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16. Abstract

The sensitivity of the design variables to the behavior of continuously reinforced concrete pavement (CRCP) has been investigated using mechanistic models of CRCP. The objective of the sensitivity study was to understand how much each variable affects the CRCP behavior, and to determine the relative importance of each variable, and to compare the results from CRCP-8 and CRCP-10. The practical ranges of the design variables have been selected and the typical values of the variables have been determined. In the sensitivity analysis, one variable is selected and changes within the practical range while the other variables remain at their typical values, and the analysis results such as mean crack spacing, crack width, and steel stress at crack are obtained. From this study, the relationships between the design variables and the CRCP behavior have been obtained. It has been found that the zero-stress temperature and the coefficient of thermal expansion of concrete are the most sensitive design variables, and the steel bar diameter and the vertical stiffness of underlying layers are the least sensitive variables. The other variables can be defined as moderately sensitive variables. Since engineers have only limited resources and time to use in estimating a large number of design variables, the findings described in this report can be applied to aid in solving real problems more efficiently.

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Sensitivity Analysis of CRCP Computer Programs

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Research Report 1700-4

Research Project 0-1700
Improving Portland Cement Concrete Pavement Performance

Conducted for the
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by the
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1. Introduction

The overall objectives of Project 1700, "Improving Portland Cement Concrete Pavement Performance," are to improve the performance of Portland Cement Concrete pavements and to mitigate premature failures. Task 7 of the study pertains to improving the rigid pavement computer programs so that more reliable pavement designs may be developed. The current program in the development sequence is the CRCP-10 Program. This report documents the initial validation step for the program. The first section of this chapter provides the sequential evolution of CRCP-10 followed by a section briefly describing revisions in progress.

1.1 Background

The first mechanistic model, CRCP-1, was developed in the mid-1970s under a study sponsored by the National Cooperative Highway Research Program (NCHRP) (Ref 1). CRCP-2 was developed in 1977 by extending the original steel stress model to cover situations where development length under the influence of high frictional resistance might exceed half the crack spacing (Ref 2). In 1991 Won et al. developed an improvement to the CRCP program, CRCP-5, which simulates material variance to concrete tensile strength and includes fatigue failure models (Ref 3). The normalized curing curves were determined for different coarse aggregates commonly used in Texas pavements (Ref 4), and these curves and the calibrated failure prediction model were included in CRCP-7 (Ref 5). In 1995 previous versions of the CRCP programs were integrated into one program, CRCP-8, with simplification of the user input process (Ref 6).

Although CRCP-8 has permitted pavement engineers to develop and evaluate designs of CRCP, there are some limitations due to the simplified assumptions in the one-dimensional analysis. In 1996 a research project was conducted to expand the ability of the mechanistic model by incorporating the variations in temperature and moisture changes through the depth of concrete slab. As a result of the project, a two-dimensional finite element model of CRCP was developed (Refs 7, 8). In 1998 the Texas Department of Transportation (TxDOT) decided to extend the project to complete the development of a new mechanistic model, CRCP-9. CRCP-9 uses two-dimensional finite element theories to reduce the cost of computation, but to increase the accuracy of the 2-D model, three-dimensional analyses were also performed, and the differences between 2-D and 3-D analyses results were investigated (Ref 9). In CRCP-9 the external wheel load stresses are calculated considering a static single wheel load (Ref 10). To include the effect of the moving dynamic tandem-axle loads, a new wheel load stress calculation procedure was developed and integrated into the CRCP-10 computer program (Refs 11, 12, 13).

1.2 Improvements in Progress

As a result of developments in Task 1, the program PavePro was developed to predict the concrete temperature development during the first three days, considering mixture proportions, properties, admixtures, ambient temperatures, etc. This program is being inserted into CRCP-10 to predict the concrete temperature spectrum. This modification of the program will not change the results of the sensitivity analysis, since the concrete temperature is one of the parameters considered in the sensitivity analysis.

In addition, the CRCP-10 program is being revised to be more “user-friendly” using a windows-based user interface. These changes will not impact on the findings herein. Thus, the CRCP-10 improvements currently underway in other tasks will not alter the guidelines, conclusions, and recommendations developed herein.

1.3 Maximizing CRCP-10 Accuracy and Reliability

To maximize the accuracy and reliability of the program, a calibration and validation with field data needed to be performed. Since CRCP-8 has been calibrated previously, and validation studies have shown very close agreement with field data, the results from CRCP-10 were compared with those from CRCP-8 before performing the calibration with field data.

The design variables in CRCP are sensitive to various degrees to crack spacing, crack width, and stresses in concrete and steel bars. When a new CRCP is designed or an existing CRCP is evaluated, engineers should review a large number of design variables that affect the CRCP behavior. Since engineers have only limited resources and time to use in estimating the design variables, it will be useful if the relative importance of each design variable is determined.

Hence, the process of maximizing the accuracy and reliability of CRCP-10 is a three-step process as follows:

- The first step is to evaluate the viability of the program by comparing it to the CRCP-8 program and to apply a “test of reasonableness” to the output for realistic input values.
- The second step is to rank the input variables as to their significance on affecting the output.
- The third step is to calibrate if needed and to validate using existing data or from test sections constructed with a range of the significant variables.

The material presented herein pertains to the first two steps. Thus, after the results are evaluated, the third step will be organized, developed, and then used for calibration and/or validation.

1.4 Report Objectives

The objective of this report is to document the results of the initial steps in the process of maximizing the accuracy and reliability of the CRCP-10 program. The secondary objectives are as follows:

- Compare the output of the CRCP-8 and CRCP-10 programs using identical input insofar as possible that reflects the range of variables that may be experienced. These results are then used to apply a “test of reasonableness to the output values.”
- Once the CRCP-10 output is deemed satisfactory, the input variables will be ranked as to their effect on the sensitivity of the output.

1.5 Scope of Study and Report

As described in section 1.3, the process of maximizing the accuracy and reliability of CRCP-10 includes three steps. This report presents the studies for the first and second steps of the process. The study for the third step, calibration and validation, is being conducted and will be documented in a separate report.

The outputs of mean crack spacing, crack width, and steel stress have been used in thi s study to investigate the CRCP behavior. The output as to the prediction of failure has not been used, since the behavior output is used as input into the failure algorithm.

This report consists of seven chapters. The background and objective of this study are presented in Chapter 1. The experiment concepts for design variables are explained in Chapter 2. In Chapter 3 the practical ranges of the design variables are presented. Chapter 4 describes the sensitivity analysis with medium basic level. The sensitivity analysis with high and medium basic levels is presented in Chapter 5. Chapter 6 describes the discussion of the results. Chapter 7 includes summary, conclusions, and recommendations.

2. Experiment Concepts for Design Variables

In the CRCP computer program there are many input variables including material properties, external wheel loads, and climatic loads. To perform a sensitivity study effectively, one should consider what method of analysis will be used and how the input variables will be grouped.

2.1 Characterization of CRCP Programs

Figure 2.1 shows the conceptual diagram of CRCP program. A large number of input variables are used to define geometry, concrete and steel material properties, bond-slip relationships between concrete and steel and between concrete slab and base layer, and climatic and wheel loads. The outputs include crack spacing, crack width, steel stress, and punchouts. The prediction of spalling and horizontal cracking will be included in the next v ersion of the CRCP program.

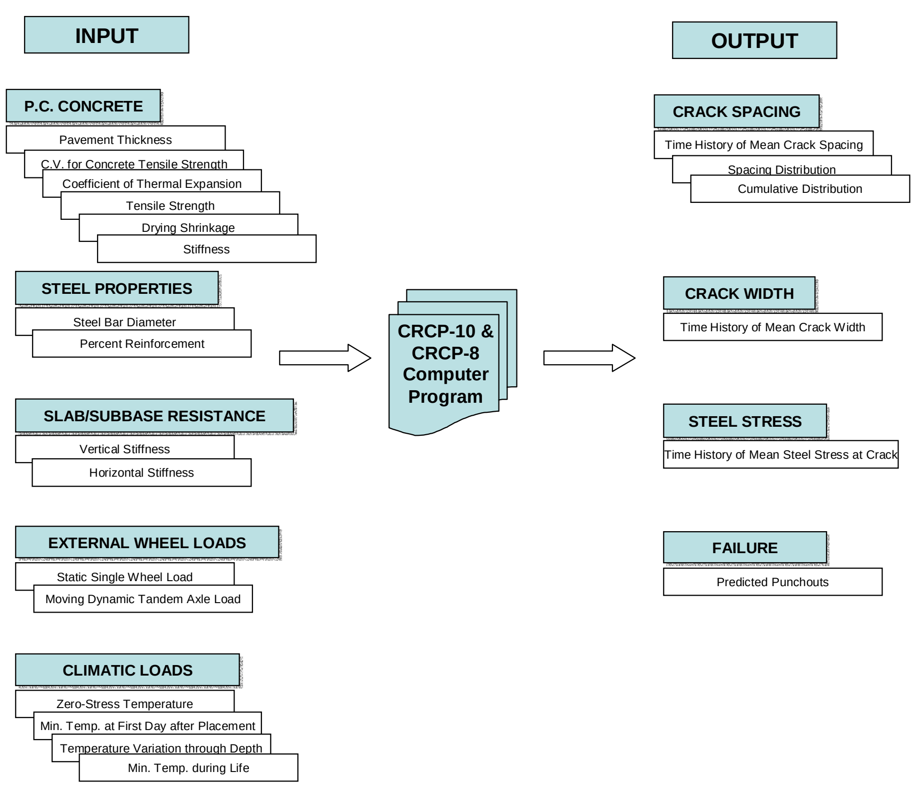


Figure 2.1 Conceptual diagram of the CRCP program

2.1.1 Inputs

Input variables can be grouped as time-related variables such as tensile strength and temperature, and fixed variables such as steel properties and pavement thickness. Input variables can also be grouped as PCC properties, steel properties, slab/subbase resistance, external wheel loads, and climatic loads. In this report, the last of these is selected for grouping purposes.

2.1.2 Outputs

The analysis results from the CRCP program include time histories of mean crack spacing, crack width and steel stress at crack, crack spacing distribution, cumulative crack spacing, distribution, and the number of punchouts related to the wheel load applications.

The punchout failure is predicted using the crack spacings obtained as an output behavior. In the CRCP-10 program users should define moisture and temperature variations through the depth of the concrete slab. This input process is very important and not easy. In the next version of the CRCP program, the moisture and temperature variations through the slab depth will be predicted using the computer programs developed as part of the 1700 project, such as PavePro and TMAC[2]. The distress manifestation prediction in CRCP-10 includes only punchouts. Spalling and horizontal cracking predictions will be included in the next version of the CRCP program.

2.2 Method of Analysis

2.2.1 Selection of Limits for Input Variables

Before conducting the sensitivity study of input variables, the practical ranges of the variables should be determined. In this study, a typical value and two extreme values of each variable are selected and denoted by medium, low, and high values of the variable, respectively. Intermediate values are adapted when needed to develop break points on output curve.

2.2.2 Description of Process

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, 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. That is, 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. Similar procedures have been conducted to investigate the effect of each variable when all the other variables are held at their low or high levels.

2.2.3 Output Presentation

Output presentations are divided into two parts: absolute values and relative values. Absolute values mean the predicted output values from the program. To understand easily the sensitivity of each input variable, the results with medium input values assign one hundred percent, and the results with other input values are transferred as relative percentages of the results with medium values. These values are denoted *relative values* in this report.

Each output result will be demonstrated with a table and then a graph.

2.3 Evaluating Output

2.3.1 Comparison of CRCP-8 and CRCP-10

The CRCP-10 program should be examined to evaluate the viability of the program that can be done by comparing the results from CRCP-10 and CRCP-8. Regarding sensitivity analysis, relative values are more effective in comparing results.

2.3.2 Test of Reasonableness and Comparison to Field Data

Since CRCP-8 has previously been calibrated and validation studies have shown good agreement with field data, the results from CRCP-10 have been compared with those from CRCP-8 (i.e., absolute values and relative values).

In CRCP cracks are allowed to develop randomly over time. However, the pavement is designed to produce a stable crack spacing after a year or two that generally has a mean value between 3 ft. and 8 ft. Figure 2.2 shows four conceptual crack spacing distributions to demonstrate the range of conditions found in the field. Notice that the "ideal" crack spacing has all cracks at a uniform spacing between 5 ft. and 8 ft. apart. "Poor" distribution results when punchouts are likely to occur due to a large number of small crack spacings, e.g., 50% of the spacings are less than 3 ft. for the illustration. The "fair" distribution has a small number of crack spacings under 3 ft., but may not be desirable because the steel stress may become too high since the cracks are very far apart, especially with SRG coarse aggregates. The "good" distribution represents realistic acceptable crack spacing because only 10% of the cracks are less than 3 ft apart (Ref 14).

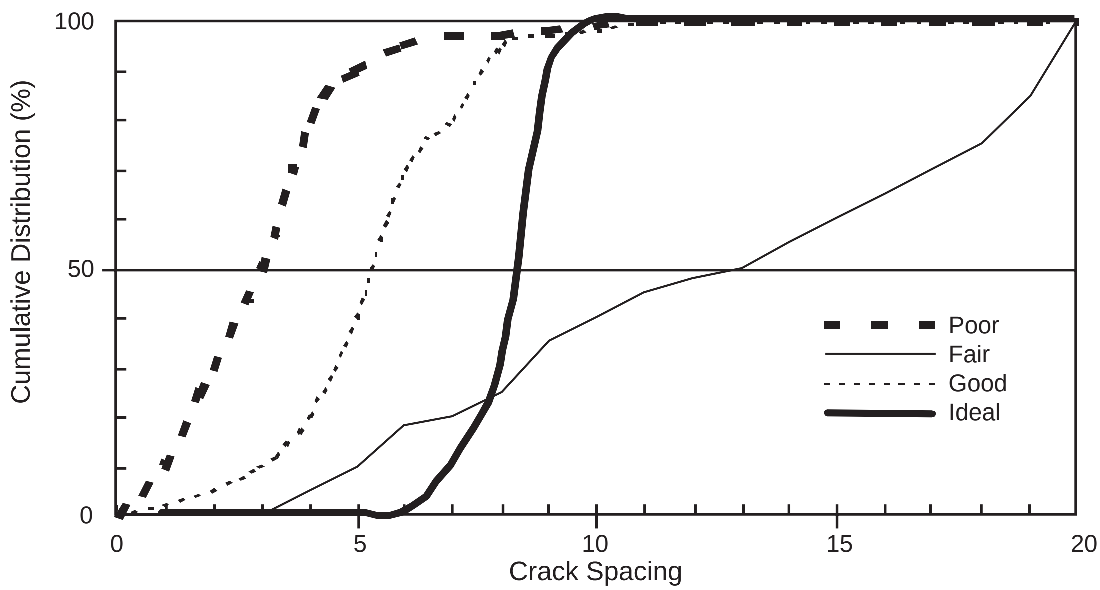


Figure 2.2   Conceptual crack spacing distributions (Ref 14)

The pavement's crack width is important in CRCP and generally should be no more than 0.025 in. at 32°F (0 °C), i.e., the freezing point of water. Steel is, therefore, used in CRCP to resist the concrete contraction so that the crack widths will remain small. By so doing, water will not penetrate the pavement, and load transfer is maximized. As the crack width increases the load transfer due to aggregate interlock is reduced. Eventually, deflection spalling will occur at the cracks.

For design temperatures below freezing, the crack widths may be more than 0.025 in., since the frozen conditions will not permit penetration of water. If the cracks are too large and material enters into them, crushing or other distresses of the pavement can result as the cracks attempt to close when hot or moist conditions prevail. If that occurs, the pavement can no longer function as it was designed (Ref 14).

Recently, although steel stresses in CRCP were measured by using strain gauges in the field, the database is not extensive enough to be utilized for calibration and/or validation.

2.4 Ranking for Implementation

2.4.1 Methodology

To rank the input variables as to their significance, relative graphs are used to obtain percentage change in behavior parameter for expected range of input predictor variable (i.e., low to high). Then, levels of significance for the behavior parameters are developed by inputting into the distress prediction algorithms.

2.4.2 Implementation

Using the results from the sensitivity study, significant input variables for design can be identified. The significant input variables should then be included in specifications, construction, guidelines, etc.

3. Characterization of Input Variables

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. A three-level experiment was established here; each input variable was given low, medium, and high values, based on engineering judgment and literature reviews (Refs 3, 4, 5,14, 15). Medium levels are those that 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.

3.1 Portland Cement Concrete

In the CRCP computer program, the parameters of Portland cement concrete properties include pavement thickness, tensile strength and its variation, and coefficient of thermal expansion.

3.1.1 Pavement Thickness

Over the years, a majority of pavements were 8 inches, the maximum thickness allowed by FHWA. Sometimes pavement thicknesses as low as 6 inches were used. Recently thicknesses of 15 inches on heavy-duty highways are used. A typical pavement thickness is 12 inches in Texas. Table 3.1 shows the examples of field data for pavement thickness on recent projects in Texas.

An increase in slab thickness reduces wheel load stresses, and thicker slabs result in larger crack spacing (Ref 5). In this study, three pavement thicknesses 6, 12, and 15 inches are selected.

Table 3.1 Typical pavement thickness used on the projects

Project	Date	Thickness	Project	Date	Thickness
SH 6-Summer	June 1989	11 in.	El Paso 1	Sep, 1995	13 in.
BW 8-Winter	Nov. 1981	10 in.	El Paso 2	Sep, 1996	13 in.
SH 6-Winter	Jan. 1990	11 in.	El Paso 3	Jan., 1997	13 in.
IH-45 Winter	Jan. 1990	15 in.	Fort Worth	July, 2001	9 in.

3.1.2 Coefficient of Variation for Concrete Tensile Strength

Concrete strength varies considerably with mixing properties and curing conditions. Material variability, especially that of tensile strength, has a large influence on the crack development pattern.

Table 3.2 is a summary of coefficients of variation for concrete tensile strength as recorded by the indicated authors and studies. The studies include values measured from construction as well as laboratory studies. The coefficient of variation may be calculated by equation 3.1 (Ref 16).

$$CV = \frac{S_x}{\bar{x}} \tag{3.1}$$

where

CV = Coefficient of variation

S_x = Standard deviation estimate

$\bar{x}$ = Average

Table 3.2 Previously recorded coefficients of variation for concrete tensile strength (Ref 16)

Test Variables	C.V. (%)
AASHO road test, flexural strength (Hudson, 1963)	11~18
Texas Highway Department, flexural strength (Schleider, 1959)	14~21
Splitting tensile test lab study, 6 × 12” concrete cylinders (Wright, 1967)	5
Flexural beam test lab study, concrete (Wright, 1967)	6
Splitting tensile test lab study, asphaltic concrete (Hudson & Kennedy, 1968)	2~9
Splitting tensile test lab study, cement treated gravel (Hudson & Kennedy, 1968)	8~19
Splitting tensile test lab study, 6 × 12” concrete cylinders (Melis, 1985 et al.)	6
Splitting tensile test lab study, 4 × 8” concrete cylinders (Melis, 1985 et al.)	8
Flexural beam test lab study, concrete (Melis, 1985 et al.)	6
Splitting tensile test, concrete cylinders at 28 days (Dallas Test sections, 1995)	6~11
Splitting tensile test, concrete cores at 28 days (El Paso Test sections, 1995)	5~11

The lower the coefficient of variation for concrete tensile strength, the smaller the variation of crack spacing. Under the same conditions, larger variability leads to smaller crack spacings. From a previous study (Ref 3), it was found that when the tensile strength has a 20% coefficient of variation, only 20% of the slab segments are in a desirable range. On the other hand, more than 50% of the slab segments are within the desirable range, if a 5% coefficient of variation is maintained in concrete tensile strength. Figure 3.1 presents cumulative crack spacing distributions for three levels of the concrete tensile strength variabilities. In this study three levels of coefficient of variation are studied, corresponding to 10%, 15%, and 20%.

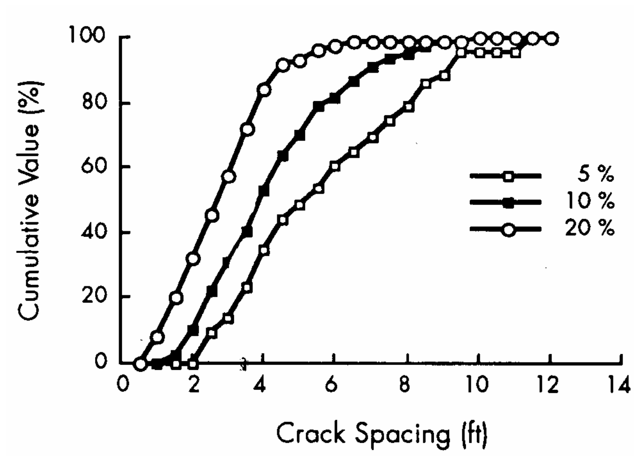


Figure 3.1 Cumulative predicted crack spacing distributions for different variables in concrete tensile strength (Ref 3)

3.1.3 Coefficient of Thermal Expansion (COTE)

The COTE of concrete is affected by a large number of factors that can be generally grouped into the two major components of concrete: cement paste and aggregate. The COTE of the paste is primarily affected by the moisture content of the paste; thus, it will vary in a significant manner during the hydration process and will stabilize thereafter (Ref 14).

Since dimensional changes in the Portland cement concrete influence the formation of transverse cracks, the thermal characteristics of concrete affect the crack pattern. The COTE of concrete is also directly related to coarse aggregate type. Because coarse aggregates form a large part of concrete by volume, it is to be expected that the COTE of the aggregates would have a large effect on the COTE of the concrete (Ref 14). Since there exists an interaction between the factors of coarse aggregate type and slab temperature, the effect of coarse aggregate type should be interpreted, along with the effect of slab temperature (Ref 5). The effect of coarse aggregate type on crack width is shown in Figure 3.2. The use of siliceous river gravel (SRG) results in larger crack widths than does the use of limestone (LS), and the difference is greater at lower temperatures. This difference is the result of the higher SRG COTE. The typical values of COTE depending on coarse aggregate types are listed in Table 3.3.

