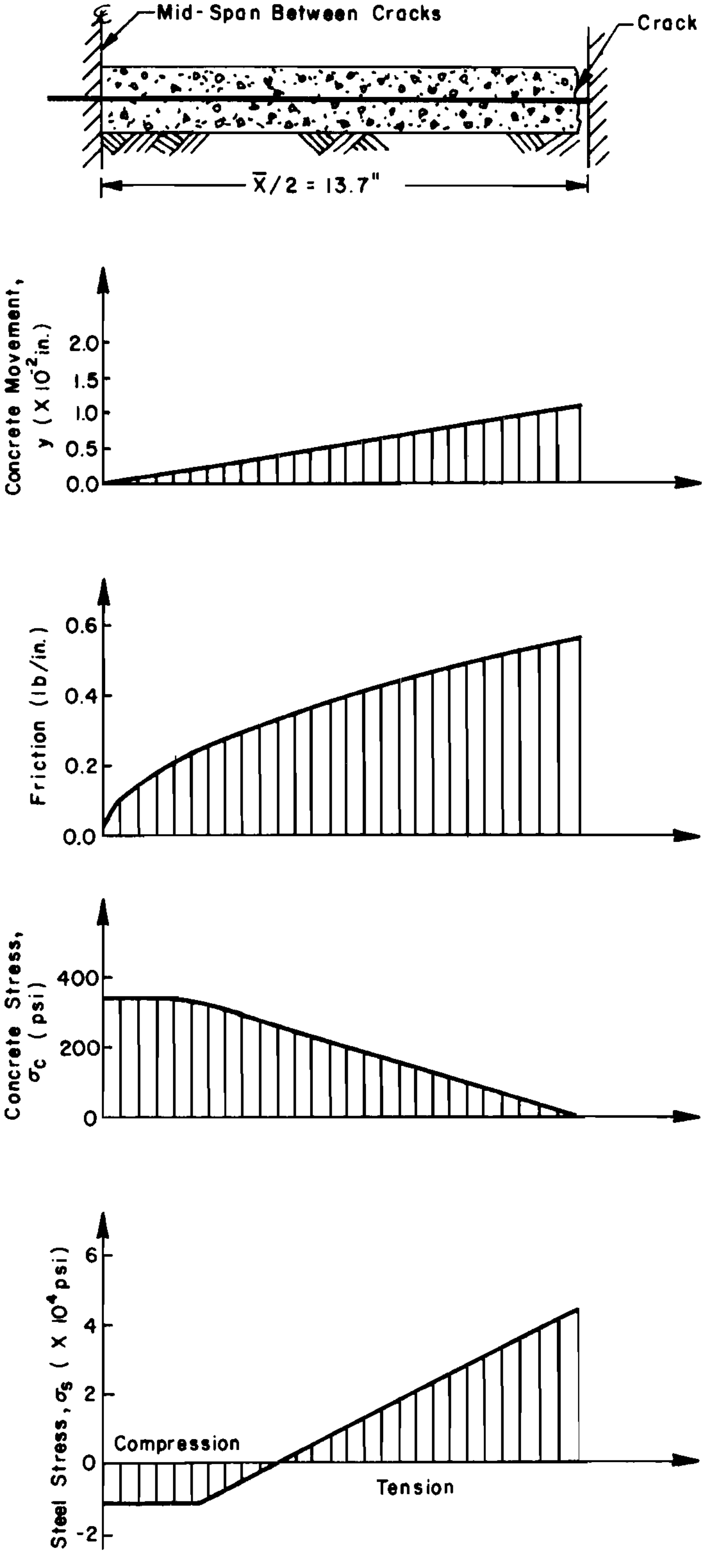


Fig 5.5. Variation of concrete movement, friction force, concrete and steel stress along the CRCP model for 0.6 percent reinforcement.

are highly significant. Thus, it is logical that variations in the concrete should also be highly significant in this study.

Excessive concrete strength will result in large crack widths, which can not be tolerated if the continuity in the continuously reinforced concrete pavement is to be maintained. Therefore, if an optimum crack width is to be maintained, the maximum allowable concrete strength deserves closer attention and study. The predicted crack spacing in the study of the low variable value of concrete tensile strength, 385 psi, is too small. A recent study by the Illinois Department of Transportation (Ref 15) indicated that a crack spacing of four to five feet would minimize steel rusting. McCullough in his deflection investigation on the in-service CRCP in Texas (Ref 16) also found that the optimum load transfer characteristics, to minimize deflection, occurred with a crack spacing range of five to eigth feet. According to this study, a minimum concrete tensile strength of 400 psi should be used in its quality control to improve pavement performance.

Bar Diameter

In this study, three sizes of bar diameter have been studied to investigate its effect on pavement behavior. These are 0.5-inch (No. 4), 0.624-inch (No. 5), and 0.75-inch (No. 6). The results show that the crack spacing and crack width are directly proportional to the diameter of the steel. It should be noted that the larger the steel bar, the lower the bond area per steel cross-section area. The studies conducted by McCullough and Ledbetter (Ref 17) indicated that crack spacing is also inversely associated with the ratio of steel bond area to concrete volume. This study demonstrates that the reinforcing bar sizes have a definite effect on the crack pattern and should be carefully evaluated in the design. The variation in crack spacing is more severe forthe low level studies than the medium level studies. The variation maximum steel stress at the end of the analysis period due to the changes of bar diameter and concrete strength is insignificant.

Elastic Modulus of Steel

The studies show that crack spacing and crack width are inversely proportional to the elastic modulus of steel. The moduli of steel has only a small effect on the maximum steel stress.

Drying Shrinkage of Concrete

Drying shrinkage is an essential characteristic of concrete and it is one of the principal creators of cracking. To investigate its effect on pavement performance, three values for total drying shrinkage, 300, 500, and 650 $\times 10^{-6}$ inch per inch, were studied. Computed results of crack spacing, crack width, maximum stress in the concrete, and maximum stress in the steel are shown in Table A3.2. The discrete values of the pavement response are plotted (Fig 4.6), because the variation of responsive items with drying shrinkage may not be continuous over a different set of conditions. The plot indicates that the higher the drying shrinkage of concrete, the smaller the crack spacing. The change in crack width is not very significant for the three levels of drying shrinkage investigated, but the computed variation of maximum steel stress due to changes of concrete drying shrinkage is significant.

Factors known to influence the magnitude of drying shrinkage are the amount of water per unit volume of concrete, type of gradation of aggregate, chemical admixtures, moisture, and temperature conditions. In order to provide better pavement performance, it is recommended that the pavement designer control the appropriate variable on concrete drying shrinkage to minimize volumetric changes.

Curing Temperature of Concrete

At various times of the year, concrete pavements will be subjected to different curing conditions. In addition, the extended period of paving operations for continuously reinforced concrete pavements usually results in a large range of variation in curing temperature on sections of the pavement. In this study, three curing temperatures of concrete, 45 degrees, 75 degrees, and 85 degrees Fahrenheit (Fig 4.10), were examined. A curing temperature of 75 degrees Fahrenheit yielded a crack spacing of 2.3 feet for medium level study, while at 85 degrees Fahrenheit, the predicted crack spacing declined to 1.8 feet. This prediction apparently conforms to the field observations (Figs 5.6 and 5.7) which have shown the crack spacing is inversely proportional to the curing temperature. The computed crack width as well as the stress in the steel and concrete is less for the high curing temperature.

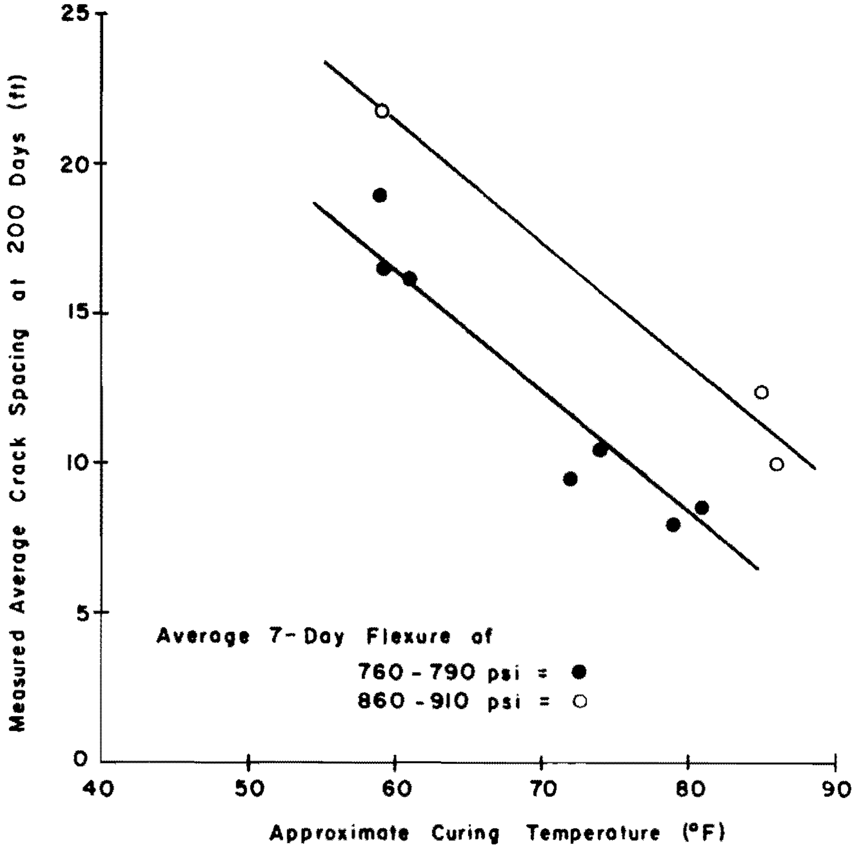


Fig 5.6. Relation between average crack spacing and air temperature at the time of curing (Ref 18).

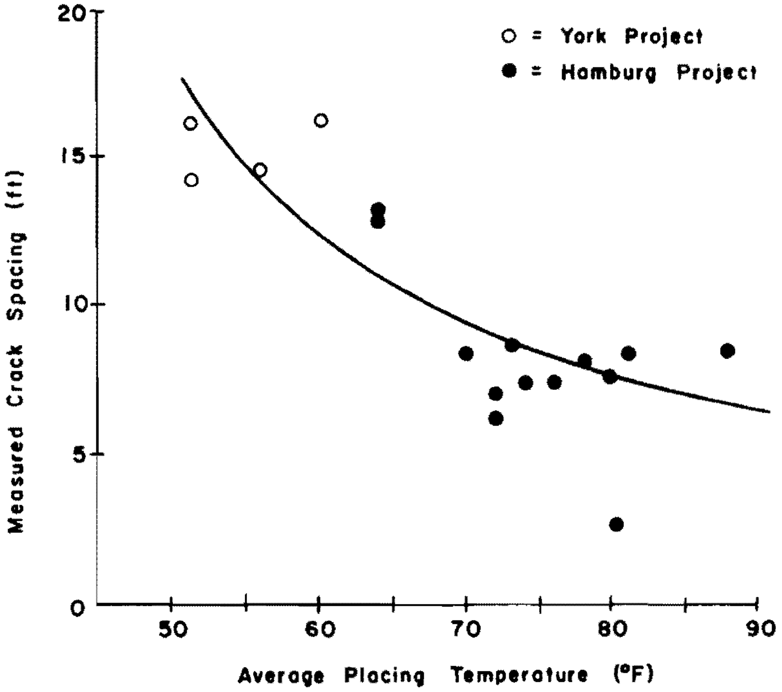


Fig 5.7. Effect of placing temperature on crack spacing (Ref 19).

A condition survey of CRCP conducted in Indiana by Faiz and Yoder (Ref 20) indicated that much of the distress took place during the cold months of the year. With regard to these field observations, it is suggested that extreme temperature drops during early curing be avoided in order to prevent drastic effects on pavement performance. Thus, selection of curing temperature and specified curing time may have a profound influence on the development of crack spacing and consequently, on the performance of pavement. After further evaluation, it may appear that different specification requirements are needed for fall and summer placement. The pavement engineer should be aware of this impact and possibly evaluate it for use in his decision-making process during the design and construction period.

Thermal Coefficient

Since dimensional changes in concrete influence the formation of transverse cracks, the thermal characteristics of concrete obviously affect the crack pattern. In this study, three values were investigated (Fig 4.5), 3.2×10^{-6}, 5.0×10^{-6}, and 7.0×10^{-6} inch per inch per degree Fahrenheit. The crack spacing is inversely proportional to the values of the thermal coefficient. The predicted crack width, and steel stress indicate insignificant effects due to changes of thermal coefficient.

