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16. Abstract

The purpose of this study was to investigate material properties of CRC pavements that used siliceous river gravel or crushed limestone as the coarse aggregate material. Laboratory measurements of the concrete mix properties were made for both coarse aggregates. These measurements were used to develop a set of predictive equations to simulate concrete behavior by coarse aggregate type. Predictive equations of concrete behavior were used as input to CRCP-4 program analysis. A strategy for developing CRCP steel specifications was formulated on the basis of CRCP-4 program analysis results.

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COARSE AGGREGATE FOR PCC — PILOT STUDY EVALUATION

by

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Research Report Number 422-1

Evaluation of Pavement Concrete Using Texas Coarse Aggregates
Research Project 3-8-86-422

conducted for

Texas State Department of Highways
and Public Transportation

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

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

PREFACE

This is the first report in a series of reports that describes the work done on the project entitled "Evaluation of Pavement Concrete Using Texas Coarse Aggregates". The project is being conducted at the Ferguson Structural Engineering Laboratory at the Balcones Research Center and at the Center for Transportation Research, The University of Texas at Austin, as part of the Cooperative Highway Research Program sponsored by the Texas State Department of Highways and Public Transportation and the Federal Highway Administration.

This report presents the results of CRCP-4 program analysis using concrete properties, taken from tests conducted at the Balcones Research Center Laboratory on concretes containing siliceous river gravel and crushed limestone coarse aggregates.

Our thanks are extended to Mrs. Peggy Carasquillo for her long hours on the project and timely analysis of the concrete property measurements. Mr. Moon C. Won, Mr. Mohammed Aslam, and Mr. Terry Dossey are to be commended for their support in program analysis and computer modeling. Special thanks are extended to Mr. Jim Brown and Mr. Jerry Daleiden, SDHPT Highway Design Division, for their participation and guidance during the project development. Thanks are also due to Ms. Joyce E. Green and Ms. Denise Koltys for typing the drafts, Mr. Curt Garner for creating the table templates, and Ms. Michele Mason Sewell for developing the illustrations.

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LIST OF REPORTS

Report No. 422-1, "Coarse Aggregate for PCC - Pilot Study Evaluation," by William J. Green, Ramon L. Carasquillo, B. Frank McCullough, and C. L. Saraf, presents the laboratory measurements of concrete properties for Texas coarse aggregates siliceous river gravel and crushed limestone, determines their respective pavement performance, and develops a set of predictive equations which can forecast concrete property behavior by coarse aggregate type.

ABSTRACT

The purpose of this study was to investigate material properties of CRC pavements that used siliceous river gravel or crushed limestone as the coarse aggregate material. Laboratory measurements of the concrete mix properties were made for both coarse aggregates. These measurements were used to develop a set of predictive equations to simulate concrete behavior by coarse aggregate type. Predictive equations of concrete behavior were used as INPUT to CRCP-4 program analysis. A strategy for developing CRCP steel specfications was formulated on the basis of CRCP-4 program analysis results.

Keywords: CRCP, siliceous river gravel, crushed limestone, elastic modulus, thermal expansion coefficient, drying shrinkage, tensile strength, flexural strength, curing temperature, curing time, relative humidity, design temperature drop, minimum daily temperature drops, daily temperature differential, bar size, percent reinforcement, modulus of subgrade reaction, JRCP, crack spacing, crack width, steel stress, regression analysis, design criteria, equivalent pavement performance, design chart.

SUMMARY

This is the first report in a series of reports that describe studies evaluating the CRC pavement made using siliceous river gravel and crushed limestone. This report analyzes and compares the concrete properties of test specimens cast and cured under similar conditions, with variable coarse aggregate types.

An initial evaluation of concrete property measurements was made so that these measurements could be used as input in a CRCP-4 program analysis. Additional input models were developed for steel, environmental, and subgrade properties.

A series of computer runs was made on the initial combination of inputs and a comparison analysis was made of CRC pavement performance by type of coarse aggregate. Comparison was made in terms of crack spacing and it was verified by a similar analysis of like inputs using the JRCP computer program.

Revisions to the material properties inputs and combination strategies were made in an attempt to reflect actual field conditions and to develop an equivalent design strategy based upon pavement performance. A series of predictive equations that model the concrete input properties, along with a modification to the CRCP-4 program software, were direct results of this review. Design criteria were established for the future development of a design chart that would allow the designer options for design, dependent upon the type of coarse aggregate selected.

IMPLEMENTATION STATEMENT

Actual laboratory measurements of concrete specimens were used to develop predictive concrete property equations by means of a multiple regression technique. These equations allow a designer to input the expected environmental conditions and the type of coarse aggregate used directly into the program for analysis and design criteria comparison.

The CRCP computer program was modified to reflect the actual laboratory measurements of the concrete properties, facilitating the choice of design inputs for a CRC pavement. A data file was written so that a series of combinations of input variables could be analyzed to allow the designer to home in on a series of viable design choices.

A model of daily temperature by geographic location was developed for input of environmental factors. The methodology explained readily lends itself to application for any particular location in Texas. All that is required of the designer is a compilation of the appropriate local historical weather data.

Use of the predictive equations and modified CRCP-4 program, along with the acceptable design criteria, can lead to the development of design charts, or nomographs, that can be evaluated in terms of equivalent pavement performance.

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CHAPTER 1. INTRODUCTION

BACKGROUND

The Texas State Department of Highways and Public Transportation (SDHPT) has 7,000 lane miles of Continuously Reinforced Concrete Pavements (CRCP) currently in service, and, at the present time, design plans call for the construction of additional miles of CRCP overlay and of new pavements. Essentially, the design and construction of CRCP is based on the premise that the concrete volume changes are controlled by the steel reinforcement whereas the randomly occurring transverse cracks develop due to shrinkage and temperature changes. The movement at the cracks is minimized by longitudinal steel that is placed in the slab to ensure a narrow crack width. This is one of the most important physical aspects of the design of CRCP.

Unfortunately, the effect of the coarse aggregate type on the crack pattern developed in a CRCP is substantial and has not been fully recognized in the design-construction sequence. The principal properties of concrete that vary with coarse aggregate type are the modulus of elasticity, the coefficient of contraction and expansion, and the tensile strength. All of these, in turn, influence CRCP performance.

In the past, it was common practice to design and construct portland cement concrete pavements without taking into account any variation in concrete properties that may be attributed to the use of different coarse aggregate types. In 1981, as a result of the findings presented in Report 177-22F, "Summary and Recommendations for the Implementation of Rigid Pavement Design, Construction and Rehabilitation Techniques" (Ref 1), a new design procedure was issued by the SDHPT Highway Design Division that permits a more rational analysis of all the factors influencing CRCP performance (Ref 2). Although the design process now recognizes the performance differences of the coarse aggregate types, the selection of the coarse-aggregate types used during construction is left to the contractor by the present specifications (Ref 3). Hence, as long as the aggregate meets the gradation and physical requirements, the basic assumption is that all aggregates are equivalent in performance and, thus, are acceptable. However, field performance has demonstrated that the pavements constructed with different coarse aggregate types exhibit substantial differences in performance life, even though it is assumed that they will have the same life (Refs 4, 5, and 6).

At the present time in Texas, many of the concrete pavements are constructed with aggregates in the basic categories of crushed limestone and siliceous river gravel. During the competitive bidding process, a contractor generally selects the aggregate type, based upon prices quoted from the various aggregate suppliers. The contractor will then construct the slab thickness required in the project plan with the coarse aggregate of his own choice, even though field performance indicates this is not a realistic approach.

THE PROBLEM AND THE STUDY OBJECTIVES

The primary objective of this study is to develop information, using the CRCP-4 computer program, that may be used in design algorithms and specifications to differentiate between the two primary coarse aggregates, crushed limestone and siliceous river gravel, used in concrete pavements in the state of Texas. This study focuses on the following:

(1) Understanding the differences in engineering properties of pavement concrete using crushed limestone and siliceous river gravel coarse aggregates.

(2) Analyzing and comparing the results obtained from CRCP-4 computer program runs on predicted pavement performance by aggregate type.

(3) Developing predictive equations which may lend themselves to the future development of design charts which provide design specifications for equivalent pavement performance for either crushed limestone or siliceous river gravel coarse aggregates.

SCOPE OF THE STUDY

This study analyzes laboratory measurements of concrete mix properties tested at The University of Texas at Austin and their effect on the performance of portland cement concrete pavements. Specimens cast and tested used both crushed limestone and siliceous river gravel in batch mixes similar to existing field designs. The test results were then input into the CRCP-4 program for analysis and development of alternative design recommendations by coarse aggregate type.

This report covers the initial analysis of specimen data through the final development of predictive equations which may be used to identify equivalent pavement performance requirements. Chapter 2 develops the concepts used for determining the performance based specifications and design detail criteria. Chapter 3 describes the selection of the CRCP-4 program for model solution. Introduced are the initial concrete, environmental, steel and other input variables selected for program solution. A pilot factorial is presented which describes the model strategy adopted for initial study. Chapter 4 describes the initial intuitive input of concrete material inputs and presents pavement performance analysis taken from the pilot program solution. Chapter 5 reviews the development of concrete input regression equations derived from laboratory measurements. Other input variable modifications for both environmental and steel inputs are also presented as recommended by the SDHPT Highway Design Division. A modified project model factorial is presented for future application in analyzing and determining equivalent pavement performance criteria along with additional input modifications to the CRCP-4 program. Chapter 6 summarizes the findings of the pilot study and provides recommendations for future investigation to include the development of Equivalent Design Charts for specific aggregate type selection in pavement construction.

CHAPTER 2. CONCEPTS FOR A PERFORMANCE BASED SPECIFICATION AND DESIGN DETAILS

BACKGROUND

Present specifications for material quality for portland cement concrete construction are based upon past design practice experience and field results. Although these concrete specifications have served well in the past, they lack the total information needed for sound design practice, as they are deterministic by nature. Additionally, no preventative measure really exists that provides timely information on the quality of the concrete material. For example, when a certain concrete strength at day 7 or 28 is specified, it is impractical to correct field deficiencies (if determined to be below design criteria) because the entire job may have already been completed before test results for field concrete samples become available. Field engineers and project inspectors are faced with two options: (1) if the measured properties of concrete and other material specifications fall within an acceptable range of design criteria, then accept the job; (2) if these measurable items fail to meet specified standards, then reject the job.

Given the nature of PCC construction, from a practical point of view, it is nearly impossible to reject a completed project, especially one that does provide a degree of useful service life. Some agencies currently will accept a job below specifications if the measured values are within certain specified lower limits and provided the contractor agrees to pay some penalty for falling below the acceptable design criteria. The purpose of performance-based specifications is to develop rational criteria for estimating the rewards or penalties for a job which may or may not meet the design criteria.

This chapter outlines one rational approach which can establish procedures for estimating the performance of a rigid pavement "as built" in the field which is then compared with the standard "expected" design criteria. This chapter is a departure, somewhat, from the rest of the study (as investigation focuses on a methodology to predict the "expected" design criteria), but it may hold an important key to future research in determining what are the parameter measures that qualify a concrete pavement as meeting the design criteria.

METHODOLOGY

In order to determine whether a concrete pavement project has met design criteria, some measureable parameters must be identified.

(1) Define the performance parameters and estimate the performance measure of a standard pavement against that of the "as built" pavement.

There are several performance parameters that have been used as indicators of rigid pavement performance. For the purpose of illustration, suppose the performance of the concrete pavement is measured by the amount of transverse cracking which develops upon completion of construction and is then subjected to environmental and traffic effects. Assume that the specified standards produce the transverse crack spacings (X) which are normally distributed with a mean of $\overline{X}$ and a standard deviation of σ_x. Then, the probability of crack spacing being between a specified design criteria, say a and b ($a < b$), can be estimated by use of the standardized parameter, Z [Z is N (0,1)], as shown below:

$$Z_a = \frac{a - \overline{X}}{\sigma_x}$$

$$Z_b = \frac{b - \overline{X}}{\sigma_x} \tag{2.1}$$

where Z_a and Z_b are the standardized values of crack spacings a and b.

The probability P_a of crack spacing being less than or equal to a can be obtained from a standard table of normal distribution which contains the values of the area under the curve defined by

$$P_a\,[X \le a] = \frac{1}{\sqrt{2p}} \int_{-\infty}^{a} e^{-1/2\, Z_a^2}\, dZ_a \tag{2.2}$$

Similarly, probability of crack spacing being less than or equal to b (P_b) can also be determined from this table. This will allow us to estimate the probability, P_{ab}, of crack spacing being between a and b, as

$$P_{ab} = P_b - P_a \tag{2.3}$$

The value of P_{ab} defines the minimum probability of cracks between the specified range of a and b. In case the estimates of this probability for "as built" pavement exceed the specified value for standard pavement, the pavement is considered to be better than specified. However, if the probability P_{ab} of the pavement "as built" is lower than the probability P_{ab} of the standard pavement, then "as built" is considered to be of lower quality than specified. Therefore, this method can be used to compare the performance of a "standard" and "as built" pavements.

(2) Establish criteria for a standard pavement for the purpose of evaluating "as built" pavement compliance.

If the performance of a standard pavement can be translated into the total cost of maintenance and rehabilitation over the specified period of service life, then a model of the following form might be used:

$$C_S = f(p) \tag{2.4}$$

where

C_s = the total cost of maintenance and rehabilitation for service life/mile, and

p = the probability that transverse crack distribution falls between a and b (see Eq 2.3).

From Eq 2.4, an incremental cost for "as built" concrete pavements failing to meet design criteria can be estimated as follows:

$$\text{Incremental Cost} = (C_S - C_{S1}) \text{ x total length of section in question in miles} \tag{2.5}$$

where C_s and C_{S1} are the total cost of maintenance and rehabilitation for service life/mile of "standard" and "as built" pavements, respectively.