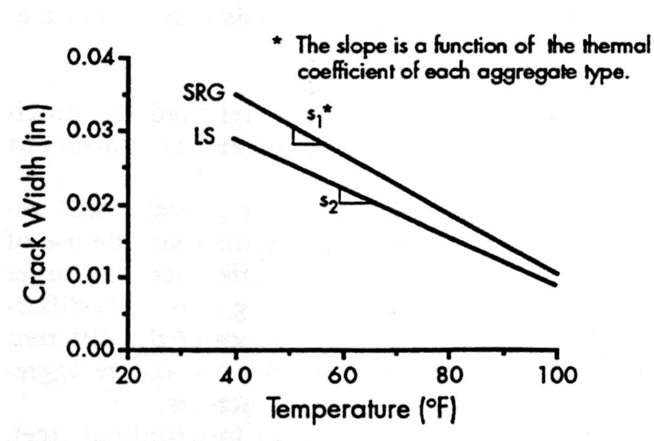


Figure 3.2 Effect of COTE of slab temperature on crack width (Ref 5)

Using the information in Table 3.3, three values of thermal coefficient were investigated: 3, 5, and 8 microstrain/°F, which represents the range in COTE from low to high. The crack spacing is inversely proportional to the values of COTE, and the aggregate type has the greatest influence on the thermal properties of the concrete (Ref 16).

Table 3.3 COTE of concrete depending on coarse aggregate sources

Aggregate Types	Yucatan	Bridgeport/ Tin Top	Ferris	Granite	Dolomite	Western Tascosa	Vega	Limestone River Gravel	SRG
COTE (microstrain/F)	3.0	4.84	5.44	5.74	5.9	6.15	6.5	6.29	8.18

3.1.4 Material Properties of Concrete

In this study three tensile strength values (or compressive strength and elastic modulus) were used to investigate the influence of concrete strength on pavement behavior. These strength values are 430, 530, and 650 psi (or compressive strength of 4,100, 5,500, and 7,500, and elastic modulus of 3,640, 4,220, and 4,930 ksi). LS and SRG are the most widely used coarse aggregate types in Texas. In the previous study (Ref 5), significant crack spacing and crack width differences exist between the SRG sections and the LS sections. The LS sections showed fewer cracks (larger crack spacings) than the SRG sections during the short-term monitoring of the test sections. In addition, the LS sections showed smaller crack widths than the SRG sections, even though the crack spacings were larger. The factors that might account for the fewer cracks and smaller crack widths observed in the LS sections include that pavement's lower thermal coefficient and lower elastic modulus. The difference in the patterns (both crack spacing and crack width) for concrete with various coarse aggregate types can be predicted satisfactorily using the CRCP program.

The high, medium, and low values of each variable have been determined based on the previous research (Ref 4). Table 3.4 shows comparisons of means for 28-day tensile strength, elastic modulus, and drying shrinkage of concrete for various coarse aggregate types.

Table 3.4 Material properties of concrete at 28 days

Aggregate Types	Granite	Dolomite	Vega	Bridgeport /Tin Top	Western Tascosa	Ferris	LS	SRG
Tensile strength (psi)	529	494	455	441	432	476	432	441
Elastic modulus (ksi)	3471	4866	3882	4094	3626	4114	3371	4229
Drying shrinkage ($\times 10^{-3}$)	330	157	227	170	217	317	206	187

3.2 Steel Reinforcement

Steel bar diameter and percent reinforcement are the major inputs of steel properties in the CRCP program. Steel properties are time-independent variables.

3.2.1 Steel Bar Diameter

For this study, three different bar diameters were selected to investigate its effect on pavement behavior. These are 0.625 (No.5), 0.75 (No.6), and 0.875 (No.7) inches. These bar diameters are the typical ones used in CRCP construction. Previously, No. 5 was standard when 8-inch pavement thickness was used, but moved to No. 6 and No. 7 with increasing pavement thickness.

In a previous study crack spacing and crack width are directly proportional to the diameter of the steel bar. The steel bar size has a definite effect on the crack pattern and should be carefully evaluated in the design. The use of a larger bar, for the same total amount of steel, resulted in slightly greater crack width. For instance, the use of No. 7 bars (0.875 in. diameter) instead of No. 6 bars (0.75 in. diameter) showed a little wider crack. This might be a result of the smaller total bond area existing between steel and concrete of the larger bar; the crack width is minimized by the bond between steel and concrete. It should be noted, however, that the increase in crack width by use of No.7 bars instead of No.6 bars was very small. It was observed in the winter projects (Ref 5) that at the end of the short-term monitoring, the use of different bar sizes (i.e., No.6 and No.7 bars) had not shown a significant difference in cracking. Theoretically, for the same percentage of longitudinal steel, a larger bar provides a smaller steel/concrete bond area, which in turn should reduce the restraint of the slab movement and result in fewer cracks.

3.2.2 Percent Reinforcement

For percent reinforcement, three levels were selected to be 0.4%, 0.6%, and 0.8%. Various data from both laboratory and field studies provide the design engineer with an insight into the characteristic of crack width: a value of 0.023 inches can generally be used as a limiting amount from the standpoint of water flow or spalling. Less than 0.5% reinforcement may not provide satisfactory performance (Ref 15).

The effect of the amount of longitudinal steel on the crack width was statistically significant. In general, the greater the amount of longitudinal steel, the narrower the crack width. From the previous study (Ref 5) the test sections having greater longitudinal steel quantities generally had more cracks and narrower crack widths. The greater quantity of longitudinal steel more effectively restrained slab movement, resulting in more and tighter cracks.

Most agencies base the required percentage of longitudinal reinforcement on experience or empirical data obtained from experimental pavements. Table 3.5 shows the one of the examples of field data about percent reinforcement in the Houston area (Ref 5). In this study the medium level of the percent reinforcement was selected to be 0.6% because that is the typical value used in the field. The minimum and maximum values were selected to be 0.4% and 0.8%.

Table 3.5 Typical percent reinforcement used on the projects

Project	SH 6 Summer						BW 8 Winter					
Aggregate type	SRG			LS			SRG			LS		
Percent reinforcement (%)	Low	Med.	High	Low	Med.	High	Low	Med.	High	Low	Med.	High
	0.42	0.53	0.63	0.52	0.61	0.68	0.38	0.5	0.62	0.45	0.58	0.67
Project	SH 6 Winter						IH-45 Winter					
Aggregate type	SRG			LS			SRG			LS		
Percent reinforcement (%)	Low	Med.	High	Low	Med.	High	Low	Med.	High	Low	Med.	High
	0.42	0.53	0.63	0.52	0.63	0.68	0.65	0.55	0.67	0.63	0.74	0.84

3.3 Slab/Subbase Resistance

The vertical stiffness of underlying layers, such as base, subbase, and subgrade, depends largely on the thickness and material properties of the underlying layers. Although all layers can be modeled using finite elements, computer memory and run time will be very large. An alternative would be to use equivalent springs for underlying layers. The stiffness of the equivalent spring would be a function of the depth and material properties of the layers as well as the pressure area if there is an external load (Ref 7). In this study three levels are studied; 300, 700, and 1,200 pci.

The frictional bond-slip stiffness/unit area depends on the subbase types. There are frictional stresses in the horizontal direction at the interface between the concrete layer and the base layer. The frictional bond-slip between the two layers can be modeled using horizontal spring elements. Although five different subbase types can be selected in the programs, asphalt-stabilized (55.9 pci), flexible (145.5 pci), and cement-stabilized (15,400 pci) subbase types are selected in this study.

3.4 External Wheel Loads

The CRCP-8 computer program calculates wheel load stresses using Westergaard equations, which means that only a static single wheel load is considered for the stress calculation, and the effect of the dynamic variation of moving loads and the effect of multiple wheel loads such as dual tires, single axle, and tandem axle are ignored. To improve the accuracy of the wheel load stress calculation, CRCP-10 includes the effect of the moving dynamic tandem-axle loads using the transformed field domain analysis (Ref 12).

3.4.1 Days after Concrete Sets before Wheel Load Applied

In this study, three different values are studied: 3, 7, and 28 days. Those are selected based on the different field situations. The soonest after concrete sets before a wheel load can be applied is three days, and specification value is seven days. Twenty-eight days can be selected as the latest opening day because the concrete material properties are assumed to be constant after that age.

3.4.2 Static Single-Wheel Load

In this study three different values are selected: 6,000, 9,000, and 12,000 pounds. Wheel load 9,000 pounds represent an 18 kip single-axle load, and 12,000 pounds means 33 % overloaded case. In the CRCP program the critical wheel load stress is calculated using the Westergaard equation assuming that the load is static, the loaded area is circular, and the stress is induced by only single-wheel load.

3.4.3 Dynamic Tandem-Axle Load

In the CRCP-10 program the critical wheel load stress is calculated assuming that the loads are moving, each loaded area is rectangular, and the critical stress is induced by multiple wheels in a tandem axle and by their dynamic variations. The input variables for the load time history are defined as shown in Figure 3.3. The average single-axle load (A), the half amplitude (B), the load frequency (f), and the phase angle are major input variables.

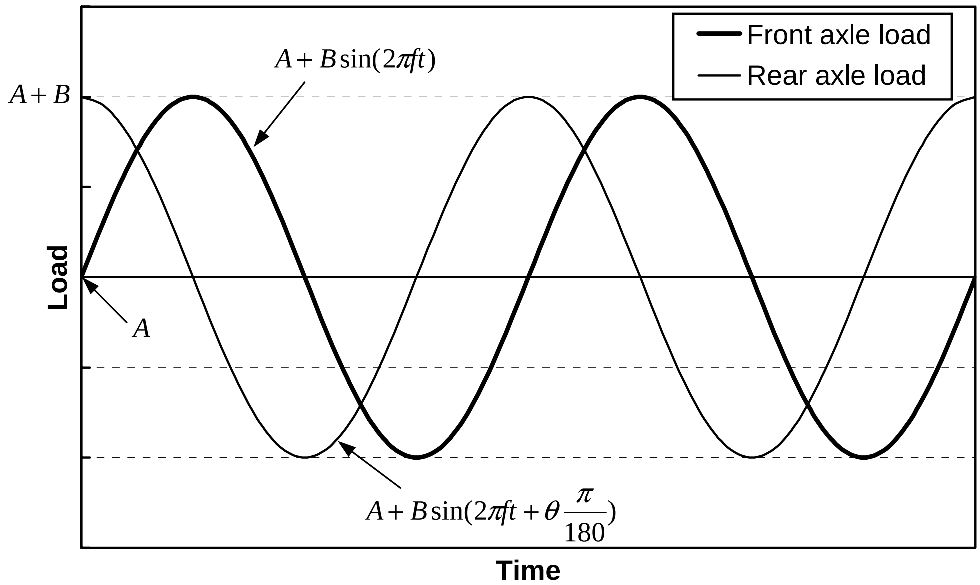


Figure 3.3 Definition of load time history

3.5 Climatic Loads

The loads affecting the CRCP behavior and performance can be divided into two types; one is the load imposed by vehicles and the other is climatic loads such as changes in temperature and moisture. The climatic loading is more significant during the early-age behavior of CRCP. In this study zero-stress temperature and minimum temperature at first day after placement are used as variables regarding climatic loads

3.5.1 Zero-Stress Temperature

Hydration of the fresh concrete is accompanied by the release of energy in the form of heat, with the actual rate of heat release varying with time. Mixing Portland cement compounds with water results initially in a rapid release of heat, which then ceases within about 15 minutes. This reaction probably represents the heat of the solution of aluminates and sulfates in the mixture. The primary heat-generation cycle begins hours after the cement compounds are mixed with water. Before this primary cycle concrete is in a plastic state and is relatively inactive chemically. The peak of the primary cycle is reached several hours after concrete is mixed with water. At this stage, the major hydration products crystallize from the solution of the mixture. This stage includes the time of initial and/or final set of the concrete. As hydration products grow, they form a barrier to the infiltration of additional water; the reaction slows and may eventually stop when there is no room for further growth of crystals or when hydration is theoretically completed. It should be noted that, because the reaction is chemically controlled, the rate of hydration is chemically controlled. The rate of hydration is very sensitive to temperature, especially during the primary cycle (Ref 5). Therefore, the temperature condition during construction is an important factor affecting the rate of hydration. Figure 3.4 (Ref 5) shows the effect of the curing temperature on the hydration of tricalcium silicate. It can be seen that the higher the curing temperature, the faster the heat release and the higher the peak.

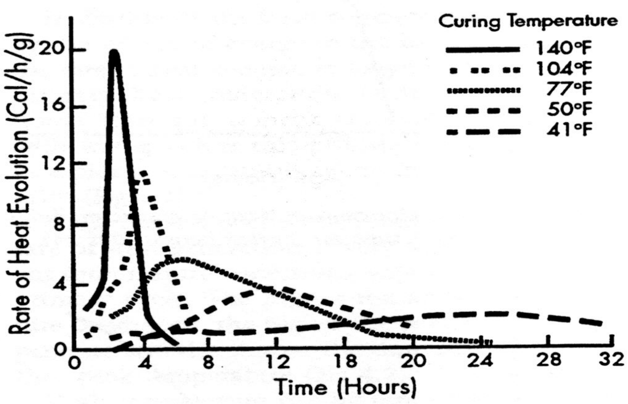


Figure 3.4   Effect of curing temperature on hydration (Ref 5)

Heat generation and buildup depend on many factors, including the chemical composition of the cement, water-cement ratio, fineness of the cement, amount of cement, admixture, dimension of the concrete, ambient temperature, and fresh concrete temperature. Tricalcium silicate ($3CaO \cdot SiO_2$) and tricalcium aluminate ($3CaO \cdot Al_2O_3$) are the compounds of cement primarily responsible for the high heat generation. An increase in the water-cement ratio, fineness of cement, and/or zero-stress temperature increases the heat of hydration (Ref 5).

Three zero-stress temperatures of 60, 90 and 125 degrees Fahrenheit were examined. The crack spacing is inversely proportional to the zero-stress temperature. Extreme temperature drops during early curing should be avoided in order to prevent drastic effects on pavement performance (Ref 13). A large temperature rise by hydration may cause excessive internal stresses when differences exist in thermal expansion factors of various concrete constituents. Many specifications now use as the zero-stress temperature the fresh-concrete temperature recorded at the time of placement. Theoretically, the zero-stress temperature should be the temperature at which the concrete begins to display stresses induced by shrinkage or temperature change (Ref 5).

Figure 3.5 presents a typical plot of the air temperature and the concrete temperature: The left-hand portion of the upper curve represents a typical day when concrete is placed in the early morning hours. As the ambient temperature increases, the concrete temperature also increases, owing to both the ambient temperature and the heat of hydration. At some point, it peaks, then drops off, and eventually, after the curing operation, starts to mirror the ambient temperature relationship. In the lower part of the figure, the concrete stresses are indicated for condition "a," where the concrete sets; this then is the reference point. As the temperature continues to build up, the slab goes into compression, as indicated at the peak heat condition. Then, as the concrete temperature decreases, the stresses go from compression to tension; at the point where the stress exceeds the tensile strength, it will crack (Ref 14).

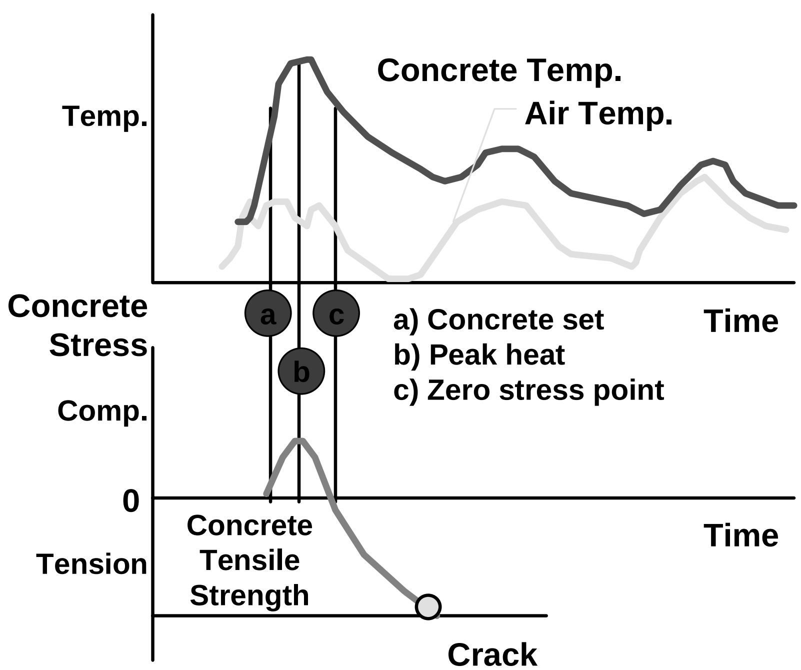


Figure 3.5 Relationship of air and concrete temperatures to stress (Ref 14)

3.5.2 Minimum Temperature at First Day after Placement

Most of the heat of hydration is generated during the early age of concrete. When a concrete is volumetrically restrained, the expansion force by the hydration heat will cause compressive stress. This compressive stress is relatively low, owing to the stress relief provided by creep and to the relatively low elastic modulus characteristic of early-age concrete (Ref 21). The compressive stress will be relieved soon after the concrete begins to cool after the peak of hydration. A further decrease in temperature and subsequent contraction of the concrete will cause tensile stress to develop. This contraction occurs at a later age when the elastic modulus is greater and stress relief provided by creep is less. The tensile stress will cause cracking if the stress exceeds the tensile strength of the concrete. The higher the temperature drop, the greater the possibility of cracking (Ref 22).

Heat of hydration can be useful in cold weather placement: It often generates enough heat to provide a satisfactory zero-stress temperature. In hot weather, however, heat of hydration can be detrimental to the concrete. As one of the climatic loads, a daily temperature change after placement is an important factor that affects the early-age behavior of CRCP. To consider different situations of daily temperature change during the curing period, three different first day's minimum temperatures are selected; 50, 60, and 70 degrees Fahrenheit.

3.6 Summary of Input Values

The low, medium and high values of each variable selected in this study are listed in Table 3.6. Medium levels are what 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. Because there are different input variables in some cases between CRCP-8 and CRCP-10, Table 3.6 shows both input parameters.

Table 3.6 Summary of low, medium, and high values of each variable

CRCP-10	Low	Medium	High	CRCP-8
Concrete Properties				**Concrete Properties**
Pavement Thickness (in.)	6	12	15	Pavement Thickness (in.)
Poisson's Ratio of Concrete	0.15	0.15	0.15	
Specific Weight of Concrete (pcf)	100	145	145	
Coefficient of Variation for Concrete Tensile Strength (%)	10	15	20	Coefficient of Variation for Concrete Tensile Strength (%)
Coarse Aggregate Type				**Coarse Aggregate Type**
COTE (microstrain/F)	3	5	8	COTE (microstrain/F)
Elastic Modulus at 28 Days (psi)	3,640,000	4,220,000	4,930,000	Elastic Modulus at 28 Days (psi)
Tensile Strength at 28 Days (psi)	430	530	650	Tensile Strength at 28 Days (psi)
Drying Shrinkage at 256 Days	0.000342	0.000394	0.000461	Drying Shrinkage at 28 Days
Steel Properties				**Steel Reinforcement Properties**
Elastic Modulus of Steel Bar (psi)	29,000,000	29,000,000	29,000,000	Elastic Modulus (psi)
Steel Bar Diameter (in.)	0.625(No.5)	0.75(No.6)	0.875(No.7)	Steel Bar Diameter (in.)
Thermal Coefficient (microstrain/F)	5	5	5	Thermal Coefficient (microstrain/F)
Specific Weight of Steel (pcf)	490	490	490	
Percent Reinforcement (Steel Ratio) (%)	0.4	0.6	0.8	Percent Reinforcement (Steel Ratio) (%)
Slab/Subbase Resistance				
Vertical Stiffness of Subgrade (psi/in.)	300	700	1,200	
Subbase Type	Asphalt	Flexible	Cement	***Slab-Base Friction Curve Type***
Horizontal Stiffness/Unit Area (psi/in.)	55.9	145.5	15,400	
External Wheel Loads				**External Load**
Days after Concrete Sets before Wheel Load Applied	3	7	28	Days after Concrete Sets before Wheel Load Applied
Static Single Wheel Load				**Static Single Wheel Load**
Wheel Load (lbs.)	6,000	9,000	12,000	Wheel Load (lbs.)
Wheel Base Radius (in.)	6	6	6	Wheel Base Radius (in.)
Climatic Loads				**Environmental Load**
Zero-Stress Temperature (F)	60	90	125	Zero-Stress Temperature (F)
Min. Temperature at First Day after Placement (F)	50	60	70	Minimum Temperature (F)
Advanced Inputs				
Punchout Prediction Parameters				**Punchout Prediction Parameters**
Reliability (%)	50	75	95	Reliability (%)

4. Sensitivity Analysis with Medium Basic Level

The results from the CRCP-10 and CRCP-8 computer programs have been compared in this chapter to investigate difference and sensitivity. It should be recognized that rating variables on the basis of data developed during this sensitivity study are affected by several factors involved in the data generation, including numerical values used for input variables and basic levels of variables. Because the input parameters in those two computer programs are not the same, efforts have been made to have close input values for both programs.

The data outputs using medium input values are presented in Table 4.1. As shown in Table 4.1, when all the input values are at their medium levels, mean crack spacing is 8.43 ft., crack width is 0.0224 in., and steel stress is 30.41 ksi from CRCP-10. In the case of CRCP-8, the results of crack spacing, crack width, and steel stress are 9.26 ft., 0.0265 in., and 48.63 ksi, respectively. Comparing the results of CRCP-8 and CRCP-10 at the medium level, the values of crack spacing and crack width are similar, but the steel stress from CRCP-8 is 60% higher than that from CRCP-10.

Table 4.1 Analysis results using medium input values

	CRCP-10	**CRCP-8**
Input Values	Medium	Medium
Crack Spacing (ft.)	8.43	9.26
Crack Width (in.)	0.0224	0.0265
Steel Stress (ksi)	30.41	48.63

4.1 Portland Cement Concrete

Sensitivity analyses of pavement thickness, coefficient of variation for concrete tensile strength, coefficient of thermal expansion, and tensile strength of concrete are conducted in this section. Crack spacing, crack width, and steel stress are investigated in the aspect of absolute and relative values. The results from CRCP-10 are compared with those from CRCP-8 and field data to obtain a test of reasonableness.