The thermal expansion and contraction of concrete vary with factors such as aggregate type, richness of mixture, water-cement ratio, temperature range, concrete age, and relative humidity. Of these factors, the aggregate type has the greatest influence on the thermal properties of concrete, thus the aggregate type should also be evaluated in the design of CRCP.

Unit Weight of Concrete

The predicted changes in crack spacing, crack width, and maximum steel stress at the end of the analysis period, due to the change of the concrete unit weight from 120 to 160 pounds per cubic foot indicate a decreasing trend of less than ten percent (Fig 4.7).

Slab-Base Friction and Movement

The sensitivity study indicated changes in frictional resistance had very little effect on the crack spacing and crack width; therefore, the low rating for this parameter in connection with this study. A further study of available data indicates the initial selection of low and high levels may have been too restrictive, relative to field observations. Subsequent information shows the range of maximum slab-base friction should be from 0.05 lbs/ft^2 (smooth surface such as polyethylene) to 20 lbs/ft^2 (rough surface such as a unfinished cement stablized base) rather than 1.0 lbs/ft^2 to 2.3 lbs/ft^2, as used in the study. These extreme values would probably have a significant effect on crack spacing and crack width, whereas in the middle range, as used in this study, changes in friction resistance are small.

For one solution, the maximum slab-base friction resistance was increased to 10 lbs/ft^2. The result in crack spacing dropped from 2.3 feet to 2.0. However, the danger is not in the high values of sub-base friction, but rather the low values that may occur in the field. In these cases excessive stresses and crack widths may be experienced.

Based on the above observations, it appears that the desired slab behavior may be achieved with a lower percent of longitudinal reinforcement where high frictional resistance is experienced. However, this is not a practical solution, since with a decrease in the percent reinforcement, the computed crack width will increase, and may adversly affect the pavement performance. In the decision-making process, a pavement designer should therefore evaluate the frictional resistance carefully.

Yielding Stress of Steel

In this paper, three levels were studied, 4.0×10^4, 6.0×10^4, and 7.0×10^4 psi, respectively. It appears that computed crack spacing, crack width, and stresses in steel are unvaried by the variation of these three levels. This occurs because the program was not designed to recognize when the yield point is exceeded. In reality, the crack spacing and crack width would be affected, and consequently the performance. Thus, the designer should check to see that the yield point is not exceeded.

CHAPTER 6. SUMMARY OF COMMON USER ERRORS

An effort has been made in various stages of this study to document the most common errors made by program users of the continuously reinforced concrete pavement model CRCP-1, so that the user will be able to detect and avoid possible mistakes. The computer program specifies certain error messages which will help the user to evaluate the input information. Nevertheless, some of the errors complicate the analysis unless the user is familiar with their characteristics and relation to other variables.

The diagnostic errors will be discussed separately in terms of input variables. A sample computer output is presented in Appendix 2 to show the user the kind of information received if he mades a mistake in the program input.

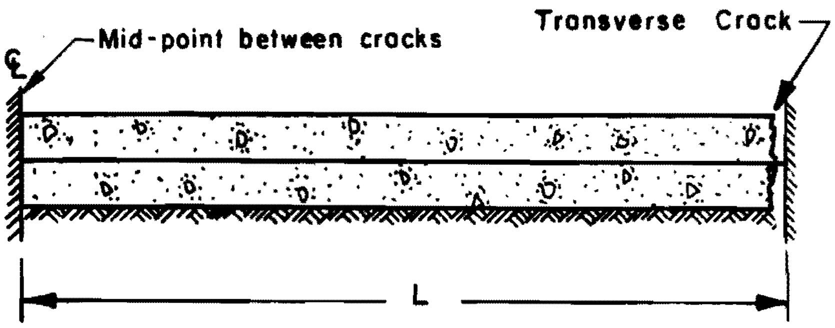
Errors Caused by Steel Variables

The pavement responses in CRCP-1 are very sensitive with respect to percentage of longitudinal reinforcement variable and may cause termination of the program. The common error occurs when the value of percentage reinforcement exceeds or equals 0.8. For this case, Fig 6.1, which shows a free-body diagram for the CRCP model and stress distribution in the steel and concrete for a given temperature drop ΔT and drying shrinkage strain Z may be used to explain the problem. In the figure,

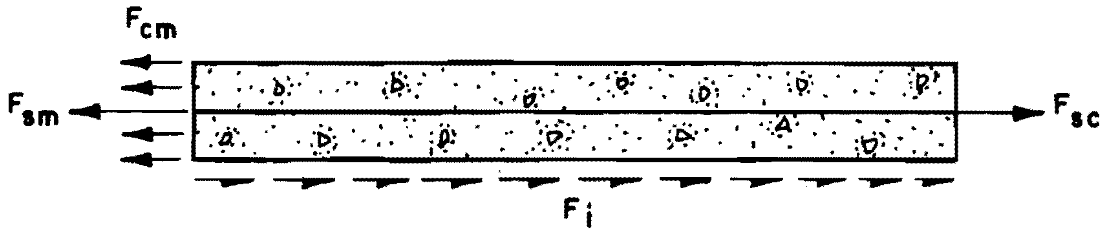
F_{sc}, σ_{sc} = force or stress in the steel at the crack,

F_{sm}, σ_{sm} = force or stress in the steel between cracks,

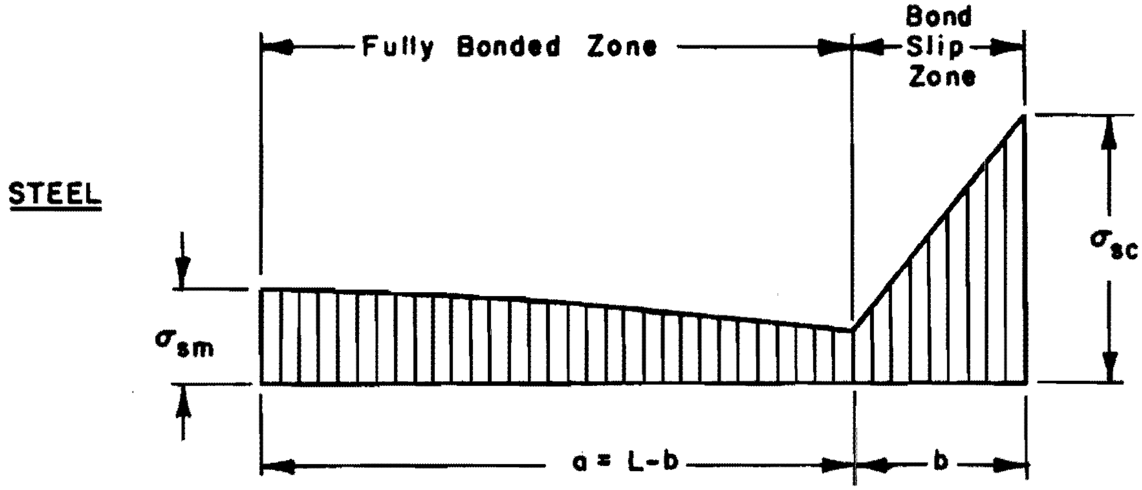
F_{cm}, σ_{cm} = force or stress in the concrete between cracks.



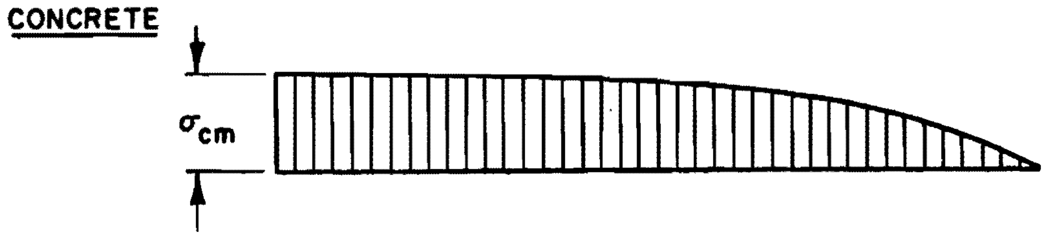
(a) CRCP model.



(b) Free-body diagram of CRCP model.



(c) Stress distribution in steel.



(d) Stress distribution in concrete.

Fig 6.1. Free-body diagram and corresponding stress distribution of the CRCP model.

If the computed bond length b in Fig 6.1C is greater than the crack spacing, then the theoretical equations in the program do not hold true and the program will be terminated.

Errors Caused by Concrete Variables

There are limitations attached to the numerical values of total drying shrinkage of concrete, concrete compressive strength, and curing temperature of concrete. If the program fails to run, it is advisable to revise the input values of these design variables. For example, at medium level study, if the designer uses the shrinkage variable with a value of 7.0×10^{-4} inch per linear inch, then he will find that the computed length of the fully-bonded section indicated in the CRCP-1 (Ref 21) is a negative value; in other words, the computed bond length is greater than that already specified in the CRCP-1. Consequently, an error will be detected by the subroutine program DEBAR, which solves for stress in the steel at the predicted transverse crack and between cracks. An error will also be detected if the designer uses the compressive strength with a value of less than 2300 pounds per square inch and the curing temperature with a value of 90° F.

Errors Caused by Slab-Base Frictional Relationship

If the relationship between the maximum slab base friction and movement at sliding has not been reasonably established, the computer program will be terminated. For instance, at medium level study, if the frictional force and movement are designated as 12 pounds per linear inch and 0.01 inch respectively, the error is detected for NA (the number of increments in the program computation) greater than NT (equals to one hundred, which is the total number of increments specified in the CRCP-1 model).

The frictional relationship is primarily dependent on the type of base, for which the range of these two input variables should be carefully examined and selected through updated laboratory studies and field observations.

Errors Caused by Thermal Coefficient

In the study of effect of thermal coefficient, if the thermal coefficient of steel is not equal to or greater than that of concrete, the error is detected in the computation of predicted crack width which indicates a minus value. The associated program subroutine DFBAR (Ref 21) computes the stresses and strains in the concrete and steel due to a temperature drop and/or concrete shrinkage, for which the theoretical equations are written for a frictionless system.

Errors Caused by Input Variables Assigned as High Level

The data outputs in CRCP-1 are very sensitive at high level studies and can cause several common errors. The program is terminated if the computed bond length is greater than that of the CRCP-1 model, and the theoretical equations do not hold true. The user can recognize that the program termination was due to the combined effects from the high values of input variables.

Errors Caused by Compressive Strength of Concrete

If the compressive strength of concrete is not provided in the input by the user, the program will be terminated; hence, the compressive strength data on concrete must be provided whether it is required by the user or not. The program will also terminate if the calculated number of iterations is greater than the maximum number of allowable iterations, which was specified as twenty.

CHAPTER 7. CONCLUSIONS, RECOMMENDATIONS, AND IMPLEMENTATION GUIDELINES

CONCLUSIONS

This study was conducted to determine the sensitivity of the pavement responses as predicted by computer program CRCP-1 to practical variations in the input variables and adopt it for usage by the Texas Highway Department. The investigation was made to gain information and determine where more study effort should be spent in developing inputs for the system. An additional intent was to recommend revisions to the program, if needed. It should be recognized that the conclusions made in this study are limited to the range of variables selected in the study.

(1) Computer program CRCP-1 can be used by the State Department of Highways and Public Transportation to develop design, contruction and maintenance guidelines for CRC pavements.

(2) Following is list of design variables in decreasing order of importance based on the premise that the more important design variable will produce greater changes in the predicted pavement behavior.

  (a) The percentage of longitudinal reinforcement and concrete strength are the most important factors and require careful consideration in order to insure pavement performance in the field.

  (b) The bar diameter of steel is the third most important factor.

  (c) The elastic modulus of steel and drying shrinkage of concrete are important factors and their variation produce significant changes in pavement behavior.

  (d) The curing temperature of concrete at concrete placement has a significant influence on pavement behavior; thus, the designer needs to consider the time of year a pavement is to be constructed when designing for an optimum crack spacing and crack width.

  (e) The thermal coefficient, unit weight of concrete, slab thickness, and frictional resistance are the least important factors.

  (f) The yielding stress of steel can be considered as a constant.

(3) Quality control requirements are necessary in various stages of design and construction to improve pavement performance in the field. The

results from the sensitivity analysis discussed in Conclusion (2) provides preliminary guidelines for quality control priorities.

(4) Depending on the circumstances, a uniform design, i.e., thickness and reinforcement, used under a wide variety of conditions may give from poor to excellent pavement performance. Careful consideration must be given during the design stage to fit into the specific project conditions using rational design procedures.

