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16. Abstract

Membrane curing compounds are widely used to cure concrete in highway construction. The function of these compounds is to form a membrane that helps retain moisture in the concrete slab, otherwise lost through evaporation. The amount of evaporation loss varies as a function of the environmental conditions and the temperature of the concrete mass during the curing period.

This report provides an evaluation of the performance of membrane curing compounds as related to concrete material properties such as tensile and flexural strength, stiffness, surface durability, and density. In addition to traditional testing methods, the non-destructive, in-situ, Spectral Analysis of Surface Waves method is also used to observe and measure material properties as a function of time. Testing can start at initial set or when the modulus of elasticity for concrete is about 10,000 psi.

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by

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C. G. Papaleontiou
A. H. Meyer
D. W. Fowler

Research Report Number 1118-1F

Research Project 3-6-86-1118
The Effectiveness of Membrane Curing Compounds for Portland Cement Concrete Pavements

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

Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

November 1988

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.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacturer, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

PREFACE

This report describes work carried out by the Center for Transportation Research at the University of Texas at Austin to evaluate the effectiveness of membrane curing compounds as used in concrete pavement construction in Texas.

The authors are indebted to many people for the material included in this report. A large part of this study involved field testing throughout the State of Texas. The help and cooperation of personel in all the districts involved is sincerely appreciated.

The contribution of Dr. Kenneth H. Stokoe and his graduate students James Bay and Roberto Lopez in conducting the SASW testing has been instrumental in the successful completion of this report. We sincerely appreciate their help.

Several people in the Department of Civil Engineering of the University of Texas provided invaluable technical and administrative help. Among them, Messrs. David Whitney, Fred Barth, and a great number of often forgotten undergraduate research assistants deserve special gratitude.

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C. G. Papaleontiou
Alvin H. Meyer
David W. Fowler

ABSTRACT

Membrane curing compounds are widely used to cure concrete in highway construction. The function of these compounds is to form a membrane that helps retain moisture in the concrete slab, otherwise lost through evaporation. The amount of evaporation loss varies as a function of the environmental conditions and the temperature of the concrete mass during the curing period.

This report provides an evaluation of the performance of membrane curing compounds as related to concrete material properties such as tensile and flexural strength, stiffness, surface durability, and density. In addition to traditional testing methods, the non-destructive, in-situ, Spectral Analysis of Surface Waves method is also used to observe and measure material properties as a function of time. Testing can start at initial set or when the modulus of elasticity for concrete is about 10,000 psi.

KEYWORDS: membrane curing compounds, curing method, concrete, moisture, evaporation, surface durability, density, tensile and flexural strength.

SUMMARY

This report presents the evaluation of membrane curing compounds (MCCs) for use as curing agents in concrete highway construction.

The study is broadly divided in two parts: field testing and laboratory testing.

During field tests, the effect of several variables upon flexural, tensile, durability, density, and stiffness properties was measured with a variety of test methods. Testing variables included the depth of the tested concrete in the slab, the application rate of the curing compound, and the calculated evaporation rate. A test method of particular interest is the Spectral Analysis of Surface Waves (SASW).

SASW is a seismic method that measures the response of the tested material to externally-introduced vibrations which produce very low strains. It is, therefore, a non-destructive method which can be used in-situ to track the development of material properties on a continuous basis starting at initial set or as soon as concrete develops a modulus of about 10,000 psi.

The laboratory testing comprised tensile and flexure tests on Membrane Curing Compound treated specimens that were cured with various application rates and under different environmental conditions.

An important part of the study is the statistical analysis of the field and laboratory test concrete. Several statistical models were developed in order to better evaluate specific specific characteristics. These models are discussed in the text.

Finally, the conclusions resulting from the analysis of the experimental data are presented, as well as recommendations for further use of membrane curing compounds and suggestions for further research.

IMPLEMENTATION STATEMENT

Based on the results of this study no implementation for change in the standards and specifications for using membrane curing compounds in concrete pavement construction-can be made at this time.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

GENERAL

The initial period of up to 28 days after placing is considered to be the most critical stage in the life of concrete in terms of developing desirable properties such as strength and durability. These properties are affected by the humidity of the concrete mass as it hydrates. This, in turn, may be dependent on factors such as the curing method used during the initial period, the ambient temperature and humidity, the wind velocity, and the temperature of the concrete mass itself. Curing can thus be defined as any process where fresh concrete is treated to ensure that an adequate level of humidity is maintained in the concrete mass during the initial period of its life.

The use of membrane curing compounds (MCCs) in concrete paving construction has been widely accepted in the past few decades as one of the predominant and successful ways of concrete curing. These compounds, which generally have the consistency of thick paint, are sprayed on the concrete surface, and when correctly applied, form a membrane that is resistant to the passage of water or vapor and thus helps retain a part of the internal moisture of the concrete mass. In that respect the use of curing compounds differs from other methods of curing, including spraying or using wet burlap, in that no addition of water is necessary in excess of that used in the mix.

The objective of this report is to study the effectiveness of MCCs, as applied in pavement construction. This was measured in terms of flexural and tensile strength, surface durability, and density of MCC-treated specimens. The modulus of elasticity was also measured by the Spectral Analysis of Surface Waves (SASW) method.

Tests were conducted on several pavement construction sites in the State of Texas, as well as in the laboratory. The field sites were selected from three environmental zones to allow a variety of environmental conditions. In the laboratory, specimens were also treated under various combinations of ambient and concrete temperature, and humidity.

Several application rates of curing compound were used in the field and in the laboratory to investigate the effect this might have on the properties mentioned above. In addition, several specimens were left completely untreated for comparison purposes.

The results of all tests described above were analyzed using the statistical software package SAS.

ORGANIZATION

Chapter 2 offers a review of relevant literature in the topic of membrane curing compounds. Chapter 3 presents a description of all tests performed in the course of this study, both in the field and in the laboratory. Chapter 4 gives a description of all variables used in the statistical models and offers a general discussion of these models. Chapter 5 contains the results that were obtained in all tests performed, and a discussion of these results. Finally, Chapter 6 offers conclusions and specific recommendations regarding the current and future use of membrane curing compounds in highway paving construction.

CHAPTER 2. LITERATURE REVIEW

The use of membrane curing compounds in concrete highway construction has been the subject of several research reports in the past few decades. One conclusion common to many studies is that successful MCC curing depends on the uniformity and continuity of the membrane. Consequently, a large part of the research has been focused on determining the application rate that would be sufficient to form a continuous membrane and which at the same time would be as economical as possible.

Various agencies specify or suggest different application rates. For example the American Concrete Institute in its *Standard Practice for Curing Concrete* suggests a rate between 150 and 200 square feet/gallon[1]. AASHTO[2] and ASTM[3] specify 200 square feet/gallon, while the Texas State Department of Highways and Public Transportation specifies a rate of 180 square feet/gallon[4].

In a study conducted by Carrier and Cady[5], the relative humidity of concrete specimens at various depths and for different application rates was measured at different times after placing the concrete. The results indicated that the specimens that were sprayed at 400 square feet/gallon lost almost as much moisture as those that were sprayed at 100 square feet/gallon. Additionally, it was found that in all cases if a curing compound was used the moisture loss was significantly smaller than that of unprotected specimens and that the membrane broke down at an application rate of about 400 square feet/gallon.

It has been shown[6] that the hydration process continues as long as a relative humidity of 80 percent is maintained in the concrete mass. In the above mentioned study, all MCC treated specimens had a relative humidity level greater than 80 percent for an average of 9 to 13 days after placing as compared to one day for untreated specimens. In all specimens, treated or not, the depth to which the surface treatment – or the lack of it – had any effect on the moisture content did not exceed one inch.

A second study by Papaleontiou, Loeffler, Meyer, and Fowler[7] has suggested that, in fact, increased application rates such as 150 square feet/gallon may have adverse effects in terms of moisture retention as compared to lower application rates. The reason for this is considered to be the fact that at high application rates excessive pooling occurs in the pavement grooving. This observation has also been made by Shariat and Pant[8].

The effect of membrane curing compound usage on strength of concrete specimens, as opposed to moisture retention, was examined in a study by Wrbas, Ledbetter, and Meyer[9]. Additionally, the effect of environmental conditions on strength was also investigated. It was found that high curing temperatures (in excess of 100°F), resulted in a significant reduction of strength in the top portion of the tested specimens, and that the combination of such high curing temperatures with wind conditions of 8 to 20 mph produced even larger reductions in strength.

CHAPTER 3. TEST DESCRIPTIONS

INTRODUCTION

All tests for which there exist applicable test specifications (TEX or ASTM) were performed accordingly. Nevertheless, some of these test procedures had to be modified to accommodate special requirements. The deviations from the standard presented in this introduction were common to all the tests described in this chapter.

The upper surfaces of all specimens were textured by an Astrograss® drag and transverse tine grooving. The grooves were on the average 1/16 inch deep, with 3/4-inch center-to-center spacing. This is a typical concrete pavement texturing as required by Texas SDHPT.

All beams and cylinders were kept in the molds for the duration of the curing period to avoid moisture loss from surfaces other than the top. The specimens were cured with different rates of curing compound or were left untreated, according to the experimental model described in the next chapter. The metal mold joints were sealed with silicone caulking for the same reason. The top surface was treated as required in each particular test.

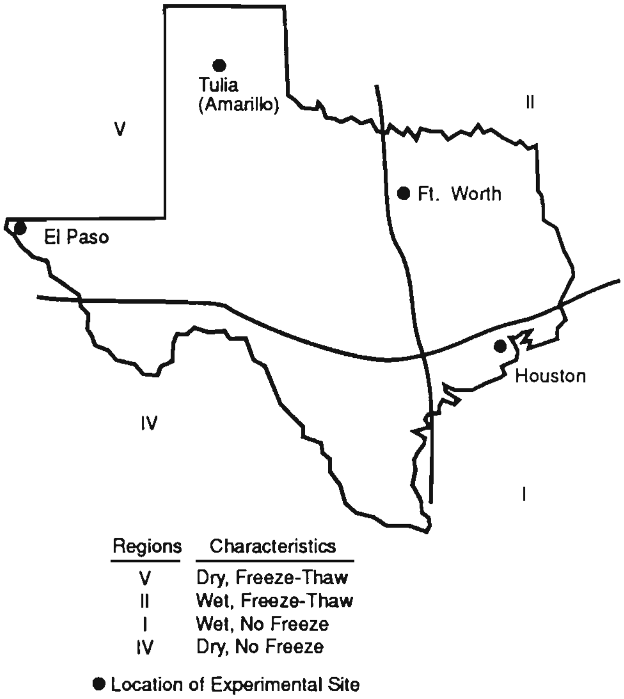

Fig 3.1. Location of the experimental sites in the climatic regions of Texas.

FIELD TESTING

Four sites in the State of Texas were selected to evaluate the effectiveness of membrane curing compounds on PCC pavements under various environmental conditions. These sites, in Districts 2, 5, 12, and 24, are located in environmental zones I, II, and V. Table 3.1 shows the distribution of these sites in the State and the test schedule. Figure 3.1 shows the location of the sites in the climatic regions of Texas.

At each of these sites, after consultation with the District Engineer and the contractor, two pavement sections were set aside to be tested (except in site #6, in El Paso, where only one section was tested due to scheduling difficulties). These sections were textured mechanically by the contractor with burlap or Astrograss® drag and transverse tining as shown in Fig 3.2. On site #6 the transverse tining was done by hand as shown in Fig 3.3. The curing treatment was applied manually by the research crew.