A negative incremental cost would represent a decrease in useful pavement service life which could require the contractor to provide compensation for the estimated loss. However, if the incremental cost is positive, it indicates that the concrete pavement will exceed its expected service life, suggesting that a reward to the contractor by the inspecting agency is appropriate.

SUMMARY

Emphasis is given in this study to the expected measurable parameters that describe design criteria for a "standard" concrete pavement. Investigations of the contributing influences of the coarse aggregate selected for pavements in Texas, siliceous river gravel and crushed limestone, are made so that stochastic rather than deterministic parameters of the various performance measures (crack spacing, crack width, and steel stress, for example) can eventually be established. This study is the first step in a long line of research that could be carried out determining stochastic measures of performance on design criteria that are presently deterministic in nature.

CHAPTER 3. SELECTION OF PROGRAM MODEL INPUT PARAMETERS AND FACTORIAL STRATEGY

BACKGROUND

Emphasis was placed on testing concrete made with one source of limestone and one source of siliceous river gravel commonly used in concrete pavements in Texas. Test results of the concrete samples, along with other material and environmental variables, were then evaluated using the CRCP-4 (Continuously Reinforced Concrete Pavement, Version 4.0) program previously developed by the Center for Transportation Research, The University of Texas at Austin. The primary purpose of this evaluation was to develop the basic materials data necessary to provide a better understanding of the observed significant differences in performance of pavements constructed with the two basic aggregate types found in Texas highways.

Basic assumptions inherent, with the application of the CRCP-4 program model, include the following:

(1) Pavement cracks occur when the concrete tensile stresses exceed the concrete strength.
(2) The effects of concrete compressive stresses are considered minimal. Emphasis is placed on those tensile stresses which develop as a result of drop in air temperature below the slab casting temperature.
(3) Concrete and steel materials behave in a linear elastic fashion.
(4) In those fully-bonded developed areas of the pavement structure, there is no relative slip between the concrete and steel materials.
(5) There may exist an internal temperature variation throughout the pavement structure depth due to the difference in moisture content within the structure thickness caused by varying rate of moisture loss.
(6) Shrinkage is considered uniform throughout the structure, acting in a horizontal direction along the longitudinal X axis.
(7) All materials are considered as homogeneous.
(8) The effect of slab movement due to concrete creep is ignored.

CRCP-4 program analysis requires the input of specific concrete properties: elastic modulus, thermal expansion coefficient, drying shrinkage and tensile strength. Values of these properties were determined from specimens tested at the Ferguson Structural Engineering Laboratory.

Environmental conditions for curing the concrete specimens were selected to meet existing field conditions. Concrete mix properties, such as water/cement ratio, quantities of sand and coarse aggregate, and cement content were also proportioned, to meet existing concrete specifications for pavement concrete. Laboratory mix specimens were batched in different material proportions by aggregate type–crushed limestone and siliceous river gravel. These mix proportions were similar to field mix proportions used on existing pavements from which comparative performance field measurements may be taken. This approach will allow for a future comparison between predictive laboratory and field measurement performance of concrete with the same properties. Important items related to these mixes are listed in Table 3.1.

TABLE 3.1. ***MIX DESIGN (PROJECT 422)***

	Weights Per Cubic Yard	
Item	**1-1/4-in Fordyce Gravel**	**1-1/4-in Texas Crushed Stone**
Cement	492 lb	492 lb
Sand	1,023 lb	1,279 lb
Coarse Aggregate	2,148 lb	1,838 lb
Water	226 lb	222 lb
Air Entraing Agent	3.4 oz	2.5 oz
Air	4.8 percent	4.8 percent
CAF	0.78	0.78
Slump	1-1/2 in	1-1/2 in

Laboratory specimen measurements were taken at one, three, seven, twenty-eight, and ninety days of curing. Simulated curing conditions were controlled at 50°F, 75°F, and 100°F curing temperatures and 40 percent and 100 percent relative humidity conditions. These conditions represented the range of field conditions expected in Texas. For each concrete mix and curing condition, three separate specimens were made and tested in order that any statistical outlier could be identified and eliminated. Figure A.1 (see Appendix A) shows the experimental factorial designed for this study. The laboratory specimen test results that provide the raw data for CRCP-4 program solution are found in Appendix A.

Additional input requirements for CRCP-4 program solution include steel reinforcement properties, temperature data, subbase friction, and external load application. The selected properties of steel reinforcement were within criteria recommended by the SDHPT Highway Design Division. Standard design parameters for environmental and subbase friction effects were also selected to reflect common current practice for CRCP construction. Environmental considerations were modeled to reflect actual existing conditions of the various geographic regions of the state of Texas. Compilation of these various input factors, along with the concrete property inputs, led to the development of a pilot input factorial which served as the basis of the study investigation.

CONCRETE PROPERTY INPUTS

In the following sections, the test procedures and techniques used to measure the required concrete properties are discussed.

Concrete Modulus of Elasticity

The concrete modulus of elasticity values were obtained by the use of a beam tested under third point loading, the ASTM C-78 test procedure (Ref 7). Load-deflection curves were developed from the beam center point deflections (Y axis) and the applied load (X axis). Two points from the deflection-stress curve at 20 percent and 50 percent of ultimate stress values were used to determine a connecting chord. The slope of this connecting chord was then measured to determine the beam specimen's modulus of elasticity. Figure 3.1 provides a comparison of elastic modulus development over time between crushed limestone and siliceous river gravel specimens.

Concrete Tensile Strength

The concrete tensile strength was determined by using a Split Cylinder Test, following ASTM C-496 test procedure (Ref 8). Figure 3.2 provides a typical comparison of tensile strength developed over time between the coarse aggregates, crushed limestone and siliceous river gravel.

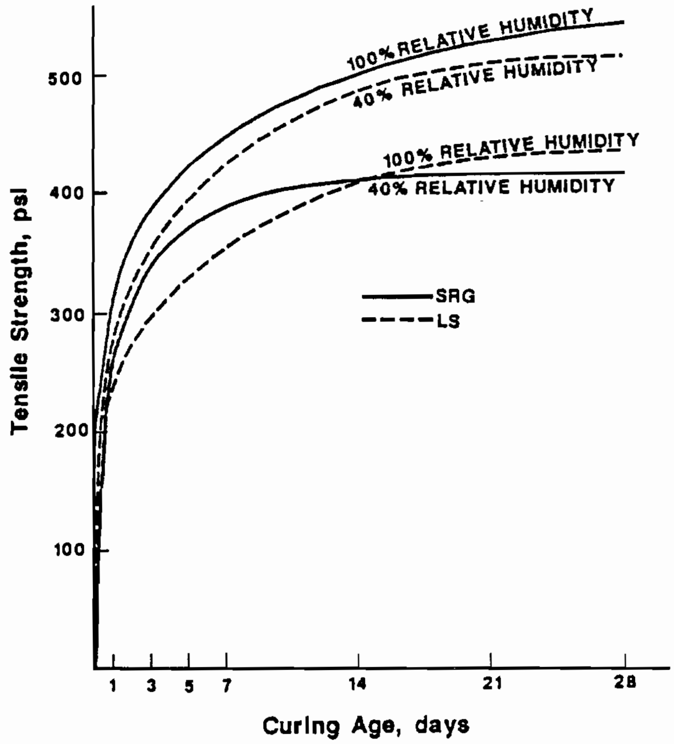


Fig 3.2. *Typical fitted tensile strength input curves for SRG and limestone at 75°F curing temperature.*

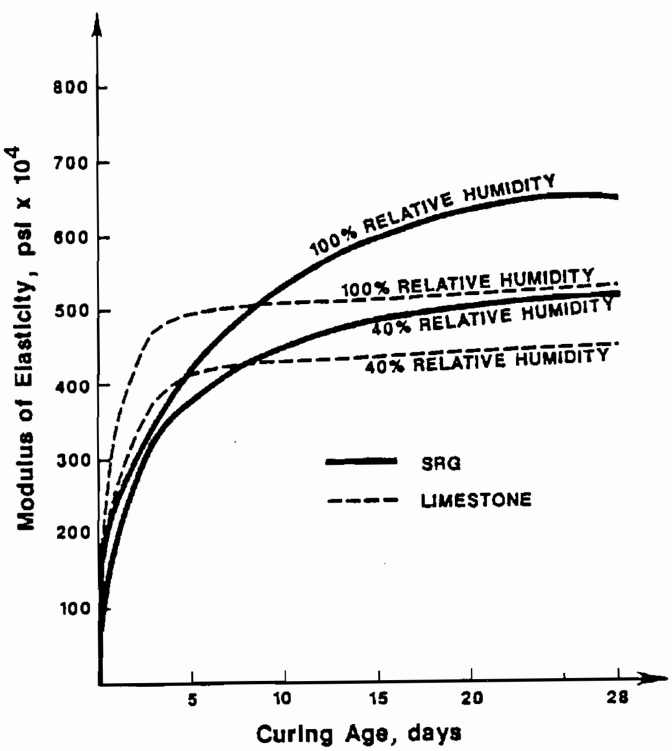


Fig 3.1. *Typical fitted modulus of elasticity input curves for SRG and limestone at 75°F curing temperature.*

Concrete Flexural Strength

The concrete flexural strength was measured according to the Third Point Loading Test, ASTM C-78 test procedure (Refs 7 and 9). The data is listed in Appendix A (see Tables A.5 and A.6). Modulus of Rupture at seven days was also measured using a centerpoint loading method (ASTM C-293) as shown in Table A.9. These values were not used as a property input into the CRCP-4 program analysis, but were measured for future reference.

Concrete Drying Shrinkage

The concrete drying shrinkage was measured using a modified version of ASTM C–157 specifications (Ref 10) as described in Appendix B. Table 3.2 provides a summary of the shrinkage model parameters values used as input for the CRCP-4 program. Shrinkage measurements for both the crushed limestone and siliceous river gravel specimens were taken for only the 40 percent relative humidity condition. It was assumed that no expansion or contraction would occur under the 100 percent relative humidity condition. Values found in Table 3.2 were taken directly from Figs 3.3 and 3.4, for crushed limestone and siliceous river gravel, respectively.

The concrete drying shrinkage input for solution of the CRCP-4 program previously required the input of one value, the total shrinkage (or Z_f) measured. A shrinkage development over time was then back-calculated by the CRCP-4 program using the "exponential law" in the form of Eq 3.1:

$$Z_t = Z_f e^{-\beta/t} \qquad (3.1)$$

where

Z_t = specific shrinkage at time t,
Z_f = total shrinkage,
b = experimental parameter expressing the shrinkage rate of development (=6), and
t = time of reference in days.

TABLE 3.2. *SUMMARY OF SHRINKAGE INPUT VALUES FOR 40 PERCENT RELATIVE HUMIDITY*

Curing Temp. (°F)	Z_f (10^{-4} in/in)		β	
	SRG	LS	SRG	LS
50	2.10	1.96	4.9	6.7
75	2.20	2.17	6.2	0.63
100	2.35	2.38	5.7	7.8

Note: Values for 100 percent relative humidity were input as zero.

Because actual laboratory shrinkage measurements, as a function of time, were available for use, the CRCP-4 program input requirement was modified to capture all of the values found in Table 3.1 for the 40 percent relative humidity condition. Figures 3.3 and 3.4 are the typical plots of the data used in developing the values listed in Table 3.2. These values were used by the CRCP-4 program rather than calculating shrinkage values from Eq 3.1 (using b = 6). For the 100 percent relative humidity condition, a shrinkage value of zero was provided for CRCP-4 program analysis.

Concrete Thermal Expansion

The thermal expansion of concrete was measured by placing two strain gages on each specimen, which recorded specimen deformation in every 30°F over an increasing curing temperature within the range of 45°F up to 135°F and then through a decreasing temperature range back down to 45°F. The specimens were measured under simulated conditions that could be experienced under a daily temperature drop range. Values used for CRCP-4 program analysis for