(5) Continuously reinforced concrete pavements are complicated physical systems involving the interaction of a number of complex and interrelated factors. Therefore, a systematic and conceptual approach must be used in the development of a rational and generally applicable method of pavement design (Ref 23). To manage such a design method, a systems approach has been proposed, Fig 7.1. An essential step in this approach is the formulation of block diagrams that show the relationship between the various input factors in the CRCP-1 system and identifing the limited criteria for the decision-making process. In this chart the limiting criteria for these factors are presented for use in design and construction.

RECOMMENDATIONS

On this basis of this study, the following improvements are recommended:

(1) Since the early cracking of continuous pavements is primarily due to temperature drop and concrete drying shrinkage, more emphasis should be given to studying their interaction effects with the concrete strength.

(2) The accurate prediction of final crack spacing and crack width will depend upon the characterization of the slab-base friction-movement curve. The need to evaluate the effects of the other two types of frictional relationship, i.e., straight line and multilinear, on the system output is apparent.

(3) Slab-base frictional test data from laboratory and field studies are required for more definite inputs into the computer program.

(4) In this study, the temperature data are specified as fixed input to the computer program, except the curing temperature of concrete. A range in temperature conditions should be selected on the basis of geographic areas in Texas to study variations in performance with respect to temperature and shrinkage cracking.

(5) The present computer program does not take into account the load stresses in the crack prediction models. Since previous studies have shown this need (Ref 1), the program should be modified to include wheel load stresses.

(6) In the present analysis of the CRCP-1 computer program, the concrete temperature is considered to be the same as the air temperature. A study should be carried out to allow prediction of the concrete temperature from the air temperature, solar radiation, and other thermal properties of the concrete. The model developed by Shahin

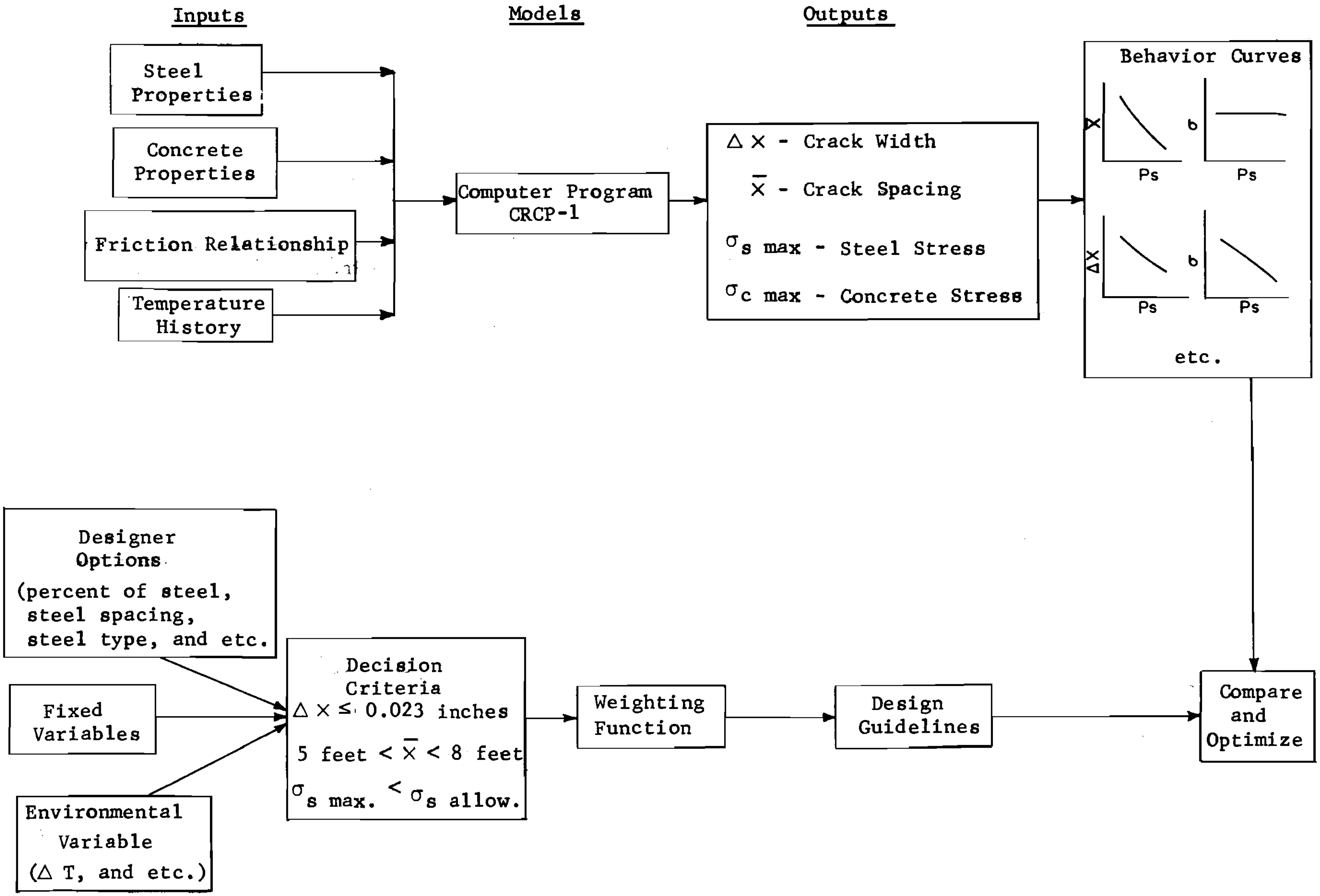


Fig 7.1. Conceptual CRCP-1 management system.

and McCullough (Ref 22) for predicting temperature in asphalt concrete could be modified for a better simulation.

(7) For future operations of CRCP the relative closure tolerance and the initial length may be fixed at 5 percent and 100 feet, respectively, to minimize computational time.

IMPLEMENTATION

On the basis of this study and the inclusion of Recommendation (5) into computer program CRCP-1, the following steps of implementation are suggested:

(1) The computer program CRCP-1 should be put on line at D-19 for possible use by the State Department of Highways and Public Transportation personnel.

(2) A users manual should be prepared for the computer program using Appendix as a guide.

(3) The temperature data mentioned in Recommendation (4) should be used to develop a range of solutions of crack width, crack spacing, and steel stress for different material properties.

(4) The information from step (3) could be used to develop a design manual for CRCP that would reflect more variables then taken into account at the present time. Thus, the performance level of CRCP.

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APPENDIX 1

PROGRAM CRCP-1

OPERATIONAL GUIDE FOR DATA INPUT

revised from

MECHANISTIC BEHAVIOR OF CONTINUOUSLY REINFORCED
CONCRETE PAVEMENT (Ref 21)

CRCP-1 is a computer program written to study the behavior of continuously reinforced concrete pavements. The approach adopted, the development of the equations and the overall method of solution are discussed in Chapters 2, 4, 5, and 6 of the 1-15 Report (Ref 1). The purpose of this Appendix is to provide the program user with a concise manual which can be extracted for daily use with the program.

Program Operation

The general procedures followed in the program are described in the attached flow chart, Fig A1.1. A problem number card at the beginning of each problem controls the start of the solution. Unless an error occurs because of unacceptable data, the program will work any number of problems in sequence, finally stopping when a blank problem number card is encountered.

The data deck starts with two cover cards used to identify the program and the particular run being made. The problems to be solved together in one run are stacked behind the cover cards in sequence, as illustrated in Fig A1.2. Each problem consists of one problem number card with an alphanumeric description of the problem. This is followed by steel properties, concrete properties, slab-base friction relationship, temperature data, minimum allowable number of iterations, and tolerance for relative closure.

Guide for Data Input

The following pages provide a guide for data input. It is expected that revisions of these forms and instructions will be developed in the future and may supersede the present versions.

Example problems are presented in Appendix 2. By comparing these example inputs with the description

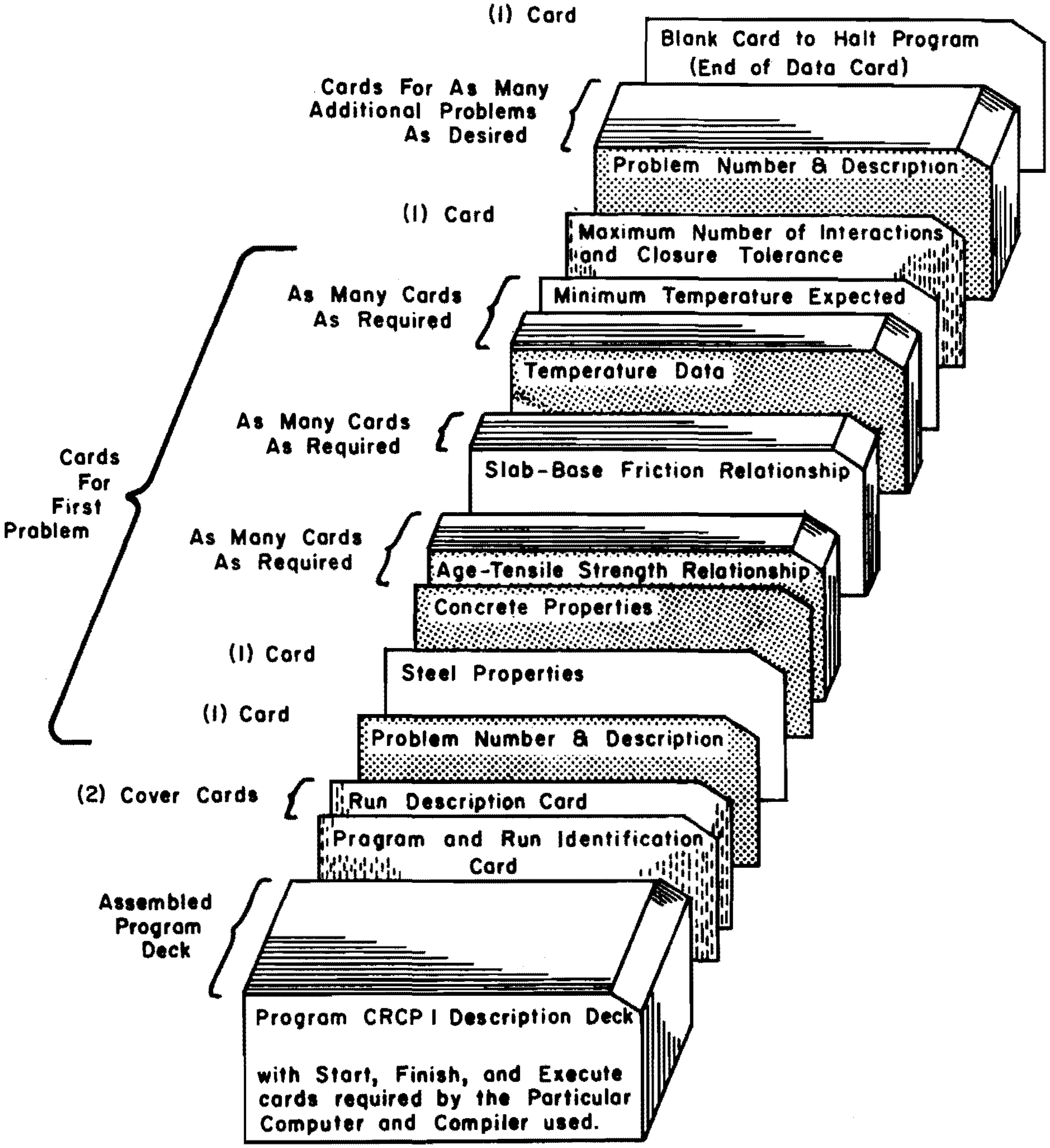


Fig A1.1. Assembly order for CRCP-1 program deck with data, ready to run.

of the problem, the user can gain practical experience in the preparation of input data. Proficiency in the use of the program can be gained only through actual coding of problems and solution in the computer.