The test sections were divided into panels having approximate dimensions of 5 feet x 12 feet. Most of the panels were sprayed with a membrane curing compound, while some were covered with polyethylene sheet, or left completely untreated. Three coverage rates were used for the curing compound: 150, 180, and 200 square feet/gallon in three of the four field test sites (Districts 2, 5, and 12). In the fourth test site (District 24) an additional rate of 250 square feet/gallon was also used on one panel. An "airless" type, electric-driven spraying gun was employed for this operation. A schematic of a typical panel layout is shown in Figs 3.4 and 3.5. Note that some curing treatments are repeated in order to provide a repetition of results for statistical purposes.

Three kinds of specimens were obtained in the field: 4-inch cores, 6-inch x 12-inch cylinders, and 6-inch x 21-inch beams. The beams and the cylinders were cast by the research crew using concrete from the same batch that was used for the test panels on the pavement and were textured by an Astrograss® drag and transverse tine grooving (Fig 3.6). The grooves were on the average 1/16 inch deep with 3/4-inch center-to-center spacing. The specimens were allowed to cure for seven days in the field under the same conditions as the pavement and they were then transported to the laboratory for testing. At every test site in the

TABLE 3.1. PROJECT 1118 FIELD TESTING SCHEDULE

Test Site, Contractor	Location	District	Placing Date	Coring Date	Environmental Zone
#1	Tulia, Tx	5	7/23/87	7/30/87	V
#2	Tulia, Tx	5	7/24/87	7/31/87	V
#3	Ft. Worth, Tx	2	1/29/88	2/4/88	II
#4	Houston, Tx	12	6/23/88	6/30/88	I
#5	Houston, Tx	12	6/24/88	7/1/88	I
#6	El Paso, Tx	24	7/22/88	7/29/88	V

Fig 3.2. Mechanical texturing of pavement in the field.

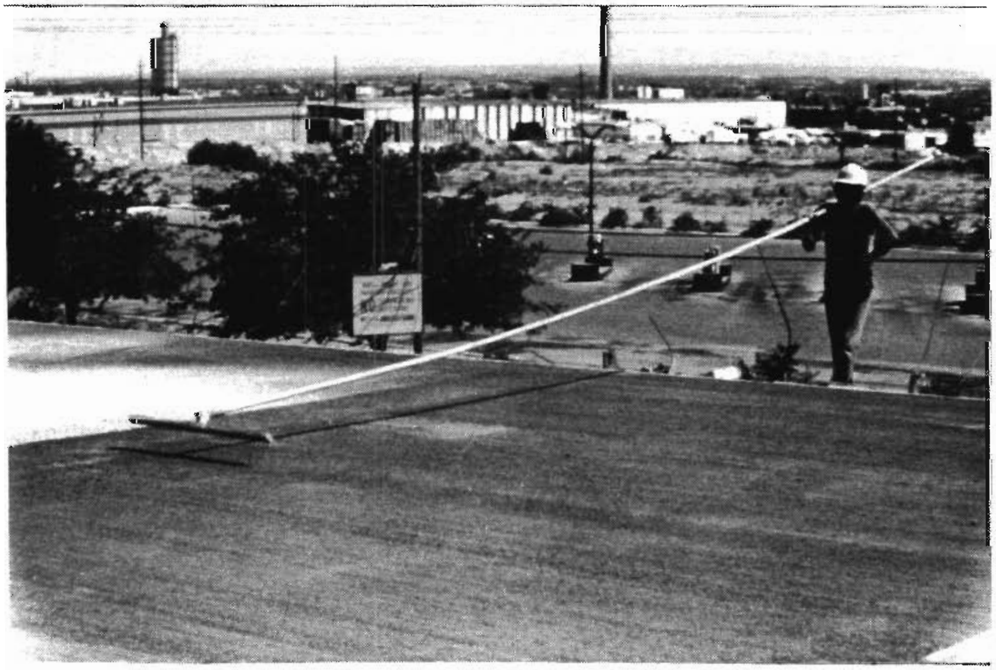

Fig 3.3. Manual texturing of pavement surface (IH10, El Paso, Texas).

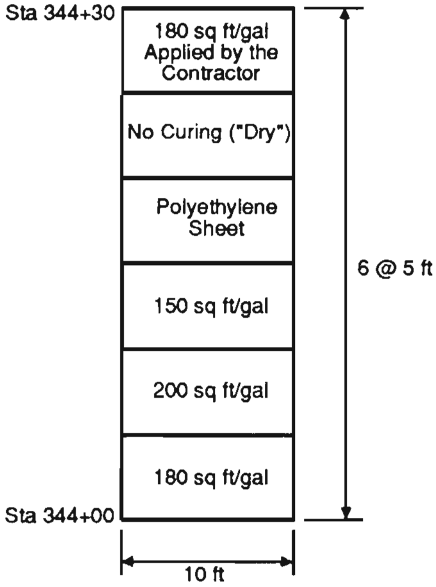

Fig 3.4. Section indicating the types of curing applied to different panels (IH-45, Houston, Texas).

field the concrete was tested for slump, air content, and temperature at the time of placing.

Splitting Tensile Test

The splitting tensile strength test was performed on 6-inch x 12-inch cylinders cast in the field, and on 2-inch slices cut at different depths from 4-inch cores extracted from each panel. The latter test was performed to investigate the effect, if any, of the depth from the cured surface on the splitting tensile strength of the specimens. A schematic of a typical core and the slices cut from it is shown in Fig 3.7.

The experimental procedure conforms with the ASTM Standard Test Method C496-85[10] for the 6-inch x 12-inch cylinders. The procedure departs from the standard for the 4-inch x 2-inch specimens insofar as the diameter-to-length ratio is 2 instead of the prescribed 1/2. The thickness of 2 inches for these specimens was selected as a compromise: it had to be reasonably greater than the nominal aggregate size used in the field (1 to 1.5 inches), but it also had to be small enough to represent the material present at various depths in the pavement slab. This thickness selection may be further justified by the fact that several authors have proposed that the loss of moisture from the surface of the concrete does not extend to a depth beyond 1.0 to 1.5 inches[11]. A number of slices from the bottom of some cores had to be discarded before testing because the concrete was severely honeycombed, possibly due to under-vibration. Figure 3.8 shows a typical 6-inch x 12-inch cylinder being tested, and Fig 3.9 shows a fracture plane of such a specimen.

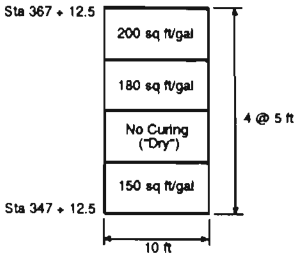

Fig 3.5. Repeat section for the one described in the previous figure (IH-45, Houston, Texas).

Flexure Test

The beam flexure test was performed on 6-inch x 21-inch beams cast and cured in the field and tested according to Test Method Tex-420-A[12]. Figures 3.10 and 3.11 show a

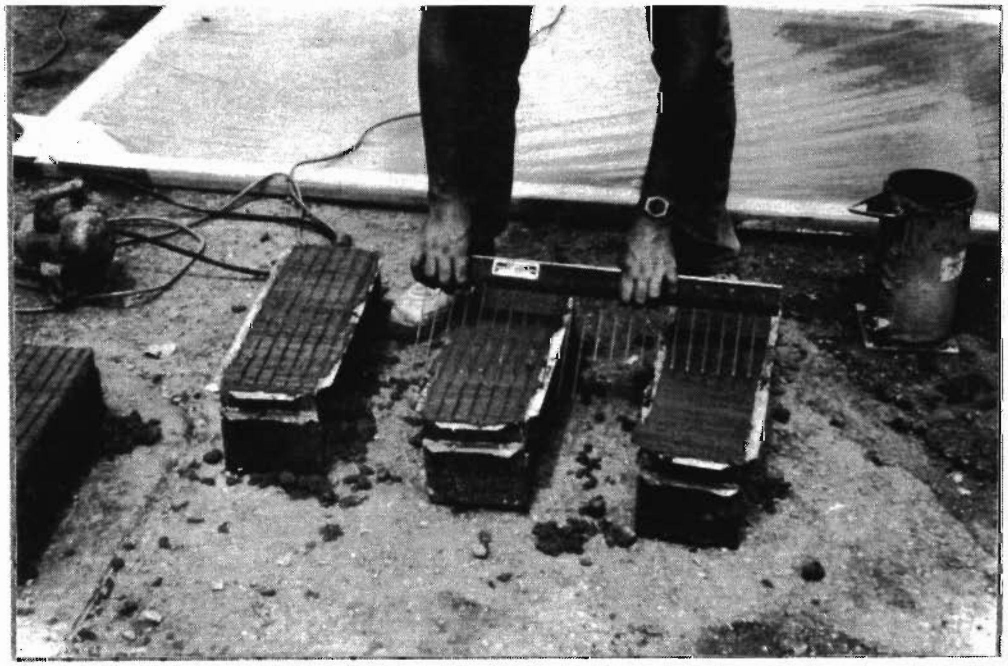

Fig 3.6. Texturing of beam specimens in the field.

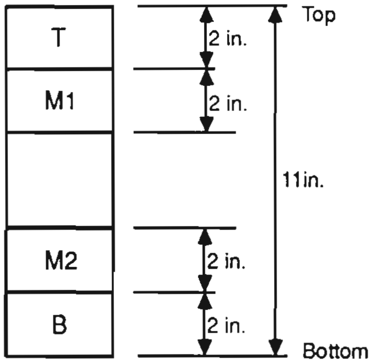

Fig 3.7. Schematic of an 11-inch core showing 2-inch "slices" at various depths.

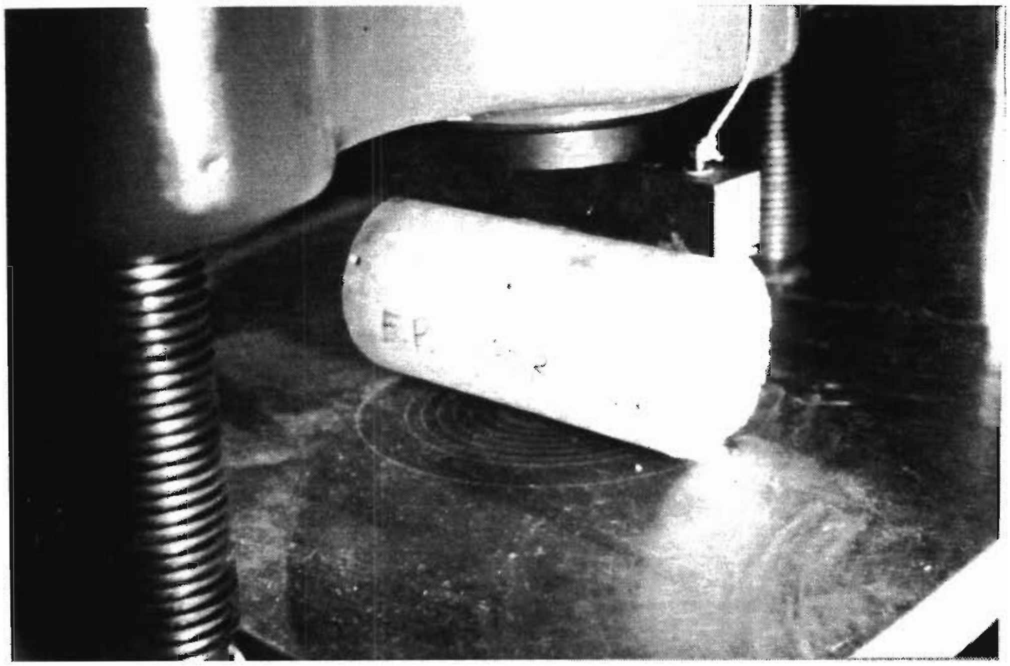

Fig 3.8. Typical 6 x 12-inch cylinder being subjected to the Splitting Tensile Strength Test.