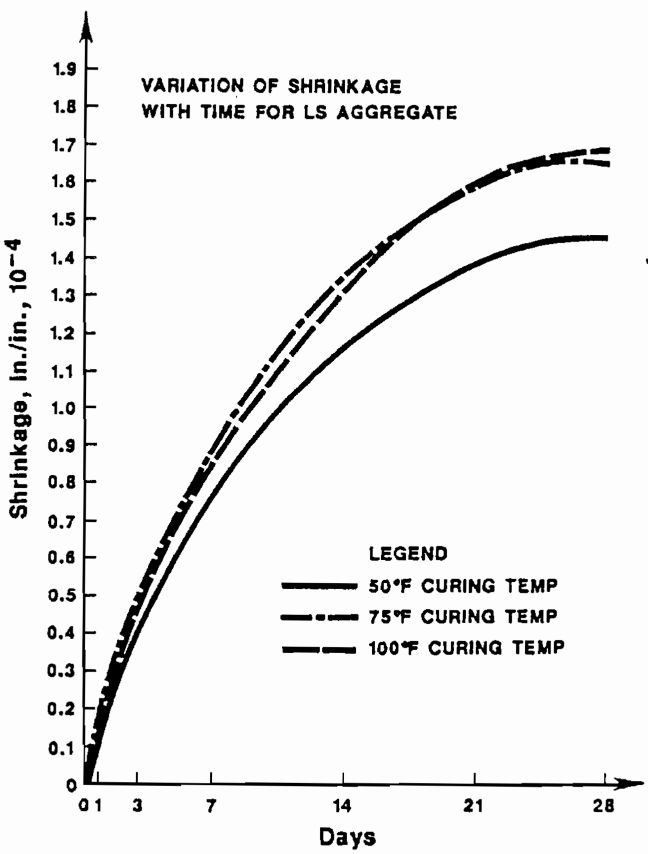


Fig 3.3. *Curing temperature shrinkage input curves for crushed limestone.*

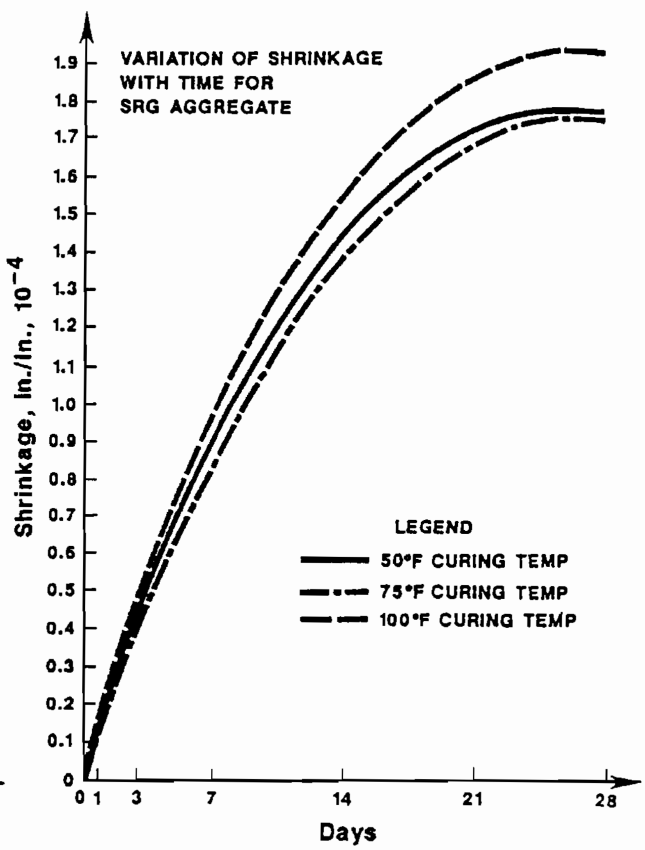


Fig 3.4. *Curing temperature shrinkage input curves for siliceous river gravel.*

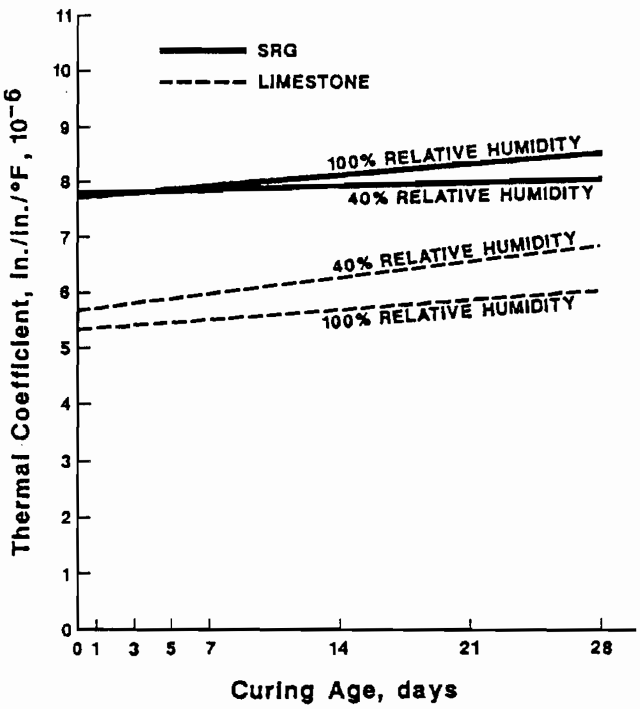


Fig 3.5. *Typical thermal coefficient input curves for siliceous river gravel and crushed limestone under both relative humidity curing conditions at a curing temperature of 75°F.*

crushed limestone and siliceous river gravel coarse aggregates are found in Fig 3.5.

ENVIRONMENTAL INPUTS

CRCP-4 program analysis requires certain environmental inputs that affect CRCP performance throughout the pavements' service life. Specific input requirements are curing temperature, minimum temperature expected after the concrete gains full strength, the number of days after the concrete is set before the minimum temperature occurs, and the minimum daily temperature.

Design Temperature Drop

As the air temperature drops below the slab casting temperature, the material contracts and causes the CRCP slab to move. This temperature drop subjects both the steel and concrete to a strain development which is a direct function of the material thermal coefficient and the temperature drop. CRCP-4 uses the daily minimum temperatures and the placement temperature to calculate distress manifestations in the form of crack development. CTR Research Report 177-9, "CRCP-2, An Improved Computer Program for the Analysis of Continuously Reinforced Concrete Pavements," provides the following expressions which describe the strains developed in the steel and concrete materials (Ref 11). These strains and their associated stresses are the forces that contribute to the development of CRCP cracking:

$$\varepsilon_c = \alpha_c \Delta T \tag{3.2}$$

and

$$\varepsilon_s = \alpha_s \Delta T \tag{3.3}$$

where

e_c = concrete strain due to temperature drop with no restraint,
e_s = steel strain due to temperature drop with no restraint,
α_c = concrete thermal coefficient,
α_s = steel thermal coefficient, and
ΔT = temperature drop below the placement temperature.

Because bond development occurs between the reinforcing steel and the concrete, a condition without restraint will not exist. For a fully bonded section, the resultant strains [see Fig 3.6(b)] are described by Eq 3.4:

$$\varepsilon_c - \varepsilon_s = \varepsilon_{c\Delta t} + \varepsilon_{s\Delta t} \tag{3.4}$$

where

$\varepsilon_{c\Delta t}$ = concrete strain in tension caused by the restraint of steel bars at fully bonded section, and

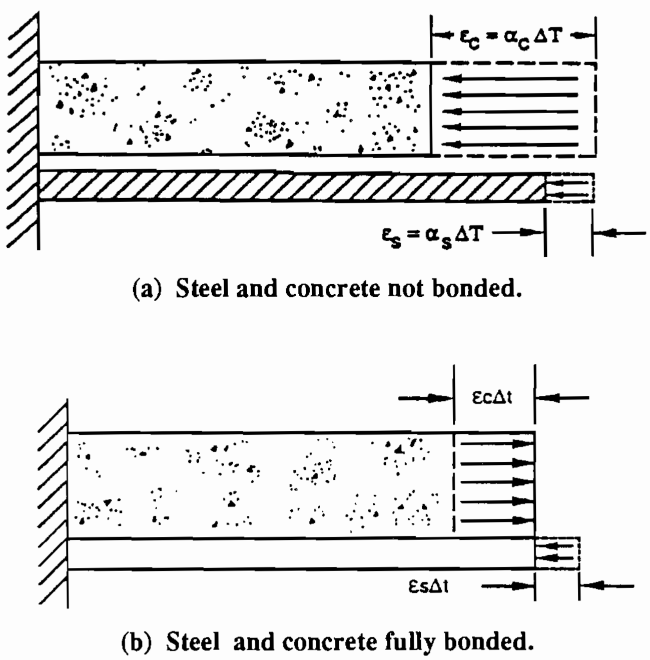


Fig 3.6. *Behavior of a reinforced slab subjected to temperature drop.*

$\varepsilon_{s\Delta t}$ = steel strain caused by shortening of concrete during temperature drop at fully bonded section.

Figure 3.6 depicts the strain development due to temperature drop.

Replacing Eq 3.4 with the associated stress and using a negative value for compression gives

$$\alpha_c \Delta T - \alpha_s \Delta T = \frac{\sigma_{c\Delta t}}{E_c} + \frac{-\sigma_{s\Delta t}}{E_s} \tag{3.5}$$

and

$$\sigma_{c\Delta t} = E_c \, \Delta T \, (\alpha_c - \alpha_s) + \frac{\sigma_{s\Delta t}}{n} \tag{3.6}$$

where

$\sigma_{c\Delta t}, \sigma_{s\Delta t}$ = stresses due to temperature drop at fully bonded section;

α_s, α_c = thermal coefficients of steel and concrete, respectively;

E_s, E_c = modulus of elasticity of steel and concrete, respectively, and

n = E_s/E_c.

From the above description it can readily be determined that the temperature drop, ΔT, will have a greater effect on the concrete material that has the higher thermal coefficient. Laboratory specimen measurements (see Fig 3.5) indicate that crushed limestone stresses will be less than those of siliceous river gravel under the fully bonded condition.

The temperature drop used in the reinforcement design is the difference between the average concrete curing temperature and a design minimum temperature. From a conservative standpoint, the average curing temperature may be taken as the average daily high temperature for the season the pavement is expected to be constructed. The design minimum temperature is defined as the average daily low temperature (T_L) for the coldest day of the month. The largest temperature differential normally occurs in the winter and spring seasons.

Curing Temperature, T_H

The average daily high temperature was previously established by the concrete specimen curing temperatures of 50°F, 75°F, and 100°F. These curing temperatures established the upper bound for the determination of the daily temperature drop. Table 3.3 reflects the model assignment of average daily high temperatures.

TABLE 3.3. ***SEASONAL AVERAGE DAILY HIGH TEMPERATURE***

Season	Months	T_H
Winter	Dec/Jan/Feb	50°F
Spring	Mar/Apr/May	75°F
Summer	June/Jul/Aug	100°F
Fall	Sep/Oct/Nov	75°F

Minimum Temperature, T_L, at Full Strength

CTR Report 249-6, "Design Charts for the Design of HMAC Overlays on PCC Pavements To Prevent Against Reflection Cracking," developed prevailing climatological conditions for the state of Texas (Ref 12). This study was used as the basis for establishing geographical regions in the state of Texas for the purpose of determining the minimum temperature expected after the concrete gains full strength and for establishing a lower temperature bound that a particular region might experience during the year after the concrete gains full strength. Table 3.4 presents a breakdown by geographical district of the expected minimum annual temperature, or coldest day of the year, that would be encountered after concrete placement.

TABLE 3.4. ***GEOGRAPHICAL DISTRICT MINIMUM ANNUAL TEMPERATURE***

Zones	Combined Region	Range of Minimum Daily Temperature	T_L
I	Gulf Coast/Valley	29-20°F	25°F
II	East/South Central	19-10°F	15°F
III	North/West Texas	9-0°F	5°F

Number of Days before Minimum Temperature, T_L

Further analysis of the local climatological weather data by geographic region determined that the coldest day of the year, T_L, generally occurred during the second week of January. It was assumed that a contractor would not place concrete in the winter season prior to the coldest day of the year without taking special curing treatment precautions. This assumption led to the derivation of an input schedule for the number of days after the concrete had set before the coldest day of the year, T_L, would occur. Table 3.5 provides the input schedule used for the CRCP-4 solution of this variable by season placement.

This interpretation allows for the amount of time the concrete has to gain strength, through curing, before the coldest day of the year is encountered.

TABLE 3.5. ***NUMBER OF DAYS BEFORE MINIMUM TEMPERATURE***

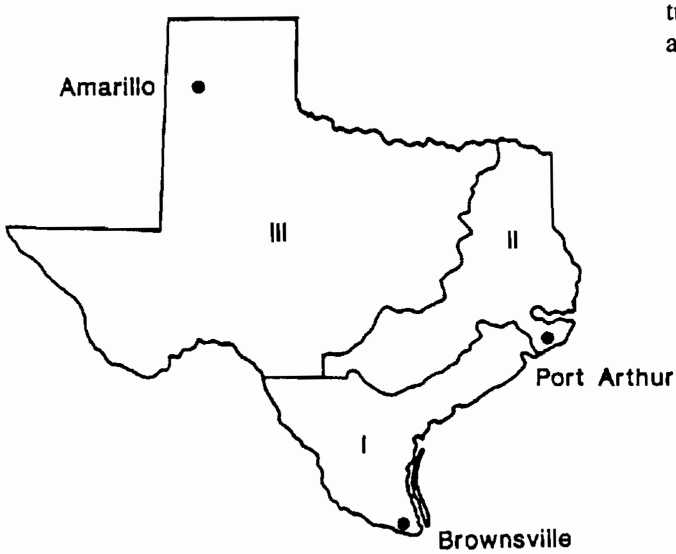
Season	No. of Days
Winter	360
Spring	270
Summer	180
Fall	90

Daily Temperature Drop, DT_D

The daily temperature drop was determined for three representative cities by geographic region: Brownsville (Zone I), Port Arthur (Zone II), and Amarillo (Zone III).

These cities were selected for the purpose of modeling daily temperature drops by region and for season of CRCP construction. The local Climatological Data, 1984 Monthly Summary, compiled by the National Oceanic and Atmospheric Administration, was used to develop each representative region city's seasonal daily temperature drops (Ref 13).

Daily temperature drops were developed by season for each of the three representative regions, as illustrated in Fig 3.7. This was accomplished by finding the difference between the high and low temperature for a particular day of a season. All of these differences were then tabulated and a cumulative percentage vs. a daily temperature differential (defined as the difference between the daily high and daily low air temperatures) curve was developed for a particular location and season. A typical plot of this data for Brownsville (Zone I) is shown in Fig 3.8. These plots were used to determine the 15, 50, and 85 percentiles of daily temperature differentials for each city (zone) and season selected for this study. For example, 15, 50, and 85 percentile values of daily temperature differential for Brownsville, winter season are 6, 15, and 27°F, respectively. Table 3.6 lists the percentile values of daily temperature differentials for all three zones and four seasons selected for this study.