CRCP-1 - GUIDE FOR DATA INPUT -- Card forms

IDENTIFICATION OF PROGRAM AND RUN (2 alphanumeric cards per run)

Description of Run	
1	80

1	80

IDENTIFICATION OF PROBLEM (one card each problem; program stops if PROB NUM is left blank)

PROB NUM	
A5	Description of Problem (alphanumeric)
1 5	11 80

STEEL PROPERTIES (one card each problem)

ITPYER	PERCENT REINFORCEMENT	BAR DIAMETER	YIELD STRESS	ELASTIC MODULUS	THERMAL COEFFICIENT	TRANSVERSE WIRE SPACING*
I5	E10.3	E10.3	E10.3	E10.3	E10.3	E10.3
1 5	11	21	31	41	51	61 70

ITYPER = 1 for deformed bar

= 2 for deformed wire fabric

*Required only in the case of deformed wire fabric

CRCP-1 - GUIDE FOR DATA INPUT -- Card forms

CONCRETE PROPERTIES

CONSTANTS (one card each problem)

SLAB THICKNESS	THERMAL COEFFICIENT	DRYING SHRINKAGE STRAIN	UNIT WEIGHT OF CONCRETE (pcf)	28-DAY COMPRESSIVE STRENGTH
E10.3	E10.3	E10.3	E10.3	E10.3
11	21	31	41	51 60

AGE-TENSILE STRENGTH RELATIONSHIP

NTS
I5
1 5

AGE(1)	TS(1)	AGE(2)	TS(2)									AGE(7)	TS(7)
F5.1	F5.1	F5.1	F5.1									F5.1	F5.1
11	16	21	26	31	36	41	46	51	56	61	66	71	76 80

AGE(8)	TS(8)									AGE(NTS)	TS(NTS)		
F5.1	F5.1									F5.1	F5.1		
11	16	21	26	31	36	41	46	51	56	61	66	71	76 80

NTS = 0 if no tensile strength data are available, data are generated.

= Total number of points on age-strength relationship (maximum is 20)

AGE(1) = Age of concrete in days

TS(1) = Tensile strength

CRCP-1 - GUIDE FOR DATA INPUT -- Card forms

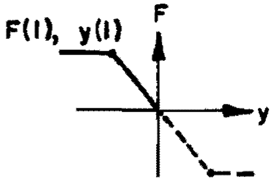
SLAB-BASE FRICTION RELATIONSHIP (F-y curve)

IFY
I5
1 5

F(1)	y(1)	F(2)	y(2)									F(7)	y(7)
F5.2	F5.2	F5.2	F5.2									F5.2	F5.2
11	16	21	26	31	36	41	46	51	56	61	66	71	76 80

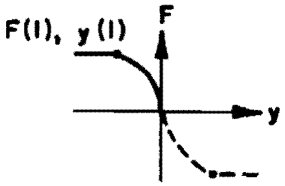
F(8)	y(8)							F(IFY)	y(IFY)				
F5.2	F5.2							F5.2	F5.2				
11	16	21	26	31	36	41	46	51	56	61	66	71	76 80

IFY = 1*



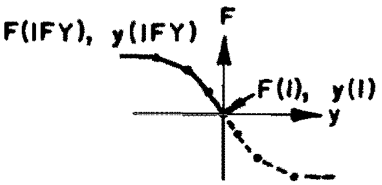
Straight Line

IFY = 2*



Parabola

IFY = Total Number of Points*



Multilinear

F(1) = Force per unit length

y(1) = Movement

*Only the solid portion of the curve needs to be defined; the dotted portion is generated by symmetry with respect to the origin.

CRCP-1 - GUIDE FOR DATA INPUT -- Card forms

TEMPERATURE DATA

Average curing temperature and minimum daily temperature (F)

CURT	NTEMP	TD(1)	TD(2)	TD(3)										TD(13)	TD(14)
F5.1	I5	F5.1	F5.1	F5.1										F5.1	F5.1
1	6	11	16	21	26	31	36	41	46	51	56	61	66	71	76 80

TD(15)	TD(16)							TD(NTEMP)					
F5.1	F5.1							F5.1					
11	16	21	26	31	36	41	46	51	56	61	66	71	76 80

CURT = Average curing temperature of concrete

NTEMP = Number of days (maximum is 50)

TD(I) = Minimum daily temperature

Plot of temperature drop vs. time

IPLOT		TMSCALE	FINAL
I5	5X	E10.3	E10.3
1	6	11	21 30

IPLOT = Plot option of temperature time data

TMSCALE = Time scale for plot option

FINAL = Number of days

Minimum temperature expected after concrete gains full strength

DTMAX
F5.1
11 15

CRCP-1 - GUIDE FOR DATA INPUT -- Card Forms

ITERATIONS AND TOLERANCE CONTROL

MAXITE	TOL
I5	F5.1
1	6 10

MAXITE = Maximum number of iterations
TOL = Relative closure tolerance in percent

STOP PROGRAM	One blank card to end program
1	21 80

GENERAL PROGRAM NOTES

The data cards must be stacked in the proper order for the program to run.

All 10-space words are floating point decimal numbers . . . . -6 . 0 0 0 E - 0 1

All 5-space words are understood to be intergers or whole decimal numbers . . . . + 2 0

All numbers must be right justified.

The problem number may be alphanumeric.

Sign convention adopted is as follows:

(1) tension is positive,

(2) friction forces in the positive x-direction are positive,

(3) movements in the positive x-direction are positive, and

(4) temperature drop at a given time is defined as the difference between the temperature at which concrete has set and the temperature at the given time.

STEEL PROPERTIES

Only one card is required per problem. Program CRCP-1 has the capability of analyzing the most commonly used types of longitudinal reinforcement deformed bars and deformed wire fabric. The desirable type of reinforcement can be specified by the ITYPER option. ITYPER = 1 is for deformed bars while ITYPER = 2 is for deformed wire fabric. The units to be used are pounds and inches. The unit of temperature used in the analysis should be consistent in the thermal coefficient and temperature data.

CONCRETE PROPERTIES

The input of concrete properties consist of two or more cards. The first card has slab thickness, thermal coefficient, final drying shrinkage, unit weight and 28-day compressive strength. Units are pounds and inches except for unit weight of concrete, where pounds per cubic foot should be used. In case the thermal coefficient and/or final drying shrinkage of the concrete mix used are not available, Table A1.1 contains recommended values obtained from the present state-of-the-art.

The second card contains the age-tensile strength relationship of the concrete. If the data are not provided, the recommendations given by the United States Bureau of Reclamation will be used to generate the age-tensile strength relationship. In this case, the 28-days compressive strength of concrete is required, and NTS should be zero.

SLAB-BASE FRICTION RELATIONSHIP (F-y curve)

Various relationships can be input to define the F-y curve used in the computations. Immaterial of the type of curve, symmetry is assumed with respect to the origin of the axes. This implies that only one portion of the curve is needed, while the remainder is generated by the program.

The three types of frictional resistance relationships are straight line, parabola, and multilinear curves. The desired relationship is specified by the control IFY , where a value of one, two, or greater than two indicates that the F-y curve is a straight line, parabola, or multilinear relationship respectively. In the case of a straight line or a parabola, only one point is required to define the curve. This point is where sliding occurs. If the multilinear curve is used, then the first point should be the origin [F(1) = 0 , y(1) = 0], while the last point [F(IFY), y(IFY)] should be at sliding. Appendix 7(Ref 1) conducts a literature review of frictional resistance in various types of subbases.

TABLE A1.1. RECOMMENDED VALUES OF THERMAL COEFFICIENT OF CONCRETE AND FINAL DRYING SHRINKAGE*

Type of Coarse Aggregate	Thermal Coefficient (millions per degree F)	Final Drying Shrinkage (millions)
Quartz	6.6	320
Sandstone	6.5	1160
Gravel	6.0	560
Granite	5.3	470
Basalt	4.8	800
Limestone	3.8	410

---

*Type of coarse aggregate by itself does not, by any means, define the magnitudes of thermal coefficient and drying shrinkage.

TEMPERATURE DATA

In the temperature data, the average curing temperature and the minimum daily temperature over a period of NTEMP days should be specified. NTEMP should be equal to the time when the tensile strength reaches its maximum value, as specified in the age-tensile strength relationship. If no tensile strength data are available, then, as discussed previously, strength values will be generated by the program, in which case NTEMP should be 28 days, and 28 minimum daily temperatures will be required.

One more piece of information is required for the analysis: minimum temperature expected after concrete gains full strength.

MAXIMUM NUMBER OF ITERATIONS AND CLOSURE TOLERANCE

The maximum number of iterations should be set to prevent excessive computation. Most continuous pavement problems should close to a reasonable tolerance within 10 iterations; an allowed maximum of 20 is usually adequate.

The closure tolerance is *relative* closure and should be expressed in percent. If it is unreasonably small, closure may be difficult to achieve. For many structural road problems, a value of one percent is satisfactory.