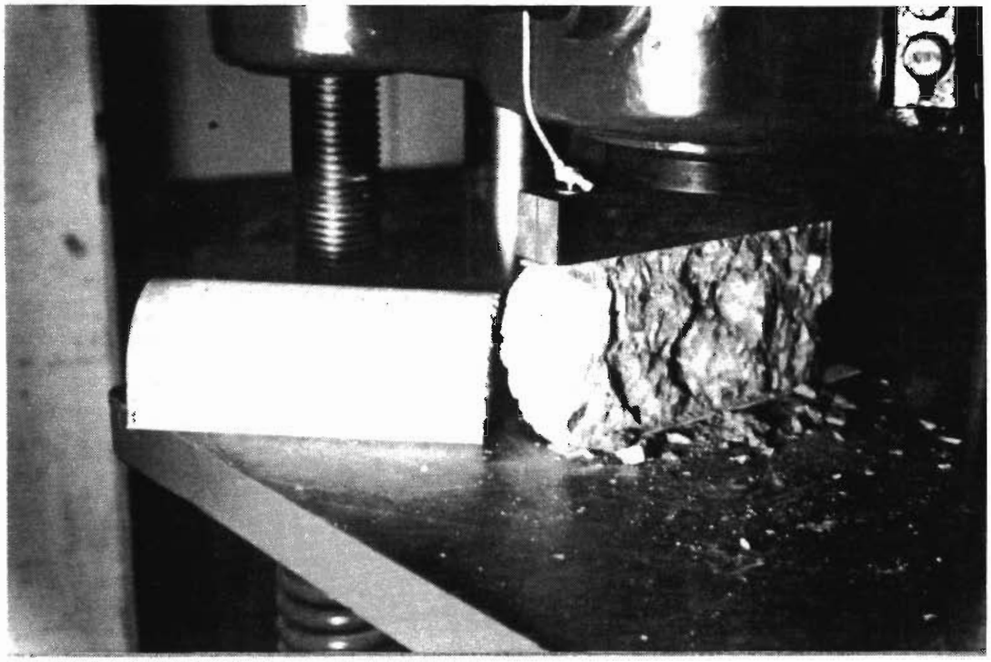

Fig 3.9. Typical fracture plane of a specimen tested as shown in the previous figure.

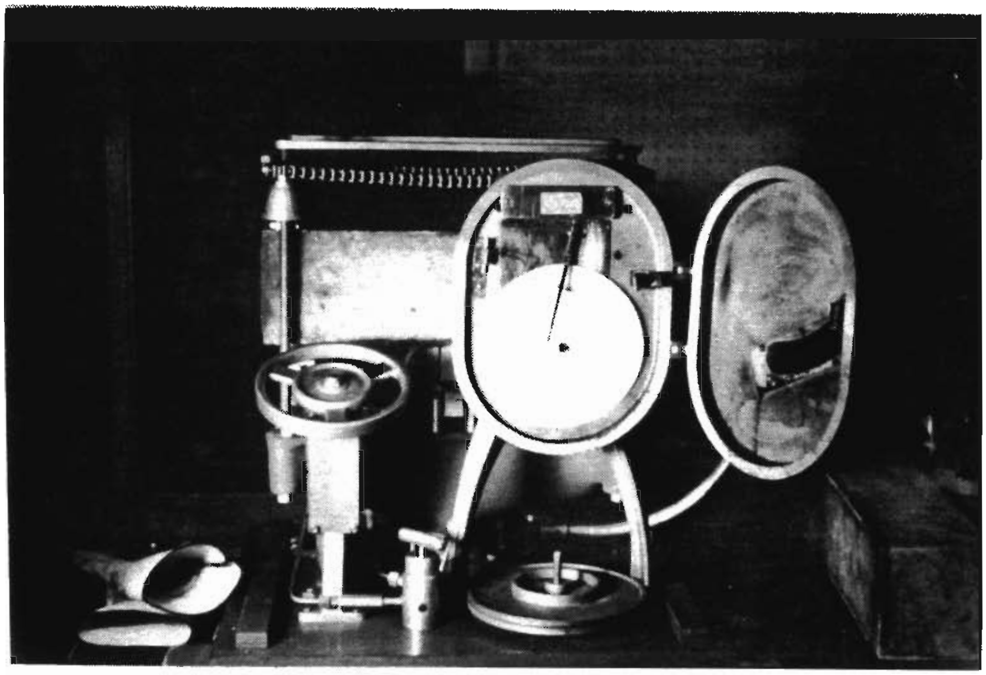

Fig 3.10. Typical flexure beam being tested in the Reinhard Beam Tester.

typical beam being tested, and a fracture plane of such a specimen.

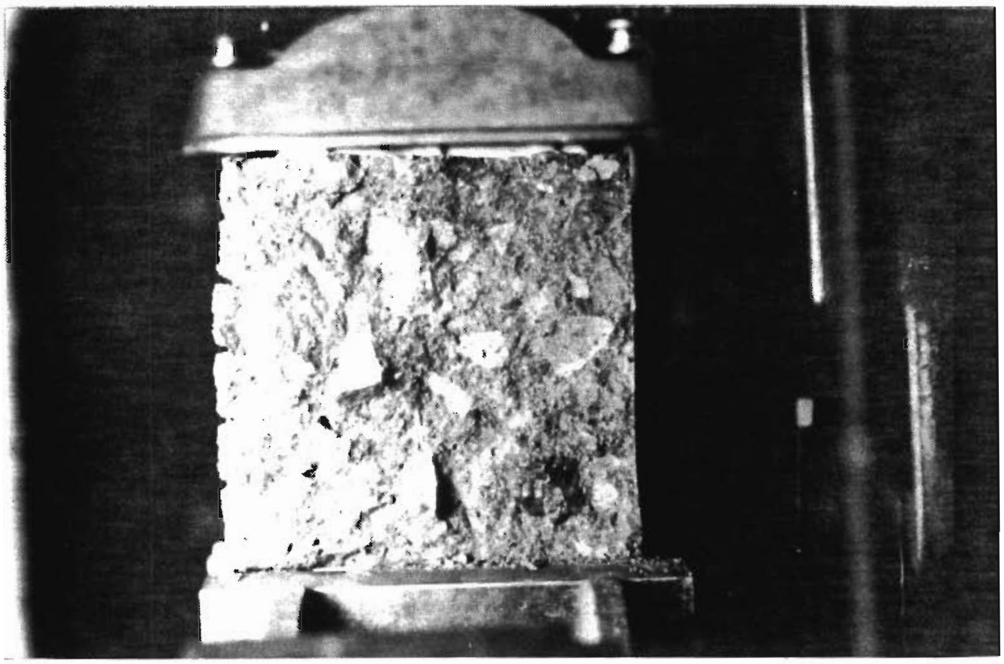

Fig 3.11. Typical fracture plane of a specimen tested as shown in the previous figure.

Surface Durability Test

The testing procedure used to determine the variation in surface durability, between differently cured specimens, is based on the ASTM Standard Test Method C418-81[13]. In the standard ASTM method, the specimen surface is initially assumed flat and the volume of the abraded cavities is measured using a oil-based clay. Because the initial surface in this experiment was textured, the use of clay was not considered practical. Instead, the specimens were weighed before and after the test to determine the weight loss caused by the sandblasting.

The specimens used were 4-inch cores obtained in the field similar to the ones used for the splitting tensile test. The top surface of each core was sandblasted at eight different locations. Figure 3.12 shows the apparatus used in the test.

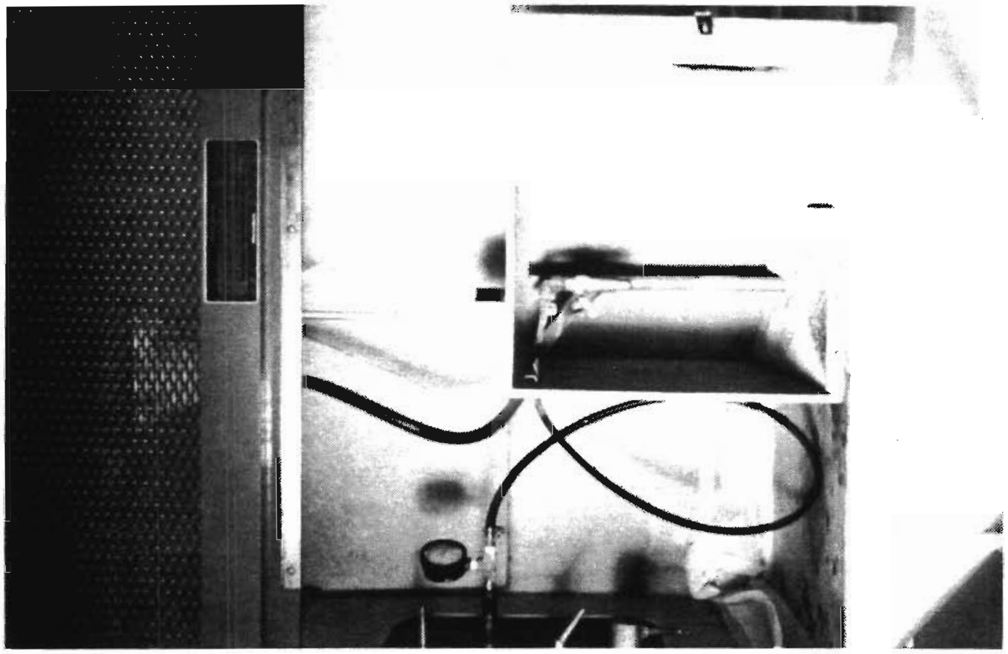

Fig 3.12. The sandblasting cabinet used for the Sandblasting Abrasion Test.

Core Density Test

A concrete density test was performed on 2-inch slices taken from the top and the bottom of cores obtained from test panels in the field to determine if various curing methods have any effect on the density of the pavement material. The test was performed according to the ASTM Standard Test Method C642-82[14].

Spectral Analysis of Surface Waves (SASW)

The SASW method is a non-destructive, seismic test procedure primarily used in the field of soil mechanics for in-situ measurements of soil characteristics such as constrained and shear moduli and layer depth. In the study of pavements it has also found uses in the determination of structural integrity and stiffness profiling.

Its application in fresh concrete has been rather limited. One of the general objectives of the present study is to determine if the advantage of non-destructiveness offered by SASW can be utilized for testing concrete at its early stages when such a requirement is absolute. Since most other concrete testing procedures are either destructive or can only be performed on hardened concrete, the advantage of using SASW is obvious. Additional SASW advantages stem from the fact that all testing is performed in-situ and essentially instantaneous. Therefore, the material tested is not only of considerably larger volume than that of laboratory specimens – and thus is more representative – but it is also the actual material that will be required to perform during the lifetime of the pavement.

Finally, there is an additional advantage to SASW, as compared to traditional testing methods, which is especially useful in the case of concrete. This is the fact that SASW allows the researcher to trace the change of material properties during the curing period on an almost continuous basis by taking measurements at close time intervals beginning shortly after placing. A particular objective of this study was to utilize SASW as an alternate method in evaluating the effect of the application rate of membrane curing compounds (MCCs) on the modulus of elasticity, and therefore the strength, of freshly placed concrete. It was envisioned that the SASW would not only measure such properties at a given time, but also measure their rate of change in time, and compare the different rates of change resulting from different MCC application rates.

The general principle in all seismic test methods is that the response of a body of material to induced stress waves can yield useful information about its properties. An explanation of the theoretical basis of seismic testing in general, and SASW in particular, is quite involved and is beyond the scope of this report. An excellent discussion with some emphasis on concrete applications is a report on several factors affecting SASW and is found in Reference 15.