4.1.1 Pavement Thickness

In this study various pavement thicknesses between 6 and 15 inches are selected. Table 4.1 and Figure 4.1 show the sensitivity of the pavement thickness. It appears that computed crack spacing, crack width, and steel stress increase with increasing pavement thickness in both programs. When the pavement thickness is over 10 in. for CRCP-10 and over 12 in. for CRCP-8, the pavement thickness increase does not affect the crack spacing. The slab thicknesses ranging from 6 to 12 in. are very sensitive when the other input values are at the medium level. One of the reasons of constant crack spacing obtained with over 12 in. pavement thickness may be related to concrete stress. If the concrete tensile stress exceeds the tensile strength of concrete, cracks develop to relieve stress. In case of pavement thickness over 12 in., the concrete stress is less than the strength, and no more cracks develop. Compared to field data mentioned in subsection 2.3.2 of Chapter 2, most crack spacings are between 4 ft. and 9 ft. apart when all input variables except pavement thickness are at their medium values.

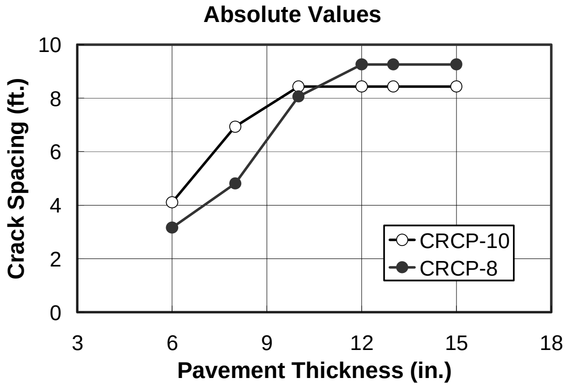
The crack widths are usually directly proportional to the crack spacings. It should be noted from Figure 4.1 that the difference in crack width between the high and the medium pavement thickness is much less than that between the low and the medium pavement thickness, like the behaviors of crack spacing in both programs. Most crack widths listed in Table 4.2 are less than or about 0.025 inches, that is, the suggested limit of crack width as described in subsection 2.3.2 of Chapter 2.

In case of steel stress, although the patterns of steel stress for CRCP-10 and CRCP-8 due to increasing of pavement thickness are similar, the absolute value of CRCP-8 is almost 70% higher than that of CRCP-10 in Figure 4.1. CRCP-8 uses one-dimensional analytical methods to calculate stresses and strains, but CRCP-10 uses totally different two-dimensional numerical methods to calculate them. This may be the one of the reasons for different results between CRCP-8 and CRCP-10 as well as the nature of the concrete-steel bond relationship.

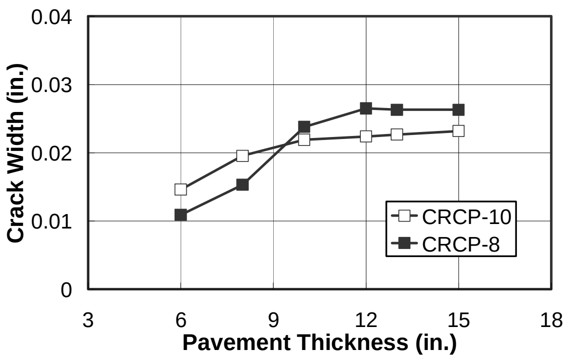
Table 4.2 Sensitivity of pavement thickness

Absolute Values	CRCP-10						CRCP-8					
Pavement Thickness (in.)	6	8	10	**12**	13	15	6	8	10	**12**	13	15
Crack Spacing (ft.)	4.11	6.93	8.43	**8.43**	8.43	8.43	3.16	4.81	8.06	**9.26**	9.26	9.26
Crack Width (in.)	0.015	0.02	0.022	**0.022**	0.023	0.023	0.011	0.015	0.024	**0.027**	0.026	0.026
Steel Stress (ksi)	20.71	27.7	30.54	**30.41**	30.14	30.14	29.24	35.99	45.34	**48.63**	47.5	47.5
Relative Values	CRCP-10						CRCP-8					
Crack Spacing (%)	48.68	82.22	100	**100**	100	100	34.13	51.94	87.04	**100**	100	100
Crack Width (%)	65.28	87.28	97.77	**100**	103.6	103.6	41.13	57.74	89.81	**100**	99.25	99.25
Steel Stress (%)	68.1	91.09	100.4	**100**	99.1	99.1	60.13	74.02	93.24	**100**	97.68	97.68

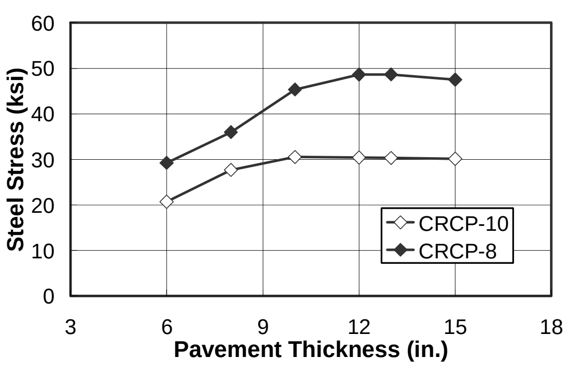
Figure 4.2 shows the comparison of crack spacings caused by only climatic loading (wheel load is zero) and by both climatic and wheel loadings. When only climatic loads are applied, the crack spacing does not change with increasing pavement thickness in both programs except for pavement thickness of 3 inches. If a wheel load (climatic loads plus 9,000 lbs.) is applied, the crack spacing is less than that caused by climatic loads when the pavement thickness is less than 10 and 12 inches for CRCP-10 and CRCP-8, respectively. That means the wheel load severely affects the crack spacing when the pavement thickness is under 12 inches.



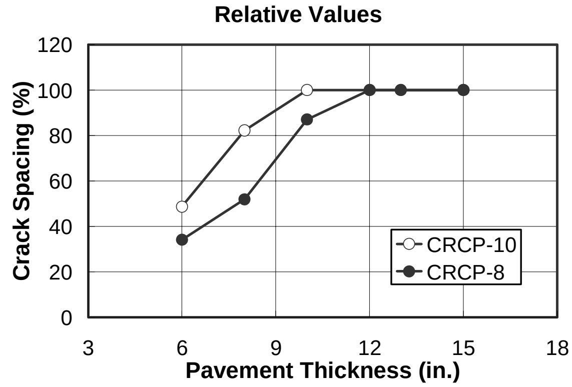
(a) Mean Crack Spacing



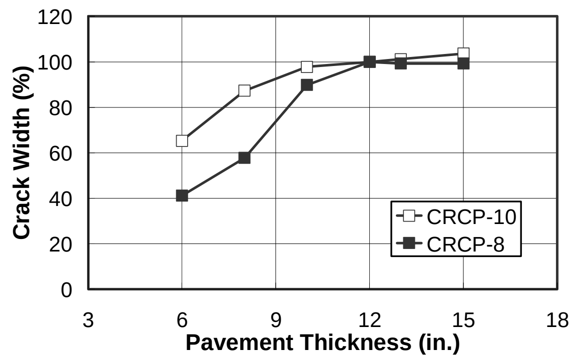
(b) Crack Width



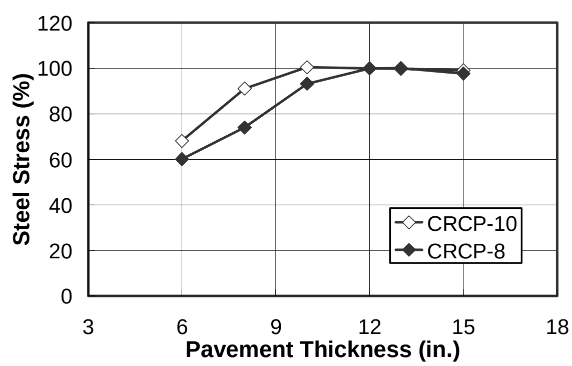
(c) Steel Stress



(d) Mean Crack Spacing



(e) Crack Width



(f) Steel Stress

Figure 4.1 Sensitivity of pavement thickness

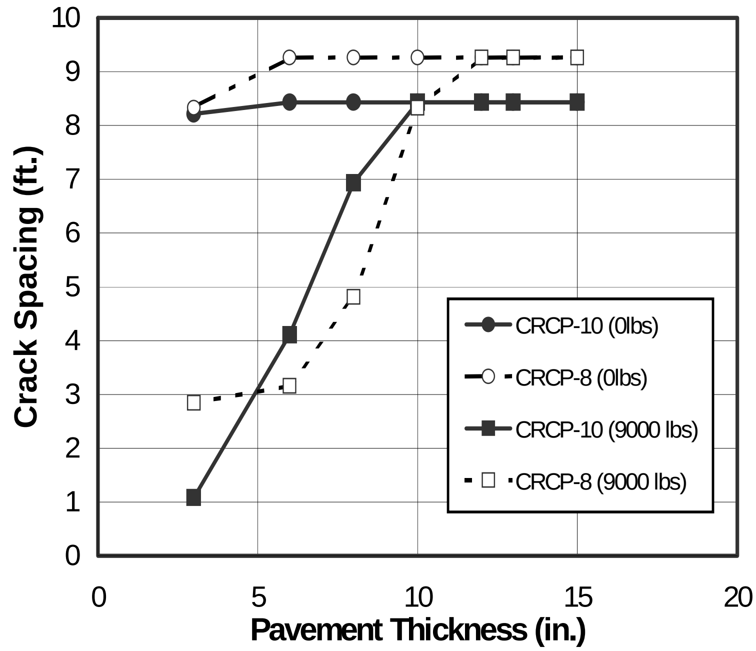


Figure 4.2 Comparison of crack spacing developed with depending of different loading for a fixed steel ratio

4.1.2 Coefficient of Variation for Concrete Tensile Strength

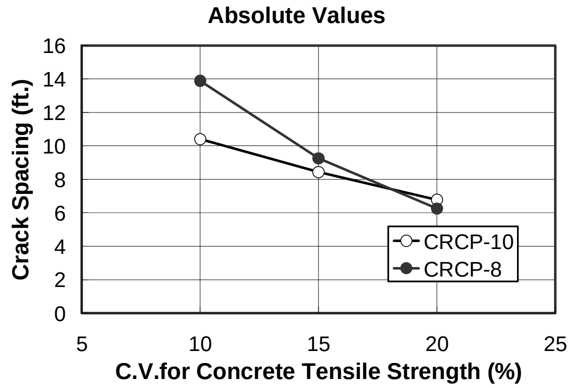
In this study three levels are studied, corresponding to 10%, 15%, and 20% of coefficient of variation for concrete tensile strength. The concrete strength varies significantly depending on the age, component properties, and content and curing conditions. Material variability, especially that of tensile strength, has a large influence on the crack development, as discussed in section 3.1.2. The lower coefficient of variation for concrete tensile strength, the more uniform the distributions. In a previous study by Won et al. (Ref 3), under the same conditions, larger variability leads to smaller crack spacings, crack widths, and steel stresses.

Table 4.3 and Figure 4.3 reveal that the difference in cracking spacing between the high and medium input values is much less than the difference between the low and medium input values, even though the change in the coefficient of variation for concrete tensile strength is the same in CRCP-10 and CRCP-8. This shows the importance of quality control of concrete. The variations of crack spacing, crack width, and steel stress from CRCP-8 are more sensitive than those from CRCP-10.

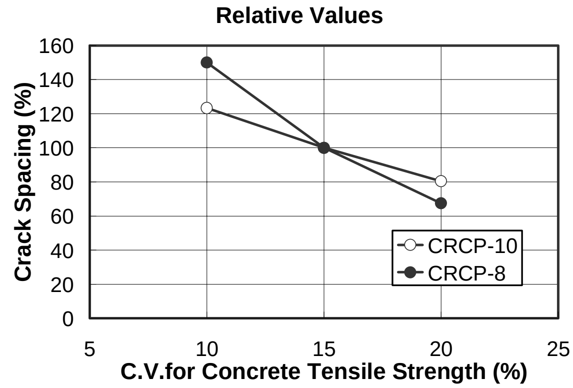
Figure 4.4 shows cumulative crack spacing distributions for three levels of the concrete tensile strength variabilities in CRCP-10. Compared to Figure 3.1, similar trends can be observed, although cumulative values are different.

Table 4.3 Sensitivity of coefficient of variation for concrete tensile strength

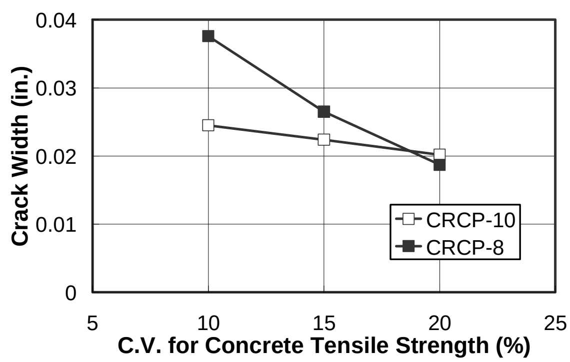
Absolute Values	CRCP-10			CRCP-8		
C.V. values (%)	10	**15**	20	10	**15**	20
Crack Spacing (ft.)	10.4	**8.43**	6.78	13.89	**9.26**	6.25
Crack Width (in.)	0.0245	**0.0224**	0.0202	0.0376	**0.0265**	0.0187
Steel Stress (ksi)	33.51	**30.41**	27.17	56.88	**48.63**	39.95
Relative Values	CRCP-10			CRCP-8		
Crack Spacing (%)	123.34	**100**	80.44	150	**100**	67.49
Crack Width (%)	109.33	**100**	90.14	141.89	**100**	70.56
Steel Stress (%)	110.19	**100**	89.35	116.98	**100**	82.16



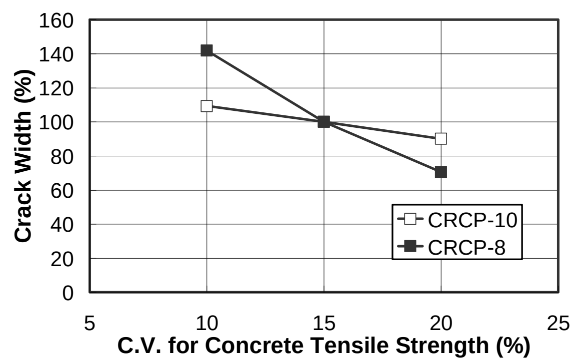
(a) Mean Crack Spacing



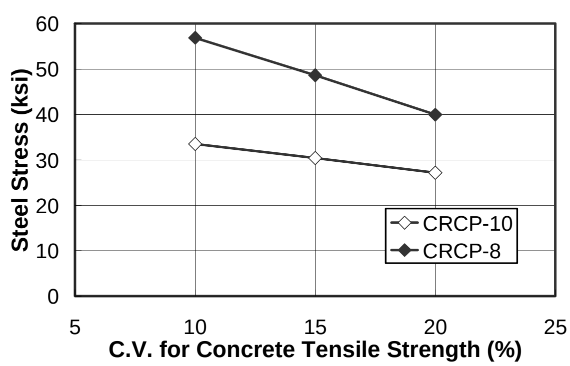
(d) Mean Crack Spacing



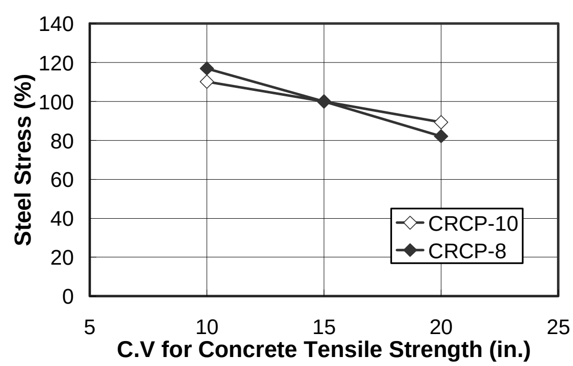
(b) Crack Width



(e) Crack Width



(c) Steel Stress



(f) Steel Stress

Figure 4.3 Sensitivity of coefficient of variation for concrete tensile strength

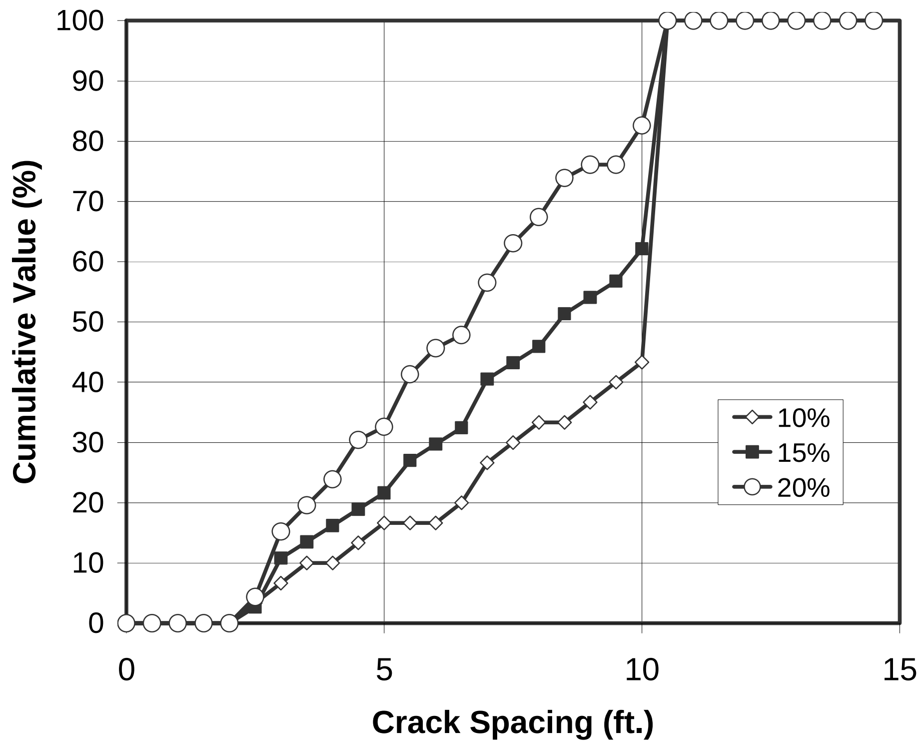


Figure 4.4 Cumulative predicted crack spacing distributions for different variables in concrete tensile strength

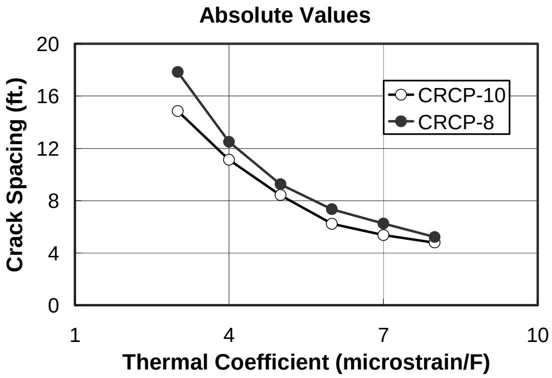
4.1.3 Coefficient of Thermal Expansion (COTE)

In this study various COTEs were investigated for a range of 3 to 8 microstrain/ °F. The analysis results presented in Table 4.4 and Figure 4.5 show that crack spacing is inversely proportional to the COTE values; however, the crack width and steel stress show insignificant effects with changing the COTE as shown in Figure 4.5. The difference between the crack spacing from CRCP-10 and CRCP-8 decreases with increasing the COTE. Considering the relative values of crack spacing, the variations of crack spacings are almost the same in both programs.

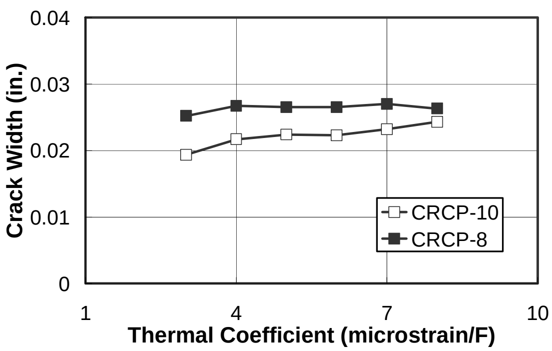
The variation of crack spacing is almost 13 ft. when the thermal coefficient changes from 3 to 8 microstrain/°F. It shows that the COTE is significantly sensitive comparing with the other input variables. The variation of the crack width and steel stress due to changes in the concrete COTE are small but there is a large difference in steel stress absolute values in Figure 4.5 (c).