APPENDIX 2. SAMPLE PROGRAM OUTPUTS

```
PROGRAM CRCP-1 FOR HIGHWAYS,CFHR PROJECT 177
SENSITIVITY ANALYSIS BY C.P.CHIANG,FALL*74

PROB
   1     THE STUDY OF EFFECTS OF INPUT VARIABLES ASSIGNED AS MEDIUM VALUE

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


               TYPE OF LONGITUDINAL REINFORCEMENT IS
                          DEFORMED BARS


               PERCENT REINFORCEMENT = 6.000E-01
               BAR DIAMETER          = 6.250E-01
               YIELD STRESS          = 6.000E+04
               ELASTIC MODULUS       = 2.900E+07
               THERMAL COEFFICIENT   = 5.000E-06


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


               SLAB THICKNESS      = 9.000E+00
               THERMAL COEFFICIENT = 5.000E-06
               TOTAL SHRINKAGE     = 5.000E-04
               UNIT WEIGHT CONCRETE= 1.500E+02
               COMPRESSIVE STRENGTH= 3.500E+03


              TENSILE STRENGTH DATA
              *********************

               NO TENSILE STRENGTH DATA IS INPUT BY USER
               THE FOLLOWING AGE-TENSILE STRENGTH RELATIONSHIP
               IS USED WHICH IS BASED ON THE RECOMMENDATION
               GIVEN BY U.S. BUREAU OF RECLAMATION

               AGE.  TENSILE
              (DAYS) STRENGTH

                0.0    0.0
                1.0  116.0
                3.0  249.5
                5.0  316.8
                7.0  355.4
               14.0  417.8
               21.0  451.3
               28.0  466.7
```

```
*********************************************
*                                           *
*     SLAB-BASE FRICTION CHARACTERISTICS    *
*             F-Y RELATIONSHIP              *
*                                           *
*********************************************


     TYPE OF FRICTION CURVE IS A PARABOLA

      MAXIMUM FRICTION FORCE=    1.300
      MOVEMENT AT SLIDING   =    -.060


****************************
*                          *
*      TEMPERATURE DATA    *
*                          *
****************************


     CURING TEMPERATURE= 75.0


          MINIMUM       DROP IN
DAY     TEMPERATURE   TEMPERATURE

  1         62.0          13.0
  2         53.0          22.0
  3         43.0          32.0
  4         52.0          23.0
  5         62.0          13.0
  6         66.0           9.0
  7         58.0          17.0
  8         12.0          63.0
  9         66.0           9.0
 10         69.0           6.0
 11         64.0          11.0
 12         65.0          10.0
 13         61.0          14.0
 14         65.0          10.0
 15         63.0          12.0
 16         64.0          11.0
 17         68.0           7.0
 18         57.0          18.0
 19         48.0          27.0
 20         51.0          24.0
 21         59.0          16.0
 22         59.0          16.0
 23         50.0          25.0
 24         45.0          30.0
 25         47.0          28.0
 26         49.0          26.0
 27         49.0          26.0
 28         52.0          23.0

     MINIMUM TEMPERATURE EXPECTED AFTER
     CONCRETE GAINS FULL STRENGTH      =     0 DEGREES FARENHITE
```

```
*************************************************
*                                               *
*       ITERATION AND TOLERANCE CONTROL         *
*                                               *
*************************************************

 MAXIMUM ALLOWABLE NUMBER OF ITERATIONS=   20

 RELATIVE CLOSURE TOLERANCE=  1.0 PERCENT
```

```
PROGRAM CRCP-1 FOR HIGHWAYS,CFHR PROJECT 177
SENSITIVITY ANALYSIS BY C.P.CHIANG,FALL*74

PROB
  1      THE STUDY OF EFFECTS OF INPUT VARIABLES ASSIGNED AS MEDIUM VALUE

                                                                         MAXIMUM
 TIME    TEMP     DRYING     TENSILE   CRACK      CRACK        CONCRETE      STRESS IN
(DAYS)   DROP    SHRINKAGE   STRGTH   SPACING     WIDTH         STRESS       THE STEEL

   .39   10.0   1.769E-06     48.7     875.0   1.451E-03     4.461E+01     8.340E+03
   .42   11.4   1.902E-06     52.1     437.5   1.866E-03     5.028E+01     9.568E+03
   .50   13.0   2.268E-06     61.6     218.8   2.297E-03     5.777E+01     1.105E+04
  1.35   13.0   6.079E-06    142.8     218.8   3.345E-03     9.029E+01     1.627E+04
  1.50   22.0   6.742E-06    153.7     218.8   7.662E-03     1.399E+02     2.519E+04
  2.37   22.0   1.057E-05    212.1     218.8   8.832E-03     1.670E+02     2.951E+04
  2.50   32.0   1.114E-05    220.1     109.4   9.958E-03     1.783E+02     3.168E+04
  3.50   23.0   1.545E-05    267.6     109.4   7.151E-03     1.619E+02     2.835E+04
  4.50   13.0   1.970E-05    301.2     109.4   4.026E-03     1.269E+02     2.188E+04
  5.50    9.0   2.386E-05    326.9     109.4   3.059E-03     1.141E+02     1.944E+04
  6.34    9.0   2.730E-05    343.1     109.4   3.328E-03     1.214E+02     2.056E+04
  6.50   17.0   2.796E-05    346.1     109.4   6.213E-03     1.664E+02     2.846E+04
  7.29   17.0   3.116E-05    358.2     109.4   6.503E-03     1.727E+02     2.942E+04
  7.32   27.0   3.127E-05    358.5     109.4   1.045E-02     2.189E+02     3.755E+04
  7.35   37.0   3.139E-05    358.8     109.4   1.464E-02     2.593E+02     4.462E+04
  7.38   47.0   3.152E-05    359.1     109.4   1.901E-02     2.955E+02     5.098E+04
  7.43   57.0   3.171E-05    359.6     109.4   2.350E-02     3.287E+02     5.681E+04
  7.50   63.0   3.199E-05    360.3     109.4   2.626E-02     3.478E+02     6.014E+04
  8.50    9.0   3.594E-05    369.8     109.4   3.988E-03     1.370E+02     2.299E+04
  9.50    6.0   3.984E-05    379.1     109.4   3.260E-03     1.252E+02     2.077E+04
 10.34    6.0   4.306E-05    386.7     109.4   3.497E-03     1.307E+02     2.164E+04
 10.50   11.0   4.366E-05    388.1     109.4   5.313E-03     1.614E+02     2.698E+04
 11.50   10.0   4.743E-05    396.9     109.4   5.252E-03     1.620E+02     2.696E+04
 12.38   10.0   5.068E-05    404.4     109.4   5.518E-03     1.674E+02     2.779E+04
 12.50   14.0   5.113E-05    405.4     109.4   7.077E-03     1.898E+02     3.168E+04
 13.50   10.0   5.477E-05    413.7     109.4   5.877E-03     1.737E+02     2.874E+04
 14.41   10.0   5.802E-05    419.8     109.4   6.171E-03     1.781E+02     2.938E+04
 14.50   12.0   5.836E-05    420.3     109.4   6.972E-03     1.893E+02     3.133E+04
 15.50   11.0   6.188E-05    425.3     109.4   6.899E-03     1.883E+02     3.105E+04
 16.50    7.0   6.535E-05    430.2     109.4   5.667E-03     1.707E+02     2.786E+04
 17.31    7.0   6.814E-05    434.1     109.4   5.908E-03     1.744E+02     2.840E+04
 17.45   17.0   6.859E-05    434.8     109.4   9.948E-03     2.263E+02     3.742E+04
 17.50   18.0   6.877E-05    435.0     109.4   1.038E-02     2.311E+02     3.827E+04
 18.37   18.0   7.168E-05    439.1     109.4   1.067E-02     2.344E+02     3.873E+04
 18.50   27.0   7.213E-05    439.8     109.4   1.457E-02     2.739E+02     4.560E+04
 19.50   24.0   7.544E-05    444.4     109.4   1.361E-02     2.648E+02     4.389E+04
 20.50   16.0   7.870E-05    449.0     109.4   1.052E-02     2.329E+02     3.823E+04
 21.50   16.0   8.191E-05    452.4     109.4   1.083E-02     2.363E+02     3.871E+04
 22.36   16.0   8.464E-05    454.4     109.4   1.108E-02     2.390E+02     3.910E+04
 22.50   25.0   8.507E-05    454.7     109.4   1.502E-02     2.783E+02     4.591E+04
 23.41   25.0   8.790E-05    456.7     109.4   1.529E-02     2.808E+02     4.627E+04
 23.50   30.0   8.819E-05    456.9     109.4   1.755E-02     3.008E+02     4.973E+04
 24.50   28.0   9.126E-05    459.1     109.4   1.696E-02     2.958E+02     4.875E+04
 25.50   26.0   9.428E-05    461.3     109.4   1.636E-02     2.906E+02     4.775E+04
 26.50   26.0   9.726E-05    463.4     109.4   1.666E-02     2.932E+02     4.811E+04
 27.50   23.0   1.002E-04    465.6     109.4   1.561E-02     2.838E+02     4.639E+04
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 AT THE END OF THE ANALYSIS PERIOD

CRACK SPACING        = 2.279E+00 FEET
CRACK WIDTH          = 2.238E-02 INCHES
MAX CONCRETE STRESS= 3.384E+02 PSI
MAX STEEL STRESS     = 4.453E+04 PSI


STA-   DIS-    CONCRETE      FRICTION     CONCRETE       STEEL
TION   TANCE   MOVEMENT       FORCE        STRESS        STRESS

   1    0.0   0.            0.            3.384E+02   -1.176E+04
   2     .1  -1.067E-04     5.483E-02     3.383E+02   -1.176E+04
   3     .3  -2.135E-04     7.754E-02     3.383E+02   -1.176E+04
   4     .4  -3.202E-04     9.497E-02     3.383E+02   -1.176E+04
   5     .5  -4.269E-04     1.097E-01     3.383E+02   -1.176E+04
   6     .7  -5.337E-04     1.226E-01     3.383E+02   -1.176E+04
   7     .8  -6.404E-04     1.343E-01     3.383E+02   -1.176E+04
   8    1.0  -7.471E-04     1.451E-01     3.383E+02   -1.176E+04
   9    1.1  -8.539E-04     1.551E-01     3.383E+02   -1.176E+04
  10    1.2  -9.606E-04     1.645E-01     3.383E+02   -1.176E+04
  11    1.4  -1.067E-03     1.734E-01     3.383E+02   -1.176E+04
  12    1.5  -1.174E-03     1.819E-01     3.383E+02   -1.176E+04
  13    1.6  -1.281E-03     1.899E-01     3.383E+02   -1.176E+04
  14    1.8  -1.388E-03     1.977E-01     3.383E+02   -1.176E+04
  15    1.9  -1.494E-03     2.052E-01     3.383E+02   -1.176E+04
  16    2.1  -1.601E-03     2.124E-01     3.383E+02   -1.176E+04
  17    2.2  -1.708E-03     2.193E-01     3.383E+02   -1.176E+04
  18    2.3  -1.814E-03     2.261E-01     3.383E+02   -1.176E+04
  19    2.5  -1.921E-03     2.326E-01     3.383E+02   -1.176E+04
  20    2.6  -2.028E-03     2.390E-01     3.383E+02   -1.176E+04
  21    2.7  -2.135E-03     2.452E-01     3.365E+02   -1.147E+04
  22    2.9  -2.242E-03     2.513E-01     3.323E+02   -1.077E+04
  23    3.0  -2.349E-03     2.572E-01     3.281E+02   -1.007E+04
  24    3.1  -2.456E-03     2.630E-01     3.239E+02   -9.366E+03
  25    3.3  -2.563E-03     2.687E-01     3.197E+02   -8.666E+03
  26    3.4  -2.671E-03     2.743E-01     3.155E+02   -7.966E+03
  27    3.6  -2.778E-03     2.798E-01     3.113E+02   -7.266E+03
  28    3.7  -2.886E-03     2.851E-01     3.071E+02   -6.566E+03
  29    3.8  -2.994E-03     2.904E-01     3.029E+02   -5.866E+03
  30    4.0  -3.102E-03     2.956E-01     2.987E+02   -5.166E+03
  31    4.1  -3.211E-03     3.007E-01     2.945E+02   -4.466E+03
  32    4.2  -3.319E-03     3.058E-01     2.903E+02   -3.766E+03
  33    4.4  -3.428E-03     3.107E-01     2.861E+02   -3.066E+03
  34    4.5  -3.537E-03     3.156E-01     2.818E+02   -2.366E+03
  35    4.6  -3.646E-03     3.205E-01     2.776E+02   -1.666E+03
  36    4.8  -3.755E-03     3.252E-01     2.734E+02   -9.657E+02
  37    4.9  -3.864E-03     3.299E-01     2.692E+02   -2.657E+02
  38    5.1  -3.973E-03     3.346E-01     2.650E+02    4.343E+02
  39    5.2  -4.083E-03     3.391E-01     2.608E+02    1.134E+03
  40    5.3  -4.193E-03     3.437E-01     2.566E+02    1.834E+03
  41    5.5  -4.303E-03     3.481E-01     2.524E+02    2.534E+03
  42    5.6  -4.413E-03     3.526E-01     2.482E+02    3.234E+03
  43    5.7  -4.523E-03     3.569E-01     2.440E+02    3.934E+03
  44    5.9  -4.633E-03     3.613E-01     2.398E+02    4.634E+03
  45    6.0  -4.744E-03     3.656E-01     2.356E+02    5.334E+03
  46    6.2  -4.855E-03     3.698E-01     2.314E+02    6.034E+03
  47    6.3  -4.966E-03     3.740E-01     2.272E+02    6.734E+03
  48    6.4  -5.077E-03     3.782E-01     2.230E+02    7.434E+03
  49    6.6  -5.188E-03     3.823E-01     2.188E+02    8.134E+03
  50    6.7  -5.299E-03     3.864E-01     2.146E+02    8.834E+03
  51    6.8  -5.411E-03     3.904E-01     2.104E+02    9.534E+03
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 52    7.0  -5.523E-03   3.944E-01   2.062E+02   1.023E+04
 53    7.1  -5.634E-03   3.984E-01   2.019E+02   1.093E+04
 54    7.2  -5.746E-03   4.023E-01   1.977E+02   1.163E+04
 55    7.4  -5.859E-03   4.062E-01   1.935E+02   1.233E+04
 56    7.5  -5.971E-03   4.101E-01   1.893E+02   1.303E+04
 57    7.7  -6.083E-03   4.140E-01   1.851E+02   1.373E+04
 58    7.8  -6.196E-03   4.178E-01   1.809E+02   1.443E+04
 59    7.9  -6.309E-03   4.216E-01   1.767E+02   1.513E+04
 60    8.1  -6.422E-03   4.253E-01   1.725E+02   1.583E+04
 61    8.2  -6.535E-03   4.290E-01   1.683E+02   1.653E+04
 62    8.3  -6.648E-03   4.327E-01   1.641E+02   1.723E+04
 63    8.5  -6.762E-03   4.364E-01   1.599E+02   1.793E+04
 64    8.6  -6.875E-03   4.401E-01   1.557E+02   1.863E+04
 65    8.8  -6.989E-03   4.437E-01   1.515E+02   1.933E+04
 66    8.9  -7.103E-03   4.473E-01   1.473E+02   2.003E+04
 67    9.0  -7.217E-03   4.509E-01   1.431E+02   2.073E+04
 68    9.2  -7.331E-03   4.544E-01   1.388E+02   2.143E+04
 69    9.3  -7.446E-03   4.580E-01   1.346E+02   2.213E+04
 70    9.4  -7.560E-03   4.615E-01   1.304E+02   2.283E+04
 71    9.6  -7.675E-03   4.650E-01   1.262E+02   2.353E+04
 72    9.7  -7.790E-03   4.684E-01   1.220E+02   2.423E+04
 73    9.8  -7.905E-03   4.719E-01   1.178E+02   2.493E+04
 74   10.0  -8.020E-03   4.753E-01   1.136E+02   2.563E+04
 75   10.1  -8.136E-03   4.787E-01   1.094E+02   2.633E+04
 76   10.3  -8.251E-03   4.821E-01   1.052E+02   2.703E+04
 77   10.4  -8.367E-03   4.855E-01   1.010E+02   2.773E+04
 78   10.5  -8.483E-03   4.888E-01   9.678E+01   2.843E+04
 79   10.7  -8.599E-03   4.921E-01   9.257E+01   2.913E+04
 80   10.8  -8.715E-03   4.955E-01   8.836E+01   2.983E+04
 81   10.9  -8.831E-03   4.988E-01   8.415E+01   3.053E+04
 82   11.1  -8.948E-03   5.020E-01   7.995E+01   3.123E+04
 83   11.2  -9.064E-03   5.053E-01   7.574E+01   3.193E+04
 84   11.3  -9.181E-03   5.085E-01   7.153E+01   3.263E+04
 85   11.5  -9.298E-03   5.118E-01   6.732E+01   3.333E+04
 86   11.6  -9.415E-03   5.150E-01   6.311E+01   3.403E+04
 87   11.8  -9.533E-03   5.182E-01   5.891E+01   3.473E+04
 88   11.9  -9.650E-03   5.214E-01   5.470E+01   3.543E+04
 89   12.0  -9.768E-03   5.245E-01   5.049E+01   3.613E+04
 90   12.2  -9.886E-03   5.277E-01   4.628E+01   3.683E+04
 91   12.3  -1.000E-02   5.308E-01   4.207E+01   3.753E+04
 92   12.4  -1.012E-02   5.340E-01   3.787E+01   3.823E+04
 93   12.6  -1.024E-02   5.371E-01   3.366E+01   3.893E+04
 94   12.7  -1.036E-02   5.402E-01   2.945E+01   3.963E+04
 95   12.9  -1.048E-02   5.432E-01   2.524E+01   4.033E+04
 96   13.0  -1.060E-02   5.463E-01   2.103E+01   4.103E+04
 97   13.1  -1.071E-02   5.494E-01   1.683E+01   4.173E+04
 98   13.3  -1.083E-02   5.524E-01   1.262E+01   4.243E+04
 99   13.4  -1.095E-02   5.554E-01   8.408E+00   4.313E+04
100   13.5  -1.107E-02   5.585E-01   4.200E+00   4.383E+04
101   13.7  -1.119E-02   5.615E-01  -8.520E-03   4.453E+04
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PROGRAM CRCP-1 FOR HIGHWAYS,CFHR PROJECT 177
SENSITIVITY ANALYSIS BY C.P.CHIANG,FALL#74

PROB
   6     THE STUDY OF INTERACTION EFFECT,THREE FACTOR AT THREE LEVEL , PL DH FH

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


               TYPE OF LONGITUDINAL REINFORCEMENT IS
                          DEFORMED BARS


               PERCENT REINFORCEMENT = 5.500E-01
               BAR DIAMETER          = 7.500E-01
               YIELD STRESS          = 6.000E+04
               ELASTIC MODULUS       = 2.900E+07
               THERMAL COEFFICIENT   = 5.000E-06


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


               SLAB THICKNESS      = 9.000E+00
               THERMAL COEFFICIENT = 5.000E-06
               TOTAL SHRINKAGE     = 5.000E-04
               UNIT WEIGHT CONCRETE= 1.500E+02
               COMPRESSIVE STRENGTH= 4.000E+03


              TENSILE STRENGTH DATA
              *********************

               NO TENSILE STRENGTH DATA IS INPUT BY USER
               THE FOLLOWING AGE-TENSILE STRENGTH RELATIONSHIP
               IS USED WHICH IS BASED ON THE RECOMMENDATION
               GIVEN BY U.S. BUREAU OF RECLAMATION

               AGE,  TENSILE
              (DAYS) STRENGTH

                0.0     0.0
                1.0   130.4
                3.0   275.4
                5.0   346.4
                7.0   386.5
               14.0   450.5
               21.0   484.5
               28.0   500.0
```