SASW testing was performed at the test site in District 24. Measurements were taken during a period of six days, on five panels, each cured differently.

Figures 3.13 and 3.14 show close-up views of the instruments used. Figures 3.15 and 3.16 show the arrangement of all sources and receivers in a test section. All signals from these instruments were transmitted to a Dynamic Signal Analyzer that performed a partial analysis of the data on-site as it was being received. The data was then saved on floppy disks for further analysis.

P-Wave Test

In addition to the SASW test, the P-wave test was performed on all panels discussed in the preceding section and also on cores taken from each of those panels.

The difference between the SASW and the P-wave tests is that the former uses Rayleigh surface waves while the latter uses compressive body waves in the tested material. The objective of the P-wave test is to measure the time interval required for a compressive wave to travel the distance between the wave source and the receiver. This, in turn, allows for the calculation of material properties such as Young's modulus. The formula used is:

$$E = \rho v_p^2 [(1+\mu)(1-2\mu)] / (1-\mu)$$

These are based on small strains and represent initial tangent modulus.

where

E = modulus of elasticity,
ρ = mass density,
v_p = compression wave velocity, and
μ = Poisson's ratio (0.25).

Figure 3.17 shows the configuration for the P-wave test performed on cores.

Modulus of Elasticity Test

Six cores from the test site in District 24 where the SASW testing was performed were also tested to measure their modulus of elasticity for comparison purposes with the values derived from SASW. The cores were tested according to the ASTM Standard Test Method C469-83[16].

The dimensions of the cores were 3.7 inches x 7.5 inches. After testing for the modulus of elasticity the cores were tested in compression according to the ASTM Standard Test Method C39-86[17].

LABORATORY TESTING

A limited amount of testing was conducted during the laboratory phase of the project to complement the field phase. For every batch of concrete mixed in the laboratory the following tests were performed: Slump (ASTM C143-78[18]), air content (ASTM C231-82[19]), and unit weight (ASTM C29-78[20]). In addition, the concrete temperature was measured at the time of placing. The beams and cylinders were prepared according to Tex-420-A[21], and ASTM C496-85[22], respectively. The curing was performed as described at the beginning of this chapter.

Splitting Tensile Test

The splitting tensile test was used to investigate the effect, if any, of different curing methods on the indirect tensile strength of 6 x 12-inch cylindrical specimens.

The test was performed according to the ASTM Standard Test Method C496-85[23].

Flexure Test

The beam flexure test was performed to investigate the effect, if any, of different curing methods on the flexural strength of 6 x 21-inch concrete beams. The test specification followed was TEX-420-A[24].

Spectral Analysis of Surface Waves (SASW)

The feasibility of applying the SASW method to fresh concrete was tested in the laboratory before it was applied in the field. For testing a concrete beam was made, measuring 12 feet x 11 inches x 4 inches Two sources and three receivers were placed as shown in Fig 3.18. Measurements were taken in the interval between 2 and 13 hours after the concrete was mixed.

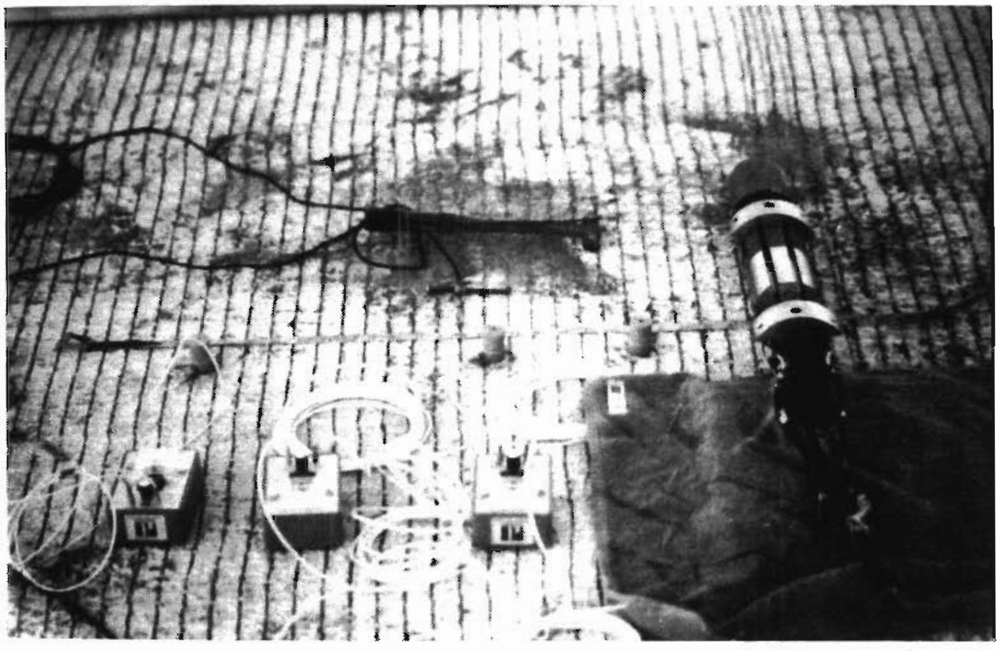

Fig 3.13. Close-up view of the source and receivers used in the SASW test.

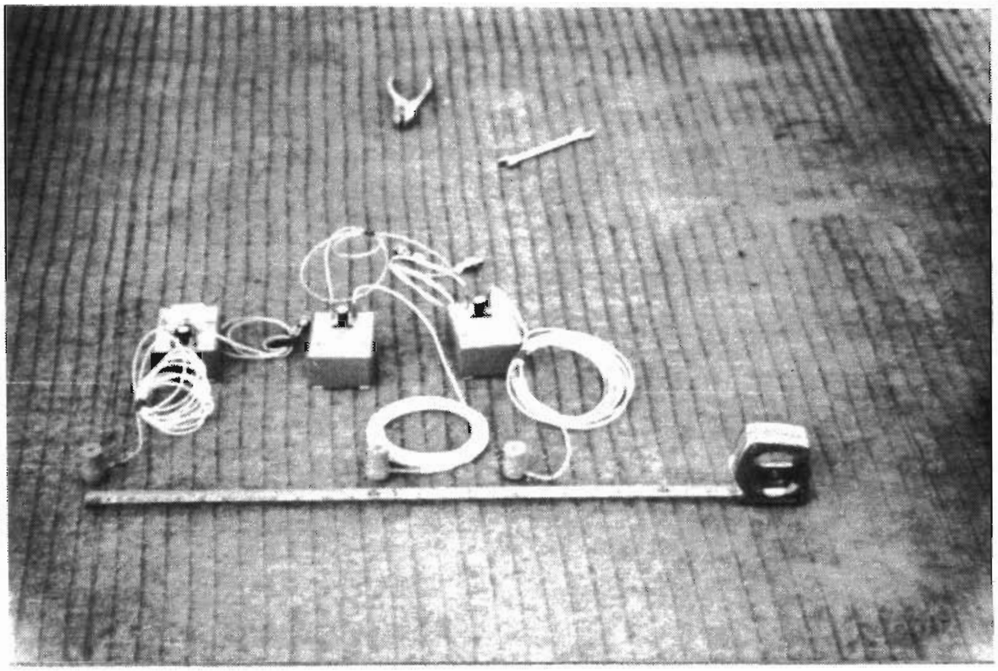

Fig 3.14. Close-up view of the receivers used in the SASW test. The spacing between the first and the second receivers from the left is one foot, and the spacing between the second and the third receivers is 0.5 foot.

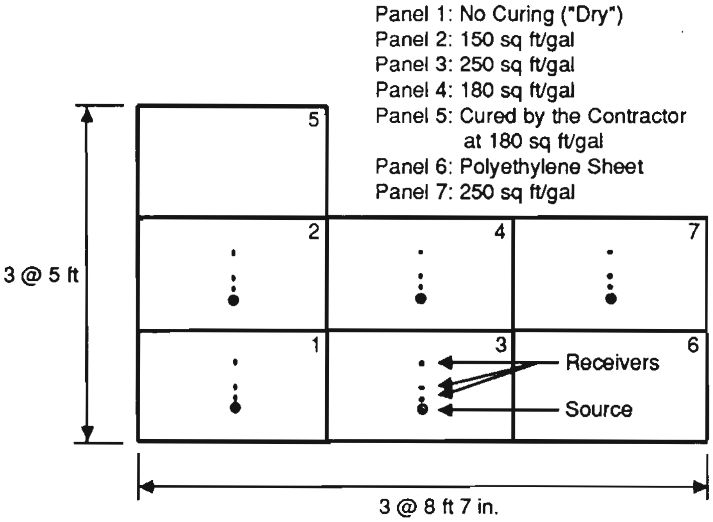

Fig 3.15. SASW panel configuration. Only panels 1, 2, 3, 4, and 7 were tested (IH-10, El Paso, Texas).

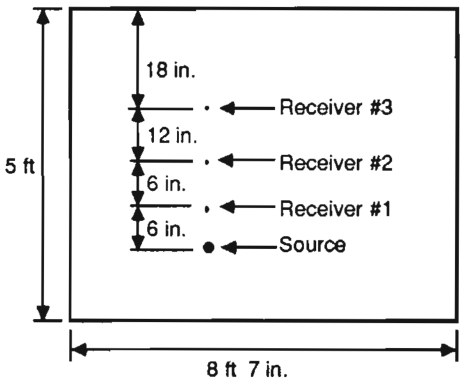

Fig 3.16. Detail of a SASW test panel showing the source-receiver configuration. The slab has a thickness of 11 inches (IH-10, El Paso, Texas).

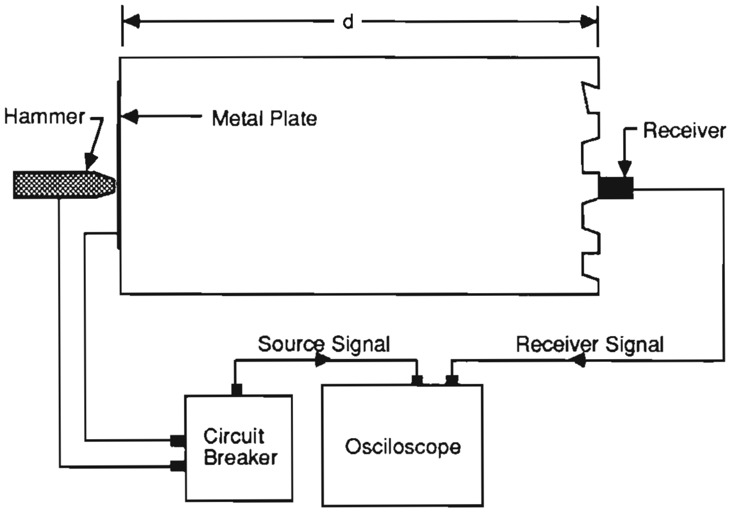

Fig 3.17. Configuration for a P-Wave test on a core. Drawing not to scale.

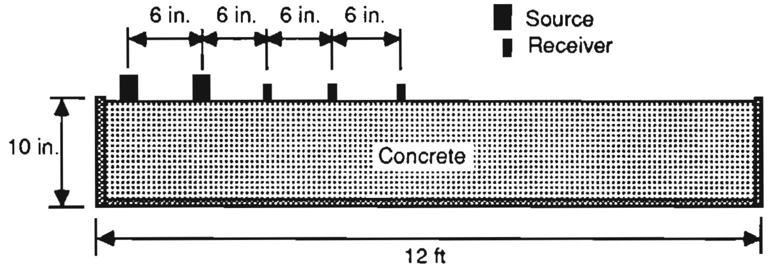

Fig 3.18. SASW experimental setup on a 12-foot beam showing source and receiver spacing. The beam has a width of four inches. (Drawing not to scale.)