Table 4.4 Sensitivity of coefficient of thermal expansion

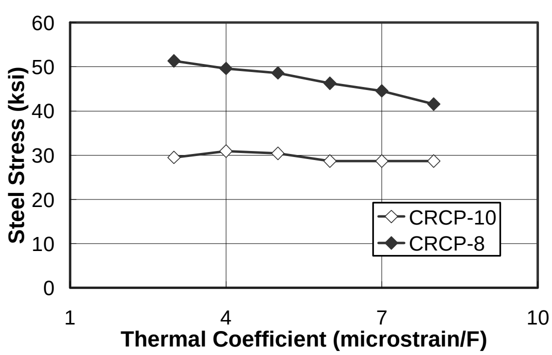
Absolute Values	CRCP-10						CRCP-8					
COTE	3	4	**5**	6	7	8	3	4	**5**	6	7	8
Crack Spacing (ft.)	14.86	11.14	**8.43**	6.24	5.379	4.8	17.86	12.5	**9.26**	7.35	6.25	5.21
Crack Width (in.)	0.019	0.022	**0.022**	0.022	0.023	0.024	0.025	0.027	**0.027**	0.027	0.027	0.026
Steel Stress (ksi)	29.5	30.91	**30.41**	28.65	28.65	28.66	51.34	49.65	**48.63**	46.29	44.55	41.59
Relative Values	CRCP-10						CRCP-8					
Crack Spacing (%)	176.2	132.2	100	74.01	63.79	56.93	192.9	134.9	**100**	79.38	67.49	56.26
Crack Width (%)	86.39	96.74	100	99.33	103.5	208.4	95.09	100.7	**100**	100	101.9	99.25
Steel Stress (%)	97.01	101.6	100	94.21	94.21	94.25	105.6	102.1	**100**	95.19	91.62	85.52



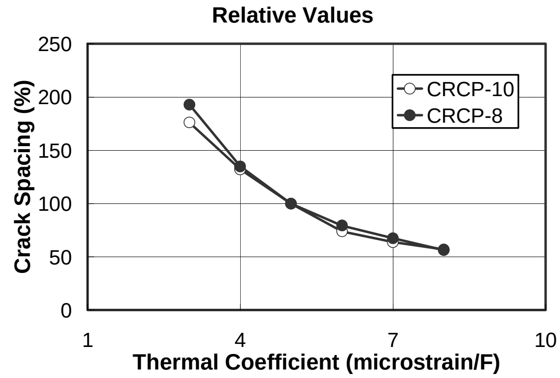
(a) Mean Crack Spacing



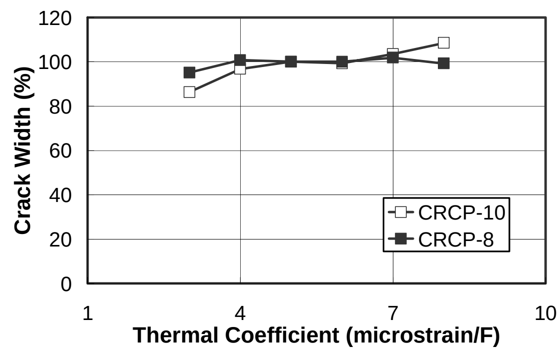
(b) Crack Width



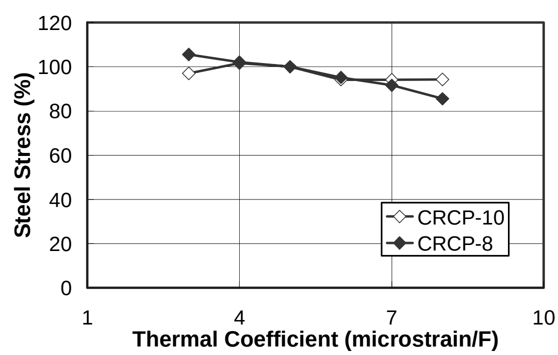
(c) Steel Stress



(d) Mean Crack Spacing



(e) Crack Width



(f) Steel Stress

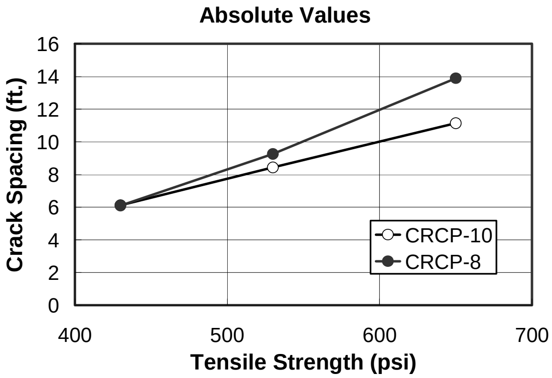
Figure 4.5 Sensitivity of coefficient of thermal expansion

4.1.4 Tensile Strength

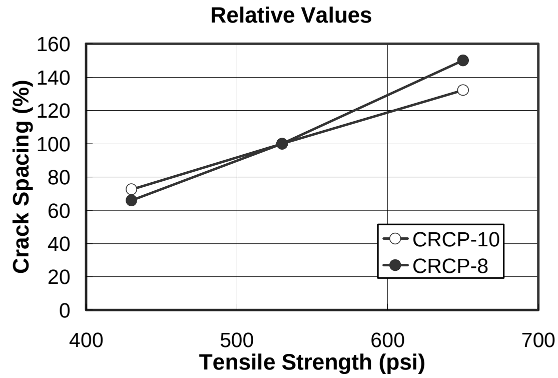
The concrete tensile strength at 28 days has been selected as a standard value to characterize the strength-age relations. This section investigates the influence of concrete strength on the pavement behavior. The tensile strength values considered in this study are 430, 530, and 650 psi. Table 4.5 and Figure 4.6 indicate that the crack spacing, crack width, and steel stress increase with an increasing tensile strength in both programs. It is noted that the sensitivity of crack spacing due to tensile stress from CRCP-8 is larger than that from CRCP-10 in Figure 4.6 (d). Although the results of steel stress from CRCP-8 are almost twice those from CRCP-10 in Figure 4.6 (c), the relative sensitivity from CRCP-8 and CRCP-10 are very similar in Figure 4.6 (f).

Table 4.5 Sensitivity of tensile strength at 28 days

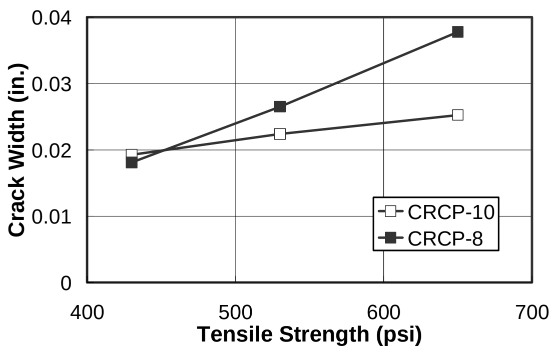
Absolute Values	CRCP-10			CRCP-8		
Tensile Strength (psi)	430	**530**	650	430	**530**	650
Crack Spacing (ft.)	6.12	**8.43**	11.143	6.1	**9.26**	13.89
Crack Width (in.)	0.0193	**0.0224**	0.0253	0.0181	**0.0265**	0.0378
Steel Stress (ksi)	25.83	**30.41**	34.62	39.91	**48.63**	58.63
Relative Values	CRCP-10			CRCP-8		
Crack Spacing (%)	72.56	**100**	132.15	65.875	**100**	150
Crack Width (%)	85.99	**100**	112.72	68.302	**100**	142.64
Steel Stress (%)	84.94	**100**	113.84	82.075	**100**	120.57



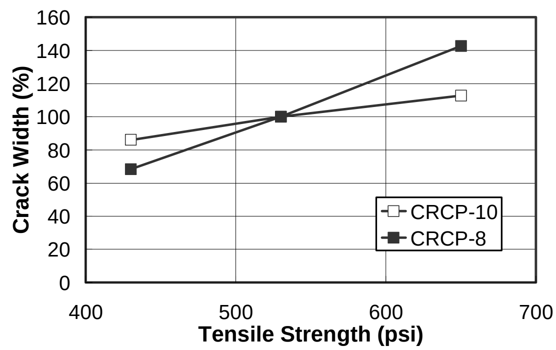
(a) Mean Crack Spacing



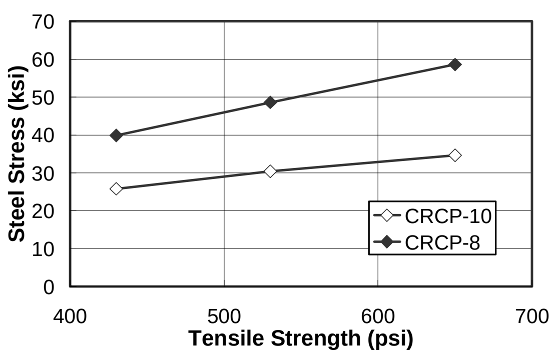
(d) Mean Crack Spacing



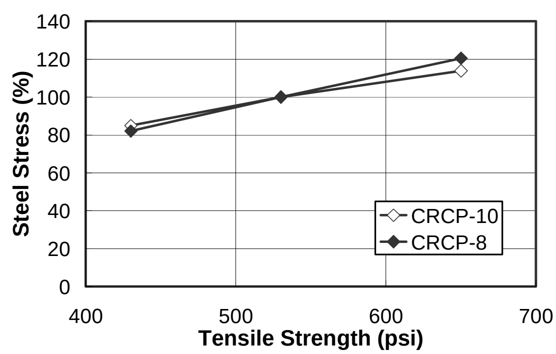
(b) Crack Width



(e) Crack Width



(c) Steel Stress



(f) Steel Stress

Figure 4.6 Sensitivity of tensile strength at 28 days

4.2 Steel Reinforcement

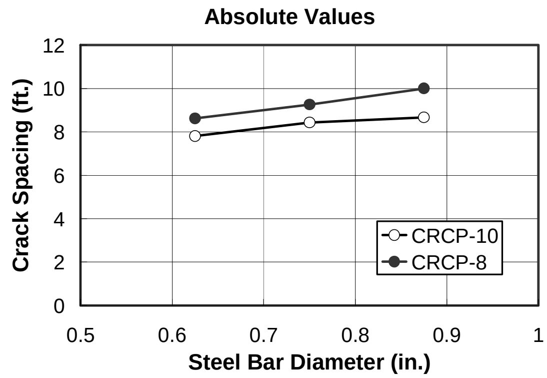
The material properties of longitudinal steel reinforcement include steel bar diameter, percent reinforcement, elastic modulus, and thermal expansion coefficient. Since the elastic modulus and the thermal expansion coefficient of steel bar are almost constant, the steel ba r diameter and percent reinforcement are selected to investigate their sensitivity to the CRC P behavior.

4.2.1 Steel Bar Diameter

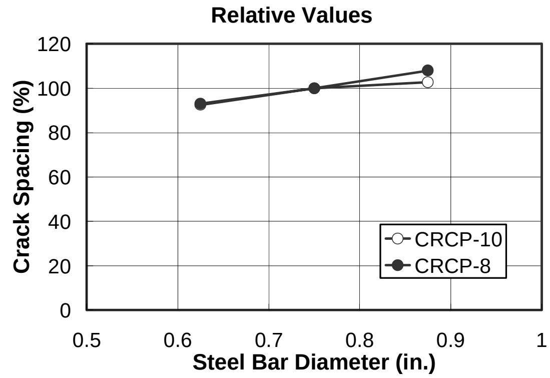
Three different bar diameters have been studied to investigate its effect on the pavement behavior. These are 0.625 (No.5), 0.75 (No.6), and 0.875 (No.7) inches. Table 4.6 and Figure 4.7 show the predicted crack spacing, crack width, and steel stress. The results show that the crack spacing and crack width are directly proportional to the diameter of the steel bar. Although the absolute values are different between the two programs, the sensitivity of crack spacing, crack width, and steel stress are almost the same as shown in Figure 4.7 (d), (e) and (f). It should be noted that the larger the steel bar diameter, the lower the total bond area. The study conducted by McCullough and Ledbetter (Ref 19) indicates that the crack spacing is also inversely associated with the ratio of steel bond area to concrete volume. This study shows that the reinforcing bar size has a slight effect on the crack pattern. From such an investigation, for the same percent of longitudinal steel, the larger bar provides a smaller steel/concrete bond area, which in turn should decrease the restraint of the slab movement and result in fewer cracks.

Table 4.6 Sensitivity of steel bar diameter

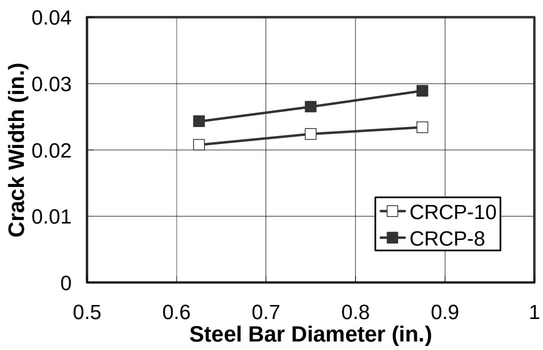
Absolute Values	CRCP-10			CRCP-8		
Steel Bar Diameter (in.)	0.625	**0.75**	0.875	0.625	**0.75**	0.875
Crack Spacing (ft.)	7.8	**8.43**	8.67	8.62	**9.26**	10
Crack Width (in.)	0.0207	**0.0224**	0.0234	0.0243	**0.0265**	0.0289
Steel Stress (ksi)	30.19	**30.41**	29.9	50.76	**48.63**	46.38
Relative Values	CRCP-10			CRCP-8		
Crack Spacing (%)	92.50	**100**	102.79	93.09	**100**	107.99
Crack Width (%)	92.73	**100**	104.51	91.70	**100**	109.06
Steel Stress (%)	99.28	**100**	98.32	104.39	**100**	95.38



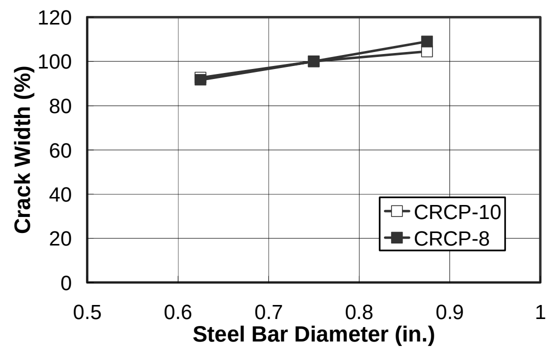
(a) Mean Crack Spacing



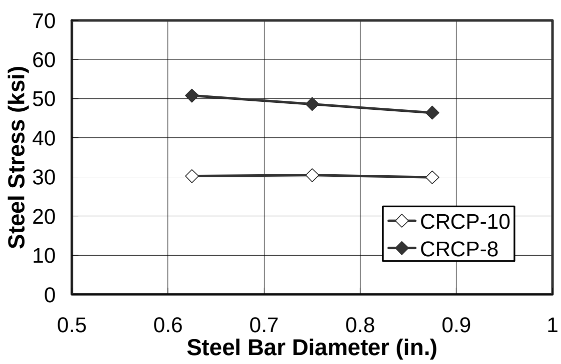
(d) Mean Crack Spacing



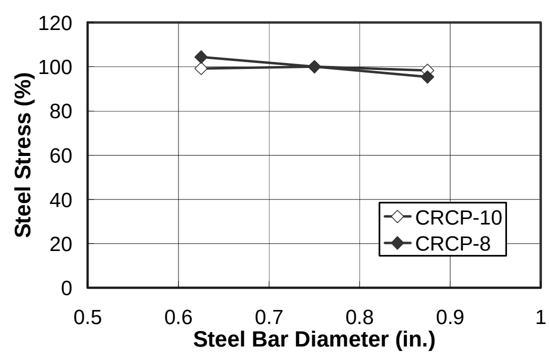
(b) Crack Width



(e) Crack Width



(c) Steel Stress



(f) Steel Stress

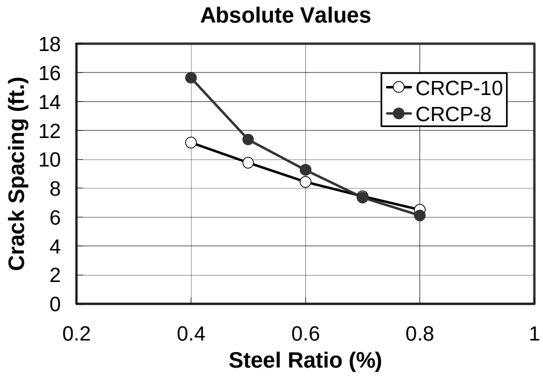
Figure 4.7 Sensitivity of steel bar diameter

4.2.2 Percent Reinforcement

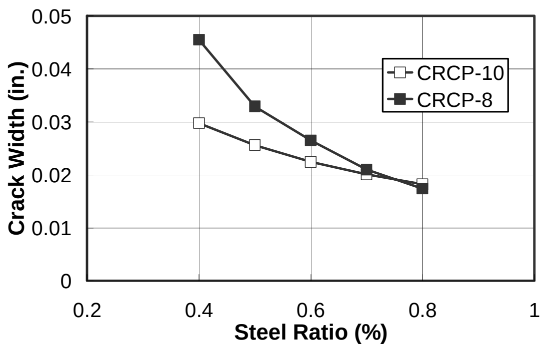
For percent reinforcement, various levels were selected from 0.4% to 0.8%. The effect of longitudinal reinforcement is shown in Table 4.7 and Figure 4.8. The crack spacing, crack width, and steel stress decrease with increasing percent reinforcement. This effect occurs because an increase in steel holds the cracks more tightly by creating a larger bond area between steel and concrete. The 0.4% longitudinal reinforcement reveals a fairly high stress in the steel bar and a large amount of crack width in Figure 4.8 (b) and (c). For CRCP-8 the variation of crack spacing from low to high steel ratio is almost 10 ft. It should be noted from Figure 4.8 (a) that the difference in the crack spacing between the high and medium steel ratios is much less than that between the low and medium steel ratios. This means that the influence of steel ratio at low level is more significant than that at high level.

Table 4.7 Sensitivity of percent reinforcement

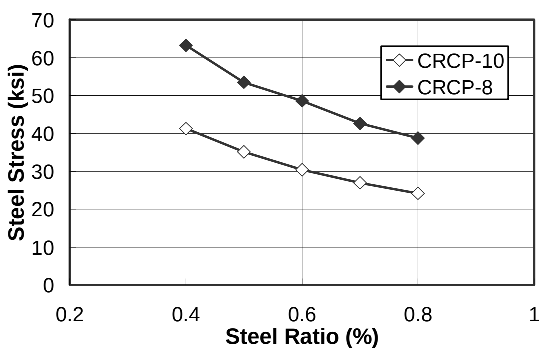
Absolute Values	CRCP-10					CRCP-8				
Percent Ratio (%)	0.4	0.5	**0.6**	0.7	0.8	0.4	0.5	**0.6**	0.7	0.8
Crack Spacing (ft.)	11.14	9.75	**8.43**	7.43	6.5	15.63	11.36	**9.26**	7.35	6.1
Crack Width (in.)	0.0298	0.0256	**0.0224**	0.0201	0.0182	0.0455	0.0329	**0.0265**	0.021	0.0174
Steel Stress (ksi)	41.28	35.15	**30.41**	26.97	24.22	63.25	53.52	**48.63**	42.65	38.75
Relative Values	CRCP-10					CRCP-8				
Crack Spacing (%)	132.15	115.63	**100**	88.11	87.49	168.79	122.68	**100**	79.374	65.875
Crack Width (%)	132.89	114.37	**100**	89.56	90.732	171.7	124.15	**100**	79.245	65.66
Steel Stress (%)	135.74	115.59	**100**	88.69	89.803	130.07	110.05	**100**	87.702	79.69



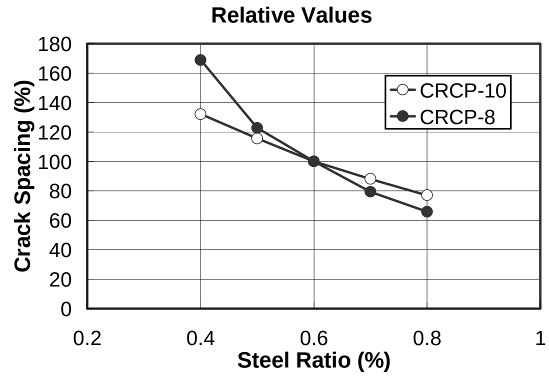
(a) Mean Crack Spacing



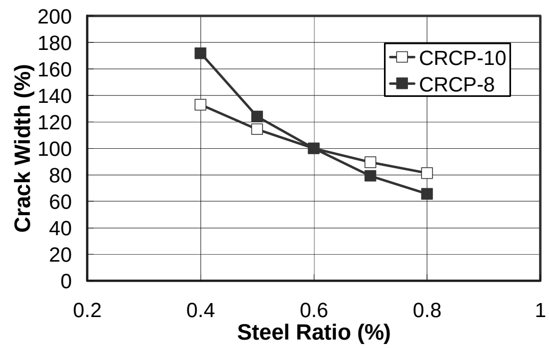
(b) Crack Width



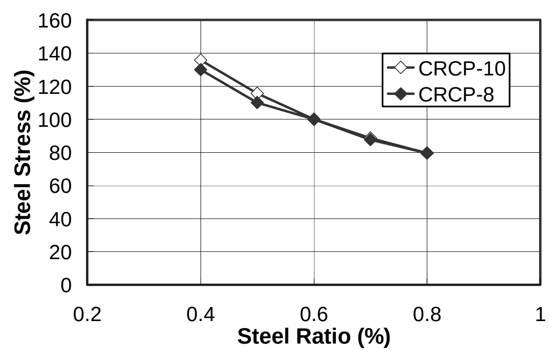
(c) Steel Stress



(d) Mean Crack Spacing



(e) Crack Width



(f) Steel Stress

Figure 4.8 Sensitivity of percent reinforcement

4.3 Slab/Subbase Resistance

The sensitivity of the vertical stiffness of underlying layers such as base, subbase, and subgrade and the horizontal stiffness at the interface between concrete slab and underlying layer are investigated in this section.

4.3.1 Vertical Stiffness

The vertical stiffness of underlying layers depends on the thickness and material properties of the underlying layers. In this study three levels are studied: 300, 700, and 1,200 pci. The sensitivity study shown in Table 4.8 and Figure 4.9 indicates that changing vertical stiffness does not affect the crack spacing, crack width, and steel stress.