ZONES	COMBINED DISTRICTS	SITES
I	Gulf Coast / Lower Valley	Brownsville
II	East Texas - South Central	Port Arthur
III	North and West Texas	Amarillo

Fig 3.7. *Climatological district assignment.*

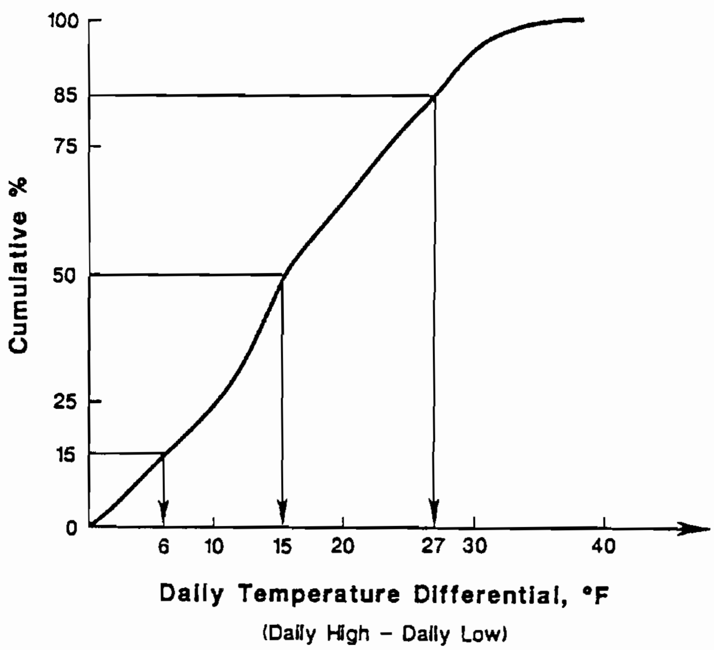


Fig 3.8. ***Typical minimum daily temperature differential model for Brownsville during the winter placement season.***

If the minimum daily temperature drop is excessive initially, the CRCP will fail before the concrete has sufficient time to gain adequate strength. Therefore, a model based upon a more gradual exposure to larger daily temperature differentials was used for CRCP-4 program input. The assumption was made that cumulative daily temperature

TABLE 3.6. *SEASONAL MINIMUM DAILY TEMPERATURE DIFFERENTIALS [DAILY MAXIMUM -*

Zone/ Season	Percentiles		
	15%	50%	85%
I/Winter	6	15	27
I/Spring	8	20	27
I/Summer	9	16	21
I/Fall	7	15	20
II/Winter	5	16	24
II/Spring	6	20	24
II/Summer	7	16	18
II/Fall	5	15	21
III/Winter	14	27	35
III/Spring	14	25	38
III/Summer	16	26	30
III/Fall	12	25	33

Weather Data Source:
National Oceanic and Atmospheric Administration Local, Climatological Data Summary, 1984 Monthly Summary

differentials of 15 percent, 50 percent, and 85 percent would be encountered during the first twenty-eight days of concrete curing according to the following schedule:

First day of placement	15 percent value,
Days 2-6 of placement	50 percent value, and
Days 7-28 of placement	85 percent value.

The values of daily temperature differential listed in Table 3.6 were used to estimate the minimum daily temperatures for input to CRCP-4 computer program. Table 3.7 shows the procedure to estimate these values and the resulting numbers obtained by this method.

STEEL INPUTS

Steel property input variables for CRCP-4 program analysis include the type of reinforcement, percent of reinforcement, bar diameter, modulus of elasticity, yield strength, and thermal coefficient. Welded wire fabric materials were not selected as input variables. Longitudinal steel reinforcement input parameters were established reflecting common construction practice and availability.

Rebar Size

Rebar size and percent of steel reinforcement were selected on the basis of pavement thickness. Pavement thicknesses considered were 8, 10, 12, and 15 inches. A rebar size of 0.75- inch diameter (#6 bar) with 0.5 percent steel was used with the 8 and 10-inch-thick pavements. A rebar size of 0.875-inch diameter (#7 bar) with 0.7 percent steel was used with pavement thicknesses of 12 and 15 inches.

Steel Properties

For both bar size and percent steel input variables, the same steel properties were input for CRCP-4 program analysis. Elastic modulus, E_s, was set at 2.9×10^7 psi and a value of 60 ksi was established for the steel yield stress, f_y. A constant steel thermal coefficient, a_s, value of 5.0×10^{-6} in./in./F was used throughout the entire program analysis.

TABLE 3.7. ***MINIMUM DAILY TEMPERATURES, °F***

Zone/ Season	T_H, °F	Day 1 (15%)	Days 2-6 (50%)	Days 7-28 (85%)
I/Winter	50	50-6=44	50-15=35	50-27=23
I/Spring	75	75-8=67	75-20=55	75-27=48
I/Summer	100	100-9=91	100-16=84	100-21=79
I/Fall	75	75-7=68	75-15=60	75-20=55
II/Winter	50	50-5=45	50-16=34	50-24=26
II/Spring	75	75-6=69	75-20=55	75-24=26
II/Summer	100	100-7=93	100-16=84	100-18=82
II/Fall	75	75-5=70	75-15=60	75-21=54
III/Winter	50	50-14=36	50-27=23	50-35=15
III/Spring	75	75-14=61	75-25=50	75-38=47
III/Summer	100	100-16=84	100-26=74	100-30=70
III/Fall	75	75-12=63	75-25=50	75-33=42

SLAB-BASE FRICTION RELATIONSHIP

Figure 3.9 describes the friction-movement relationship that was used for CRCP-4 program analysis. An ARE study (Ref 14) and a CTR study (Ref 17) served as the basic references for developing the values of this variable. This figure represents typical values found in existing field conditions throughout the state of Texas.

EXTERNAL LOAD OR STRESS VARIABLES

A wheel load of 9,000 lb was applied to the pavement structure on day fourteen of concrete curing. It was assumed that the state would prohibit the application of any substantial wheel load on the pavement structure prior to day fourteen.

MODULUS OF SUBGRADE REACTION

A modulus of subgrade reaction, K, was set at a value of 300 pci for CRCP-4 program input. This K value was selected because it represented a conservative typical value found with stabilized subbases.

PILOT FACTORIAL

The focus of the initial study was to analyze CRCP-4 performance results for both types of aggregates for highways located throughout the state of Texas. Figure 3.10 explains the variable input strategy and set of combinations analyzed by CRCP-4. Environmental considerations in-

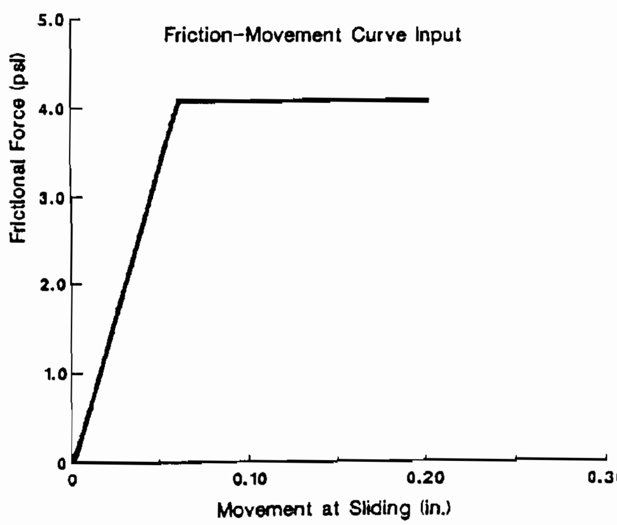


Fig 3.9. ***Friction-sliding movement input relationship (Refs14 and 17).***

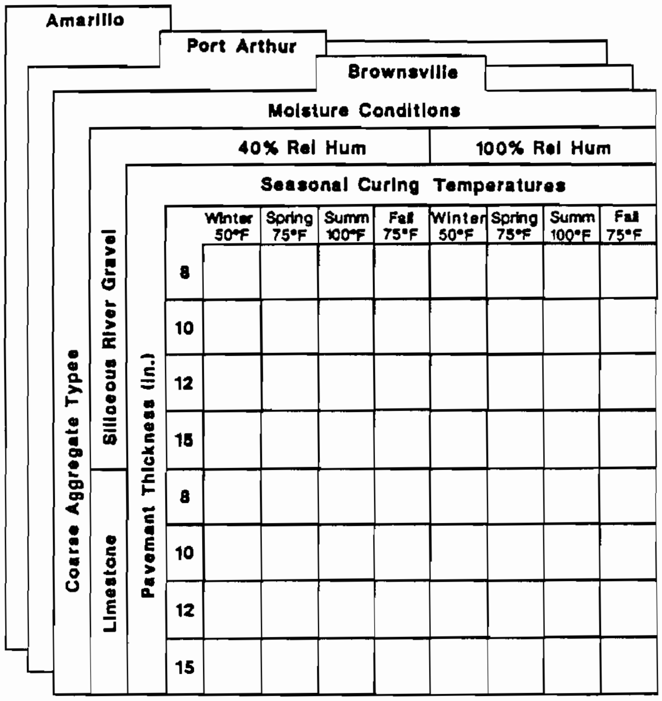


Fig 3.10. *CRCP–4 pilot factorial.*

cluded the various seasonal curing temperatures, the two relative humidity curing conditions, and the three geographic locations. Structural considerations included a range of varying pavement thicknesses and the type of coarse aggregate. Specific steel and concrete input parameters were input as previously described in this chapter.

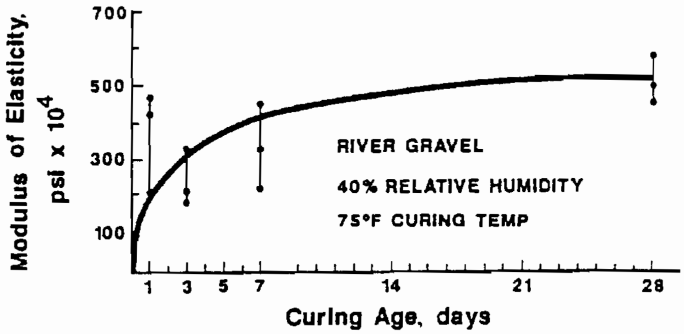
CRCP-4 PROGRAM MODIFICATIONS

Because actual laboratory measurements of concrete material properties were available for analysis, minor changes to the CRCP-4 program input format structure were made. Specific input modifications included concrete shrinkage, concrete modulus of elasticity, and concrete thermal expansion values as a function of time. Previously, only a single point value for these concrete material inputs for CRCP-4 program analysis was available. These changes allowed computer generation of solutions more aligned to the laboratory measurements made for these concrete properties.

CHAPTER 4. PILOT ANALYSIS OF PAVEMENT PERFORMANCE

BACKGROUND

Initial concrete property input curves were taken directly from laboratory measurement of raw data through an application of an intuitive interpretation of the data results. No statistical or regression analysis of the raw data was conducted for the initial input of this data. A smooth curve was "fit" between the range of values for a particular measurement, resulting in the generation of a curve that fell within the scatter range of all the data points. Specific values were then taken from these curves and used as input parameters for the respective concrete properties for CRCP-4 program analysis. A typical fitted concrete property input curve is shown in Fig 4.1.



SUMMARY OF SELECTED VALUES

DAY	1	3	5	7	14	21	28
MOD ELAS	200	325	375	415	480	505	520

Fig 4.1. *Typical fitted concrete property input curve with actual data points plotted on graph.*

Upon completion of program analysis, CRCP-4 output consists of final numerical values for the pavement crack spacing, crack width, maximum concrete stress, concrete tensile strength, and maximum steel stress. Additionally, a crack spacing development history over time is provided for analysis. CRCP-4 program solutions were made for all the variable input combinations described by the pilot factorial shown in Fig 3.10.

Performance analysis of the program results was performed on a comparative basis between the crushed limestone and siliceous river gravel pavements. Direct comparison was made between aggregate types on the following results: crack spacing vs. slab thickness, crack spacing vs. curing temperature, crack spacing vs. geographical sites, and crack spacing vs. relative humidity.

Verification of the impact of model input variables on the program solution was made by comparing the concrete strength or concrete stress gain over time with the resultant evolution of crack spacing development. A comparative analysis of the input variables was additionally made using the Jointed Reinforced Concrete Pavement (JRCP) program. A comparison of slab movement, as a function of temperature drop, resulted in generally larger crack spacings for the crushed limestone aggregate.

Illustrations found in this chapter represent typical results of sample program solutions taken from the pilot factorial. Total output results for every combination studied are not included in this report, but they are on file at the Center for Transportation Research, The University of Texas at Austin, for future reference.

CRCP ANALYSIS

In the following sections, comparisons are made of crack spacing versus the factors of slab thickness, curing temperatures, geographical sites, and relative humidity.

Crack Spacing vs. Slab Thickness

Figure 4.2 demonstrates that crack spacing increases with increasing slab thickness. This is consistent with expectations because, as the ratio of bar bond area over the volume of concrete decreases, the pavement crack spacing should increase. Crack spacing for crushed limestone was generally 3 to 4 feet greater than that of siliceous river gravel over the entire range of slab thicknesses investigated.