CHAPTER 4. EXPERIMENTAL DESIGN

FORMULATION OF THE EXPERIMENT

This chapter describes the field experiment that was conducted in order to investigate the effect of various methods of curing of concrete pavements on concrete strength and durability.

When designing an experiment it is imperative to recognize first those factors that may influence the variable under investigation. This variable is called the dependent variable where as the other factors are called the independent variables. In the particular experiment the following variables have been identified.

dependent variables: concrete strength
- flexural strength
- indirect tensile strength
- compressive strength

concrete durability

independent variables: method of curing
contractor
concrete mix design
humidity
ambient temperature
depth at which strength is obtained

The next step is to set the limits within which the results will apply. These limits are called the inference space. It is preferable the results of this experimentation to apply to all contractors and concrete strengths and at any climatic conditions. In this case the experiment should be conducted in a way to include a sufficiently large random sample of contractors evenly dispersed within the state so that all climatic regions are represented. The contractor will then become the experimental unit that will be used to receive the application of each of the selected independent variables and be representative of the inference space. In simpler terms, all the combinations of variables will be repeated for each contractor, and thus the whole experiment will be repeated for each contractor.

Next, a final selection of the variables and their levels is made, taking into consideration the desired inference space, and the limitations imposed by construction practices as well as time and cost limitations. After a careful selection, the following variables were chosen to be included in the study:

(1) contractor
(2) section of pavement for each contractor
(3) method of curing
(4) depth at which the strength is obtained
(5) number of cores
(6) rate of evaporation

These variables will be discussed in detail in subsequent sections.

The final step is the selection of the number of levels for each variable. Levels are the different values within the same variable, e.g., the different methods of curing in the method of curing variable, or the number of contractors in the contractor variable, that are under investigation. The selection of the number of levels is a very important aspect in the design, especially in experiments as large as this one. A slight increase in the number of levels may add a considerable amount of effort in running the experiment without gaining much more information from the additional data. The statistical modeling can be used to optimize the levels that will provide the desirable information at the least effort and cost. This may be demonstrated by the example. If each of the six factors is assumed to have two levels, the total number of combinations becomes $2^6 = 64$. This means that a total of 64 cores are needed to conduct the experiment. If the decision is made to obtain three cores instead of two, then the total number of cores needed becomes $2^5 \times 3 = 96$ or 33 percent more. The same principle applies to the number of contractors needed. Contractors are, like cores, a random variable meaning that it can have unlimited number of levels, as compared to the method of curing which is a fixed variable. In most cases the selection of the number of levels for the random variables depends on the type of experiment (factorial, nested, etc.) which governs the tests for significance (called F_{test}*) of the main factors and interactions. The number of levels are selected so that the variance of the error term which is the denominator in the F_{test} has at least 4 to 5 degrees of freedom. At this level of degrees of freedom the F_{value} obtained from the F distribution table becomes low enough to detect statistical differences among the tested factors. At higher degrees of freedom the F_{value} gets even lower but the difference does not justify the expense of getting more levels for each factor. Based on the above, it was decided to select a total of six contractors with the reservation to evaluate and possibly adjust this number as data was collected.

CLASSIFICATION OF VARIABLES

This section describes in detail the selected variables and their levels used in the experiment.

Field Testing

Contractor (CONTR). This is a broad variable which necessarily includes several aspects of pavement construction that are difficult to treat separately. These aspects include:

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* F_{test} = MS types/MS error
MS = mean square = sum of square deviations around the mean/df
df = degrees of freedom
F_{value} = the critical value of F for a certain probability level and df.

(1) ***The Inherent Variability in Quality Control Between Contractors.*** Some contractors are more experienced or motivated than others and therefore are able to avoid problems such as applying MCCs too late or too early, failing to mix MCCs continuously during the spraying operation, etc. These poor construction practices are difficult to detect and at times are left uncorrected. It is therefore difficult to estimate the amount of damage they may cause to the overall pavement quality.

(2) ***Mix Designs.*** The size and kind of aggregate used, the type of cement, and the quality control at the batching plant are factors that are independent from the curing practices and at the same time of great importance to the quality of the final product.

(3) ***Methods of Construction.*** Three methods of construction were encountered during the field phase of this project: one-layered and two-layered slip-forming and manually placed concrete.

The scope of this project does not allow the consideration of all of the above mentioned factors separately. Instead it was decided to "lump" them together and, if the analysis showed the variable *contractor* to be a significant source of variability, to recommend a further, more detailed study. The variable CONTR has six levels, equal to the number of sites were the test was performed.

Section (SECT). On test sites where two sections were tested, the second section contained test slabs which were treated as the corresponding slabs at the first section. The variable SECT has one or two levels depending on the number of sections per site.

Curing Method (RATE). The most obvious and important variable to be considered when evaluating the effectiveness of MCCs is their rate of application. Several rates are suggested in the literature or specified by various agencies throughout the United States: 150, 180, and 200 square feet/gallon.

In order to gain an understanding of the extent of any benefit provided by the MCCs, some concrete panels were allowed to cure without applying any curing treatment at all ("DRY" panels).

An additional curing method which was employed was the use of a polyethylene sheet. ("POLY" panels). This method is occasionally used in pavement construction.

The variable RATE has five levels:

EX, POLY, 150, 180, 200, 250

where

EX is the rate applied by the contractor at an area adjacent to the test section (specified at 180 square feet/gallon),

POLY signifies that the test panel was covered with a polyethylene sheet,

150, 180, 200 and 250 are the application rates, square feet/gallon

Position (POS). As discussed in Chapter 3, the degree to which the curing of the exposed surface affects the full mass of the concrete is not believed to extend beyond 1 to 1.5 inches. This top layer also happens to be the most important part of the pavement in terms of durability. A poorly cured surface results in cracking, which in turn, can lead to a multitude of other problems. It was therefore decided to isolate and test this part of the pavement and to compare the effect of curing on the material near the surface and at other depths.

The variable POS has four levels:

T, M1, M2, B

where

T 2-inch slice off the top of the core

M1 2-inch slice between 2 and 4 inches from the top,

M2 2-inch slice between 2 and 4 inches from the bottom, and

B 2-inch slice off the bottom of the core.

Core (CORE). The variable CORE has one to four levels depending on the number of cores extracted from each slab in each section.

Rate of Evaporation (EVAP). There exist four environmental zones in Texas in all of which concrete pavement construction takes place on a continuous basis. This fact dictates the need to determine the extent to which different environmental conditions affect the performance of MCCs. The environmental parameters that are considered important to the curing of concrete are: ambient temperature, relative humidity, and wind velocity. A fourth parameter closely related to these is the temperature of the concrete. All four parameters can be combined to yield the amount of moisture loss by evaporation from the concrete surface, expressed as the weight of water lost per unit area of the exposed surface per hour. Figure 4.1 shows a chart offered by the Portland Cement Association[25] from which the evaporation rate of a concrete surface can be found by entering the values of the four parameters mentioned above.

While it is not specified, it is assumed that the moisture loss described in the PCA chart occurs from a concrete surface that is allowed to cure without the benefit of any curing treatment. This, of course, was not the case in this study presently, where MCCs or polyethylene sheet covers were used on most panels. Therefore the values estimated from the chart could only be useful as indications of the *potential for moisture loss*, against which the applied curing method must protect.

In addition, the PCA chart does not offer any guidance as to the time frame for which it is applicable. In other words, similar environmental and PCC conditions would not necessarily produce the same evaporation rates from the same slab at different times say, at one hour and at eight hours after placing.

In order to characterize a pavement for its potential to lose moisture through evaporation, it would seem reasonable to use the calculated rate of moisture loss at the time the concrete stops bleeding and consider this as the stage were the evaporation potential is at its highest. This can be justified since the stoichiometric quantity of water required for the hydration process is less than the actual quantity used in the mix design. (It would, therefore be reasonable to assume that the bleed water is unneeded excess and that as long as it covers the concrete surface the hydration process fully takes place regardless of outside climatological conditions.) As soon as the bleed water disappears, any further evaporation loss takes place at the expense of the hydration process while it is still at its early stages and largely incomplete. At a later time, even if conditions favor a higher evaporation rate, the available water for such a process to occur is less since it has already been used in hydration. Therefore, at such a time, any moisture loss by evaporation cannot be as extensive and may not be as critical as that which takes place earlier.

The above hypothesis was used in modeling the behavior of the slabs tested in this study. The rate of moisture loss used was calculated using climatological data that were measured or estimated at the time the bleeding stopped. This was also the time when the MCCs were sprayed onto the surface of the slabs.

There is no indication that there is a theoretical basis for the PCA chart, and some objections have been raised as to its validity for some combinations of environmental conditions[26]; nevertheless it is useful as a "rule of thumb" that allows the substitution of one "resultant" variable (rate of evaporation) for four "component" variables (ambient temperature, relative humidity, wind velocity, and concrete temperature). This greatly reduces the number of variables in the statistical model.

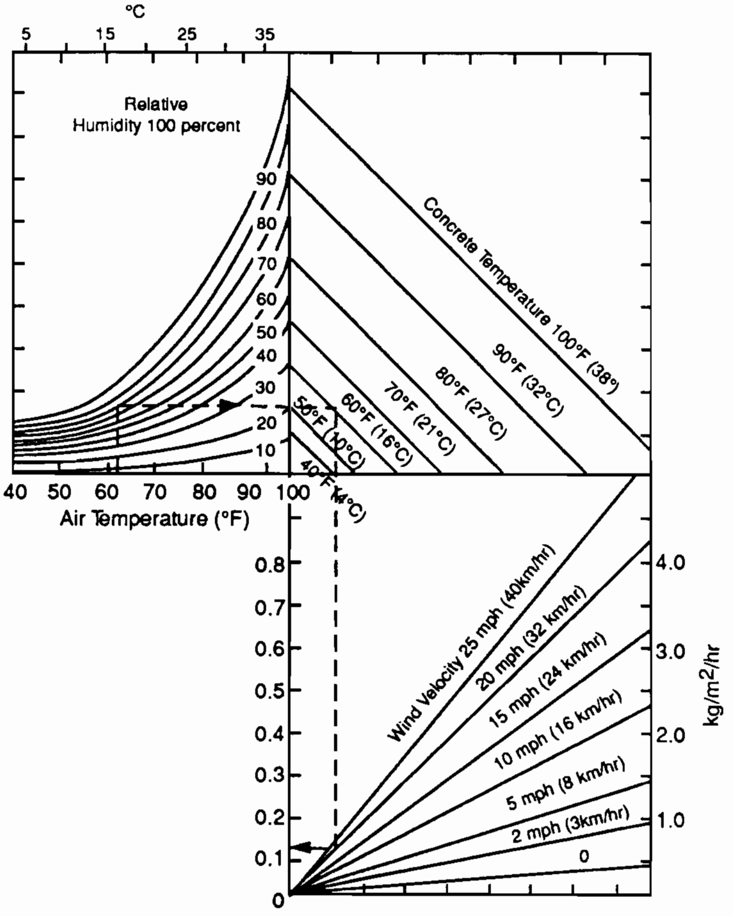

Fig 4.1. The effect of environmental conditions and of the concrete temperature on moisture evaporation from fresh concrete (Ref 25).

Specimen (SPEC). The variable SPEC refers to the 6-inch x 21-inch beams or to the 6-inch x 12-inch cylinders prepared at the test sites. It has one to four levels depending on the number of specimens prepared for each MCC application rate.

Laboratory Testing

Ambient Temperature. This variable represents the temperature ranges in which the beams and cylinders cast in the laboratory were cured. It has two levels:

H and M

where

H is 75 to 100°F, and
M is 55 to 75°F.