Table 4.8 Sensitivity of vertical stiffness of subgrade

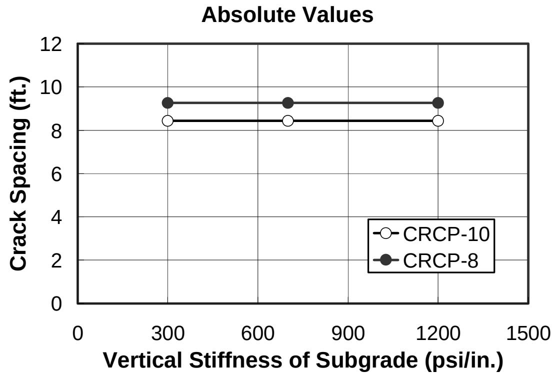
Absolute Values	CRCP-10			CRCP-8		
Vertical Stiffness (psi/in.)	300	**700**	1200	300	**700**	1200
Crack Spacing (ft.)	8.43	**8.43**	8.43	9.26	**9.26**	9.26
Crack Width (in.)	0.02251	**0.02241**	0.02236	0.0265	**0.0265**	0.0265
Steel Stress (ksi)	30.41	**30.41**	30.41	48.63	**48.67**	48.63
Relative Values	CRCP-10			CRCP-8		
Crack Spacing (%)	100	**100**	100	100	**100**	100
Crack Width (%)	100.45	**100**	99.77	100	**100**	100
Steel Stress (%)	100	**100**	100	99.99	**100**	99.99

4.3.2 Horizontal Stiffness

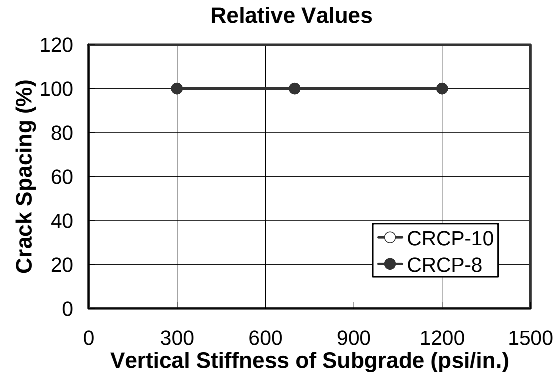
The frictional bond-slip stiffness/unit area depends on the subbase types. There are frictional stresses in the horizontal direction at the interface between the concrete layer and the base layer. In this study asphalt-stabilized (55.9 pci), flexible (145.5 pci), and cement-stabilized (15,400 pci) subbase types are selected as low, medium, and high values, respectively, and three more values of 1,000, 5,000, and 10,000 pci are added. As shown in Table 4.9 and Figure 4.10, the range from medium to high value of subbase type has a significant effect on crack spacing, crack width, and steel stress, whereas the effect for the range from low to medium is very small. The variations of crack spacing and steel stress with relative values are almost the same between CRCP-10 and CRCP-8, except for very high input ranges in Figure 4.10 (d). In the case of cement-stabilized, the crack spacing reduces over 50% of the flexible case. This means that the high frictional bond-slip stiffness/unit area leads to the narrow crack spacing, crack width, and lower steel stress.

Table 4.9 Sensitivity of horizontal stiffness

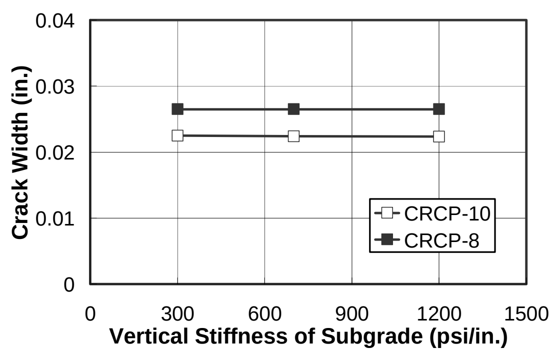
Absolute Values	CRCP-10						CRCP-8					
Horizontal Stiffness	55.9	**145.5**	1000	5000	10000	15400	55.9	**145.5**	1000	5000	10000	15400
Crack Spacing (ft.)	8.43	**8.43**	7.09	4.88	3.51	2.84	9.26	**9.26**	7.81	5.43	4.72	4.03
Crack Width (in.)	0.022	**0.022**	0.021	0.019	0.0155	0.0135	0.027	**0.027**	0.023	0.016	0.0139	0.0119
Steel Stress (ksi)	30.51	**30.41**	27.74	22.49	18.03	15.62	48.61	**48.63**	44.11	37.14	34.844	32.514
Relative Values	CRCP-10						CRCP-8					
Crack Spacing (%)	100	**100**	84.09	57.82	41.58	33.634	100	**100**	84.34	58.64	50.97	43.521
Crack Width (%)	99.54	**100**	94.28	82.91	69.17	60.33	100	**100**	85.28	60.37	52.453	44.906
Steel Stress (%)	100.3	**100**	91.22	73.96	59.37	51.365	99.97	**100**	90.70	76.39	71.657	66.865



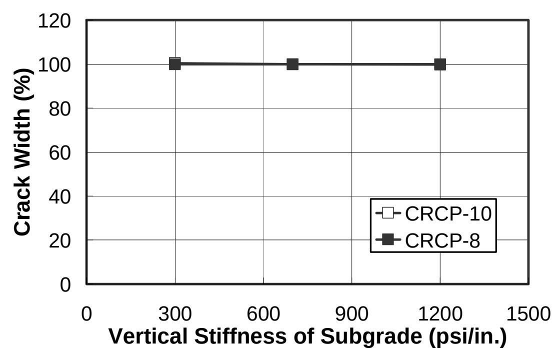
(a) Mean Crack Spacing



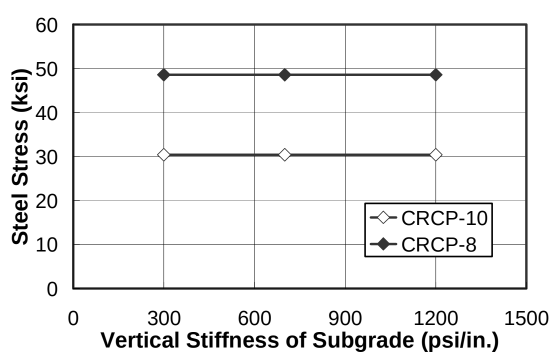
(d) Mean Crack Spacing



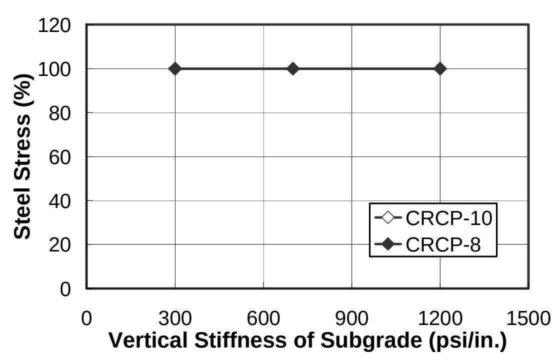
(b) Crack Width



(e) Crack Width

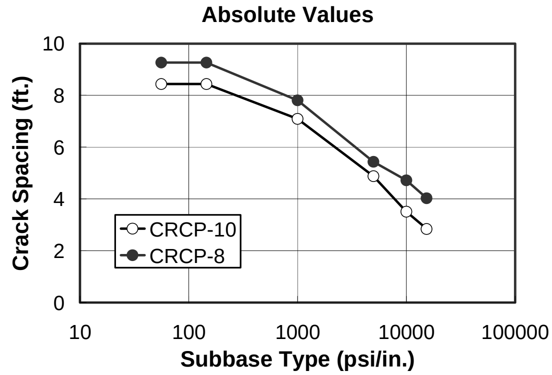


(c) Steel Stress

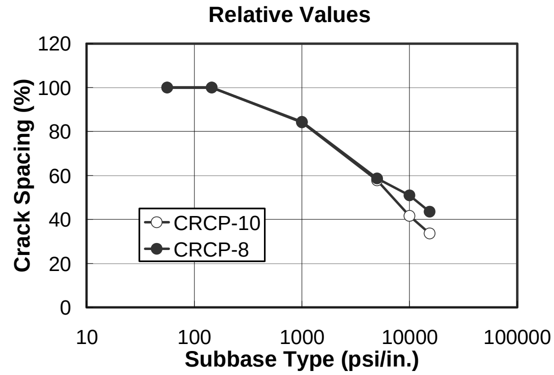


(f) Steel Stress

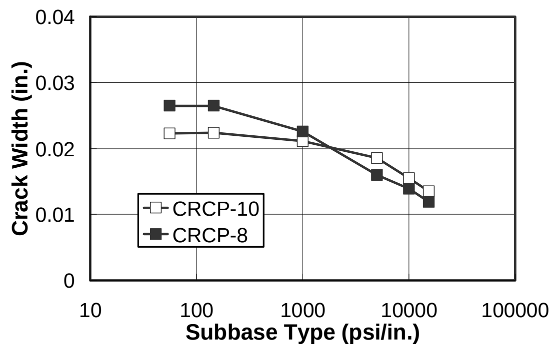
Figure 4.9 Sensitivity of vertical stiffness of subgrade



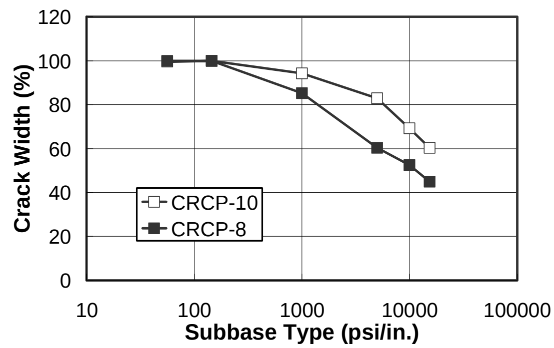
(a) Mean Crack Spacing



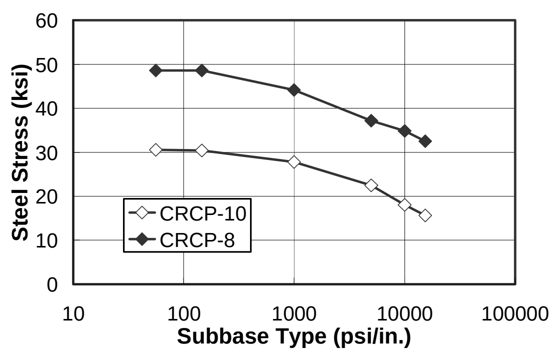
(d) Mean Crack Spacing



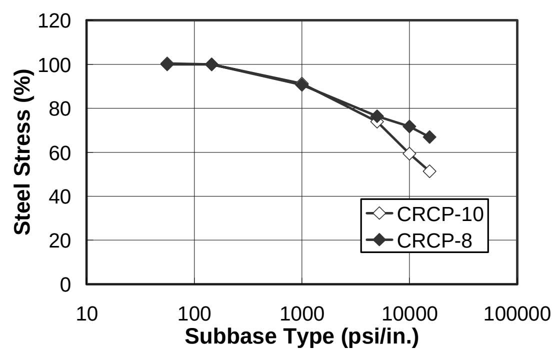
(b) Crack Width



(e) Crack Width



(c) Steel Stress



(f) Steel Stress

Figure 4.10 Sensitivity of horizontal stiffness

4.4 External Wheel Loads

The sensitivity of the wheel load to the CRCP behavior is investigated in this section. The input variables regarding the wheel load include days after concrete sets before wheel l oad applied, static single-wheel load, and dynamic tandem-axle loads.

4.4.1 Days after Concrete Sets before Wheel Load Applied

In this study, three different values are studied: 3, 7, and 28 days. Regardless of different input values of days after concrete sets before wheel load applied, the variations of crack spacing, crack width, and steel stress from CRCP-10 and CRCP-8 can be negligible in Table 4.10.

Table 4.10 Sensitivity of days after concrete sets before wheel load applied

Absolute Values	CRCP-10			CRCP-8		
Wheel Load Applied Days	3	**7**	28	3	**7**	28
Crack Spacing (ft.)	8.43	**8.43**	8.43	9.26	**9.26**	9.26
Crack Width (in.)	0.0224	**0.0224**	0.0224	0.0265	**0.0265**	0.0265
Steel Stress (ksi)	30.41	**30.41**	30.41	48.67	**48.67**	48.67
Relative Values	CRCP-10			CRCP-8		
Crack Spacing (%)	100	**100**	100	100	**100**	100
Crack Width (%)	100	**100**	100	100	**100**	100
Steel Stress (%)	100	**100**	100	100	**100**	100

4.4.2 Static Single-Wheel Load

The effect of the external wheel load has been studied and the results presented in Figure 4.11 for the static single-wheel loads of 6,000, 9,000, and 12,000 pounds and pavement thicknesses from 3 to 15 inches. If there is no wheel load and only the climatic loads are applied, the crack spacing is not affected by the pavement thickness except minimally for very thin pavements, i.e., less than 6 inches. If there is a wheel load, the crack spacing becomes larger with increasing pavement thickness. However, if the pavement thickness is over a certain value, the crack spacing is no longer affected by the pavement thickness, since the wheel load stress is low relative to the climatic stresses. The pavement thickness that makes no change in the crack spacing becomes larger as the wheel load increases, i.e., crack spacing becomes invariant with pavement thickness beyond this limit. In general, the crack spacing decreases as the wheel load increases for pavement thickness less than the invariant value. The comparison of CRCP-8 and CRCP-10 outputs indicate that the predicted crack spacing for CRCP-8 is significantly smaller than CRCP-10 for thicknesses less than the invariant value.

4.4.3 Dynamic Tandem-Axle Load

In the CRCP-10 program the critical wheel load stress is calculated assuming that the loads are moving, and the critical stress is induced by multiple wheels in a tandem axle and by their dynamic variations. The effect of the moving dynamic tandem-axle loads is shown in Figures 4.12 and 4.13.

As shown in Figure 4.11, when the pavement thickness is 12 inches, crack spacing is not affected by the types of the load (static single-wheel, static tandem-axle, and moving tandem-axle loads), i.e., invariant, as indicated by the horizontal line. When the pavement thickness is 6 inches, the crack spacing decreases as load magnitude increases. The static tandem-axle loads and the moving dynamic tandem-axle loads yield larger crack spacings than the static shingle-wheel load. For tandem-axle loads the crack spacing is not affected by the speed of vehicle.

The results obtained with the moving tandem-axle loads shown in Figure 4.12 occur when there is no variation in the load amplitude. However, there will be variations in the load amplitude when a truck is moving because of the surface roughness of the pavement and the mechanical systems of the vehicle.

Figure 4.13 compares the results obtained with the static tandem-axle loads and moving dynamic tandem-axle loads of harmonic amplitude variation. The speed of the vehicle is 70 mph, and half amplitude of the loads selected is 10% and 30% of the average load. As the pavement thickness increases, the crack spacing is clearly affected by the loads. However, if the pavement thickness is over a certain value, the crack spacing is no longer affected by the loads. Generally, moving dynamic tandem-axle loads yield smaller crack spacing than the static tandem-axle loads when the pavement thickness is smaller than a certain value. The effect of the variation in the load amplitude with heavier loads is very clear as shown in Figure 4.13 (c).

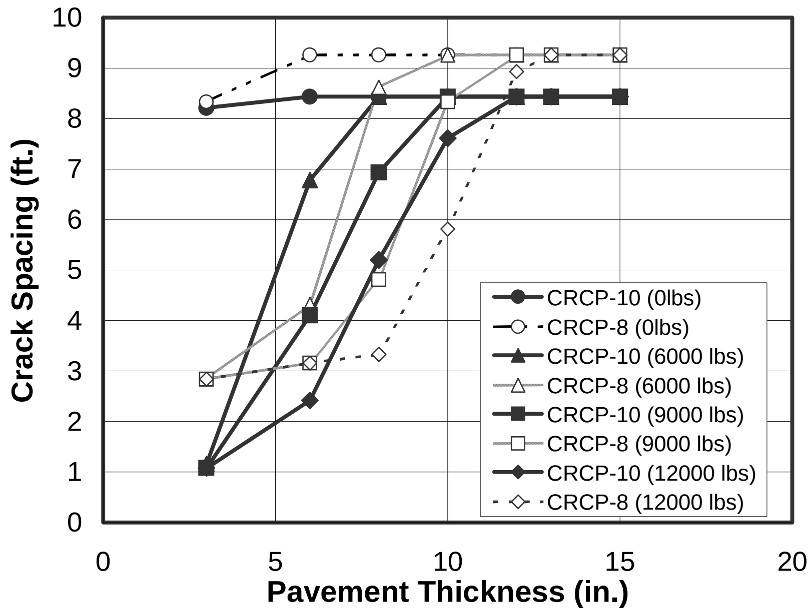


Figure 4.11 Sensitivity of crack spacing with static single wheel load and pavement thickness

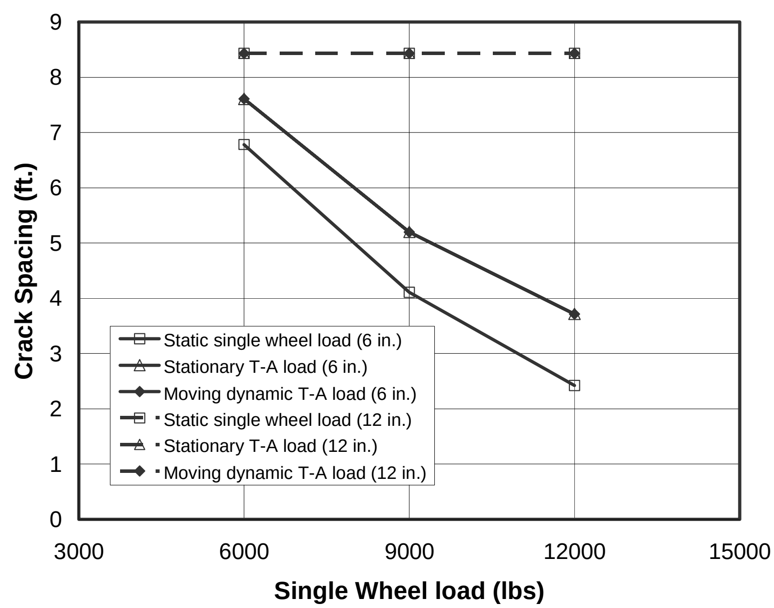


Figure 4.12 Comparisons of static single-wheel loads, static tandem-axle loads, and moving dynamic tandem-axle loads

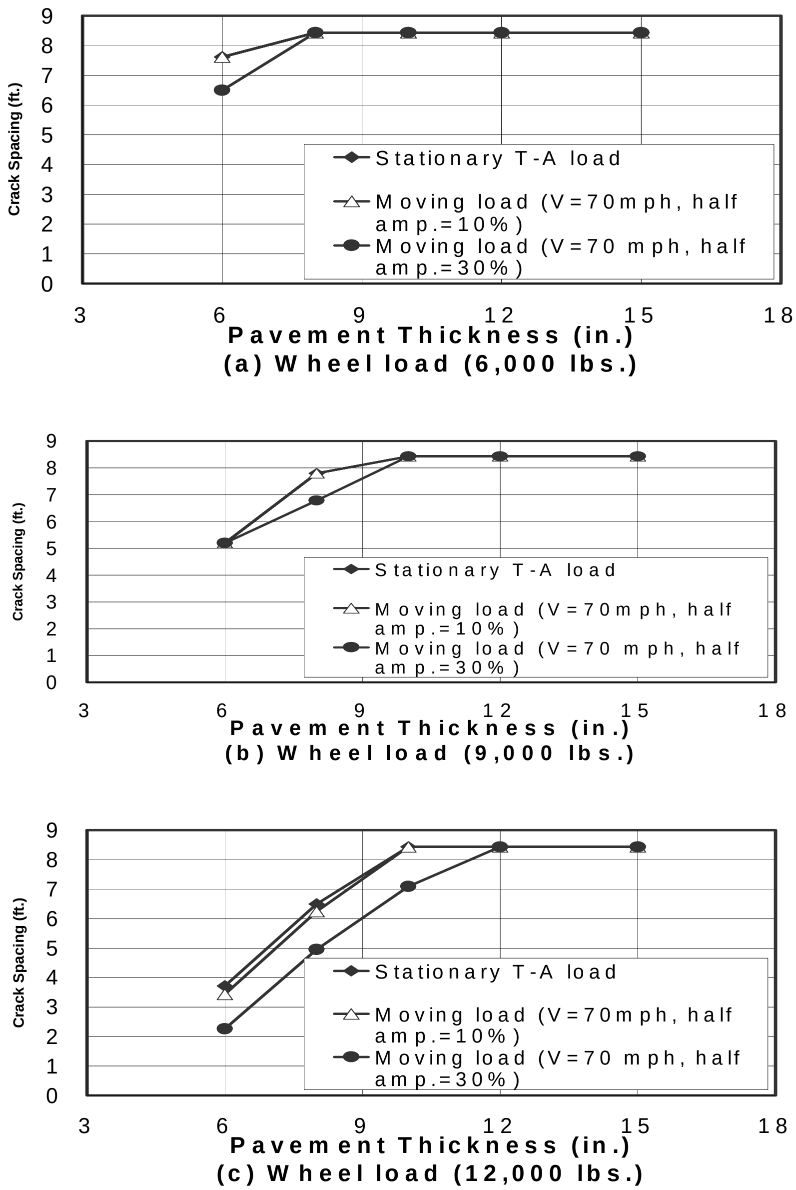


Figure 4.13 Comparisons of static tandem-axle loads and moving dynamic tandem-axle loads

4.5 Climatic Loads

As discussed previously in section 3.5, the climatic loads affect the early-age behavior of CRCP. In order to investigate the effect of the climatic loads on the CRCP behavior, zero-stress temperature and minimum temperature at first day after placement are selected.

4.5.1 Zero-Stress Temperature

The concrete pavements will be subjected to different curing conditions according to time of placement. The extended period of paving operations for continuously reinforced concrete pavements usually results in a large range of variation in zero-stress temperature on sections of the pavement. Various zero-stress temperatures within a range of 60°F to 125°F were examined in this study.

As shown in Table 4.11 and Figures 4.14 (a) and (d), the predicted crack spacings are very similar, but when the zero-stress temperature is 60°F, the difference in the crack spacing between CRCP-10 and CRCP-8 is significantly large. The zero-stress temperature of 60°F results in a crack spacing of 360% and 120% greater than the crack spacing obtained with the medium temperature of 90°F for the CRCP-10 and CRCP-8, respectively. For the other zero-stress temperatures, the differences in the crack spacing between the two programs are small. The trend of the results is similar to the general field observations that have shown that the crack spacing is inversely proportional to the zero-stress temperature. Although the variation of crack spacing is drastically changed with increasing zero-stress temperature, the computed crack width and steel stress are not much affected by the zero-stress temperature. This is a logical observation, since the crack width and steel stress are dependent on crack spacing.

A condition survey of CRCP conducted in Indiana by Faiz and Yoder (Ref 20) indicates that much of the distress took place during the cold months of the year. With regard to this field observation, it is suggested that extreme temperature drops during early curing should be avoided in order to prevent drastic effects on pavement performance. Thus, selection of zero-stress temperature and specified curing time may have a profound influence on the development of crack spacing and consequently on the performance of pavement.