Crack Spacing vs. Curing Temperature

Figure 4.3 illustrates a consistent trend noted on all factorial combinations. Crack spacing demonstrated a tendency to rise and reach a peak at the 75°F curing temperature and then fall rapidly on approach to the 100°F curing

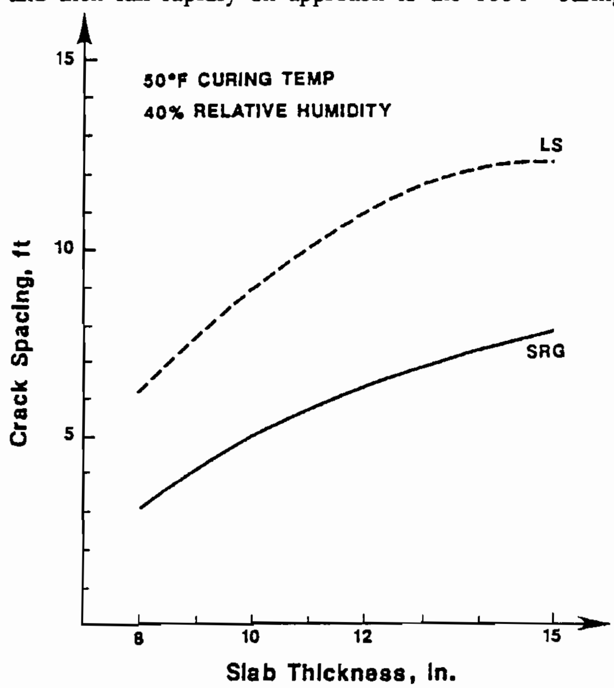


Fig 4.2. *Typical crack spacing versus slab thickness comparison between SRG and limestone under 50°F curing temperature and 40 percent relative humidity curing conditions for Port Arthur pavement.*

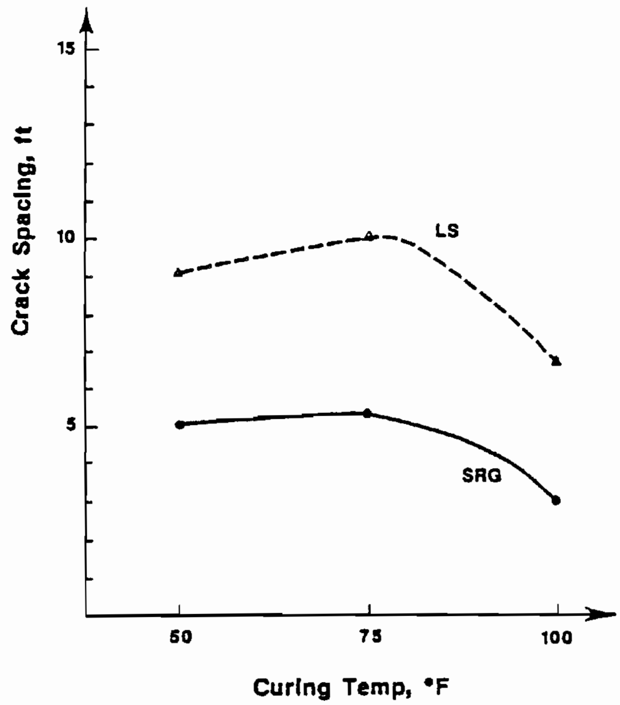


Fig 4.3. *Limestone under 40 percent relative humidity curing conditions for 12 -inch Amarillo pavement.*

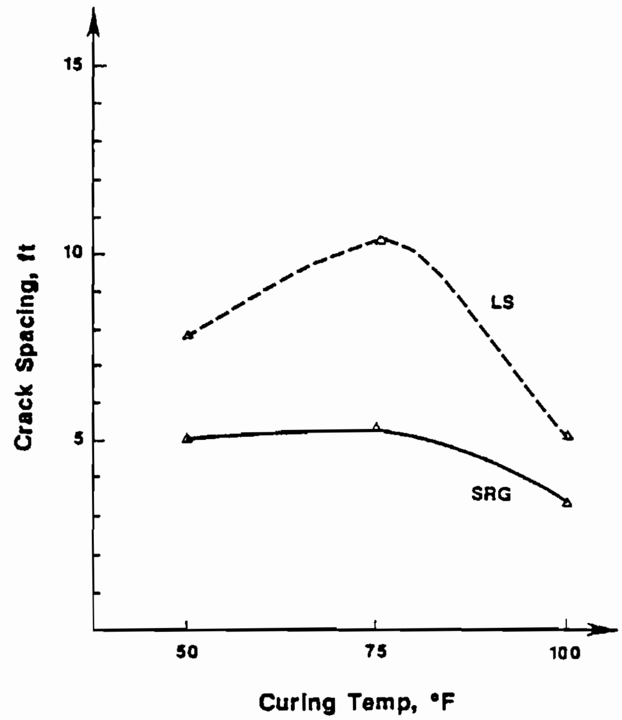


Fig 4.4. *Typical crack spacing versus curing temperature comparison between SRG and limestone under 40 percent relative humidity curing conditions for 10-inch Brownsville pavement.*

temperature. Normally, a decrease in crack spacing with increasing curing temperature is expected due to an increasing shrinkage contribution. The rise in crack spacing observed in the 50°F to 75°F curing temperature range may be attributed to the concrete properties of the specimens tested. Results indicated that crushed limestone pavement crack spacings were again 3 to 4 feet greater than those of siliceous river gravel. At the 75°F curing temperature (Spring and Fall placement) crack spacing results for crushed limestone often exceeded the upper boundary of allowable crack spacing.

Crack Spacing vs. Geographical Sites

Crack spacing results for individual geographical site locations, with all other input variables the same, are illustrated in Figs 4.4, 4.5, and 4.6. Resultant crack spacing as a function of curing temperature for each location is depicted. A wider variation in the final crack spacing results was observed for pavement constructed with crushed limestone. Crack spacing appeared to decrease with decreasing minimum daily temperatures experienced, indicating that individual location contributed separately to concrete stress development.

Crack Spacing vs. Relative Humidity

A substantial increase in crack spacing for both coarse aggregate types was observed for specimens cured under 100 percent relative humidity conditions to that of 40 percent relative humidity conditions. Figures 4.7 and 4.8 demonstrate this comparison. A wider range variation in the crushed limestone crack spacing as compared with the range

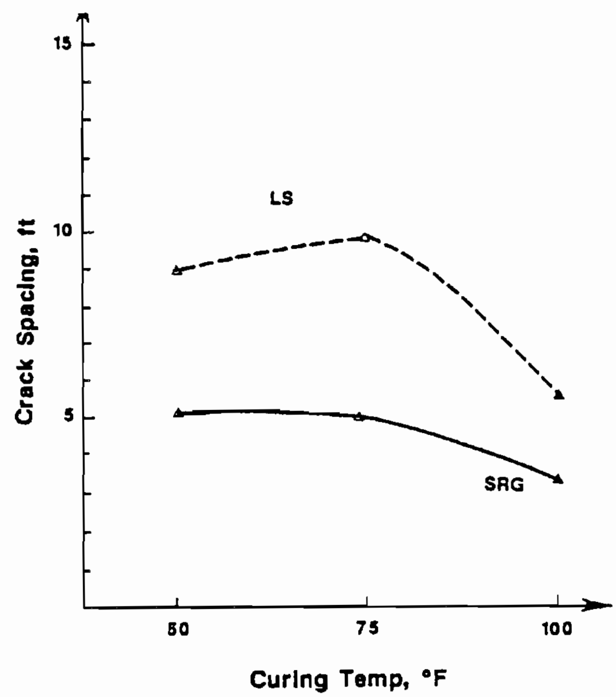


Fig 4.5. *Typical crack spacing versus curing temperature comparison between SRG and limestone under 40 percent relative humidity curing conditions for 10-inch Port Arthur pavement.*

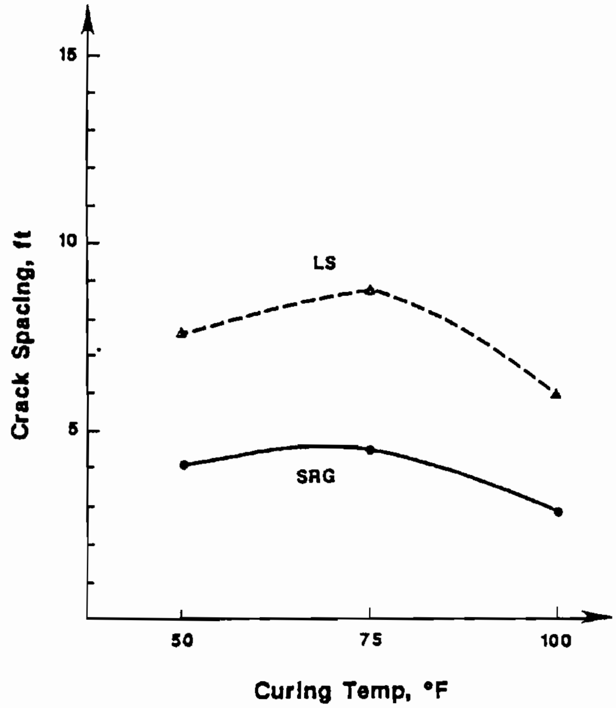


Fig 4.6. *Typical crack spacing versus curing temperature comparison between SRG and limestone under 40 percent relative humidity curing conditions for 10-inch Amarillo pavement.*

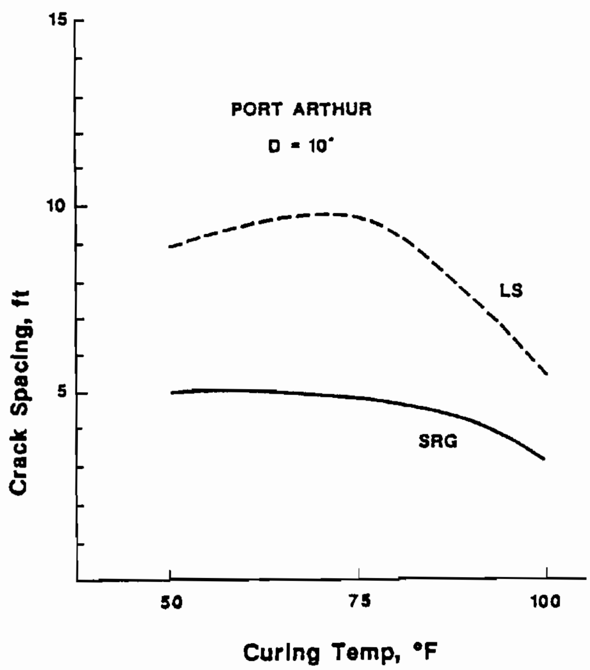


Fig 4.7. *Variation of crack spacing with curing temperature under 40 percent relative humidity curing conditions.*

observed for the siliceous river gravel was noted. Comparison by relative humidity curing condition determined that shrinkage effects generally reduced the crushed limestone crack spacing 2 to 10 feet and siliceous river gravel 2 to 8 feet.

HISTORY OF CRACK SPACING DEVELOPMENT

Input factors which cause the CRCP structure to crack are increases in the minimum daily temperature drop, pavement exposure to the coldest day of the year, and application of an external load. Figures 4.9 and 4.10 verify the CRCP-4 program solution. Cracks developed for the sample illustrated when the concrete stress met or exceeded the concrete strength. Pavement crack occurrences were noted on the day of application of the 50 percent and 85 percent minimum daily temperature drop and on day fourteen, when an external load of 9,000 lb was applied to the pavement structure. Final pavement crack spacing was determined after the pavement had encountered the coldest day of the year. The crack development history depicted in Figs 4.9 and 4.10 reflect similar developments found in actual field measurements.

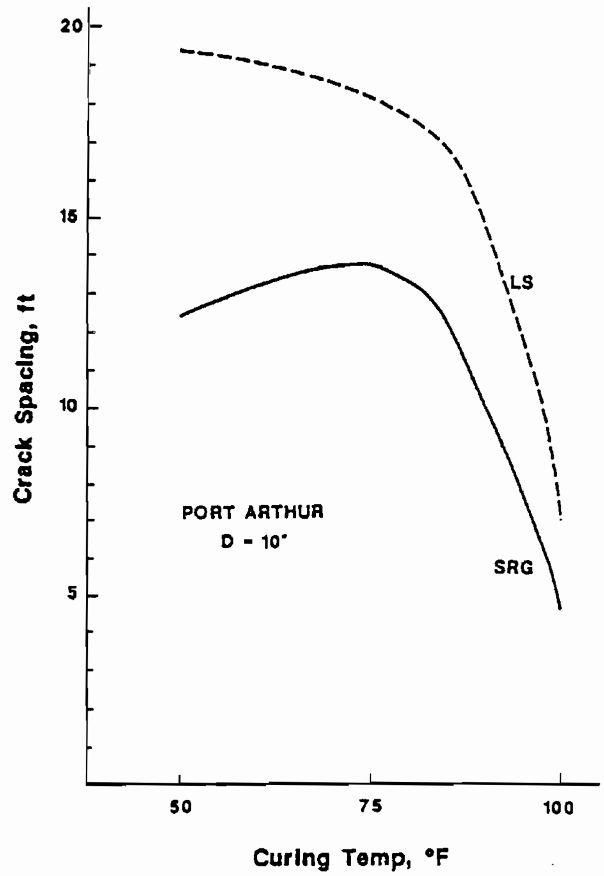


Fig 4.8. *Variation of crack spacing with curing temperature under 100 percent relative humidity curing conditions.*

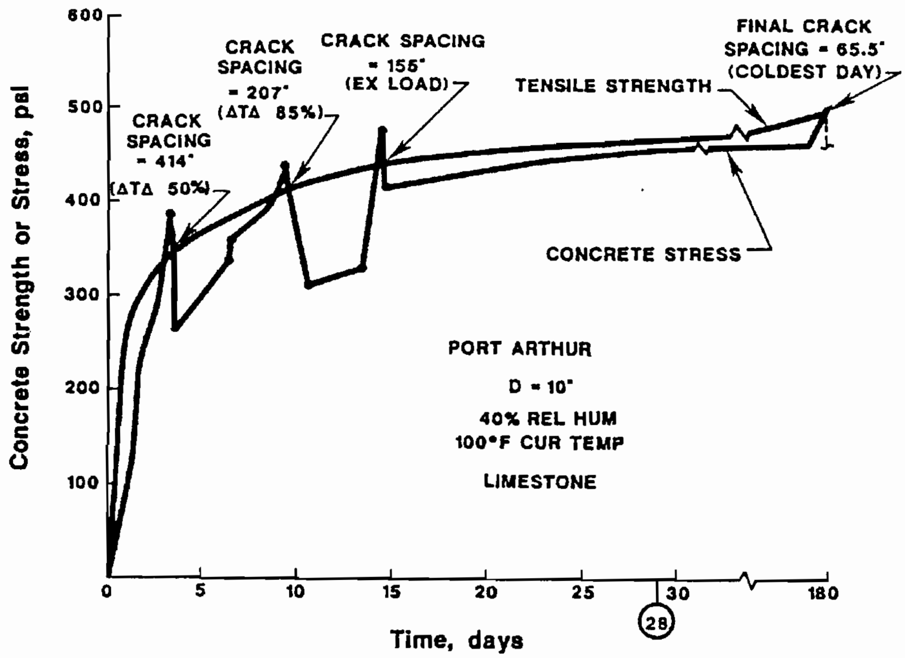


Fig 4.9. *Concrete strength/stress versus time.*

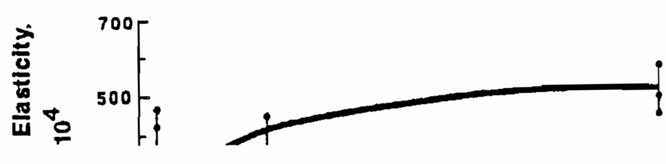


Fig 4.10. *Crack spacing development as a function of curing time.*

JRCP ANALYSIS

A Jointed Reinforced Concrete Pavement (JRCP) program solution was made for one pilot combination for the purpose of evaluating coarse aggregate performance for a jointed reinforced concrete pavement. Results obtained are shown in Fig 4.11. With increasing temperature drop, a departure in the rate of slab movement between siliceous river gravel and crushed limestone was observed, with a greater movement noted for siliceous river gravel. This increased movement of the siliceous river gravel pavement tied in directly with Eq 3.5 and crack spacing trends previously demonstrated. Siliceous river gravel pavements developed greater concrete stresses which, in turn, produced smaller crack spacings, a result consistent with observations made of the CRCP-4 program solutions.