PCC Temperature. This variable represents the temperature of the concrete at the time of placing. It has three levels:

H, M, and L

where

H is 75 to 100°F,
M is 55 to 75°F, and
L is less than 55°F.

Ambient Relative Humidity. This variable represents the relative humidity during the curing time of the specimens. It has two levels, H, and M where

H is 70 to 100 percent, and
M is 40 to 70 percent.

Application Rate. Three MCC application rates were used. These were 150, 180, and 200 square feet/gallon. In addition, one specimen from each batch was moist cured to provide a basis for normalizing the data.

STATISTICAL MODELING

The objective of the experiment was to investigate what effect different methods of curing have on concrete strength and durability. In addition, the effectiveness of each curing method as a function of the depth of the concrete in the slab was investigated.

It was intended that the results of the testing to be applicable to all climatic regions of Texas and to all contractors, construction methods, and concrete strengths. This defined the inference space of the experiment and guided the selection of variables and levels that needed to be considered to achieve credible results. An important element in the selection process was randomization. As it was explained in the previous section, contractors are the inferential unit in this experiment. It was, therefore, important to make a selection of contractors that would give each an equal chance of receiving each treatment and confounded variance. Confounded variance is a lumped variance that results from a combination of factors which are not controlled during the experiment. Since these factors are not controlled their variance can not be separated and attributed to them. It is desirable then to run the experiment in a way to allow the uncontrolled factors an equal chance of affecting the results. In this experiment the climatic differences in the four regions in Texas are assumed to have an effect. For this reason the contractors were selected at random in the four environmental zones of the state.

One very important aspect introduced in this experimental model is blocking. Blocks are experimental units that contain a complete set of treatment combinations. As a result there is only one restriction on randomization because the treatments in each block are carried out separately within each block. In this experiment contractors are the blocks. All treatment combinations (SECT, RATE, CORE) are carried out for each contractor and the whole experimental procedure is performed before proceeding with an other contractor. The contractors then, which are random repeats, become the inferential units. Inferential units are random elements that provide the basis for inference and, in general, are not of interest per se. In other words, when blocks are truly random one is not interested in differences among them and interactions of blocks with the treatments within the blocks should not be significant. What is of interest is the main factors such as RATE or POS, or their interactions. When interactions of blocks with treatments are significant then there is high probability that something was fixed during the experiment and that contractors (blocks) were not random repeats. If, for example, the CONTR * POS interaction is significant then there is high certainty that the combination of these two variables did not affect in the same way the strength of concrete in the various contractors. What might have happened is that one contractor might have under-vibrated the pavement at the bottom and this resulted in lower bottom strength. The above discussion shows the importance of blocking in an experiment in that it can detect peculiarities in the way the experiment was really performed and alert for violation in the assumptions used. Significant block-treatment interactions can be detected by comparing their mean squares. If these interactions are indeed significant then their mean squares are statistically different.

A second and most important feature of blocking is that it can remove a large variance from the error term and thus facilitate easier detection of treatment differences between important factors such as RATE and POS. If a block design experiment is analyzed like a completely randomized design then the portion of the variance that could have been attributed to blocks would go into the error term with the result of increasing the error variance. The net effect would then be a more difficult detection of treatment differences. If, on the other hand, blocking does not remove any variance from the error, then pooling of variances can be performed resulting in an error term without any blocking effects. This shows that blocking is always helpful because it can result in easier rejections and that it is never harmful because variances can be pooled back to the error term if required.

For every contractor except #6, two random repeats of the experiment were performed. That is, five to seven methods of curing were repeated at two pavement segments.called sections. The experiment was designed to eliminate the possibility of losing the blocking effects if the contractors were found to be fixed treatments. This would mean that some unique factors are confounded within the variable CONTR such as those described in the beginning of this chapter. That could cause an inflated error term and could minimize the chance for detecting treatment differences. If CONTR were found to be fixed the inferential units tests of significance would have to be the sections; the sections are true random blocks since they do not involve fixed variations but are only repeats of the concrete mix design and construction practices of the same contractor.

The experiment was designed as a nested factorial with blocking. The treatments and levels used are described in the following table:

Variable	**Treatment**	**Designation**	**No. of Levels**	**Designation**
Random	Contractor	CONTR	6	N1 - N6
Random	Contractor Replication	SECT	2	S1,S2
Fixed	Curing Method	RATE	7	150,180,200 POLY, EX, DRY
Random	Test Core	CORE	1 - 4	1 - 4
Fixed	Vertical Position of Core Slice	POS	4	T, M1, M2, B

In a nested factorial experiment all the levels of a factor that is nested in another factor are different across the level of the other factor. In such an experiment, in addition to a nested factor, a factor or factors may have the same levels across other factors and be factorial to these factors as well. In this experiment the contractor replication, (SECT), is nested within contractor, (CONTR), because all sections are different. On the other hand, the application method, (RATE), is the same across all the levels of CONTR and SECT and is therefore factorial to these factors. Likewise, cores, (CORE), are nested in contractor - contractor replica-

			CONTR										
			1		2		3		4		5		6
			SECT		SECT		SECT		SECT		SECT		SECT
			1	2	3	4	5	6	7	8	9	10	11
RATE	CORE	POS											
EX	1	T											
		M1											
		M2											
		B											
	2	T											
		M1											
		M2											
		B											
POLY	1	T											
		M1											
		M2											
		B											
		T											
	2	M1											
		M2											
		B											
		T											

Fig 4.2. Schematic of a nested factorial experiment.

tion - application method, (CONTR - SEC - RATE). Finally, position, (POS), is factorial to contractor - contractor replication - application method - core, (CONTR - SECT - RATE - CORE). The set-up of an experiment such as the one discussed but with only two curing method levels is shown schematically in Fig 4.2. Note the sequential numbering of SECT and CORE levels to represent the nesting, and the repeated numbering of POS levels to show their factorial nature.

The experimental model can be written as a linear model in the form of an equation that predicts the response variable strength (STRG) as a function of the main variables, nested factors, and interactions. This equation is of the form

$$\begin{aligned}\mathrm{STRG}_{ijklmn} = {} & \mu + \mathrm{CONTR}_i + \mathrm{SECT}_{(i)j} + \delta_{(ij)} + \mathrm{RATE}_k + \\ & \mathrm{CONTR{*}RATE}_{ik} + \mathrm{SECT{*}RATE}_{(i)jk} + \\ & \mathrm{CORE}_{(ijk)l} + \omega_{(ijkl)} + \mathrm{POS}_m + \\ & \mathrm{CONTR{*}POS}_{im} + \mathrm{SECT{*}POS}_{(i)jm} + \\ & \mathrm{RATE{*}POS}_{km} + \\ & \mathrm{CONTR{*}RATE{*}POS}_{ikm} + \\ & \mathrm{SECT{*}RATE{*}POS}_{(i)jkm} + \\ & \mathrm{CORE{*}POS}_{(ijk)lm} + \varepsilon_{(ijklm)n}\end{aligned}$$

where

STRG_{ijklmn} = strength of a specimen n obtained from contractor i, section j, treated with curing method k, occupying position m in core l;

μ = overall mean;

CONTR_i = effect of the contractor i;

$\mathrm{SECT}_{(i)j}$ = effect of contractor replication j nested within contractor i;

$\delta_{(ij)}$ = randomization restriction error on contractor replications;

RATE_k = effect of the curing method k;

$\mathrm{CONTR{*}RATE}_{ik}$ = effect of the interaction of contractor i with curing method k;

$\mathrm{SECT{*}RATE}_{(i)jk}$ = effect of the interaction of contrator replication j with curing method k nested within contractor i;

$\mathrm{CORE}_{(ijk)l}$ = effect of core l nested within contractor i, section j, and curing method k;

$\omega_{(ijkl)}$ = randomization restriction error on cores;

POS_m = effect of position m;

$CONTR*POS_{im}$ = effect of interaction of position m with contractor i;

$SECT*POS_{(i)jm}$ = effect of interaction of position m with section j, nested within contractor i;

$RATE*POS_{km}$ = effect of interaction of position m with curing method k;

$CONTR*RATE*POS_{ikm}$ = effect of interaction of position m with curing method k, and contractor i;

$SECT*RATE*POS_{(i)jkm}$ = effect of interaction of position m with curing method k and section j, nested within contractor i;

$CORE*POS_{(ijk)lm}$ = effect of interaction of position m with core l, nested within curing method k, section j, and contractor i; and

$\varepsilon_{(ijklm)n}$ = random error of the nth specimen of contractor, section j, curing method k, core l, and position m.

Contractors were selected at random in different environmental regions in Texas in order to broaden the inference space of the experiment so that the results would be applicable to any contractor at any environment. The variable CONTR includes a known variance partly resulting from the different contractors examined in the study and a confounded variance that may be a result of different concrete mix designs at the contractor level or other factors as discussed at the beginning of this chapter. Therefore it should be emphasized that inferences on this variable should be made cautiously in light of the fact that a wide variety of unmeasured effects are built into the variable.

The error $d_{(ij)}$ is the first restriction error on randomization which recognizes the peculiarity that randomization occurs over each section separately as soon as a section is considered and not over the whole experiment as would the case be in a completely randomized design. This restriction prevents any inference to be made on the variable SECT which is not of interest by itself. A second restriction on randomization, $w_{(ijkl)}$, occurs within each core because testing of each core took place after it was obtained and not over the whole experiment. This prevents any inference to be made on the variable CORE, but again, this variable is not of any interest in the evaluation of MCC treatments and therefore no information is lost. These two restrictions were not placed by design but were a physical result of the way the experiment was performed. However, the limitations they pose should be recognized as part of the analysis.

The algorithm of the expected mean square errors (EMS) for each source of variation is shown in Table 4.1. For a fixed component of variance the F notation is used, and for a random component the notation s^2 is used. The arrows show the tests for significance (F-test) for each source of variance. The CONTR mean square is the main inferential unit and is used to make all the important tests which are RATE, POS, and RATE*POS. The SECT variable is used as a "secondary" inferential unit and makes all the tests of the interactions between CONTR and the important factors: CONTR*RATE, CONTR*POS, and CONTR*RATE*POS.

It is interesting to note that CORE mean square makes the less important tests: SECT*RATE, SECT*RATE*POS. This means that it is not necessary to obtain a large number of cores for each treatment combination of CONTR, SECT, and RATE. In fact, since each treatment combination involves at least 6 contractors x 2 sections x 6 curing methods = 72 cores, it is not necessary to obtain more than one core per treatment combination. An examination of the F-distribution table shows that at a level of 0.05 and for six degrees of freedom for the treatment under consideration the $F_{5,72}$ value needed to reject equality is 2.36. The corresponding $F_{5,144}$ value for the case of two cores per treatment combination is 2.28. This suggests that the added expense of obtaining the additional specimens is not justifiable by a reduction of only 0.08 in the F-value. For this reason it was decided, after a preliminary analysis such as the one discussed above, to limit the number of cores per treatment combination from the three or four that were being taken from sites #1, #2, and #3 to only one from the remaining sites.

The maximum number of specimens obtainable if only one core were taken per treatment combination would equal 336. In actuality, the total number of specimens obtained was somewhat less because some of the specimens had to be discarded because they were severely honeycombed or damaged during transportation.

The importance of an experimental design that blends the engineering needs and limitations with the mathematical aspects of statistics can not be overemphasized. The statistical considerations become increasingly important in experiments with many factors and with construction sequences that impose restrictions to the models and derive the methods for analyzing the data. The experiment designed for this study has provided guidance for the practical and systematic application of the theory in the field. It has helped with selecting the optimum number of levels of contractors and cores for the random factors that would provide reliable information at a reasonable cost. It has helped with detecting errors introduced into the model that violate the initial assumptions.