Table 4.11 Sensitivity of zero-stress temperature

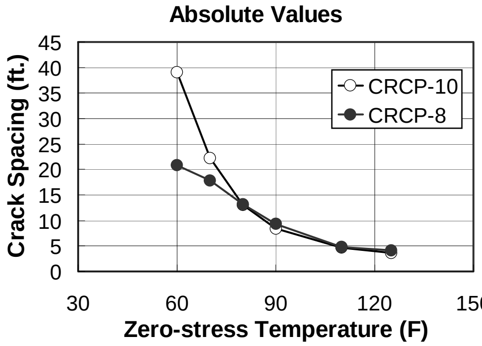
Absolute Values	CRCP-10						CRCP-8					
Curing Temperature	60	70	80	**90**	110	125	60	70	80	**90**	110	125
Crack Spacing (ft.)	39.06	22.29	13	**8.43**	4.66	3.67	20.83	17.86	13.16	**9.26**	4.81	4.17
Crack Width (in.)	0.022	0.023	0.023	**0.023**	0.021	0.021	0.024	0.028	0.029	**0.027**	0.021	0.020
Steel Stress (ksi)	30.09	31.5	31.74	**30.41**	28.52	28.85	48.03	50.33	50.57	**48.63**	41.85	41.61
Relative Values	CRCP-10						CRCP-8					
Crack Spacing (%)	463.3	264.4	154.2	**100**	55.23	43.54	224.9	192.9	142.1	**100**	51.94	45.03
Crack Width (%)	99.55	103.6	104.3	**100**	93.31	92.91	92.08	105.7	109.1	**100**	76.60	46.23
Steel Stress (%)	98.95	103.6	104.4	**100**	93.79	94.87	98.78	103.5	103.9	**100**	86.07	85.56

4.5.2 Minimum Temperature at First Day after Placement

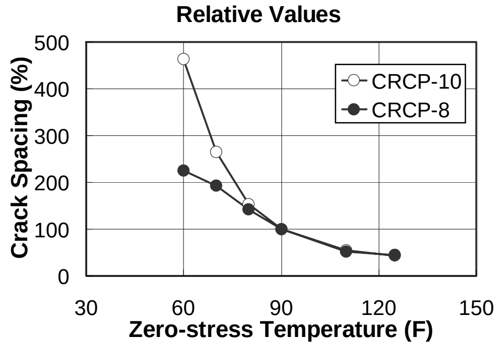
As one of the climatic loads, the daily temperature change after construction is an important factor that affects the early behavior of CRCP. To consider different situations of the daily temperature change during the curing period, three different first day's minimum temperatures are selected: 50°F, 60°F, and 70°F. Table 4.12 and Figure 4.15 show the predicted crack spacing, crack width, and steel stress when the minimum temperature at the first day after placement values. The results show that the crack spacing, crack width, and steel stress are directly proportional to the temperature changes. As the minimum temperature decreases, the crack spacing, crack width, and steel stress decrease.

Table 4.12 Sensitivity of minimum temperature on first day after placement for zero-stress temperature of 90°F

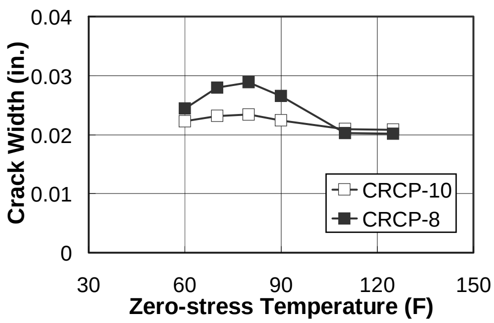
Absolute Values	CRCP-10			CRCP-8		
Min. Temperature	50	**60**	70	50	**60**	70
Crack Spacing (ft.)	5.78	**8.43**	13	6.76	**9.26**	11.9
Crack Width (in.)	0.0187	**0.0224**	0.0266	0.020	**0.0265**	0.033
Steel Stress (ksi)	25.03	**30.41**	36.63	41.52	**48.63**	53.39
Relative Values	CRCP-10			CRCP-8		
Crack Spacing (%)	68.52	**100**	154.17	73.00	**100**	128.51
Crack Width (%)	83.53	**100**	118.79	75.85	**100**	124.53
Steel Stress (%)	82.31	**100**	120.45	85.39	**100**	109.79



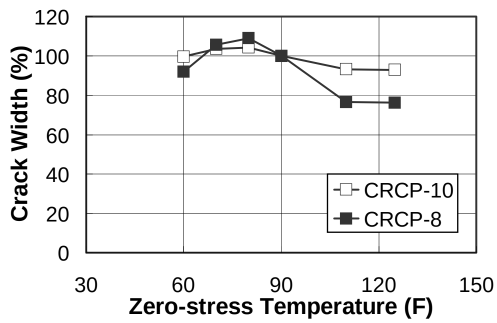
(a) Mean Crack Spacing



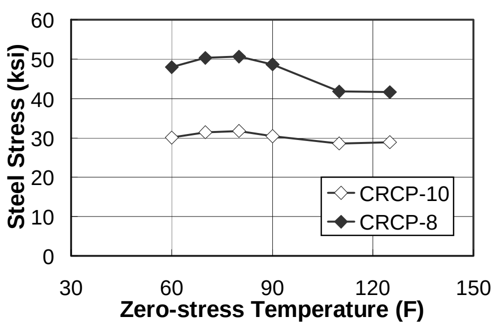
(d) Mean Crack Spacing



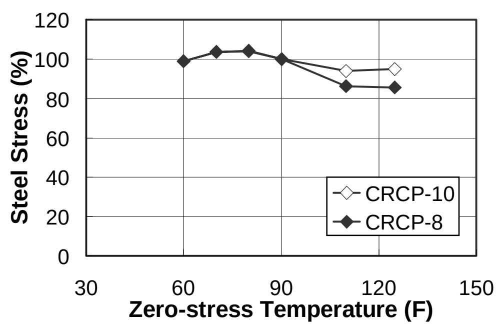
(b) Crack Width



(e) Crack Width

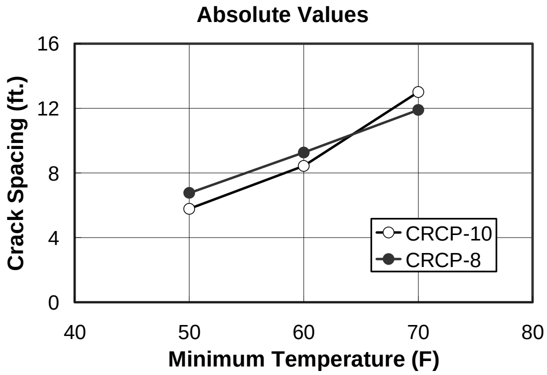


(c) Steel Stress

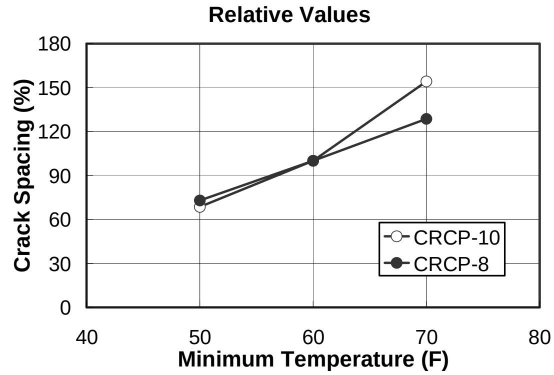


(f) Steel Stress

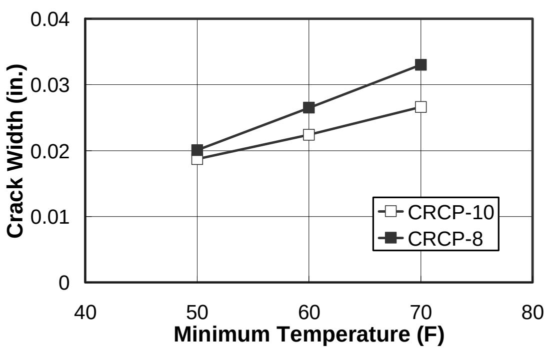
Figure 4.14 Sensitivity of zero-stress temperature for a minimum actual temperature of 60°F



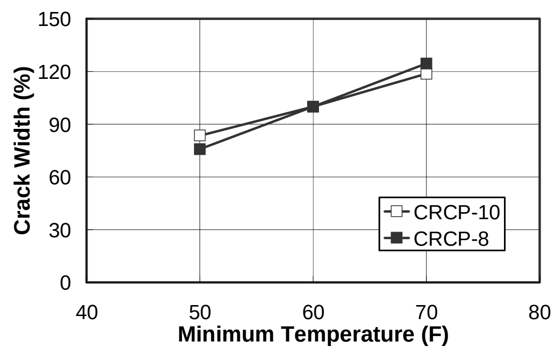
(a) Mean Crack Spacing



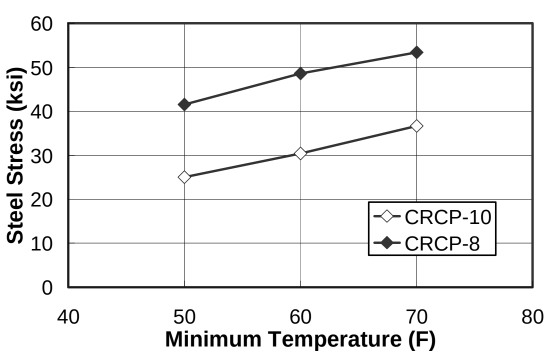
(d) Mean Crack Spacing



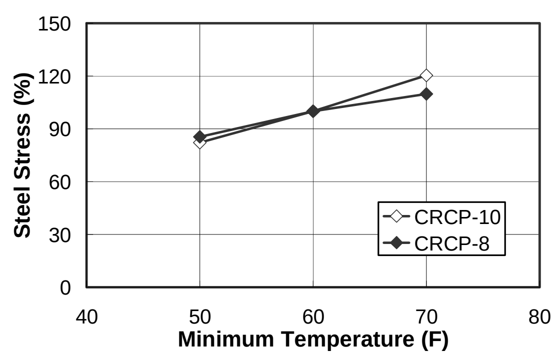
(b) Crack Width



(e) Crack Width



(c) Steel Stress



(f) Steel Stress

Figure 4.15 Sensitivity of minimum temperature at first day after placement for a zero-stress temperature of 90°F

5. Sensitivity Analysis with High and Low Basic Levels

5.1 The Method of Analysis

In Chapter 4, a sensitivity study was conducted using all variables but the one being investigated at the medium value: i.e., all the input variables were at their medium levels. In this chapter two additional problems were solved for each variable, one in which all the variables except the studied variable were held at their low values and the other case when all variables were held at their high values. Similar studies as in Chapter 4 have been conducted to investigate the effect of each variable when all the other variables are held at their low or high levels. The results are described in this chapter.

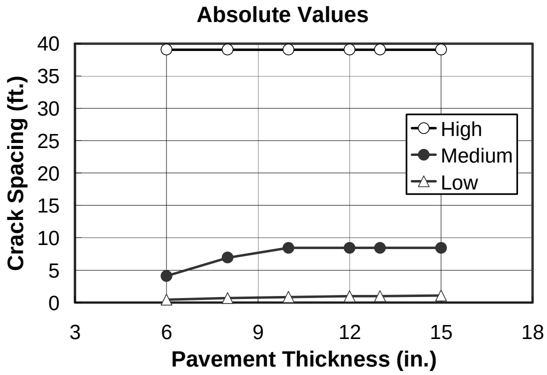
The low basic level does not necessarily mean a set of the lowest input values, but rather the set of each input value that makes the lowest output results, such as crack spacing, crack width, and steel stress. Similarly, the high basic level means a set of each input value that develops the highest output results. For example, as the coefficient of thermal expansion increases, the crack spacing becomes smaller; therefore, the low basic level of the coefficient of thermal expansion is its highest input value, and the high basic level of the coefficient of thermal expansion is its lowest input value. The results from CRCP-10 have been considered in this chapter to investigate the effects of low and high basic levels. The other processes are the same as those in Chapter 4.

5.2 High Basic Level

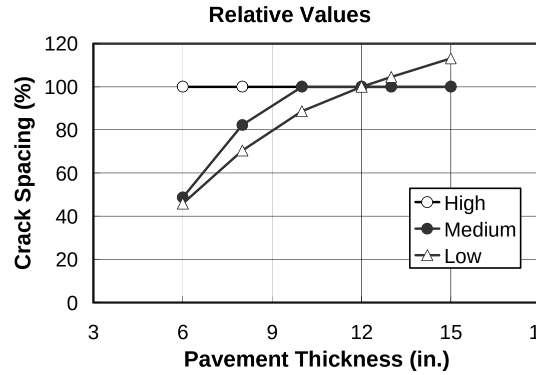
In the sensitivity study with the high basic level, the results show the extremely high output values, especially for crack spacings that are around 40 feet. The output values are almost constant regardless of changing a certain input variable, as shown in Figure 5.1. This means that there is no sensitivity with the high basic level. Because of this, the results obtained with the high basic level are not shown in most figures. For zero-stress temperature shown in Figure 5.9, the crack spacing is constant when the zero-stress temperature is lower than about 100°F. The cracking spacing, however, becomes smaller as the zero-stress temperature increases above 110° F. From this investigation, the zero-stress temperature is found to be one of the most sensitive input variables, as already demonstrated in the sensitivity study with the medium basic level.

5.3 Low Basic Level

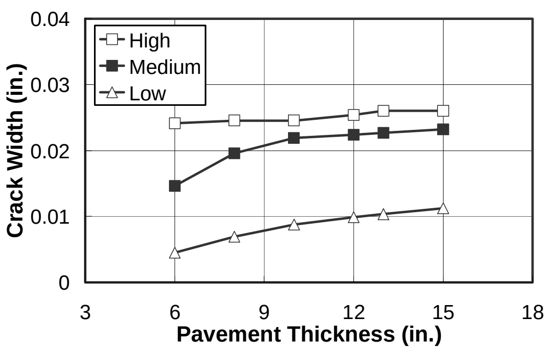
In the sensitivity study with the low basic level, the results show the extremely low output values as shown in Figures 5.1 through 5.10. For example, crack spacing is less than one foot. Therefore, the change in the output values is not very distinctive for all variables, compared with the results obtained with the medium basic level. However, if we compare the relative output values with the output value obtained with the medium input value, we can see the sensitivity as shown in the figures. The sensitivity trends are very similar to those obtained with the medium basic level. In most cases, the sensitivity of the output results with the low basic level is smaller than that with the medium basic level.



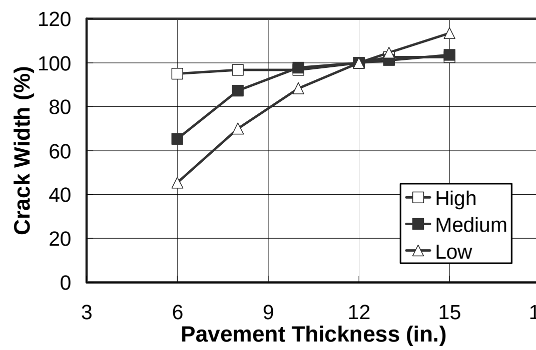
(a) Mean Crack Spacing



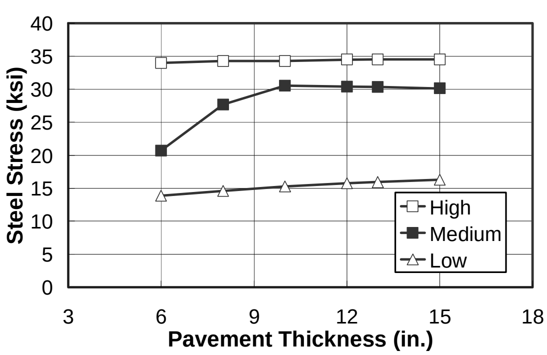
(d) Mean Crack Spacing



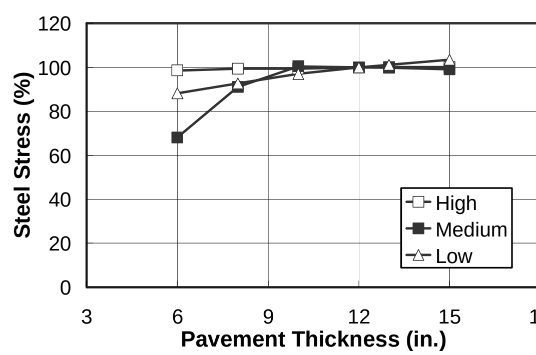
(b) Crack Width



(e) Crack Width

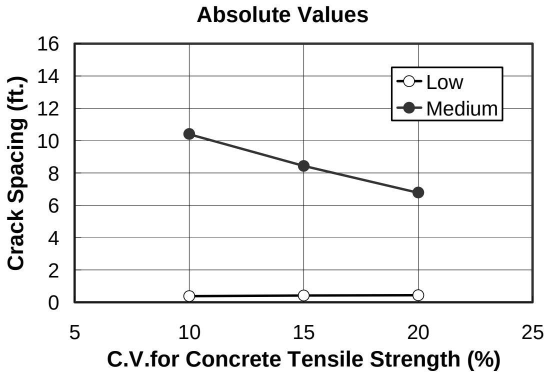


(c) Steel Stress

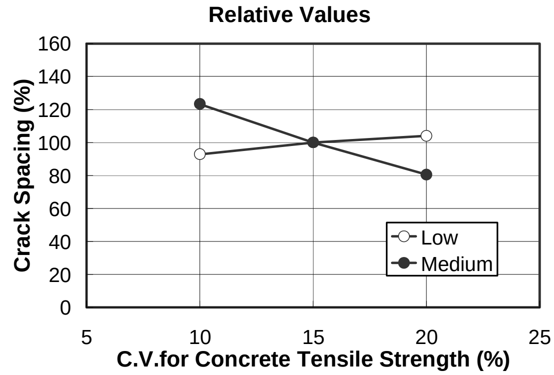


(f) Steel Stress

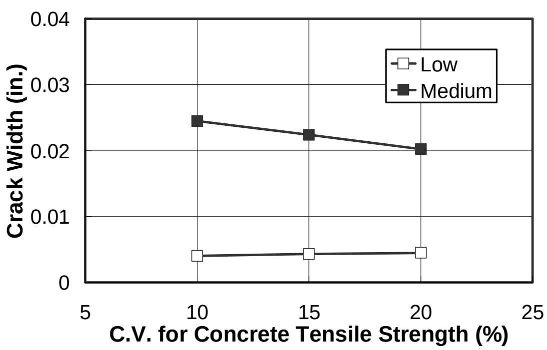
Figure 5.1 Sensitivity of pavement thickness with low, medium, and high basic levels



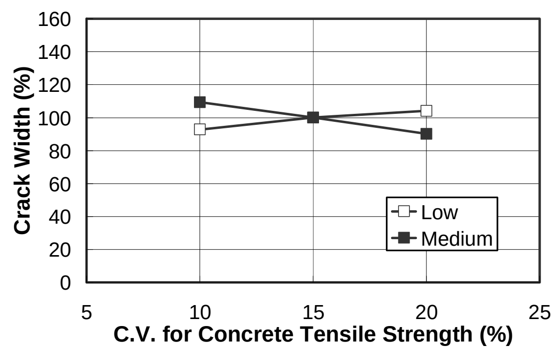
(a) Mean Crack Spacing



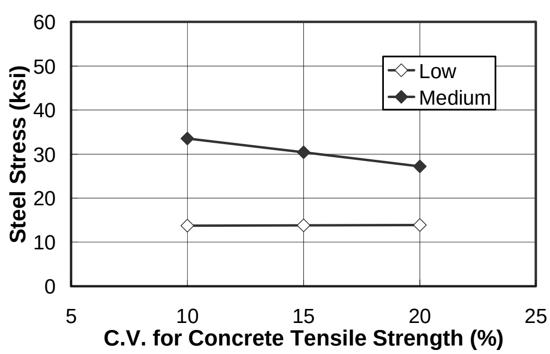
(d) Mean Crack Spacing



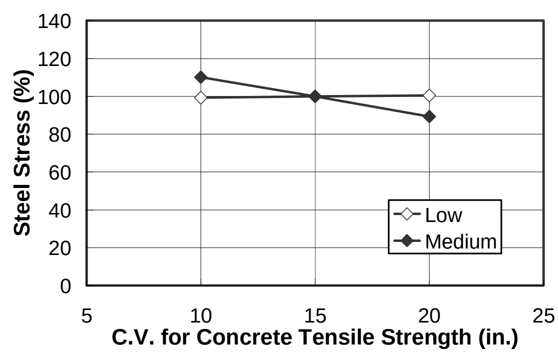
(b) Crack Width



(e) Crack Width

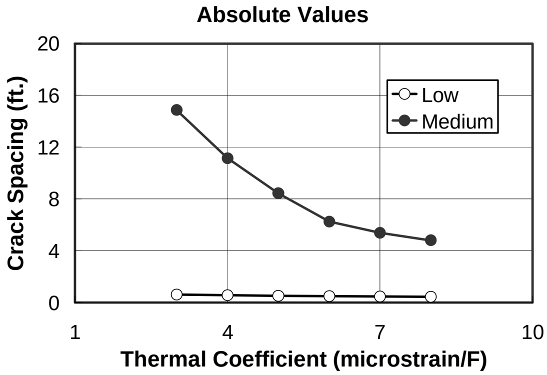


(c) Steel Stress

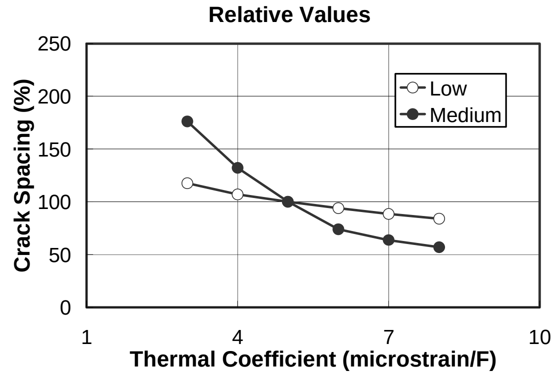


(f) Steel Stress

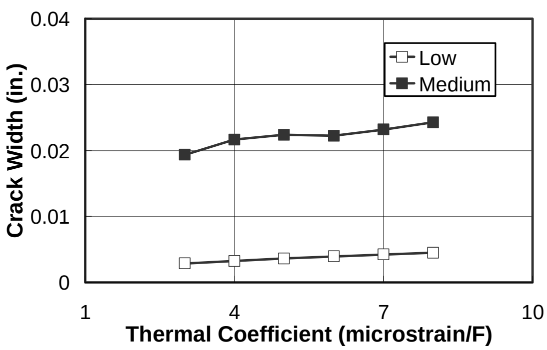
Figure 5.2 Sensitivity of coefficient of variation for concrete tensile strength with low and medium basic levels