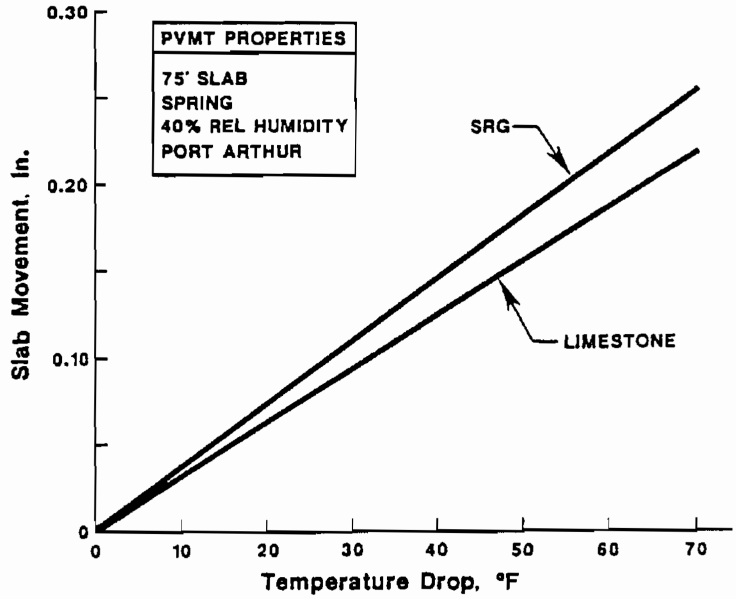


Fig 4.11. ***JRCP program analysis comparison of slab movement versus temperature drop for SRG and limestone pavements.***

SUMMARY

No significant difference in pavement performance due to different local weather conditions was noted for pavement constructed with siliceous river gravel. A greater variability was observed for crushed limestone pavements, which tended to crack more often with increasing minimum daily temperature drop.

In all cases, final crack spacing was developed on the day the concrete pavement encountered the coldest day of the year. No really significant difference in final crack spacing was noticed, however, for similar pavements constructed in the Spring (270 days) and the Fall (90 days) season. This may indicate a lack of influence on differential concrete strength gain prior to the coldest day of the year.

The range of crack spacings and their values for the crushed limestone pavement were greater than those of the siliceous river gravel pavement. As noted previously, concrete stresses exceeded concrete strength in siliceous river gravel pavements more often, resulting in a final smaller crack spacing pattern.

Analysis of other CRCP-4 output parameters were addressed in terms of design criteria as well as input variable revisions in Chapter 5. This revised investigation will focus on equivalent pavement performance results which satisfy crack spacing, crack width, and steel stress criteria.

CHAPTER 5. CRC PAVEMENT INPUT CRITERIA REVISIONS

BACKGROUND

Previous discussion of coarse aggregate performance centered upon the analysis of crack spacing development. Other CRCP-4 program output parameters deserve consideration: pavement crack width and resultant steel stress. A more complete understanding of coarse aggregate influence on pavement performance can be obtained by analyzing output results for all three output parameters. This analysis can then focus on determining a range of input combinations which satisfy pavement design criteria and produce an equivalent pavement performance.

Several modifications to the initial input variables were suggested by representatives of the SHDPT Highway Design Division. Revisions included temperature model restrictions which reflected current field practice, a greater variety of steel bar size and percent steel reinforcement combinations, and a reevaluation of laboratory measured concrete property interpretations. These modifications are described in this chapter. The objective of these revisions is to determine an equivalent range of pavement performance regardless of the aggregate type selected for construction.

ENVIRONMENTAL INPUT REVISIONS

Previous development of the design temperature drop (modeled in terms of the seasonal daily temperature drop) concentrated on determining specific minimum daily temperature drops by season and geographic location. Application of this minimum daily temperature drop never exceeded 85 percent of the cumulative daily temperature differential during the first twenty-eight days of pavement curing. Upon assessment of this model strategy, it was determined that improvements to the minimum daily temperature model that presented a more accurate portrayal of field conditions could be made.

Minimum Daily Temperature Drop

Proposed PCC specifications prohibit contractors from placing concrete pavement when environmental conditions suggest an ambient temperature of 90°F or greater without special measures being taken by the contractor. A similar restricition exists for ambient daily low temperatures of 40°F and below. Upper and lower limits of ambient temperatures for the minimum and daily temperature drop calculations were restricted to an operating range of 90°F and 40°F. New seasonal minimum daily temperature drops were again determined in a similar fashion, as described in Fig 3.8. Results of the revised seasonal daily temperature drop schedule are shown in Table 5.1. They demonstrate a general reduction in the composite values of the 50 percent and 85 percent cumulative figures.

Application of the minimum daily temperature was according to the schedule shown in Table 5.2. This gradual increase over time with a larger minimum daily temperature drop is less conservative than the previous input schedule, but was felt to represent a more accurate description of actual field conditions.

TABLE 5.1. ***REVISED SEASONAL DAILY TEMPERATURE DROP, °F***

Location	Temp. Drop (%)	Winter	Spring	Summer	Fall
Brownsville	50	15	20	19	15
	85	27	27	21	20
	100	41	36	23	32
Port Arthur	50	16	20	16	15
	85	24	24	18	21
	100	34	30	23	28
Amarillo	50	27	25	26	25
	85	35	38	30	33
	100	47	45	41	39

TABLE 5.2. ***REVISED DAILY TEMPERATURE DROP INPUT SCHEDULE***

Schedule	Daily Temp. Drop (%)
Day 1	50
Days 2-27	85
Days 28 - 90	100

CONCRETE PROPERTIES REVISIONS

Previous interpretation of the concrete specimen raw data was made by fitting a series of curves through specific point value ranges of the specific test measurement results. This approach was used to confine input values to the range of actual laboratory measurements. This approach did not consider the impact of statistical outliers, and its interpretation was of a somewhat subjective nature. A review of Fig 4.1 suggests that several interpretations could be made from the same data point ranges, generating a series of many smooth curve fits.

A better representation of the laboratory raw data was accomplished by use of a statistical computer program that generated multiple regression coefficients using all the laboratory test measurement results (Ref 15). Predictive equations for each of the concrete input properties by coarse aggregate were then developed by this regression analysis. The laboratory curing conditions curing temperature and relative humidity, along with the pavement curing time were established as the independent variables used to generate respective predictive concrete property equations. The use of a "dummy variable" was adopted in order to distinguish coarse aggregate type. The following paragraphs describe the regression equations of materials properties related to the mixes (as described in Chapter 3, Table 3.1) and under the conditions described in Appendix A (see Experimental Factorial).

Modulus of Elasticity

Equation 5.1 is the prediction model for the concrete modulus of elasticity as developed over curing time:

$$E = (e^{(5.26 + 0.104X)})(t^{0.0974})(H^{0.152}) \qquad (5.1)$$

where

E = concrete modulus of elasticity, 10^4 psi;
t = curing time in days;
H = relative humidity, percent;
X = aggregate type identifier (dummy variable);
= 0, if SRG; and
= 1, if LS.

Concrete elastic modulus strength development over time did not appear to be affected by the concrete curing temperature.

Tensile Strength

Regression Eq 5.2 predicts the tensile strength gained for either type of coarse aggregate:

$$f_t = (e^{(4.74 + 0.0642X)})(t^{0.0926})(T^{0.180})(H^{0.0301}) \qquad (5.2)$$

where

f_t = concrete tensile strength, psi; and
T = curing temperature, °F, and other variables the same as previously described.

SRG Flexural Strength

Equation 5.3 describes the flexural strength gain for concrete constructed with siliceous river gravel aggregates:

$$FS_{SRG} = (e^{4.58})(t^{0.114})(T^{0.08})(H^{0.231}) \qquad (5.3)$$

where

FS_{SRG} = flexural strength of SRG mix, psi.

All three independent variables contribute to the tensile strength development of CRC pavements constructed with siliceous river gravel, implying that local environmental conditions may deserve further consideration in the development of design specifications.

Limestone Flexural Strength

Development of crushed limestone CRC pavement flexural strength is predicted by Eq 5.4:

$$FS_{LS} = (e^{6.51})(t^{0.087})(H^{0.122})(T^{-0.144}) \qquad (5.4)$$

where

FS_{LS} = flexural strength of LS mix, psi.

Analysis of crushed limestone raw data indicated that increasing concrete curing temperature, T, reduced the concrete flexural strength gain.

Concrete Thermal Coefficient

Regression analysis for both aggregate types determined that a constant value, by selective aggregate type, was more than adequate for CRCP-4 program input. The initial evaluation demonstrated a slight increase in the aggregate thermal coefficient with increasing curing time. The regression analysis of the raw data could not, however, predict any linear trend for either coarse aggregate. Table 5.3 provides the revised concrete thermal coefficient values, by aggregate type, for CRPC-4 program input.

TABLE 5.3. ***REVISED CONCRETE THERMAL COEFFICIENT VALUES***

Coarse Aggregate Type	Thermal Coefficient
Siliceous River Gravel	8.0×10^{-6} in/in/°F
Crushed Limestone	6.0×10^{-6} in/in/°F

Constant thermal coefficient values obtained from measurements taken from the raw data were somewhat higher than those used in previous CRC pavement studies.

Concrete Drying Shrinkage

Laboratory measurement of the drying shrinkage for both the siliceous river gravel and crushed limestone aggregate mixes were taken only under the 40 percent relative humidity curing condition. Equation 5.5 describes the concrete drying shrinkage relationship:

$$Z = (e^{(-0.422 - 8.71/t - 0.0919X)})(T^{1.35}) \qquad (5.5)$$

where

Z = Concrete Drying Shrinkage, over time, microstrains.

Concrete drying shrinkage values derived from Eq 5.5 showed an increase in length change with increasing curing time and curing temperature. Drying shrinkage values for pavements with siliceous river gravel aggregates were generally larger than for those with crushed limestone which is consistent with previous drying shrinkage interpretations.

STEEL PROPERTIES REVISIONS

A larger combination of steel bar sizes and percent steel reinforcement was recommended by the SDHPT in order that a range of alternative pavement designs could be reviewed for purposes of equivalent pavement performance. The adopted design strategy was to select a specific CRC pavement thickness and analyze various steel bar sizes and percent steel reinforcement combinations and then determine which input combinations provided a satisfactory pavement design. Steel input combinations would then be selected from the CRCP-4 output results that satisfied design criteria for all seasons and geographic conditions. Optimization of the equivalent solution was then established on the basis of minimum percent steel used and maximum allowable bar size in field construction practice.

REVISED PROJECT FACTORIAL

Figure 5.1 illustrates the revised combinational factorial used to determine satisfactory design inputs for a particular placement season and geographical location. CRCP-4 results could then be tabulated on this matrix to determine an equivalent design. One cell, for example, represents the input of a SRG coarse aggregate, with a #7 bar size at 0.5 percent steel reinforcement in a 10-inch-thick slab. CRCP-4 output values can then be recorded in this matrix cell for crack spacing (x), crack width (Δ), and steel stress (σ). A comparison of the resultant output with CRC pavement design criteria can then determine whether that particular pavement combination would be satisfactory.

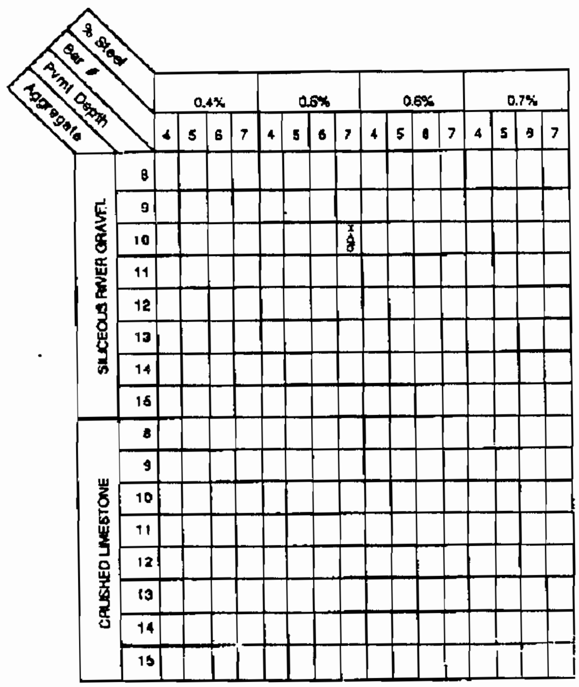


Fig 5.1. ***Modified project model factorial.***

DESIGN CRITERIA

Table 5.4 depicts the CRC pavement design limiting criteria for selection of satisfactory designs. CTR Report 177-17, "Limiting Criteria for the Design of CRCP," served as the basic reference for selection of these output parameters (Ref 16).