TABLE 4.1. DERIVATION OF THE EXPECTED MEAN SQUARE (EMS) ALGORITHM

	Fixity							
	R	R	F	R	F	R		
DF	i	j	k	l	m	n	Source	Expected Mean Squares
2	1	2	5	2	2	1	$CONTR_i$	$\sigma^2 + 2\sigma^2_{CORE} + 20\sigma^2_{\delta} + 20\sigma^2_{SECT} + 40\sigma^2_{CONTR}$
3	1	1	5	2	2	1	$SECT_{(i)j}$	$\sigma^2 + 2\sigma^2_{CORE} + 20\sigma^2_{\delta} + 20\sigma^2_{SECT}$ ↗
0	1	1	5	2	2	1	$\delta_{(ij)}$	$\sigma^2 + 2\sigma^2_{CORE} + 20\sigma^2_{\delta}$
4	3	2	0	2	2	1	$RATE_k$	$\sigma^2 + 2\sigma^2_{CORE} + 4\sigma^2_{SECT*RATE} + 8\sigma^2_{CONTR*RATE} + 24\Phi_{(RATE)}$
8	1	2	0	2	2	1	$CONTR*RATE_{ik}$	$\sigma^2 + 2\sigma^2_{CORE} + 4\sigma^2_{SECT*RATE} + 8\sigma^2_{CONTR*RATE}$ ↗
12	1	1	0	2	2	1	$SECT*RATE_{(i)jk}$	$\sigma^2 + 2\sigma^2_{CORE} + 4\sigma^2_{SECT*RATE}$ ↗
30	1	1	1	1	2	1	$CORE_{(ijk)l}$	$\sigma^2 + 2\sigma^2_{CORE}$ ↗
0	1	1	1	1	2	1	$\omega_{(ijkl)}$	$\sigma^2 + 2\sigma^2_{CORE}$
1	3	2	5	2	0	1	POS_m	$\sigma^2 + \sigma^2_{CORE*POS} + 10\sigma^2_{SECT*POS} + 20\sigma^2_{CONTR*POS} + 60\Phi_{(RATE)}$
2	1	2	5	2	0	1	$CONTR*POS_{im}$	$\sigma^2 + \sigma^2_{CORE*POS} + 10\sigma^2_{SECT*POS} + 20\sigma^2_{CONTR*POS}$ ↗
3	1	1	5	2	0	1	$SECT*POS_{(i)jm}$	$\sigma^2 + \sigma^2_{CORE*POS} + 10\sigma^2_{SECT*POS}$ ↗
4	3	2	0	2	0	1	$RATE*POS_{km}$	↑ $\sigma^2 + \sigma^2_{CORE*POS} + 2\sigma^2_{SECT*POS} + 4\sigma^2_{CONTR*POS} + 12\Phi_{(RATE)}$
8	1	2	0	2	0	1	$CONTR*RATE*POS_{ikm}$	$\sigma^2 + \sigma^2_{CORE*POS} + 2\sigma^2_{SECT*POS} + 4\sigma^2_{CONTR*POS}$ ↗
12	1	1	0	2	0	1	$SECT*RATE*POS_{(i)jkm}$	$\sigma^2 + \sigma^2_{CORE*POS} + 2\sigma^2_{SECT*POS}$ ↗
30	1	1	1	1	0	1	$CORE*POS_{(ijk)lm}$	$\sigma^2 + \sigma^2_{CORE*POS}$ ↗
0	1	1	1	1	1	1	$\varepsilon_{(ijklm)n}$	σ^2 ↗

CHAPTER 5. EXPERIMENTAL RESULTS

FIELD EXPERIMENT

Splitting Tensile Strength Test (Cores)

The analysis of the data obtained by the splitting tensile strength test on 2-inch slices of cores obtained in the field was done by constructing several statistical models which are variations of the general model described earlier, in Chapter 4. The reason for using more than one model was to take into account some particular characteristics of the data with models that emphasized those characteristics, or to conform with memory limitations of the computer systems used. The data used in the analysis are presented in Tables A.1 to A.5 in Appendix A.

Model 1A. This model is similar to the general model described earlier with the only exception being that one high order term, CORE * POS (RATE SECT CONTR), was excluded because of memory limitations in the computer used for the analysis. It is assumed that no significant amount of information is lost from this exclusion because the interaction is of very high order.

In this model all classes of all variables are used and no attempt is made to transform the data in any way. Finally, the effects of environmental conditions are not taken into account. The model is described in a concise form in Table B.1 in Appendix B.

Model 1B. The motivation for this model was a preliminary analysis of the data that indicated no statistical difference in strength between the top and the bottom positions. This, along with field observations and examinations of retrieved specimens, prompted a concern that possibly lower top concrete strengths were being masked by low bottom concrete strengths that were due to factors other than curing, such as under-vibration or other construction practices. This would lead to the erroneous conclusion that the top and bottom strengths were the same. It was therefore decided to obtain and test two specimens from the middle of each core, a position which intuitively was considered to represent the highest concrete strength. This operation was only performed for contractors four, five, and six. Model 1B represents an analysis that considers only those contractors from which specimens from all four positions were taken.

From a statistical point of view the model is similar to model 1A, the only difference being the number of levels for the variable POS. Table B.2 offers a summary description of this model. This and all subsequent tables presenting the results from the analysis of variance are divided into two parts. The top part of each table shows the variables used in each model, the number of levels in each variable, and the values of each level. The bottom part shows the sources of variation resulting from the variables and their interactions; the degree of freedom for each source of variation; the F_{value} which is obtained by dividing the mean square (variance) of the source in question by the mean square of the appropriate error term; and the probability of making an error (type α) when rejecting the hypothesis that all levels within a particular variable are equal. This probability is compared to an alpha level of 0.10 and significant differences are stated with a "yes."

Model 1C. This model is complementary to model 1B described above, in that it considers only the top and bottom levels of the variable POS over all the contractors. This was done in order to have a more balanced model in terms of treatment combinations than 1A by having an equal number of POS levels over all the contractors. This is the only difference of this model with model 1A. Table B.3 summarizes the model and its results.

Model 1D. Previous discussions have indicated the existence of a number of variables confounded within the variable CONTR, namely construction practices, concrete mix design, etc. All strength data were normalized in respect to the strength of the quality control specimens that are regularly prepared, cured, and tested by the Texas SDHPT at each jobsite. This way it was hoped that any variation introduced by the concrete mix design would be controlled, and that the detection of different strength levels for various curing methods would be easier. In all other respects this model is the same with model 1A. A summary of the model and the results obtained are shown in Table B.4.

Model 1E. In this model, the evaporation variable EVAP is introduced, while retaining the normalized values of the data. This is a second step after model 1D in trying to identify variables that are confounded within CONTR, to explain some of the variation associated with it, and to show more clearly the effects of curing methods and position on strength. Table B.5 summarizes this model.

Models 2A, 2B, and 2C. These models are similar to models 1A, 1B, and 1C respectively, but in these cases the variable CORE is excluded from the analyses and the associated variances are lumped with the error terms. All previous analyses indicated the non-significance of all interactions with CORE at a level of 0.25. This allows for pooling of the respective variances. Here, pooling is useful because it increases the chance of detecting any significance due to the increased number of available degrees of freedom in the error terms which in turn result in lower critical F-values. Figure 5.1 shows the layout of these experimental models. Note the absence of the core variable, as compared to the models shown in Fig 4.2. Tables B.6, B.7, and B.8, contain summary description of models 2A, 2B, and 2C respectively, as well as the statistical results obtained.

Discussion of Results. As indicated in the analysis of variance (Tables B1-B8) none of the models have detected any significant differences in the important variables RATE, POS and their interaction RATE *POS. This means that (1) none of the seven methods of curing evaluated in the experiment has resulted in higher or lower concrete strength; (2)

none of the strength locations (top, middle, or bottom of core) has resulted in higher or lower strength; (3) none of the seven curing methods has indicated any difference in the top, middle, or bottom strengths. The statistical results are also shown in a graphical form in Figs 5.2 to 5.4. The concrete strength data shown were normalized as a percentage of the tensile strength of control specimens. This removed any variation introduced from the different mix designs and made the comparison more meaningful. It is important to note that at this point we are not interested in the level of strength, as this varies with the randomly selected contractors and the design used by each contractor, but in the relative comparison among the methods of curing, position, etc. All figures show in the vertical scale the dependent variable which is the tensile strength and in the horizontal scale the independent variables RATE, POS, and RATE*POS. All graphs are approximately horizontal lines which verify the indifference of strength in the method of curing, the depth at which the strength was obtained, and the combination of the two. The non-significance of the RATE*POS interaction is very clearly shown in Fig 5.3 as the lines are almost parallel and difficult to distinguish.

All models have shown that the variable CONTR is highly significant. This information is not of any interest in this experiment in engineering terms but it is extremely important from a statistical point of view. It shows that the way the experiment was designed (by having contractors as random blocks) has effectively removed a very large amount of variation from other variables making the detection of significant variables much easier. Of course, no significant variables have been found but the detection would be far more difficult if the experiment was modeled otherwise.

The non-significance of RATE, POS and RATE*POS was true for both normalized and unnormalized data, as well as for the case where the evaporation conditions were taken into account. The finding that a heavier curing compound application rate does not imply significantly higher strengths, as would be intuitively expected, should not be considered extraordinary in view of the fact that other authors have reported higher evaporation rates[7] from specimens cured with heavier rates. Somewhat peculiar was the finding that specimens that were left completely uncured ("DRY") had strengths as high as those sprayed with compound. This finding was true even when top core layers were compared with bottom layers which presumably cure under more favorable conditions. This could be the result of some unmeasured factor during the experiment or could very well mean that curing does not really affect concrete strength but some other concrete property. Another possibility could be that curing affects only the strength of a very thin top layer, and that the strength of the 2-inch top layer examined in the test had apparently masked the difference.

	CONTR											
	1						2					
	SECT											
	1			2			3			4		
	RATE			RATE			RATE			RATE		
POS	150	180	200	150	180	200	150	180	200	150	180	200
T												
M1												
M2												
B												

Fig 5.1. Layout of experimental models 2A, 2B, and 2C.

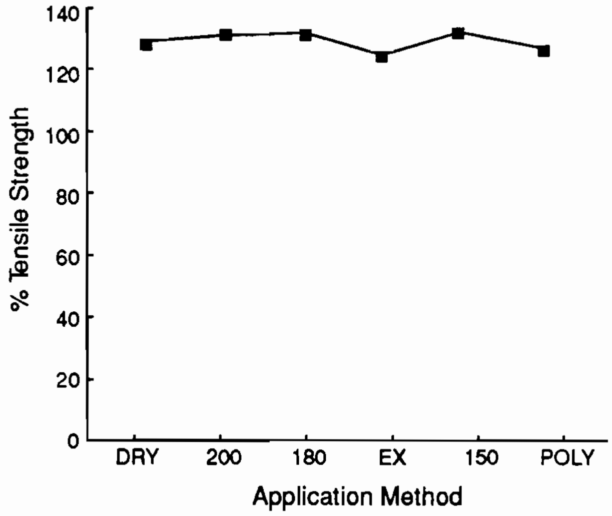

Fig 5.2. Application rate vs. tensile strength normalized as a percentage of the tensile strength of the control specimens. Field cylinders, mean values.

Splitting Tensile Strength Test (Cylinders) and Flexure Test

The results of the splitting tensile strength test and flexure test performed on 6-inch x 12-inch cylinders and 6-inch x 21-inch beams are shown in Tables A.6 and A.7 in Appendix A.