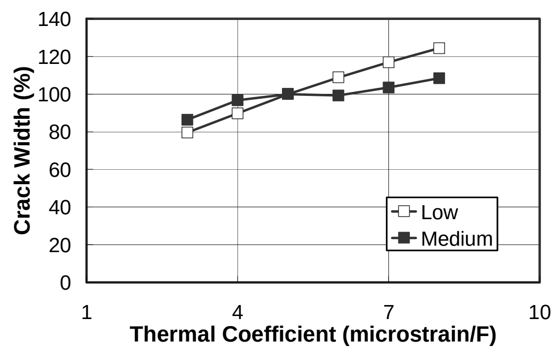
(a) Mean Crack Spacing



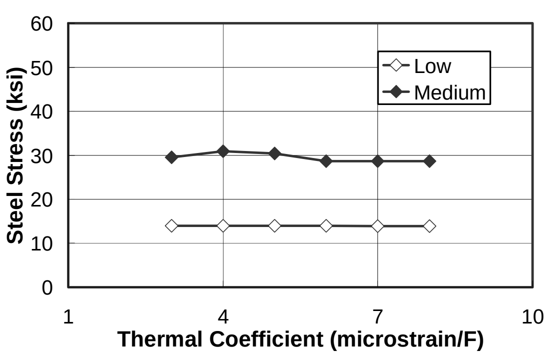
(d) Mean Crack Spacing



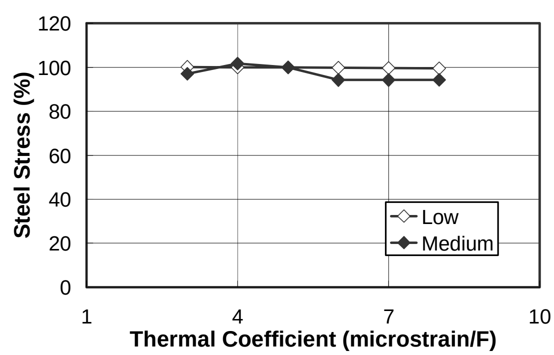
(b) Crack Width



(e) Crack Width

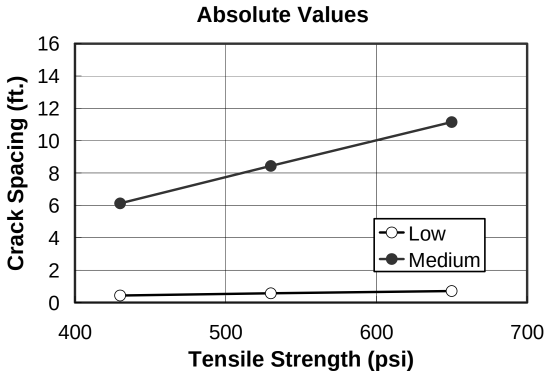


(c) Steel Stress

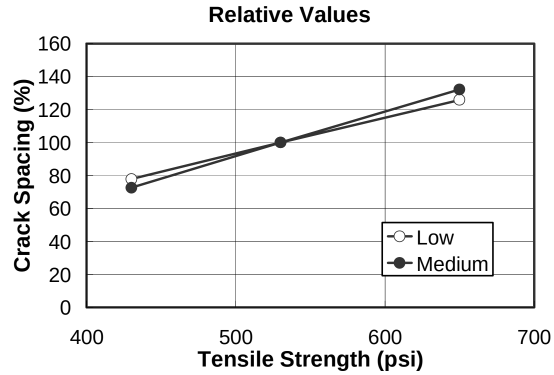


(f) Steel Stress

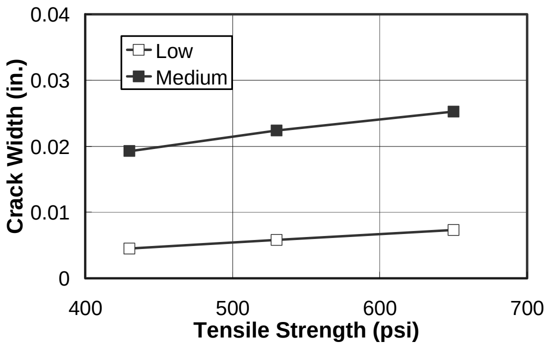
Figure 5.3 Sensitivity of coefficient of thermal expansion with low and medium basic levels



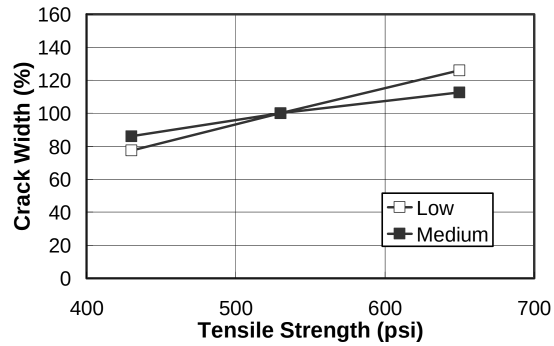
(a) Mean Crack Spacing



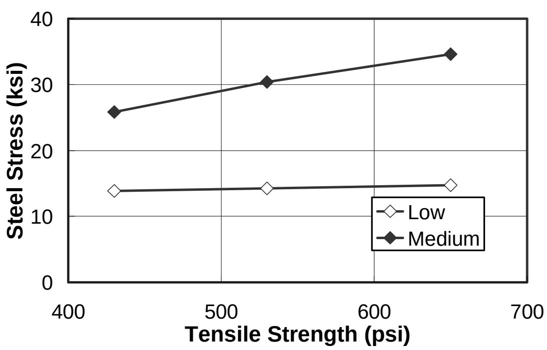
(d) Mean Crack Spacing



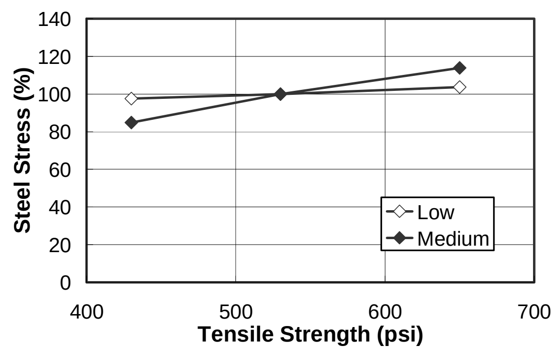
(b) Crack Width



(e) Crack Width

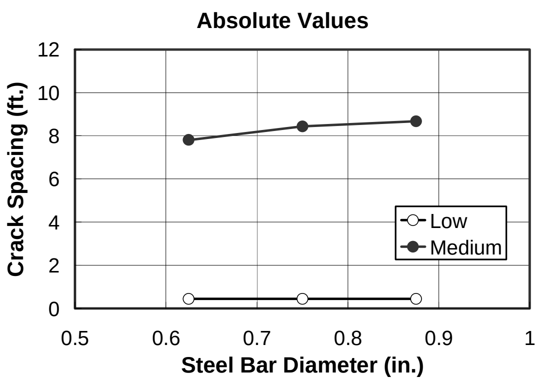


(c) Steel Stress

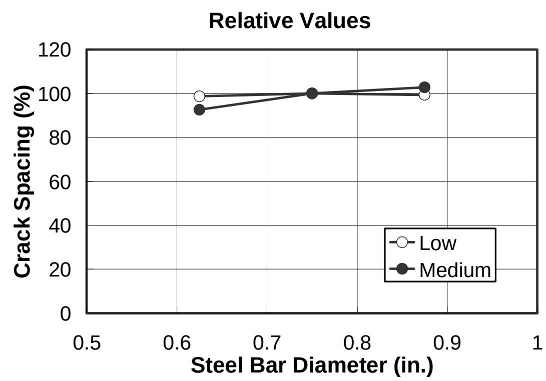


(f) Steel Stress

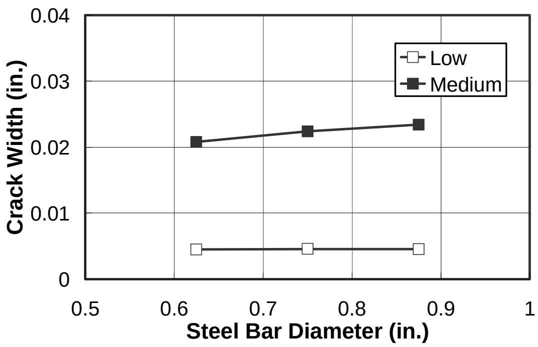
Figure 5.4 Sensitivtiy of tensile strength with low and medium basic levels



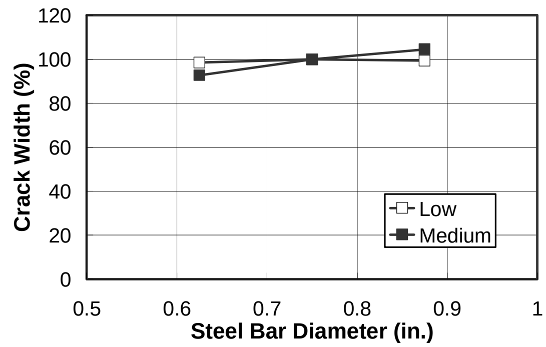
(a) Mean Crack Spacing



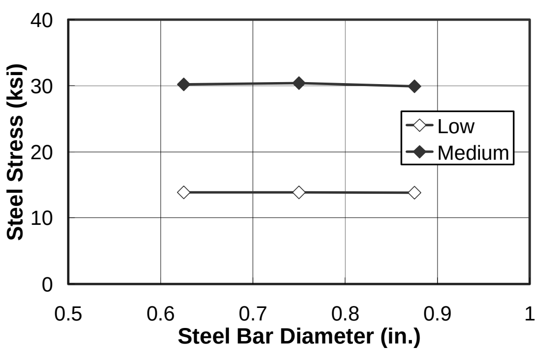
(d) Mean Crack Spacing



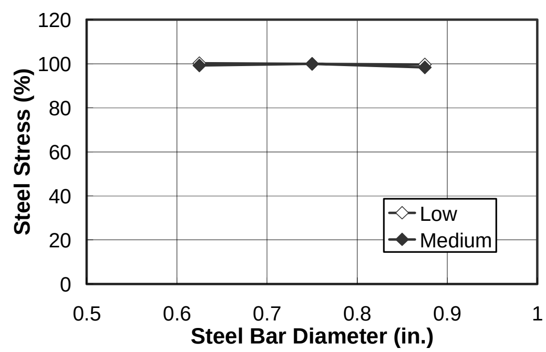
(b) Crack Width



(e) Crack Width

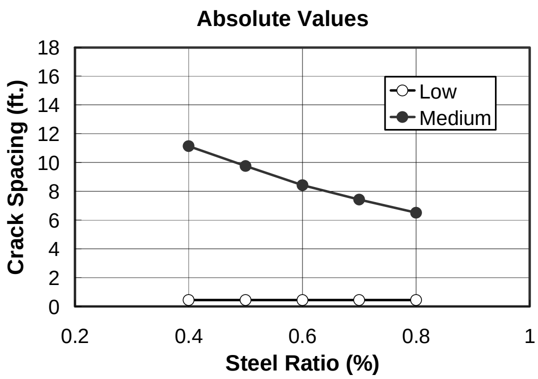


(c) Steel Stress

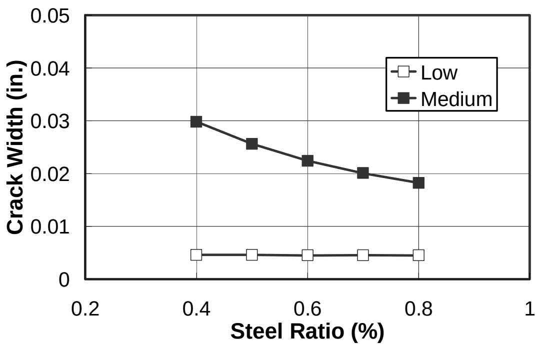


(f) Steel Stress

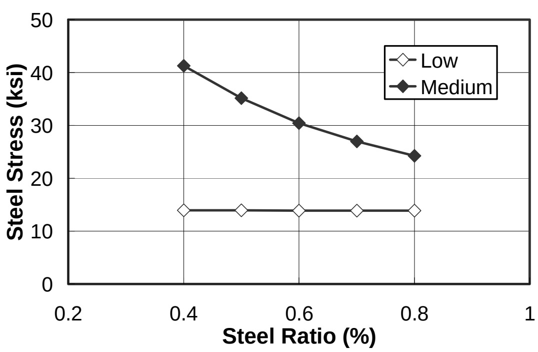
Figure 5.5 Sensitivity of steel bar diameter with low and medium basic levels



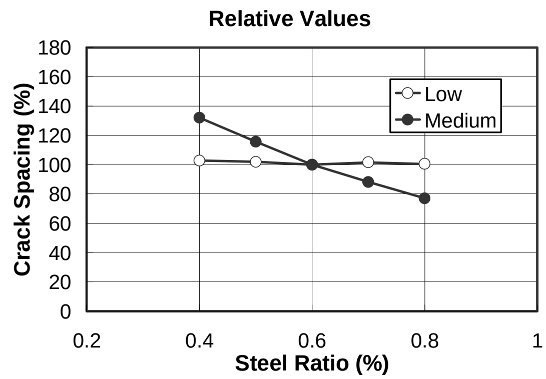
(a) Mean Crack Spacing



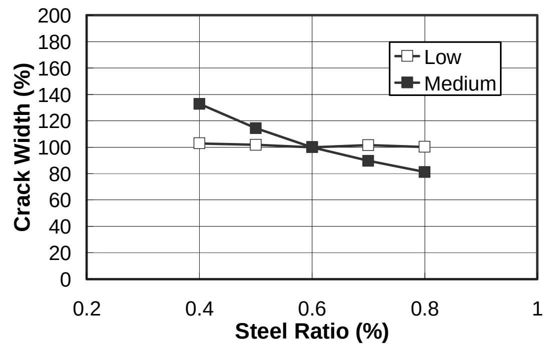
(b) Crack Width



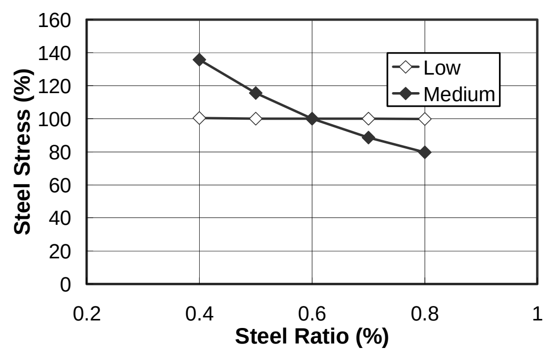
(c) Steel Stress



(d) Mean Crack Spacing



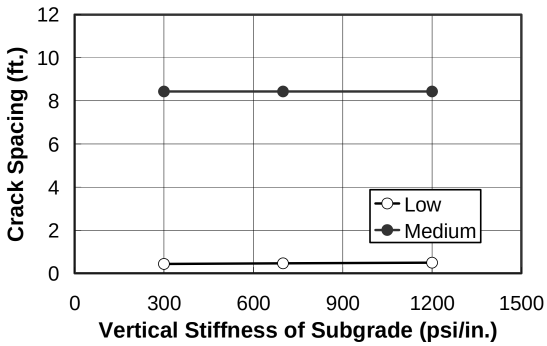
(e) Crack Width



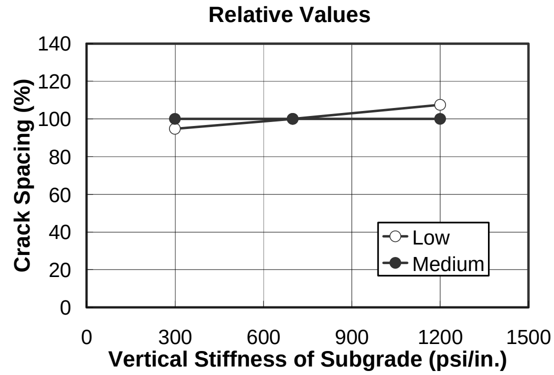
(f) Steel Stress

Figure 5.6 Sensitivity of steel ratio with low and medium basic levels

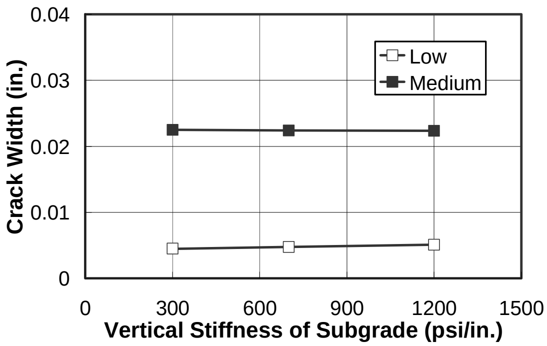
Absolute Values



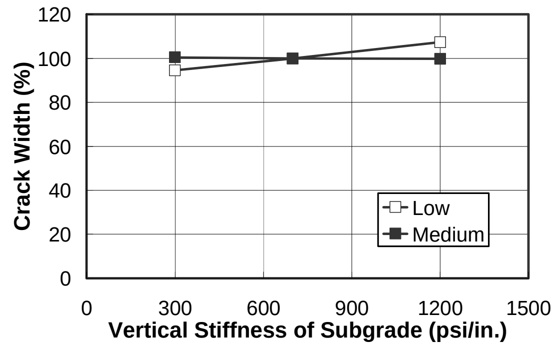
(a) Mean Crack Spacing



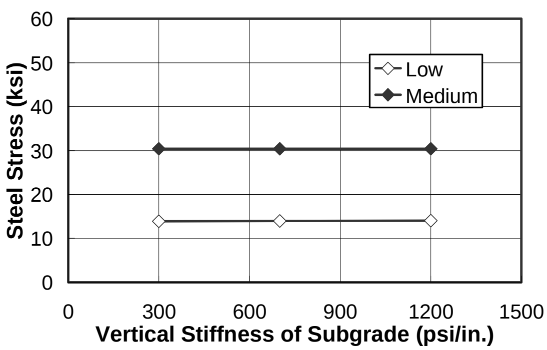
(d) Mean Crack Spacing



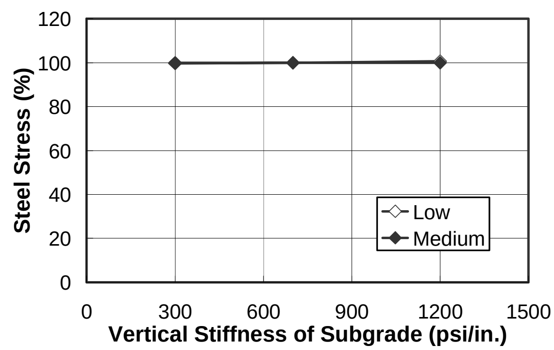
(b) Crack Width



(e) Crack Width

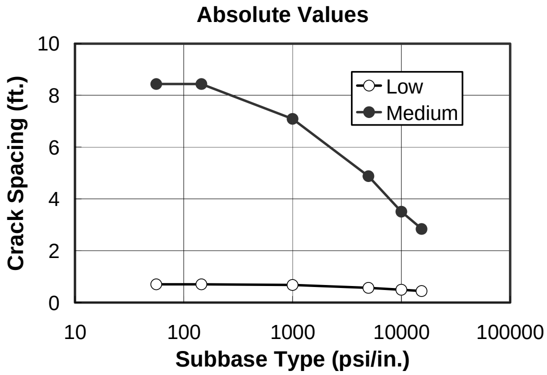


(c) Steel Stress

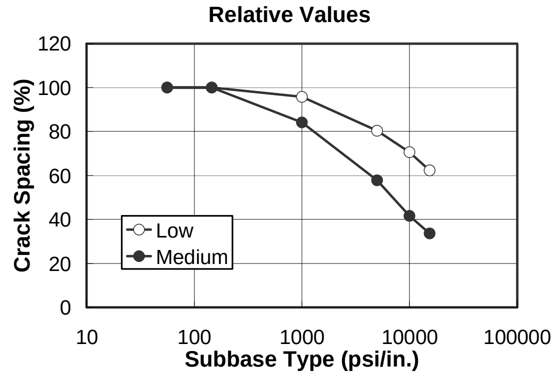


(f) Steel Stress

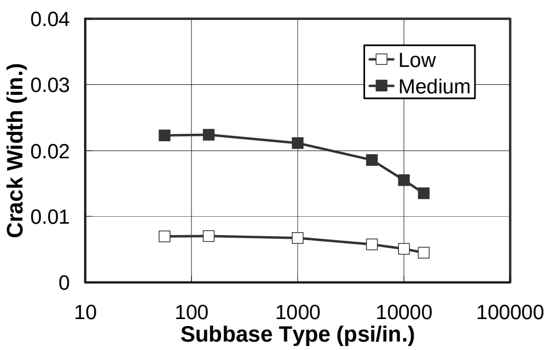
Figure 5.7 Sensitivity of vertical stiffness of subgrade with low and medium basic levels