TABLE 5.4. ***CRC PAVEMENT DESIGN CRITERIA***

Output Parameter	Limiting Criteria
Crack Spacing	$3.50' \le X_S \le 8.00'$
Crack Width	$D_X \le 0.0047$ in.
Steel Stress	$S_S \le 60$ KSI

CRCP-4 PROGRAM REVISIONS

Direct input of concrete property relationships was facilitated by changing the CRCP–4 program input format to one that calculated the concrete property values by using the developed regression equations. Concrete properties were then directly integrated into CRCP–4 program solution on the basis of aggregate type and curing condition input values selected. These values were then used for analysis of crack spacing, crack width, and steel stresses.

An iterative data input program was also developed so that the array of input variables, as shown on Fig 5.1, could be analyzed with one CRCP-4 program application. Previous CRCP-4 program inputs were made on a separate and individual set of material and environmental properties for each combination illustrated in Fig 3.10.

CHAPTER 6. SUMMARY AND RECOMMENDATIONS

SUMMARY

This report describes the details of preliminary analysis performed to determine the effect of coarse aggregates on the performance of CRC pavements using siliceous river gravel (SRG) and crushed limestone (LS) aggregates.

Laboratory samples were prepared to measure the properties of two concrete mixes containing SRG and LS aggregates. An experimental factorial was designed to include various factors which affect the pavement concrete properties (see Fig A.1). Both mixes were tested in the laboratory to obtain data for all cells of the factorial with three replicates.

An initial evaluation of concrete mix property measurements was made by plotting the laboratory data and fitting the best curve passing through the observed points. The results of this analysis indicated that the mix containing LS aggregates exhibited higher tensile strength (indirect tension test), a higher modulus of elasticity (flexural test), higher flexural strengths, and lower shrinkage values than the mix containing SRG aggregates. Results of this analysis were used as INPUT to the computer program CRCP-4.

Preliminary analysis of pavement performance was performed on a comparative basis between the LS and SRG pavements. Several hypothetical pavements using standard steel (bar size and spacing as specified in CRCP(B)-85) were analyzed with the help of CRCP and JRCP computer programs. Typical results of this analysis are included in the report. The results indicated that transverse crack spacings were generally larger in pavements built with LS concrete mixes than SRG mixes (see Figs 4.2 to 4.8).

It was evident from the results of the preliminary analysis that if CRCP(B)-85 specifications were used in pavements built with LS and SRG aggregates, some pavement thicknesses will develop transverse cracks which will be outside the allowable ranges. Also, pavements built with different coarse aggregates (SRG and LS) will perform differently if their thicknesses were same.

Considering the implications of the preliminary analysis results, it will be impractical to either restrict the use of certain coarse aggregate for a given design thickness or to specify different thicknesses for pavements built with different types of coarse aggregates. Therefore, it was decided by researchers (CTR staff) and SDHPT staff to modify the methodology so that a practical solution can be developed for steel design in pavements built with different types of coarse aggregates.

An outline of the revisions proposed for the study is included in Chapter 5 of the report. The details of analysis are described in the next report (Research Report 422-2).

RECOMMENDATIONS

Based on the results of preliminary analysis described in the report, it is apparent that a practical strategy for reinforcement specifications is needed if the use of different types of aggregates (SRG and LS) is allowed in the specifications. A reasonable solution can be obtained for this purpose if the reinforcement (bar size and spacing) can be varied according to the coarse aggregate type, keeping the pavement thickness same. Outline of the methodology described in Chapter 5 of the report is recommended for this purpose. Field verification of recommended design will be a logical and useful part of this study.

Verification of the accuracy of the predictive nature of the regression equations described in Chapter 5 warrants further investigation. Field measurements of past CRC pavement performance could serve as a baseline for comparison. Historical inputs of CRC pavement concrete, steel, and environmental inputs should be verified and analyzed using the revised CRCP-4 program. It would be expected that output generated from this computer-generated solution and the field measurements made would fall within a reasonable range in terms of CRC pavement crack width, crack spacing and steel stress. Further investigation is needed to determine what statistically allowable range of comparison criteria is satisfactory for validating the predictive equations developed in Chapter 5.

A future Work Plan that focuses on a stochastic determination of acceptable design criteria derived from design charts needs to be developed in Phase 2 of this research project. One objective might be to provide realistic predictive criteria that transform the predictive design criteria from deterministic point measures to a stochastic range of acceptable values.

REFERENCES

1. McCullough, B. Frank, W. R. Hudson, and C. S. Noble, "Summary and Recommendations for the Implementation of Rigid Pavement Design, Construction and Rehabilitation Techniques," Research Report 177-22F, Center for Transportation Research, The University of Texas at Austin, March 1981.

2. "Highway Design, Division, Operations and Procedures Manual," Appendix F, Texas State Department of Highways and Public Transportation, Austin, Texas 1982.

3. "1982 Standard Specifications for Construction of Highways, Streets and Bridges," Texas State Department of Highways and Public Transportation, Austin, Texas, 1982.

4. Machado, John Patrick, "Continuously Reinforced Concrete Pavement: Prediction of Distress Quantities," Master's Thesis, The University of Texas at Austin, May 1977.

5. Strauss, Pieter, J., B. Frank McCullough, and W. Ronald Hudson, "Continuously Reinforced Concrete Pavement: Structural Performance and Design/Construction Variables," Research Report 177-7, Center for Highway Research, The University of Texas at Austin, May 1977.

6. Gutierrez de Velasco, Manuel, and B. Frank McCullough, "Summary Report for 1978 CRCP Condition Survey in Texas," Research Report 177-20, Center for Transportation Research, The University of Texas at Austin, January 1981.

7. 1985 Annual Book of ASTM Standards, Section 4 Construction, Volume 04.02, Concrete and Mineral Aggregates, Designation: C78-84, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Third Point Loading).

8. 1985 Annual Book of ASTM Standards, Section 4 Construction, Volume 04.02, Concrete and Mineral Aggregates, Designation: C496-85, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.

9. Texas Highway Department, Materials and Testing Division, Manual of Testing Procedures, Test Method Tex-420-A: Flexural Strength of Concrete (Using Simple Beam With Center Point Loading) Rev: 1 March, 1985.

10. 1985 Annual Book of ASTM Standards, Section 4, Construction, Volume 04.02, Concrete and Mineral Aggregates, Designation: C157-80, Standard Test Method for Length of Change of Hardened Cement Mortar and Concrete.

11. Ma, James, and B. Frank McCullough, "CRCP-2, An Improved Computer Program for the Analysis of Continuously Reinforced Concrete Pavements," Research Report 177-9, Center for Transportation Research, The University of Texas at Austin, August, 1977.

12. Diaz, Alberto Mendoza and B. Frank McCullough, "Design Charts for the Design of HMAC Overlays on PCC Pavements to Prevent Reflection Cracking," Research Report 249-6, Center for Transportation Research, The University of Texas at Austin, November 1983.

13. National Oceanic and Atmospheric Administration, Local Climatological Data, 1984 Monthly Summary for Brownsville, Texas- ISSN 0198-4950, Port Arthur, Texas- ISSN 0198-5159 and Amarillo, Texas-ISSN 0198-4918.

14. Diaz, Alberto-Mendoza and B. Frank McCullough, "Report on a Mechanistic Analysis at King Fahd International Airport, Kingdom of Saudi Arabia," Austin Research Engineers, October 1985.

15. MINITAB Release 81.1, Penn State University, 1981- The University of Texas at Austin.

16. Ma, J.C., C.S. Nobel, and B. Frank McCullough, "Limiting Criteria for the Design of CRCP," Research Report 177-17, Center for Transportation Research, The University of Texas at Austin, August, 1979.

17. Diaz, Alberto-Mendoza, Ned H. Burns, and B. Frank McCullough, "Behavior of Long Prestressed Pavement Slabs and Design Methodology," Research Report 401-3, Center for Transportation Research, The University of Texas at Austin, September 1986.

APPENDIX A. FERGUSON STRUCTURAL ENGINEERING LABORATORY MEASURMENTS OF CONCRETE MIX PROPERTIES

TABLE A.1. ***SRG MODULUS OF ELASTICITY*** **(10^4 PSI)**

SILICEOUS RIVER GRAVEL							
MOISTURE CONDITION (% HUMIDITY)		40% REL. HUMIDITY			100% REL. HUMIDITY		
CURING TEMPERATURE (°F)		50°F	75°F	100°F	50°F	75°F	100°F
CURING TIME	TEST SAMPLE						
1 DAY	1	298.8	421.2	335.3	333.3	374.6	395.3
	2	248.4	199.3	322.4	234.2	230.0	766.3
	3	257.8	469.4	440.1	357.6	304.2	293.4
	AVG.	268.3	363.3	365.9	308.4	302.9	485.0
3 DAYS	1	336.3	233.2	412.6	495.1	255.0	460.8
	2	528.9	195.6	516.8	478.6	522.7	358.6
	3	526.4	325.2	443.5	420.3	664.7	480.7
	AVG.	463.9	251.3	457.6	464.7	388.9	433.4
7 DAYS	1	415.7	219.5	287.4	652.1	387.2	479.4
	2	612.2	328.4	355.4	583.7	602.1	853.4
	3	411.5	442.5	287.4	1309.9	1064.8	533.6
	AVG.	479.8	330.1	310.1	848.6	684.7	622.1
28 DAYS	1	362.5	452.8	378.3	457.1	539.0	769.0
	2	515.0	501.4	427.5	524.5	580.7	605.4
	3	410.9	575.0	354.6	375.8	662.7	599.0
	AVG.	429.5	509.7	368.8	452.5	534.1	657.8
90 DAYS	1	611.7	314.2	592.8	1440.7	238.7	1084.9
	2	506.6	602.1	215.0	467.5	668.6	1580.8
	3	602.1	524.5	650.4	787.7	452.8	1026.8
	AVG.	573.5	480.3	486.1	898.6	453.4	1230.8

TABLE A.2. ***LS MODULUS OF ELASTICITY (10^4 PSI)***

SILICEOUS RIVER GRAVEL							
MOISTURE CONDITION (% HUMIDITY)		40% REL. HUMIDITY			100% REL. HUMIDITY		
CURING TEMPERATURE (°F)		50°F	75°F	100°F	50°F	75°F	100°F
CURING TIME	TEST SAMPLE						
1 DAY	1	348.8	403.5	430.0	301.9	314.4	324.6
	2	120.9	628.4	333.3	320.0	1320.6	541.6
	3	366.9	465.6	549.5	298.0	960.4	415.7
	AVG.	278.9	499.2	437.6	306.6	865.1	427.3
3 DAYS	1	385.8	417.2	670.6	569.0	320.9	449.2
	2	479.4	392.5	489.4	560.5	563.3	461.8
	3	563.3	448.8	520.4	599.2	485.6	531.8
	AVG.	476.2	419.5	560.1	576.2	456.6	480.9
7 DAYS	1	516.8	291.2	387.2	701.4	500.7	549.3
	2	539.0	405.2	574.8	710.3	682.7	356.5
	3	428.3	414.2	373.0	663.8	426.7	450.6
	AVG.	494.7	370.2	445.0	691.8	536.7	452.1
28 DAYS	1	692.8	399.3	560.7	220.7	539.9	299.5
	2	577.7	487.3	547.6	129.2	351.7	583.8
	3	539.9	635.4	416.9	283.8	527.5	457.9
	AVG.	603.5	507.3	508.4	211.2	473.0	447.1
90 DAYS	1	638.9	1007.2	1185.6	694.0	849.4	526.9
	2	527.5	300.3	281.9	539.9	566.2	701.2
	3	577.7	—	184.9	631.9	293.3	1063.7
	AVG.	581.4	653.8	550.8	621.9	569.6	763.9

TABLE A.3. ***SRG SPLIT CYLINDER TENSILE STRENGTH (PSI)***

SILICEOUS RIVER GRAVEL							
MOISTURE CONDITION (% HUMIDITY)		**40% REL. HUMIDITY**			**100% REL. HUMIDITY**		
CURING TEMPERATURE (°F)		**50°F**	**75°F**	**100°F**	**50°F**	**75°F**	**100°F**
CURING TIME	**TEST SAMPLE**						
1 DAY	1	191.8	266.9	271.3	232.6	350.7	273.0
	2	183.2	254.3	303.3	203.6	313.9	274.3
	3	158.2	255.2	287.9	192.7	308.4	291.7
	AVG.	177.7	258.8	287.5	209.6	324.3	279.7
3 DAYS	1	249.6	345.5	318.3	334.6	380.6	377.4
	2	269.4	288.9	363.3	289.3	411.9	322.1
	3	254.1	329.8	308.1	370.3	373.0	305.9
	AVG.	257.7	321.4	329.9	331.4	388.5	335.1
7 DAYS	1	309.6	370.8	412.5	313.5	441.1	343.1
	2	325.3	397.3	383.9	333.8	457.1	344.6
	3	334.0	377.8	417.6	360.8	440.1	320.3
	AVG.	322.9	381.9	404.7	336.0	446.1	336.0
28 DAYS	1	329.0	429.2	355.3	346.8	528.2	435.3
	2	326.6	372.6	403.2	420.1	543.9	380.5
	3	340.6	374.6	337.8	399.2	492.8	390.7
	AVG.	332.1	392.2	365.5	388.7	521.6	402.2
90 DAYS	1	361.4	400.7	376.6	384.9	—	464.5
	2	399.5	422.3	428.5	387.6	—	409.9
	3	260.1	425.3	333.7	404.1	—	471.3
	AVG.	340.3	416.1	379.6	392.2	—	448.6