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*******************************************************
*                                                     *
*       SLAB-BASE FRICTION CHARACTERISTICS            *
*               F-Y RELATIONSHIP                      *
*                                                     *
*******************************************************


     TYPE OF FRICTION CURVE IS A PARABOLA

      MAXIMUM FRICTION FORCE=    1.300
      MOVEMENT AT SLIDING   =    -.060


**********************************
*                                *
*       TEMPERATURE DATA         *
*                                *
**********************************


     CURING TEMPERATURE= 75.0


             MINIMUM        DROP IN
DAY        TEMPERATURE    TEMPERATURE

  1            62.0           13.0
  2            53.0           22.0
  3            43.0           32.0
  4            52.0           23.0
  5            62.0           13.0
  6            66.0            9.0
  7            58.0           17.0
  8            12.0           63.0
  9            66.0            9.0
 10            69.0            6.0
 11            64.0           11.0
 12            65.0           10.0
 13            61.0           14.0
 14            65.0           10.0
 15            63.0           12.0
 16            64.0           11.0
 17            68.0            7.0
 18            57.0           18.0
 19            48.0           27.0
 20            51.0           24.0
 21            59.0           16.0
 22            59.0           16.0
 23            50.0           25.0
 24            45.0           30.0
 25            47.0           28.0
 26            49.0           26.0
 27            49.0           26.0
 28            52.0           23.0

     MINIMUM TEMPERATURE EXPECTED AFTER
     CONCRETE GAINS FULL STRENGTH      =    0 DEGREES FARENHITE
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**************************************************
*                                                *
*       ITERATION AND TOLERANCE CONTROL          *
*                                                *
**************************************************

 MAXIMUM ALLOWABLE NUMBER OF ITERATIONS=   20

 RELATIVE CLOSURE TOLERANCE=  1.0 PERCENT
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PROGRAM CRCP-1 FOR HIGHWAYS,CFHR PROJECT 177
SENSITIVITY ANALYSIS BY C.P.CHIANG,FALL#74

PROB
  6     THE STUDY OF INTERACTION EFFECT,THREE FACTOR AT THREE LEVEL

                                                                MAXIMUM
 TIME    TEMP     DRYING    TENSILE   CRACK      CRACK      CONCRETE     STRESS IN
(DAYS)   DROP   SHRINKAGE   STRGTH   SPACING     WIDTH       STRESS      THE STEEL

   .39   10.0   1.769E-06    55.2     718.8   2.446E-03   4.658E+01   9.159E+03
   .50   13.0   2.268E-06    69.8     718.8   4.361E-03   6.699E+01   1.295E+04
  1.35   13.0   6.079E-06   159.9     718.8   6.768E-03   1.073E+02   1.979E+04
  1.50   22.0   6.742E-06   171.8     359.4   1.305E-02   1.478E+02   2.814E+04
  2.37   22.0   1.057E-05   235.3     359.4   1.502E-02   1.759E+02   3.300E+04
  2.50   32.0   1.114E-05   243.9     359.4   2.545E-02   2.318E+02   4.352E+04
  3.50   23.0   1.545E-05   294.5     359.4   1.805E-02   2.087E+02   3.877E+04
  4.50   13.0   1.970E-05   330.0     359.4   9.797E-03   1.605E+02   2.946E+04
  5.50    9.0   2.386E-05   356.9     359.4   7.331E-03   1.431E+02   2.603E+04
  6.34    9.0   2.730E-05   373.8     359.4   8.055E-03   1.529E+02   2.771E+04
  6.50   17.0   2.796E-05   376.9     359.4   1.579E-02   2.148E+02   3.923E+04
  7.29   17.0   3.116E-05   389.5     359.4   1.663E-02   2.235E+02   4.070E+04
  7.32   27.0   3.127E-05   389.8     359.4   2.767E-02   2.884E+02   5.278E+04
  7.35   37.0   3.139E-05   390.1     359.4   3.968E-02   3.454E+02   6.340E+04
  7.38   45.8   3.151E-05   390.4     179.7   3.084E-02   3.006E+02   5.581E+04
  7.42   55.8   3.168E-05   390.8     179.7   3.824E-02   3.349E+02   6.227E+04
  7.50   63.0   3.199E-05   391.6     179.7   4.369E-02   3.583E+02   6.666E+04
  8.50    9.0   3.594E-05   401.5     179.7   6.764E-03   1.425E+02   2.581E+04
  9.50    6.0   3.984E-05   411.0     179.7   5.542E-03   1.303E+02   2.338E+04
 10.34    6.0   4.306E-05   418.8     179.7   5.939E-03   1.360E+02   2.435E+04
 10.50   11.0   4.366E-05   420.3     179.7   8.977E-03   1.675E+02   3.025E+04
 11.50   10.0   4.743E-05   429.3     179.7   8.875E-03   1.681E+02   3.024E+04
 12.38   10.0   5.068E-05   436.9     179.7   9.319E-03   1.737E+02   3.117E+04
 12.50   14.0   5.113E-05   438.0     179.7   1.192E-02   1.966E+02   3.546E+04
 13.50   10.0   5.477E-05   446.4     179.7   9.886E-03   1.806E+02   3.234E+04
 14.41   10.0   5.802E-05   452.6     179.7   1.033E-02   1.859E+02   3.321E+04
 14.50   12.0   5.836E-05   453.1     179.7   1.166E-02   1.976E+02   3.539E+04
 15.50   11.0   6.188E-05   458.2     179.7   1.150E-02   1.972E+02   3.521E+04
 16.50    7.0   6.535E-05   463.2     179.7   9.425E-03   1.795E+02   3.177E+04
 17.31    7.0   6.814E-05   467.2     179.7   9.798E-03   1.838E+02   3.248E+04
 17.45   17.0   6.859E-05   467.8     179.7   1.645E-02   2.383E+02   4.268E+04
 17.50   18.0   6.877E-05   468.1     179.7   1.716E-02   2.434E+02   4.364E+04
 18.37   18.0   7.168E-05   472.3     179.7   1.759E-02   2.475E+02   4.432E+04
 18.50   27.0   7.213E-05   472.9     179.7   2.399E-02   2.893E+02   5.212E+04
 19.50   24.0   7.544E-05   477.6     179.7   2.237E-02   2.807E+02   5.040E+04
 20.50   16.0   7.870E-05   482.2     179.7   1.726E-02   2.477E+02   4.412E+04
 21.50   16.0   8.191E-05   485.7     179.7   1.773E-02   2.520E+02   4.481E+04
 22.36   16.0   8.464E-05   487.6     179.7   1.812E-02   2.553E+02   4.534E+04
 22.50   25.0   8.507E-05   487.9     179.7   2.455E-02   2.972E+02   5.318E+04
 23.41   25.0   8.790E-05   490.0     179.7   2.498E-02   3.004E+02   5.369E+04
 23.50   30.0   8.819E-05   490.2     179.7   2.866E-02   3.219E+02   5.769E+04
 24.50   28.0   9.126E-05   492.4     179.7   2.767E-02   3.170E+02   5.668E+04
 25.50   26.0   9.428E-05   494.6     179.7   2.667E-02   3.119E+02   5.564E+04
 26.50   26.0   9.726E-05   496.8     179.7   2.713E-02   3.153E+02   5.617E+04
 27.50   23.0   1.002E-04   498.9     179.7   2.540E-02   3.057E+02   5.429E+04
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 AT THE END OF THE ANALYSIS PERIOD

CRACK SPACING        = 3.743E+00 FEET
CRACK WIDTH          = 3.651E-02 INCHES
MAX CONCRETE STRESS= 3.634E+02 PSI
MAX STEEL STRESS     = 5.410E+04 PSI

STA-   DIS-    CONCRETE      FRICTION     CONCRETE       STEEL
TION   TANCE   MOVEMENT       FORCE        STRESS        STRESS