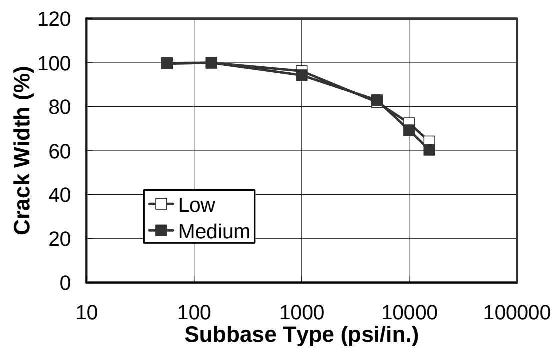
(a) Mean Crack Spacing



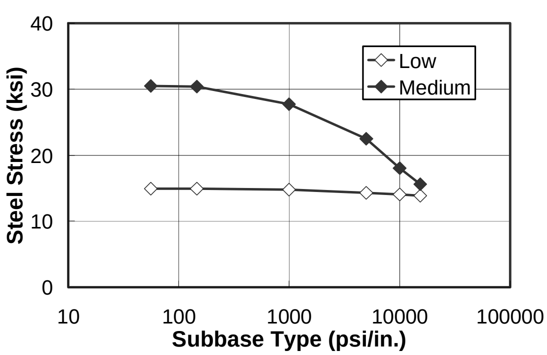
(d) Mean Crack Spacing



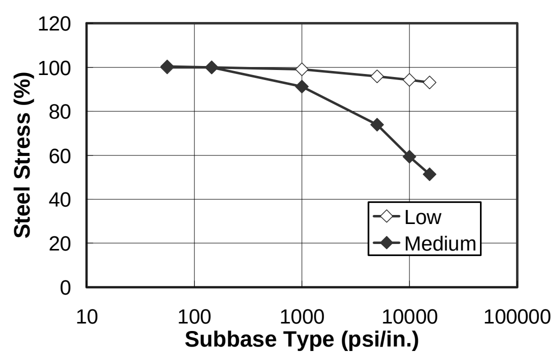
(b) Crack Width



(e) Crack Width

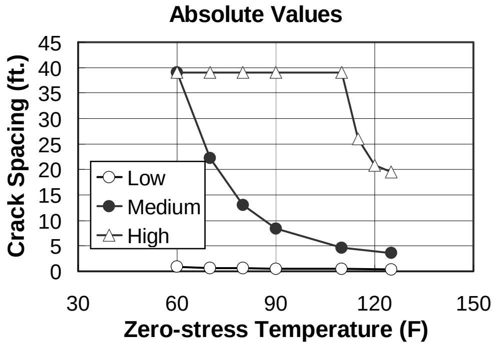


(c) Steel Stress

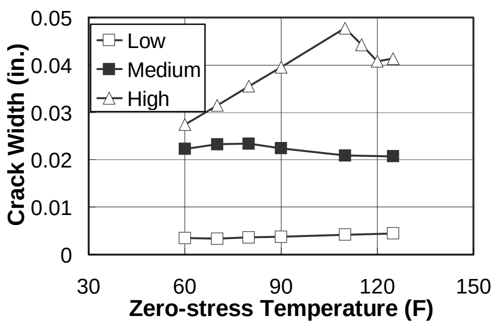


(f) Steel Stress

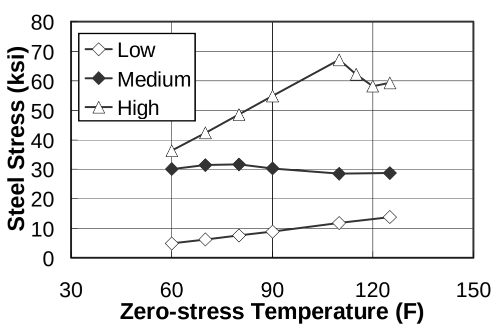
Figure 5.8 Sensitivity of horizontal stiffness with low and medium basic levels



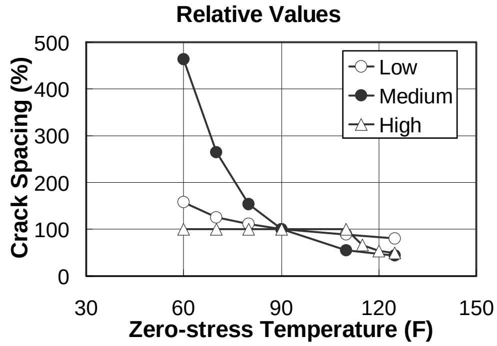
(a) Mean Crack Spacing



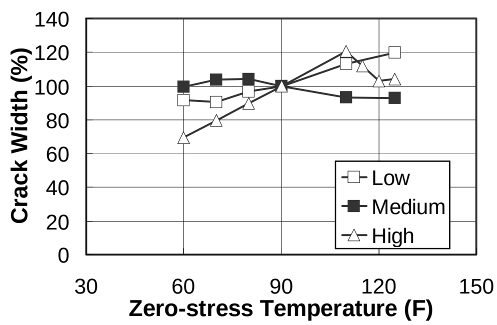
(b) Crack Width



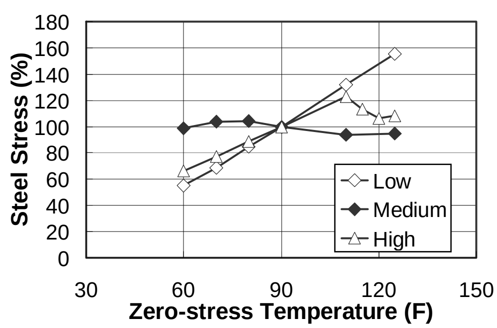
(c) Steel Stress



(d) Mean Crack Spacing

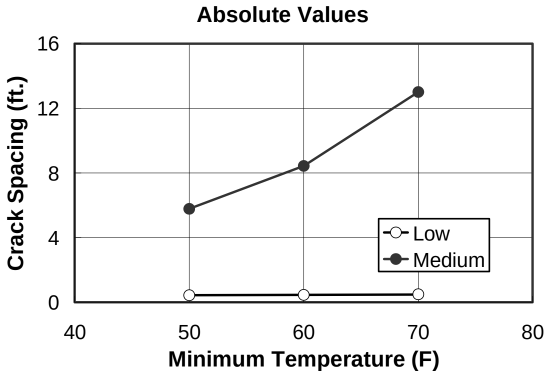


(e) Crack Width

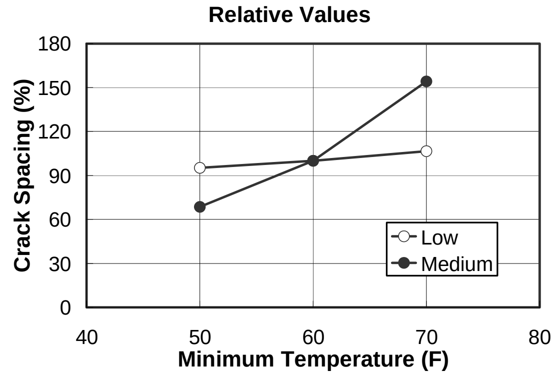


(f) Steel Stress

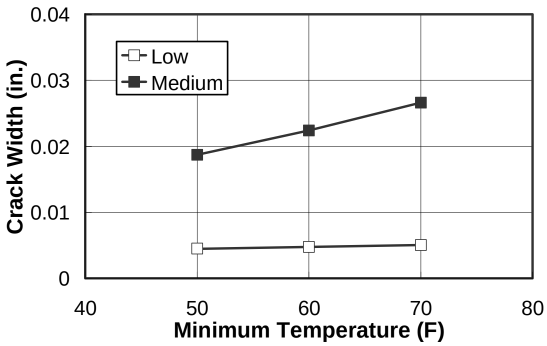
Figure 5.9 Sensitivity of zero-stress temperature with low, medium, and high basic levels



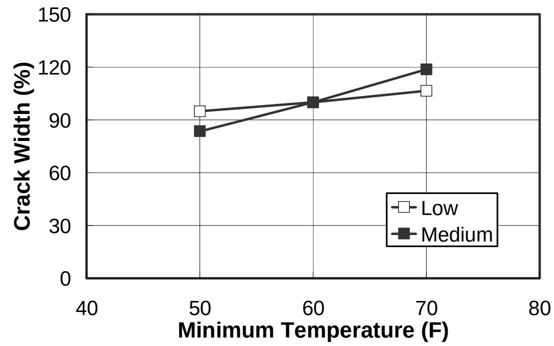
(a) Mean Crack Spacing



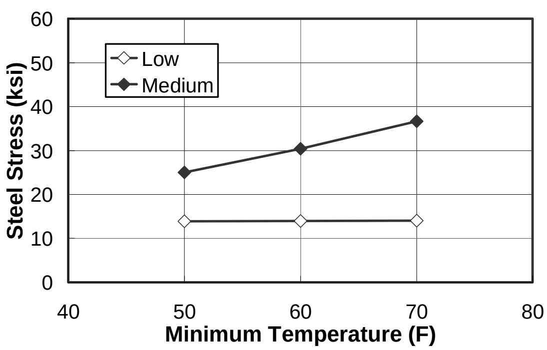
(d) Mean Crack Spacing



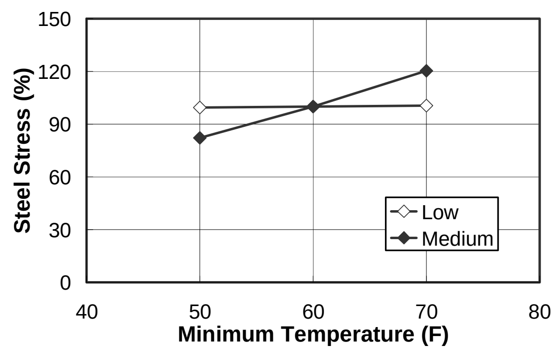
(b) Crack Width



(e) Crack Width



(c) Steel Stress



(f) Steel Stress

Figure 5.10 Sensitivity of minimum temperature at first day after placement with low and medium basic levels

6. Discussion of Results

The sensitivity analysis of the design variables has been conducted to obtain the effect of each variable on the CRCP behavior, to find the relative importance of each variable, and to compare the results between CRCP-8 and CRCP-10. In the sensitivity analysis, one variable is selected and changes within the practical range while the other variables remain at their medium values, and the analysis results such as mean crack spacing, crack width, and steel stress at crack, are obtained. In the following sections, these results are first discussed in general terms, and then in terms of specific inputs.

6.1 General Observations

The analysis results point to the following observations:

- The crack spacing, crack width, and steel stress show similar trends in the results, but the crack spacing is more affected by changes in values of the design variables than the crack width and steel stress.
- The variables that make the crack spacing larger as they increase are
  - Pavement thickness
  - Tensile strength of concrete
  - Steel bar diameter
  - Minimum temperature at first day after placement
- The variables that make the crack spacing smaller as they increase are
  - Coefficient of variation for concrete tensile strength
  - Coefficient of thermal expansion of concrete
  - Percent reinforcement
  - Horizontal stiffness between concrete slab and subbase
  - Zero-stress temperature
- The most sensitive variables to the CRCP behavior are
  - Coefficient of thermal expansion of concrete
  - Zero-stress temperature
- The moderately sensitive variables to the CRCP behavior are
  - Pavement thickness

- Coefficient of variation for concrete tensile strength
- Tensile strength of concrete
- Percent reinforcement
- Horizontal stiffness between concrete slab and subbase
- Minimum temperature at first day after placement

- The least sensitive variables to the CRCP behavior are
  - Steel bar diameter
  - Vertical stiffness of underlying layers
- Static single-wheel load and dynamic tandem-axle load have a significant influence on the pavement behavior, thus, the accurate prediction of wheel load is necessary during the design stage.
- The results from the CRCP-8 and CRCP-10 computer programs are generally in agreement. However, there is a large difference in the steel stresses between the two programs.

6.2 Concrete Properties

The sensitivity study of concrete material properties such as pavement thickness, coefficient of variation for concrete tensile strength, coefficient of thermal expansion, and tensile strength has been performed.

Three pavement thicknesses of 6, 12, and 15 inches are selected as low, medium, and high values, respectively. The crack spacing increases as the pavement thickness increases, but when the pavement thickness is over 10 inches for CRCP-10 and over 12 inches for CRCP- 8, the pavement thickness does not affect the crack spacing. The same result can be observed for the crack width and steel stress.

For coefficient of variation for concrete tensile strength, three values of 10%, 15%, and 20% are considered. With an increase in the coefficient of variation for concrete tensile strength, the crack spacing, crack width, and steel stress decrease. The decrease in the crack spacing is larger than that in the crack width and steel stress.

Three basic levels of coefficient of thermal expansion are selected to be 3, 5, and 8 microstrain/°F. The crack spacing decreases as the coefficient of thermal expansion of concrete increases. The rate of the decrease in the crack spacing is higher when the coefficient of thermal expansion is around the low values. The crack width and steel stress, however, are not significantly affected by the change of the coefficient of thermal expansion.

Three tensile strength values of 430, 530, and 650 psi are used to investigate the influence of concrete strength on the pavement behavior. The crack spacing, crack width, and steel stress increase with increasing the concrete tensile strength. The crack spacing is more affected by the change in tensile strength than the crack width and steel stress.

6.3 Steel Properties

Three different bar diameters were selected to investigate its effect on the pavement behavior. Those are 0.65 (No.5), 0.75 (No.6), and 0.875 (No.7) inches. The crack spacing increases very slightly with increasing the steel bar diameter. The crack width and steel stress are not affected as much by the steel bar diameter.

For the sensitivity of the percent reinforcement, three levels were selected to be 0.4%, 0.6%, and 0.8%. The mean crack spacing, crack width, and steel stress decrease as the percent reinforcement increases. As the amount of the steel reinforcement increases, the restraint to resist the concrete contraction due to the climatic loads, such as changes in temperature and drying shrinkage, becomes larger and the concrete stress increases. This causes more cracks and smaller crack spacings. The crack spacing can be up to 30% larger and 20% smaller than the typical crack spacing within the practical range of the percent reinforcement. It is noted that the sensitivity of the crack width and steel stress is very similar to that of the crack spacing in this case.

6.4 Slab/Subbase Resistance

The sensitivity of other design variables, including vertical stiffness of underlying layers and horizontal stiffness at the interface between the bottom of concrete slab and subbase, have been studied. Three levels of vertical stiffness were selected: 300, 700, and 1,200 pci. The vertical stiffness of underlying layers does not affect the analysis results. This means that the vertical stiffness of underlying layers is not a sensitive design variable when the other variables are at their typical values.

Asphalt-stabilized (56 pci), flexible (145.5 pci), and cement-stabilized (15,400 pci) subbase types are selected to investigate the effect of the horizontal bond stiffness at the interface between concrete slab and subbase. The crack spacing becomes smaller as the horizontal bond stiffness increases. The crack width and steel stress also decrease with increasing the horizontal bond stiffness. Because the frictional bond stiffness is directly related to the subbase type, the selection of the subbase type affects the CRCP behavior significantly.

6.5 External Wheel Loads

The effects of the static single-wheel load and dynamic tandem-axle load have been studied. In this study three different external wheel loads were selected: 6,000, 9,000 and 12,000 pounds. If there is no wheel load and only the climatic loads are applied, the crack spacing is not affected by the pavement thickness if the percent reinforcement remains the same. As the wheel load increases, the crack spacing becomes clearly affected by the pavement thickness. With increasing the pavement thickness, the crack spacing becomes larger. However, if the pavement thickness is over a certain value, the crack spacing is no longer affected by the pavement thickness. The pavement thickness that makes no change in the crack spacing becomes larger as the wheel load increases.

The static tandem-axle loads yield slightly larger crack spacings than the static single-wheel load. For moving tandem-axle loads of constant amplitude, the crack spacing is not affected by the speed of vehicle. However, moving tandem-axle loads of varying amplitude yield smaller crack spacing than that caused by the static tandem-axle loads, when the pavement thickness is smaller than a certain value.

6.6 Climatic Loads

Three zero-stress temperatures of 60°F, 90°F, and 125°F are examined. The crack spacing decreases as the zero-stress temperature increases. Although the variation of crack spacing is drastically changed with increasing zero-stress temperature, the computed crack width and steel stress are not much affected by the zero-stress temperature.

To consider different situations of daily temperature change during the curing period, three different first day's minimum temperatures are selected: 50°F, 60°F, and 70°F. The minimum temperature at first day after placement also affects the crack spacing. The crack spacing increases with increasing the minimum temperature. The crack width and steel stress show the similar results, but the variations are smaller.

6.7 Summary of Sensitivity

Table 6.1 summarizes the sensitivity of the design variables considered in this study. If the analysis results are over 30% different from the result obtained with the medium input value, the results are highlighted. From Table 6.1 it is found that the zero-stress temperature and the coefficient of thermal expansion are the most sensitive design variables. The steel bar diameter and the vertical stiffness of underlying layers are not sensitive design variables, and the other design variables can be defined as moderately sensitive design variables.

The sensitivity of the design variables to the steel stress obtained from CRCP-8 and CRCP-10 is very similar. However, the absolute values of the steel stresses from the two programs show a large difference. Further studies, including field experiments, are needed to find the actual steel stresses.

Table 6.1 Sensitivity of design variables

Input Variables	Results	CRCP-10 Low (%)	CRCP-10 High (%)	CRCP-8 Low (%)	CRCP-8 High (%)
Pavement Thickness (in.)	Crack Spacing (ft.)	-51.3	0	-65.9	0
	Crack Width (in.)	-34.7	-3.6	-58.9	0.8
	Steel Stress (ksi)	-31.9	0.9	-39.9	2.3
Coefficient of Variation for Concrete Tensile Strength (%)	Crack Spacing (ft.)	23.3	-19.6	50.0	-32.5
	Crack Width (in.)	9.3	-9.9	41.9	-29.4
	Steel Stress (ksi)	10.2	-10.7	17.0	-17.8
COTE (microstrain/F)	Crack Spacing (ft.)	76.2	-43.1	92.9	-43.7
	Crack Width (in.)	-13.6	8.4	-4.9	-0.8
	Steel Stress (ksi)	-3.0	-5.8	5.6	-14.5
Tensile Strength at 28 Days (psi)	Crack Spacing (ft.)	-27.4	32.2	-34.1	50.0
	Crack Width (in.)	-14.0	12.7	-31.7	42.6
	Steel Stress (ksi)	-15.1	13.8	-17.9	20.6
Steel Bar Diameter (in.)	Crack Spacing (ft.)	-7.5	2.8	-6.9	8.0
	Crack Width (in.)	-7.3	4.5	-8.3	9.1
	Steel Stress (ksi)	-0.7	-1.7	4.4	-4.6
Percent Reinforcement (Steel Ratio) (%)	Crack Spacing (ft.)	32.2	-22.9	68.8	-34.1
	Crack Width (in.)	32.9	-18.7	71.7	-34.3
	Steel Stress (ksi)	35.7	-20.4	30.1	-20.3
Vertical Stiffness of Subgrade (psi/in.)	Crack Spacing (ft.)	0	0	0	0
	Crack Width (in.)	0.4	-0.2	0	0
	Steel Stress (ksi)	0	0	0	0
Horizontal Stiffness	Crack Spacing (ft.)	0	-66.4	0	-56.5
	Crack Width (in.)	0	-39.7	0	-55.1
	Steel Stress (ksi)	0	-48.6	0	-33.1
Zero-stress Temperature (F)	Crack Spacing (ft.)	363.3	-56.5	124.9	-55.0
	Crack Width (in.)	-0.4	-7.1	-7.9	-23.8
	Steel Stress (ksi)	-1.1	-5.1	-1.2	-14.4
Min. Temperature at First Day after Placement	Crack Spacing (ft.)	-31.5	54.2	-27.0	28.5
	Crack Width (in.)	-16.5	18.8	-24.2	24.5
	Steel Stress (ksi)	-17.7	20.5	-14.6	9.8

Variations of Relative Values based on Medium Outputs

7. Summary, Conclusions, and Recommendations

7.1 Summary

The sensitivity analysis of the design variables has been performed using mechanistic models of CRCP to investigate the effects of the variables on the CRCP behavior, to determine the relative importance of each variable, and to compare the results from CRCP-8 and CRCP-10. The practical ranges of the variables have been selected, and the typical values of the variables have been determined. In the sensitivity analysis, one variable is selected and changes within the practical range while the other variables remain at their typical values, and the analysis results such as mean crack spacing, crack width, and steel stress at crack are obtained.

From this study the sensitivity of each design variable to the CRCP behavior has been investigated. The relationships between the design variables and the CRCP behavior have also been obtained. Engineers should pay close attention to characterizing the sensitive design variables while using the CRCP program in design or evaluation. Since engineers have only limited resources and time to use in estimating a large number of design variables, the findings described in this report can be applied to aid in solving real problems more efficiently and accurately.

7.2 Conclusions

The first two steps in maximizing the accuracy of the CRCP programs as outlined in section 1.3, which corresponds to the report objectives enumerated in section 1.4, were accomplished. This report documents the results that lead to the following primary conclusions:

- The material presented in Chapter 3, “Characterization of Input Variables,” and Chapters 4 and 5 on the sensitivity analysis demonstrate the viability of both the CRCP-8 and CRCP-10 programs.
- The comparisons between programs and with field data show that the predicted crack spacing and crack widths are similar and compare favorably with field data.

- The actual magnitude of the steel stress for the CRCP-10 is approximately 2/3 of the CRCP-8, but the trends of the relative stress magnitudes with the various input data are identical. The selection as to which program has the correct magnitude cannot be made due to unavailability of field adequate data.
- The most sensitive variable affecting the performance of a CRCP in the field is the zero-stress temperature as demonstrated by previous studies (Ref. 5), and the comparison of outputs from the two programs as shown in Table 6.1, "Sensitivity of Design Variables." Hence, the need for exercising specification and field control using the PavePro program are emphasized as a way to mitigate the occurrence of premature punchouts.
- The zero-stress temperature sensitivity is primarily related to the crack spacing, but the reduced sensitivity of the crack width and steel stress may be attributed to the fact that these behavior parameters are directly related to the crack spacing.
- The second most sensitive variable affecting CRCP performance is the concrete COTE value. The results, thus, re-emphasized the need for a viable concrete COTE test and a database of COTE values.

7.3 Recommendations

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

- As investigated in this study, the trends of the analysis results are very similar between CRCP-8 and CRCP-10. However, a large difference in the steel stress can be observed between the two programs. Therefore, further studies including field experiments should be conducted to identify the actual steel stresses.
- The mechanistic models should be calibrated and validated with field data.

Furthermore, the additional field work that is developed to calibrate/validate the CRC P-10 will also increase its acceptance by pavement engineers.

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