TABLE A.4. *LS SPLIT CYLINDER TENSILE STRENGTH (PSI)*

SILICEOUS RIVER GRAVEL							
MOISTURE CONDITION (% HUMIDITY)		40% REL. HUMIDITY			100% REL. HUMIDITY		
CURING TEMPERATURE (°F)		50°F	75°F	100°F	50°F	75°F	100°F
CURING TIME	TEST SAMPLE						
1 DAY	1	203.2	242.0	291.0	239.6	249.6	302.0
	2	194.2	316.3	276.0	248.7	249.4	313.3
	3	269.4	269.2	288.9	228.7	237.9	350.6
	AVG.	222.3	275.9	285.3	239.0	245.6	322.0
3 DAYS	1	348.1	357.3	433.2	294.9	284.4	413.5
	2	315.8	395.5	353.0	329.1	340.2	316.4
	3	337.6	351.2	391.8	383.6	322.6	339.8
	AVG.	333.8	368.0	392.7	335.8	315.7	356.6
7 DAYS	1	352.3	400.8	323.6	426.8	284.4	449.2
	2	337.9	427.9	413.9	370.4	379.3	451.2
	3	335.7	407.8	428.8	367.5	371.1	404.8
	AVG.	342.0	412.2	388.8	388.2	344.9	435.1
28 DAYS	1	456.8	515.3	465.2	398.3	423.7	463.1
	2	404.8	494.1	320.5	363.9	432.3	357.1
	3	463.0	355.1	445.9	376.4	407.9	456.3
	AVG.	441.5	454.9	410.5	379.5	421.3	425.5
90 DAYS	1	411.2	476.8	277.0	372.5	437.0	443.2
	2	456.5	370.6	339.1	362.2	419.9	408.8
	3	—	393.6	384.8	488.2	451.6	391.8
	AVG.	433.9	413.7	333.6	409.6	436.2	414.6

TABLE A.5. *SRG FLEXURAL STRENGTH (PSI)*

SILICEOUS RIVER GRAVEL							
MOISTURE CONDITION (% HUMIDITY)		40% REL. HUMIDITY			100% REL. HUMIDITY		
CURING TEMPERATURE (°F)		50°F	75°F	100°F	50°F	75°F	100°F
CURING TIME	TEST SAMPLE						
1 DAY	1	255.9	316.7	418.3	225.6	365.0	409.9
	2	237.1	414.4	384.7	195.4	325.0	465.3
	3	234.9	390.9	367.6	225.6	300.0	409.9
	AVG.	242.6	374.0	390.2	215.5	330.0	428.4
3 DAYS	1	343.2	446.2	347.8	352.1	435.5	437.8
	2	414.6	485.0	357.2	432.7	425.0	482.9
	3	413.6	470.2	361.9	393.7	410.7	487.1
	AVG.	390.5	467.1	355.6	392.8	430.2	469.3
7 DAYS	1	409.4	420.0	313.2	493.2	475.1	553.7
	2	488.8	382.3	345.2	488.5	596.4	535.8
	3	375.4	446.8	366.6	501.5	529.0	533.4
	AVG.	424.5	416.3	341.7	494.4	533.5	541.0
28 DAYS	1	460.5	470.1	398.4	599.7	600.2	652.5
	2	465.3	417.9	406.5	605.9	493.2	700.4
	3	436.9	524.1	427.0	588.9	528.9	546.1
	AVG.	454.2	470.7	410.6	598.1	544.1	633.0
90 DAYS	1	514.3	540.6	489.9	741.6	648.3	732.1
	2	519.6	597.6	480.0	651.4	653.2	707.6
	3	519.2	533.2	528.3	677.9	643.3	781.9
	AVG.	517.7	557.1	499.4	690.3	648.3	740.5

TABLE A.6. *LS FLEXURAL STRENGTH (PSI)*

SILICEOUS RIVER GRAVEL							
MOISTURE CONDITION (% HUMIDITY)		40% REL. HUMIDITY			100% REL. HUMIDITY		
CURING TEMPERATURE (°F)		50°F	75°F	100°F	50°F	75°F	100°F
CURING TIME	TEST SAMPLE						
1 DAY	1	352.5	401.6	465.2	308.7	437.2	400.7
	2	319.6	415.7	370.3	294.8	388.0	404.8
	3	386.2	426.7	446.7	323.8	411.7	418.7
	AVG.	352.8	414.7	427.4	309.1	412.3	408.1
3 DAYS	1	424.1	488.2	441.8	478.7	506.2	513.6
	2	521.1	483.9	456.0	460.6	523.8	523.2
	3	538.1	474.3	451.2	456.0	483.6	484.4
	AVG.	494.5	482.1	449.7	465.1	504.6	507.1
7 DAYS	1	551.8	383.1	479.2	544.3	550.9	442.3
	2	585.0	456.1	474.4	546.1	543.5	497.1
	3	542.7	416.0	370.3	563.1	519.9	469.7
	AVG.	559.8	418.4	441.3	551.2	538.1	469.7
28 DAYS	1	524.1	422.2	437.2	656.3	673.9	568.2
	2	583.0	475.2	484.8	676.5	612.2	547.2
	3	575.1	480.0	465.5	669.6	630.3	492.9
	AVG.	560.7	459.1	462.5	667.5	638.8	536.1
90 DAYS	1	602.5	620.6	612.3	721.9	618.9	593.7
	2	603.7	673.9	562.4	761.2	693.4	597.6
	3	585.3	—	566.4	773.9	700.5	617.4
	AVG.	597.2	647.3	580.4	752.3	670.9	602.9

TABLE A.7. *SRG THERMAL COEFFICIENT (10^{-6} IN./IN./°F)*

SILICEOUS RIVER GRAVEL							
MOISTURE CONDITION (% HUMIDITY)		40% REL. HUMIDITY			100% REL. HUMIDITY		
CURING TEMPERATURE (°F)		50°F	75°F	100°F	50°F	75°F	100°F
CURING TIME	TEST SAMPLE						
1 DAY	1	6.95	7.27	7.93	7.46	6.65	4.50
	2	7.88	7.96	7.55	7.75	5.70	7.27
	3	7.83	7.83	8.26	7.71	7.36	6.92
	AVG.	7.55	7.69	7.91	7.64	6.57	6.23
3 DAYS	1	8.88	8.02	6.49	6.84	8.16	7.04
	2	9.51	8.86	7.10	7.16	8.33	7.51
	3	8.45	8.42	7.32	6.89	—	7.27
	AVG.	8.95	8.43	6.97	6.96	8.24	7.27
7 DAYS	1	10.07	7.41	7.51	8.13	6.78	6.61
	2	8.96	7.21	7.92	8.06	10.50	6.87
	3	7.92	7.56	7.20	8.18	7.27	6.83
	AVG.	8.98	7.39	7.54	8.12	8.18	6.77
28 DAYS	1	8.48	8.17	8.82	8.58	7.72	8.50
	2	9.21	8.18	9.36	8.35	7.77	8.27
	3	8.91	8.21	9.36	9.48	7.58	7.90
	AVG.	8.87	8.18	9.18	8.80	7.69	8.22

TABLE A.8. *LS THERMAL COEFFICIENT (10^{-6} IN./IN./°F)*

SILICEOUS RIVER GRAVEL							
MOISTURE CONDITION (% HUMIDITY)		40% REL. HUMIDITY			100% REL. HUMIDITY		
CURING TEMPERATURE (°F)		50°F	75°F	100°F	50°F	75°F	100°F
CURING TIME	TEST SAMPLE						
1 DAY	1	5.40	5.10	6.06	7.13	5.41	5.75
	2	4.38	4.89	6.66	7.42	5.53	5.83
	3	5.04	6.09	5.21	6.23	5.07	—
	AVG.	4.94	5.36	5.98	6.93	5.34	5.84
3 DAYS	1	5.32	5.66	5.70	4.62	4.58	5.33
	2	3.72	5.65	—	4.64	4.87	4.45
	3	5.59	6.77	—	2.82	5.19	5.59
	AVG.	4.88	6.02	5.70	4.03	4.88	5.12
7 DAYS	1	5.64	6.03	5.13	5.31	5.11	4.44
	2	6.03	6.12	5.20	5.49	5.16	4.78
	3	5.77	6.31	4.68	5.57	4.69	4.21
	AVG.	5.81	6.15	5.00	5.45	4.99	4.48
28 DAYS	1	6.38	5.86	6.30	5.26	5.68	7.85
	2	6.23	6.42	6.69	6.00	6.11	8.81
	3	6.47	6.60	6.71	6.15	6.12	7.67
	AVG.	6.36	6.29	6.57	5.80	5.97	8.11

TABLE A.9. *MODULUS OF RUPTURE AT 7 DAYS (PSI)*

SILICEOUS RIVER GRAVEL							
MOISTURE CONDITION (% HUMIDITY)		40% REL. HUMIDITY			100% REL. HUMIDITY		
CURING TEMPERATURE (°F)		50°F	75°F	100°F	50°F	75°F	100°F
CURING TIME	TEST SAMPLE						
7 DAYS	1	498.2	534.3	400.7	552.7	717.5	649.9
	2	554.6	530.4	381.5	554.6	846.2	704.7
	3	496.5	483.9	413.6	646.7	591.5	693.2
	AVG.	516.4	516.2	398.6	584.7	718.4	682.6
7 DAYS	1	589.6	531.1	507.4	618.4	628.1	575.3
	2	635.6	487.5	473.7	633.9	618.7	488.0
	3	580.5	588.3	548.1	601.8	635.6	576.9
	AVG.	601.9	535.6	509.8	618.0	627.5	546.7

TABLE A.10. *SGR DRYING SHRINKAGE (IN./IN.) (10^{-4})*

Curing Time (Days)	Curing Temp. (°F)	Specimen 1				Specimen 2			
		1	2	3	Avg.	1	2	3	Avg.
.91	69	17.05	13.81	54.31	28.39	59.17	2.47	30.01	30.55
3.74	71	22.80	35.76	71.40	43.32	57.53	35.76	62.49	51.96
6.27	70	40.58	61.64	97.28	66.50	83.51	53.54	85.94	74.33
11.86	69	108.58	105.34	143.41	119.11	115.87	94.81	135.31	115.33
19.84	69	157.18	154.75	176.62	162.85	165.28	132.88	173.38	157.18
25.93	69	179.86	177.43	199.30	185.53	182.29	152.32	196.06	176.89
39.04	69	209.83	204.16	236.56	216.85	217.12	184.72	230.89	210.91
61.24	69	238.99	241.41	273.82	251.41	251.95	209.02	262.48	241.15
89.14	79	315.53	320.39	350.36	328.76	328.49	284.75	328.49	313.91
131.04	73	265.88	300.71	363.08	309.89	295.04	268.31	282.08	281.81
261.12	75	358.30	366.40	390.70	371.80	373.59	320.23	371.26	355.06

TABLE A.11. *LS DRYING SHRINKAGE (IN./IN.) (10^{-4})*

Curing Time (Days)	Curing Temp. (°F)	Specimen 1				Specimen 2			
		1	2	3	Avg.	1	2	3	Avg.
1.04	70	20.64	28.74	10.92	20.10	18.21	42.51	19.02	26.58
2.52	69	16.20	16.20	5.67	12.69	21.06	40.50	27.54	29.70
5.86	69	48.60	54.27	51.84	51.57	46.17	81.00	59.94	61.37
12.59	69	124.74	121.50	132.84	126.36	100.44	140.94	119.88	120.42
20.69	69	179.82	166.05	171.72	172.53	139.32	184.68	155.52	159.84
34.03	69	222.75	220.32	223.56	222.21	196.02	233.28	204.12	211.14
56.23	69	284.31	268.11	287.55	279.99	243.81	273.78	249.48	255.69
84.12	78	355.86	331.56	356.67	348.03	307.26	334.80	313.74	318.60
126.04	73	348.24	340.14	351.48	348.62	281.01	329.61	306.12	305.58
256.10	75	448.65	432.45	465.66	448.92	375.75	416.25	403.29	398.43

APPENDIX B. DESCRIPTION OF SHRINKAGE TEST PROCEDURE

Shrinkage tests were conducted on 6-inch x 12-inch concrete cylinders stored in environments having temperatures of 50°F, 75°F, and 100°F, and 40 percent relative humidity after initial curing. The environmental conditions in which the specimens were kept prior to mold removal at approximately 20 hours are referred to as the initial curing conditions. The environmental conditions in which the specimens were stored during the shrinkage tests are referred to as the storage conditions.

During initial curing, the specimens which were to be cured at 100 percent relative humidity were covered with wet burlaps and plastic, while those which were to be cured at 40 percent relative humidity were placed uncovered in an environment of 40 percent relative humidity, the finished surface thus being exposed to the environment.

After initial curing, which ended approximately 20 hours after casting, the specimens were removed from their molds and prepared for shrinkage testing. Three sets of demec points were epoxied onto each cylinder, each set being alighned with the longitudinal axis of the cylinder and placed at 120 degrees along the circumference of the cylinder with respect to the other two sets of points. Two cylinders were tested per specified storage condition, thus yielding six sets of demec points from which shrinkage readings were taken for each storage condition. A demec gage having a gage length of approximately eight inches was used. After the demec points had been affixed to the shrinkage specimens, the specimens were sealed in plastic bags and placed in the specified storage conditions. The specimens were allowed to come to thermal equilibrium with the storage environment, being sealed to avoid shrinkage wile thermally-induced length changes were occurring, before the initial gage length reading was taken. Once the specimens reached thermal equilibrium with the environment, they were removed from the plastic bags and the shrinkage tests were begun, at approximately 24 hours after casting.

For every initial curing temperature, shrinkage tests were conducted at a storage temperature equal to the initial curing temperature and at 100°F. Thus, if the initial curing temperature was 50°F, shrinkae tests were conducted at storage tempertures of both 50°F and 100°F.