   1    0.0    0.            0.            3.634E+02   -1.175E+04
   2     .2   -1.752E-04    7.026E-02     3.634E+02   -1.175E+04
   3     .4   -3.505E-04    9.936E-02     3.634E+02   -1.175E+04
   4     .7   -5.257E-04    1.217E-01     3.634E+02   -1.175E+04
   5     .9   -7.010E-04    1.405E-01     3.634E+02   -1.175E+04
   6    1.1   -8.762E-04    1.571E-01     3.634E+02   -1.175E+04
   7    1.3   -1.051E-03    1.721E-01     3.634E+02   -1.175E+04
   8    1.6   -1.227E-03    1.859E-01     3.634E+02   -1.175E+04
   9    1.8   -1.402E-03    1.987E-01     3.633E+02   -1.175E+04
  10    2.0   -1.577E-03    2.108E-01     3.633E+02   -1.175E+04
  11    2.2   -1.752E-03    2.222E-01     3.633E+02   -1.175E+04
  12    2.5   -1.928E-03    2.330E-01     3.633E+02   -1.175E+04
  13    2.7   -2.103E-03    2.434E-01     3.633E+02   -1.175E+04
  14    2.9   -2.278E-03    2.533E-01     3.633E+02   -1.175E+04
  15    3.1   -2.453E-03    2.629E-01     3.633E+02   -1.175E+04
  16    3.4   -2.629E-03    2.721E-01     3.633E+02   -1.175E+04
  17    3.6   -2.804E-03    2.810E-01     3.633E+02   -1.175E+04
  18    3.8   -2.979E-03    2.897E-01     3.633E+02   -1.175E+04
  19    4.0   -3.154E-03    2.981E-01     3.633E+02   -1.175E+04
  20    4.3   -3.330E-03    3.063E-01     3.633E+02   -1.175E+04
  21    4.5   -3.505E-03    3.142E-01     3.633E+02   -1.175E+04
  22    4.7   -3.680E-03    3.220E-01     3.633E+02   -1.175E+04
  23    4.9   -3.855E-03    3.296E-01     3.633E+02   -1.175E+04
  24    5.2   -4.031E-03    3.370E-01     3.632E+02   -1.175E+04
  25    5.4   -4.206E-03    3.442E-01     3.632E+02   -1.175E+04
  26    5.6   -4.381E-03    3.513E-01     3.632E+02   -1.175E+04
  27    5.8   -4.557E-03    3.583E-01     3.632E+02   -1.175E+04
  28    6.1   -4.732E-03    3.651E-01     3.632E+02   -1.175E+04
  29    6.3   -4.907E-03    3.718E-01     3.632E+02   -1.175E+04
  30    6.5   -5.082E-03    3.784E-01     3.632E+02   -1.175E+04
  31    6.7   -5.258E-03    3.848E-01     3.632E+02   -1.175E+04
  32    7.0   -5.433E-03    3.912E-01     3.632E+02   -1.175E+04
  33    7.2   -5.608E-03    3.975E-01     3.594E+02   -1.106E+04
  34    7.4   -5.784E-03    4.036E-01     3.541E+02   -1.011E+04
  35    7.6   -5.960E-03    4.097E-01     3.488E+02   -9.147E+03
  36    7.9   -6.136E-03    4.157E-01     3.435E+02   -8.189E+03
  37    8.1   -6.313E-03    4.217E-01     3.382E+02   -7.230E+03
  38    8.3   -6.489E-03    4.276E-01     3.330E+02   -6.272E+03
  39    8.5   -6.667E-03    4.333E-01     3.277E+02   -5.314E+03
  40    8.8   -6.844E-03    4.391E-01     3.224E+02   -4.355E+03
  41    9.0   -7.022E-03    4.447E-01     3.171E+02   -3.397E+03
  42    9.2   -7.200E-03    4.504E-01     3.118E+02   -2.439E+03
  43    9.4   -7.378E-03    4.559E-01     3.066E+02   -1.480E+03
  44    9.7   -7.557E-03    4.614E-01     3.013E+02   -5.218E+02
  45    9.9   -7.736E-03    4.668E-01     2.960E+02    4.365E+02
  46   10.1   -7.916E-03    4.722E-01     2.907E+02    1.395E+03
  47   10.3   -8.095E-03    4.775E-01     2.854E+02    2.353E+03
  48   10.6   -8.275E-03    4.828E-01     2.801E+02    3.311E+03
  49   10.8   -8.455E-03    4.880E-01     2.749E+02    4.270E+03
  50   11.0   -8.636E-03    4.932E-01     2.696E+02    5.228E+03
  51   11.2   -8.817E-03    4.984E-01     2.643E+02    6.187E+03
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 52   11.5  -8.998E-03   5.035E-01   2.590E+02   7.145E+03
 53   11.7  -9.180E-03   5.085E-01   2.537E+02   8.103E+03
 54   11.9  -9.361E-03   5.135E-01   2.484E+02   9.062E+03
 55   12.1  -9.544E-03   5.185E-01   2.432E+02   1.002E+04
 56   12.4  -9.726E-03   5.234E-01   2.379E+02   1.098E+04
 57   12.6  -9.909E-03   5.283E-01   2.326E+02   1.194E+04
 58   12.8  -1.009E-02   5.332E-01   2.273E+02   1.289E+04
 59   13.0  -1.028E-02   5.380E-01   2.220E+02   1.385E+04
 60   13.3  -1.046E-02   5.428E-01   2.167E+02   1.481E+04
 61   13.5  -1.064E-02   5.475E-01   2.115E+02   1.577E+04
 62   13.7  -1.083E-02   5.523E-01   2.062E+02   1.673E+04
 63   13.9  -1.101E-02   5.569E-01   2.009E+02   1.769E+04
 64   14.2  -1.120E-02   5.616E-01   1.956E+02   1.864E+04
 65   14.4  -1.138E-02   5.662E-01   1.903E+02   1.960E+04
 66   14.6  -1.157E-02   5.708E-01   1.850E+02   2.056E+04
 67   14.8  -1.175E-02   5.754E-01   1.797E+02   2.152E+04
 68   15.0  -1.194E-02   5.799E-01   1.745E+02   2.248E+04
 69   15.3  -1.213E-02   5.844E-01   1.692E+02   2.344E+04
 70   15.5  -1.231E-02   5.889E-01   1.639E+02   2.439E+04
 71   15.7  -1.250E-02   5.934E-01   1.586E+02   2.535E+04
 72   15.9  -1.269E-02   5.978E-01   1.533E+02   2.631E+04
 73   16.2  -1.287E-02   6.022E-01   1.480E+02   2.727E+04
 74   16.4  -1.306E-02   6.066E-01   1.427E+02   2.823E+04
 75   16.6  -1.325E-02   6.110E-01   1.375E+02   2.919E+04
 76   16.8  -1.344E-02   6.153E-01   1.322E+02   3.014E+04
 77   17.1  -1.363E-02   6.196E-01   1.269E+02   3.110E+04
 78   17.3  -1.382E-02   6.239E-01   1.216E+02   3.206E+04
 79   17.5  -1.401E-02   6.282E-01   1.163E+02   3.302E+04
 80   17.7  -1.420E-02   6.324E-01   1.110E+02   3.398E+04
 81   18.0  -1.439E-02   6.366E-01   1.057E+02   3.494E+04
 82   18.2  -1.458E-02   6.408E-01   1.005E+02   3.589E+04
 83   18.4  -1.477E-02   6.450E-01   9.517E+01   3.685E+04
 84   18.6  -1.496E-02   6.492E-01   8.988E+01   3.781E+04
 85   18.9  -1.515E-02   6.533E-01   8.459E+01   3.877E+04
 86   19.1  -1.534E-02   6.574E-01   7.931E+01   3.973E+04
 87   19.3  -1.554E-02   6.615E-01   7.402E+01   4.069E+04
 88   19.5  -1.573E-02   6.656E-01   6.873E+01   4.164E+04
 89   19.8  -1.592E-02   6.697E-01   6.344E+01   4.260E+04
 90   20.0  -1.611E-02   6.737E-01   5.816E+01   4.356E+04
 91   20.2  -1.631E-02   6.777E-01   5.287E+01   4.452E+04
 92   20.4  -1.650E-02   6.818E-01   4.758E+01   4.548E+04
 93   20.7  -1.669E-02   6.857E-01   4.229E+01   4.644E+04
 94   20.9  -1.689E-02   6.897E-01   3.700E+01   4.739E+04
 95   21.1  -1.708E-02   6.937E-01   3.172E+01   4.835E+04
 96   21.3  -1.728E-02   6.976E-01   2.643E+01   4.931E+04
 97   21.6  -1.747E-02   7.016E-01   2.114E+01   5.027E+04
 98   21.8  -1.767E-02   7.055E-01   1.585E+01   5.123E+04
 99   22.0  -1.786E-02   7.094E-01   1.056E+01   5.219E+04
100   22.2  -1.806E-02   7.133E-01   5.274E+00   5.314E+04
101   22.5  -1.826E-02   7.171E-01  -1.437E-02   5.410E+04
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PROGRAM CRCP-1 FOR HIGHWAYS,CFHR PROJECT 177
SENSITIVITY ANALYSIS BY C.P.CHIANG,FALL 74

PROB
   7     THE STUDY OF EFFECTS OF REINFORCEMENT PERCENTAGE P=0.8

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


               TYPE OF LONGITUDINAL REINFORCEMENT IS
                          DEFORMED BARS


               PERCENT REINFORCEMENT = 8.000E-01
               BAR DIAMETER          = 6.250E-01
               YIELD STRESS          = 6.000E+04
               ELASTIC MODULUS       = 2.900E+07
               THERMAL COEFFICIENT   = 5.000E-06


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


               SLAB THICKNESS      = 9.000E+00
               THERMAL COEFFICIENT = 5.000E-06
               TOTAL SHRINKAGE     = 5.000E-04
               UNIT WEIGHT CONCRETE= 1.500E+02
               COMPRESSIVE STRENGTH= 3.500E+03


              TENSILE STRENGTH DATA
              *********************

               NO TENSILE STRENGTH DATA IS INPUT BY USER
               THE FOLLOWING AGE-TENSILE STRENGTH RELATIONSHIP
               IS USED WHICH IS BASED ON THE RECOMMENDATION
               GIVEN BY U.S. BUREAU OF RECLAMATION

               AGE,  TENSILE
              (DAYS) STRENGTH

                0.0    0.0
                1.0  116.0
                3.0  249.5
                5.0  316.8
                7.0  355.4
               14.0  417.8
               21.0  451.3
               28.0  466.7
```

```
**********************************************
*                                            *
*      SLAB-BASE FRICTION CHARACTERISTICS    *
*              F-Y RELATIONSHIP              *
*                                            *
**********************************************


     TYPE OF FRICTION CURVE IS A PARABOLA

      MAXIMUM FRICTION FORCE=   1.300
      MOVEMENT AT SLIDING   =   -.060


****************************
*                          *
*      TEMPERATURE DATA    *
*                          *
****************************


     CURING TEMPERATURE= 75.0


          MINIMUM       DROP IN
DAY     TEMPERATURE   TEMPERATURE

  1         62.0         13.0
  2         53.0         22.0
  3         43.0         32.0
  4         52.0         23.0
  5         62.0         13.0
  6         66.0          9.0
  7         58.0         17.0
  8         12.0         63.0
  9         66.0          9.0
 10         69.0          6.0
 11         64.0         11.0
 12         65.0         10.0
 13         61.0         14.0
 14         65.0         10.0
 15         63.0         12.0
 16         64.0         11.0
 17         68.0          7.0
 18         57.0         18.0
 19         48.0         27.0
 20         51.0         24.0
 21         59.0         16.0
 22         59.0         16.0
 23         50.0         25.0
 24         45.0         30.0
 25         47.0         28.0
 26         49.0         26.0
 27         49.0         26.0
 28         52.0         23.0

     MINIMUM TEMPERATURE EXPECTED AFTER
     CONCRETE GAINS FULL STRENGTH      =    0 DEGREES FARENHITE
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*************************************************
*                                               *
*       ITERATION AND TOLERANCE CONTROL         *
*                                               *
*************************************************

 MAXIMUM ALLOWABLE NUMBER OF ITERATIONS=   20

 RELATIVE CLOSURE TOLERANCE=  1.0 PERCENT
```

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PROGRAM CRCP-1 FOR HIGHWAYS,CFHR PROJECT 177
SENSITIVITY ANALYSIS BY C.P.CHIANG,FALL 74

PROB
   7      THE STUDY OF EFFECTS OF REINFORCEMENT PERCENTAGE P=0.8


                                                                      MAXIMUM
  TIME    TEMP     DRYING    TENSILE   CRACK      CRACK       CONCRETE     STRESS IN
 (DAYS)   DROP    SHRINKAGE   STRGTH  SPACING     WIDTH        STRESS      THE STEEL

   .39    10.0   1.769E-06     48.7   1000.0   9.009E-04    4.486E+01    6.753E+03
   .42    11.2   1.886E-06     51.7    500.0   1.164E-03    5.080E+01    7.703E+03
   .42    11.6   1.925E-06     52.7    250.0   1.174E-03    5.094E+01    7.814E+03
   .50    13.0   2.268E-06     61.6    125.0   1.375E-03    5.752E+01    8.750E+03
  1.35    13.0   6.079E-06    142.8    125.0   1.968E-03    9.001E+01    1.265E+04
  1.50    22.0   6.742E-06    153.7    125.0   4.507E-03    1.395E+02    1.959E+04
  2.37    22.0   1.057E-05    212.1    125.0   5.168E-03    1.666E+02    2.280E+04
  2.50    32.0   1.114E-05    220.1     62.5   5.818E-03    1.786E+02    2.446E+04
  3.50    23.0   1.545E-05    267.6     62.5   4.165E-03    1.621E+02    2.178E+04
  4.50    13.0   1.970E-05    301.2     62.5   2.339E-03    1.271E+02    1.673E+04
  5.50     9.0   2.386E-05    326.9     62.5   1.775E-03    1.143E+02    1.479E+04
  6.34     9.0   2.730E-05    343.1     62.5   1.929E-03    1.216E+02    1.563E+04
  6.50    17.0   2.796E-05    346.1     62.5   3.605E-03    1.668E+02    2.170E+04
  7.29    17.0   3.116E-05    358.2     62.5   3.772E-03    1.730E+02    2.241E+04
  7.32    27.0   3.127E-05    358.5     62.5   6.065E-03    2.195E+02    2.867E+04
  7.35    37.0   3.139E-05    358.8     62.5   8.503E-03    2.599E+02    3.411E+04
  7.38    47.0   3.152E-05    359.1     62.5   1.104E-02    2.963E+02    3.901E+04
  7.43    57.0   3.171E-05    359.6     62.5   1.365E-02    3.297E+02    4.349E+04
  7.50    63.0   3.199E-05    360.3     62.5   1.526E-02    3.488E+02    4.606E+04
  8.50     9.0   3.594E-05    369.6     62.5   2.311E-03    1.373E+02    1.742E+04
  9.50     6.0   3.984E-05    379.1     62.5   1.888E-03    1.254E+02    1.569E+04
 10.34     6.0   4.306E-05    386.7     62.5   2.024E-03    1.310E+02    1.632E+04
 10.50    11.0   4.366E-05    388.1     62.5   3.077E-03    1.617E+02    2.043E+04
 11.50    10.0   4.743E-05    396.9     62.5   3.041E-03    1.624E+02    2.038E+04
 12.38    10.0   5.068E-05    404.4     62.5   3.195E-03    1.678E+02    2.099E+04
 12.50    14.0   5.113E-05    405.4     62.5   4.098E-03    1.903E+02    2.398E+04
 13.50    10.0   5.477E-05    413.7     62.5   3.402E-03    1.741E+02    2.168E+04
 14.41    10.0   5.802E-05    419.8     62.5   3.572E-03    1.785E+02    2.215E+04
 14.50    12.0   5.836E-05    420.3     62.5   4.036E-03    1.897E+02    2.364E+04
 15.50    11.0   6.188E-05    425.3     62.5   3.994E-03    1.888E+02    2.340E+04
 16.50     7.0   6.535E-05    430.2     62.5   3.279E-03    1.711E+02    2.092E+04
 17.31     7.0   6.814E-05    434.1     62.5   3.418E-03    1.748E+02    2.132E+04
 17.45    17.0   6.859E-05    434.8     62.5   5.759E-03    2.269E+02    2.825E+04
 17.50    18.0   6.877E-05    435.0     62.5   6.010E-03    2.318E+02    2.889E+04
 18.37    18.0   7.168E-05    439.1     62.5   6.176E-03    2.350E+02    2.922E+04
 18.50    27.0   7.213E-05    439.8     62.5   8.437E-03    2.747E+02    3.449E+04
 19.50    24.0   7.544E-05    444.4     62.5   7.880E-03    2.655E+02    3.316E+04
 20.50    16.0   7.870E-05    449.0     62.5   6.090E-03    2.335E+02    2.878E+04
 21.50    16.0   8.191E-05    452.4     62.5   6.267E-03    2.369E+02    2.913E+04
 22.36    16.0   8.464E-05    454.4     62.5   6.412E-03    2.397E+02    2.941E+04
 22.50    25.0   8.507E-05    454.7     62.5   8.693E-03    2.791E+02    3.463E+04
 23.41    25.0   8.790E-05    456.7     62.5   8.852E-03    2.817E+02    3.488E+04
 23.50    30.0   8.819E-05    456.9     62.5   1.016E-02    3.017E+02    3.754E+04
 24.50    28.0   9.126E-05    459.1     62.5   9.815E-03    2.966E+02    3.676E+04
 25.50    26.0   9.428E-05    461.3     62.5   9.471E-03    2.914E+02    3.597E+04
 26.50    26.0   9.726E-05    463.4     62.5   9.640E-03    2.941E+02    3.623E+04
 27.50    23.0   1.002E-04    465.6     62.5   9.033E-03    2.847E+02    3.489E+04
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 PROGRAM IS TERMINATED.  THE BOND
LENGTH IS GREATER THAN THE CRCP
MODEL.  UNFORTUNATELY, FOR THIS
CONDITION, THE THEORETICAL EQUATIONS
DO NOT HOLD TRUE.
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APPENDIX 3

TABLES DESCRIBING THE SINGLE FACTORIAL EXPERIMENT AND ITS OUTPUT DATA

TABLE A3.1. THE NUMERICAL VALUES OF INPUT VARIABLES FOR THE SINGLE FACTORIAL EXPERIMENT.

Variable Number	Variable	Low	Medium	High
1	Reinforcement (percent)	0.4	0.6	0.7
2	Bar diameter (inches)	0.5	0.625	0.75
3	Yielding stress (psi)	4.0×10^{4}	6.0×10^{4}	7.0×10^{4}
4	Elastic modulus of steel (psi)	2.0×10^{7}	2.9×10^{7}	3.0×10^{7}
5	Thermal coefficient of steel(in/in)	3.2×10^{-6}	5.0×10^{-6}	7.0×10^{-6}
6	Transverse wire spacing (inches)	12	18	24
7	Thickness of concrete slab (inches)	6	9	12
8	Thermal coefficient of concrete	3.2×10^{-6}	5.0×10^{-6}	7.0×10^{-6}
9	Drying shrinkage of concrete (in/in)	3.0×10^{-4}	5.0×10^{-4}	6.5×10^{-4}
10	Unit weight of concrete (pcf)	120	150	160
11	Concrete compressive strength (psi)	2.5×10^{3}	3.5×10^{3}	6.0×10^{3}
12	Concrete tensile strength (psi)	385	467	600
13	Maximum slab-base friction (lbs/in)	1.0	1.3	2.3
14	Movement at sliding (inches)	-0.01	-0.06	-0.044
15	Concrete curing temperature (°F)	45	75	85

TABLE A3.2. CRACKING AND STRESS OUTPUT DATA FOR MEDIUM LEVEL SOLUTIONS

	Low Level					High Level				
Variable	Percent of Medium Values	Crack Spacing (feet)	Crack Width (inches)	Maximum Concrete Stress (psi)	Maximum Steel Stress (psi)	Percent of Medium Value	Crack Spacing (feet)	Crack Width (inches)	Maximum Concrete Stress (psi)	Maximum Steel Stress (psi)
Reinforcement (percent)	67	5.1	0.049	337	72020	117	1.7	0.017	338	36410
Bar diameter (inches)	80	1.8	0.018	335	44030	120	2.9	0.029	339	44630
Yielding stress (psi)	67	2.3	0.022	338	44530	117	2.3	0.022	338	44530
Elastic modulus (psi)	69	3.3	0.032	336	47780	104	2.2	0.022	338	44060
Thermal coefficient (in/in)	64	2.8	0.023	339	44650	140	1.9	0.022	335	43950
Transverse wire spacing (inches)	-	-	-	-	-	-	-	-	-	-
Concrete slab thickness (inches)	67	2.3	0.022	339	44530	133	2.3	0.022	338	44530
Concrete drying shrinkage (in/in)	60	3.1	0.026	340	50590	130	1.9	0.022	335	39600
Concrete unit weight (pcf)	80	2.4	0.023	342	46170	107	2.2	0.022	334	43580
Concrete compressive strength (psi)	71	1.6	0.016	280	34610	172	3.7	0.036	435	60430
Concrete tensile strength (psi)	82	1.6	0.016	280	34610	128	3.7	0.036	435	60430
Maximum slab-base friction (lbs/in)	77	2.3	0.022	339	44530	156	2.3	0.022	339	44530
Movement at sliding (inches)	17	2.3	0.022	339	44530	73	2.3	0.022	339	44530
Concrete curing temperature (°F)	60	2.9	0.023	340	44800	113	1.8	0.019	310	39650

crack spacing: the mean value $\bar{X}$ = 2.5 feet
the standard deviation S_i = 0.79 feet
the coefficient of variation V = 31.6 percent

crack width: the mean value ΔX = 0.024 inches
the standard deviation $S_{\Delta x}$ = 0.007 inches
the coefficient of variation V = 29.17 percent

maximum concrete stress: the mean value σ_c = 339.88 psi
the standard deviation $S_{\sigma c}$ = 32.44 psi
the coefficient of variation V = 9.54 percent

maximum steel stress: the mean value σ_s = 45702 psi
the standard deviation $S_{\sigma s}$ = 7971 psi
the coefficient of variation V = 1.74 percent

TABLE A3.3. CRACKING AND STRESS OUTPUT DATA FOR LOW LEVEL SOLUTIONS

	Medium Level				High Level			
Variable	Crack Spacing (feet)	Crack Width (inches)	Maximum Concrete Stress (psi)	Maximum Steel Stress (psi)	Crack Spacing (feet)	Crack Width (inches)	Maximum Concrete Stress (psi)	Maximum Steel Stress (psi)
Reinforcement (percent)	4.9	0.019	292	44880	3.6	0.014	291	37970
Bar diameter (inches)	13.0	0.051	287	65620	17.6	0.069	284	63630
Yielding stress (psi)	10.0	0.039	287	66270	10.1	0.039	287	66270
Elastic modulus (psi)	7.2	0.028	288	65680	7.2	0.028	292	66570
Thermal coefficient (in/in)	7.8	0.039	282	65500	6.5	0.039	284	66230
Transverse wire spacing (inches)	7.8	0.033	235	53320	10.5	0.044	239	53600
Concrete slab thickness (inches)	10.4	0.040	288	67290	10.4	0.041	287	67320
Concrete drying shrinkage (in/in)	6.2	0.040	284	62450	4.7	0.039	282	59000
Concrete unit wieght (pcf)	8.8	0.038	283	64730	8.5	0.038	281	64130
Concrete compressive strength (psi)	15.0	0.057	350	81030	23.4	0.090	447	102900
Concrete tensile strength (psi)	15.0	0.057	350	81030	23.4	0.090	447	102900
Maximum slab-base friction (lbs/in)	10.4	0.040	288	67300	9.8	0.039	283	65280
Movement at sliding (inches)	10.4	0.040	288	67300	9.8	0.038	283	65280
Concrete curing temperature (°F)	7.8	0.040	287	66660	7.2	0.039	285	66300

Basic low level solution (type of longitudinal reinforcement is deformed bars):

crack spacing: the mean value $\bar{X}$ = 10.26 feet
the standard deviation S_1 = 4.86 feet
the coefficient of variation V = 47.37 percent

crack width: the mean value ΔX = 0.043 inches
the standard deviation $S_{\Delta x}$ = 0.017 inches
the coefficient of variation V = 39.53 percent

maximum concrete stress: the mean value σ_c = 299 psi
the standard deviation $S_{\sigma c}$ = 7 psi
the coefficient of variation V = 39.53 percent

maximum steel stress: the mean value σ_s = 66656 psi
the standard deviation $S_{\sigma s}$ = 13321 psi
the coefficient of variation V = 19.98 percent

TABLE A3.4. CRACKING AND STRESS OUTPUT FOR HIGH LEVEL SOLUTIONS

	Low Level				Medium Level			
Variable	Crack Spacing (feet)	Crack Width (inches)	Maximum Concrete Stress (psi)	Maximum Steel Stress (psi)	Crack Spacing (feet)	Crack Width (inches)	Maximum Concrete Stress (psi)	Maximum Steel Stress (psi)
Reinforcement (percent)	6.2	0.088	425	88070	2.9	0.041	429	54290
Bar diameter (inches)	*	*	*	*	*	*	*	*
Yield stress (psi)	*	*	*	*	*	*	*	*
Elastic modulus (psi)	3.1	0.044	426	49320	*	*	*	*
Thermal coefficient (in/in)	2.9	0.031	431	44430	2.4	0.030	428	43980
Transverse wire spacing (inches)	2.3	0.032	560	63560	*	*	*	*
Concrete slab thickness (inches)	*	*	*	*	*	*	*	*
Concrete drying shrinkage (in/in)	2.2	0.023	369	45740	*	*	*	*
Concrete unit weight (pcf)	*	*	*	*	*	*	*	*
Concrete compressive strength (psi)	*	*	*	*	*	*	*	*
Concrete tensile strength (psi)	*	*	*	*	*	*	*	*
Maximum slab-base friction (lbs/in)	*	*	*	*	*	*	*	*
Movement at sliding (inches)	*	*	*	*	*	*	*	*
Concrete curing temperature (°F)	2.8	0.030	430	44220	*	*	*	*

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*Variation at this level was not studied because the bond length is greater than the CRCP model, and the theoretical equations do not hold true. (Refer to Chapter 6.)

NOTE: The basic high level solution was not studied here for the reason described above.

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