The statistical model used to analyze the data in this experiment is a simplified version of model 1A described earlier with the exception that there are only three classes of variables, namely CONTR, SECT, and RATE. Variable CONTR has six levels, equal to the number of contractors; SECT has two levels, equal to the number of experimental sections at each site; and RATE has four levels: DRY, 150, 180, and 200.

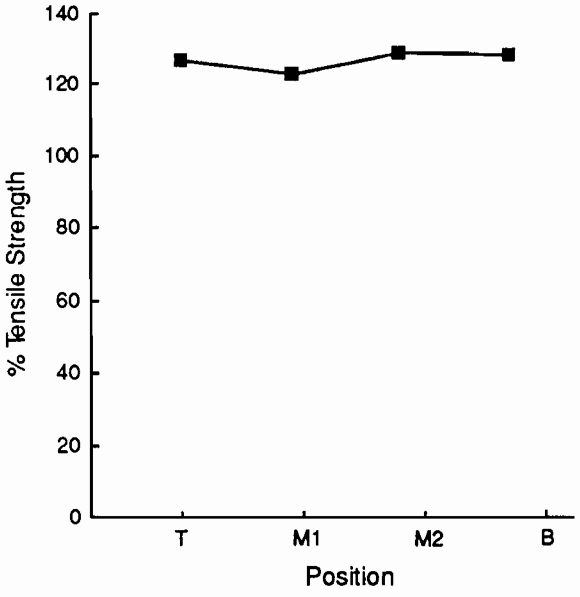

Fig 5.3. Position vs. tensile strength normalized as a percentage of the tensile strength of the control specimens. Field cylinders, mean values.

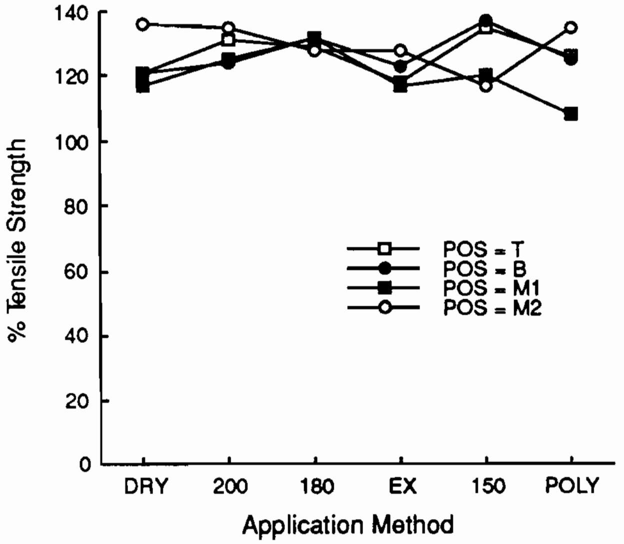

Fig 5.4. Interaction of application rate and position vs. tensile strength normalized as a percentage of the tensile strength of the control specimens. Field cylinders, mean values.

The statistical results of the tests on both cylinders and beams are presented in Tables B.9 to B.12 in Appendix B. Figures 5.5 and 5.6 are plots of the mean normalized tensile and flexural strengths of the tested cylinders and beams respectively.

As can be seen from both the tables and the graphs the results are similar with those obtained from the tensile tests on the cores. First, a change in the MCC application rate does not result in a significant change in either flexural or tensile strength even with normalized data. Second, there is a significant difference in flexural and tensile strength from

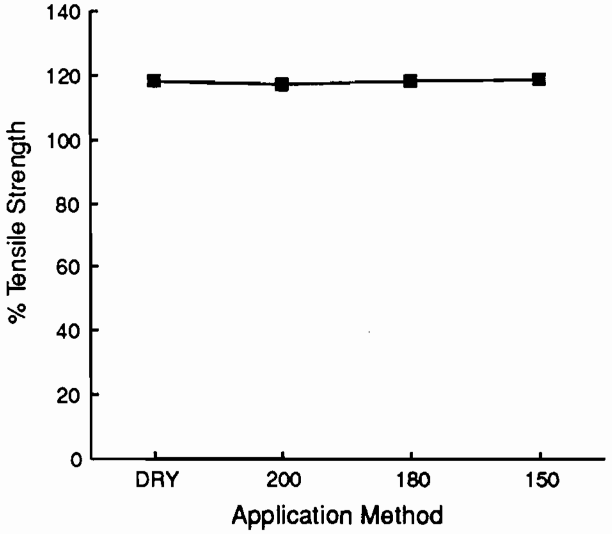

Fig 5.5. Application rate vs. tensile strength normalized as a percentage of the tensile strength of the control specimens. Field beams, mean values.

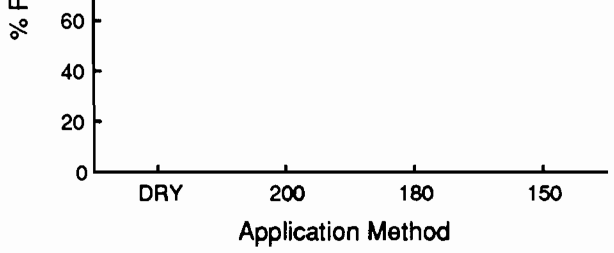

Fig 5.6. Application rate vs. flexural strength normalized as a percentage of the flexural strength of the control specimens. Field beams, mean values.

contractor to contractor. This finding is again of no significant engineering importance as strength varies by mix design, but it points out the importance of the statistical model.

Surface Durability Test

The results of the surface durability test performed on surfaces of cores obtained from sites four, five, and six are shown in Table A.8. They are are also shown in graphical form in Fig 5.7.

The statistical model used for analyzing the results is a simplified version of the nested factorial model used to analyze the results of the splitting tensile test results for the cores, as described earlier. Table B.13 shows that the rate of MCC application does not significantly affect the surface durability as measured by the sandblast test.

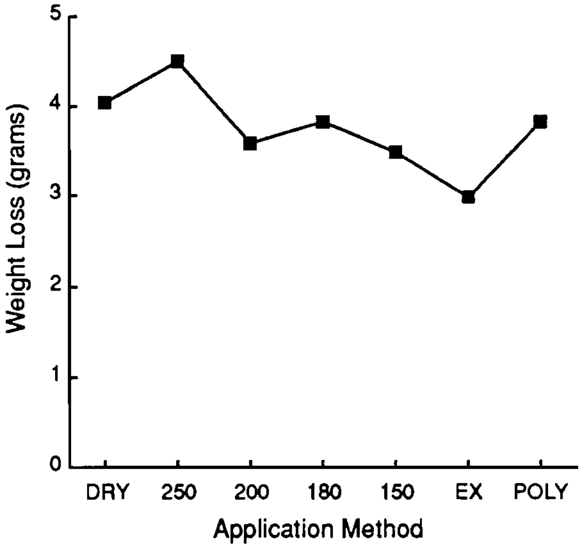

Fig 5.7. Surface durability (weight loss) vs. application method for sites #4, #5, and #6.

Core Density Test

The results of the core density test that was performed on cores obtained at sites one and two are shown in Table A.9.

The statistical model used for the statistical analysis of the data is the same with model 1A which was used for the split tensile test on the core slices and was described previously. As can be seen from Table B.14 and Figs 5.8 and 5.9, concrete density is not significantly affected by either the MCC application rate or by the position of the slice in the core from which it was taken.

Modulus of Elasticity Test and P-Wave Test

The results of the modulus of elasticity test performed on six cores obtained from site number 6 in District 24 are shown individually in Figs 5.10 to 5.15. Figure 5.16 shows all readings together in one graph for comparison purposes. It appears from this graph that the modulus increases with increasing MCC coverage although there was no significant change in performance when this coverage varies between 250 and 180 square feet per gallon.

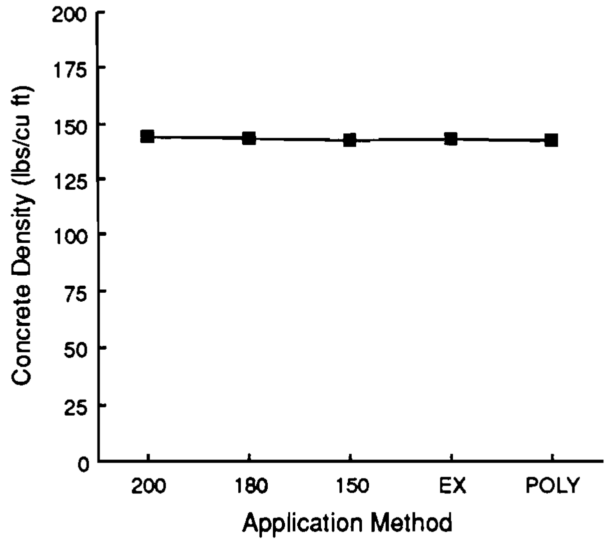

Fig 5.8. Concrete density vs. application method from field cores obtained from sites #1 and #2.

The six cores tested by the traditional ASTM method were also tested by the P-wave method to measure the modulus of elasticity as well. The results of this test are shown in Fig 5.17.

The differences between the two graphs appear in two levels; first, the results in the P-Wave graph are uniformly

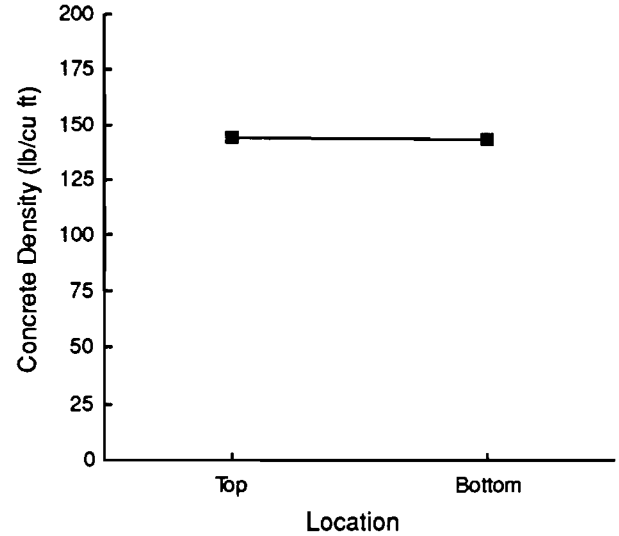

Fig 5.9. Concrete density at top and bottom 2-inch cores obtained from sites #1 and #2. (See Table 2.2.)

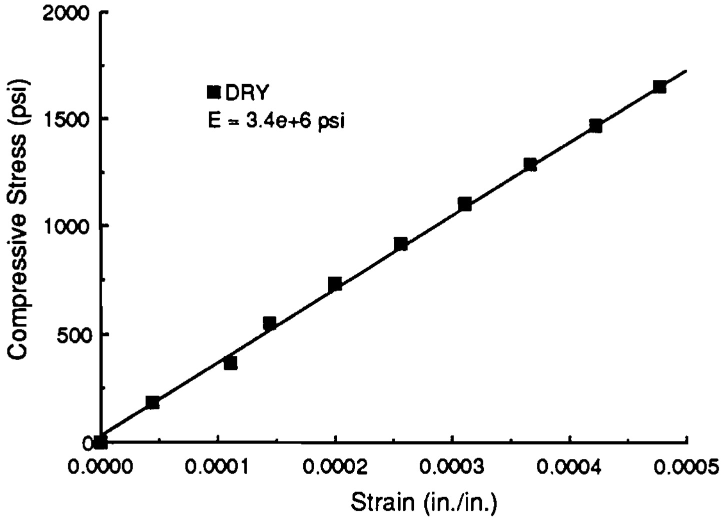

Fig 5.10. Modulus of elasticity on uncured pavement cores. Large strain method.

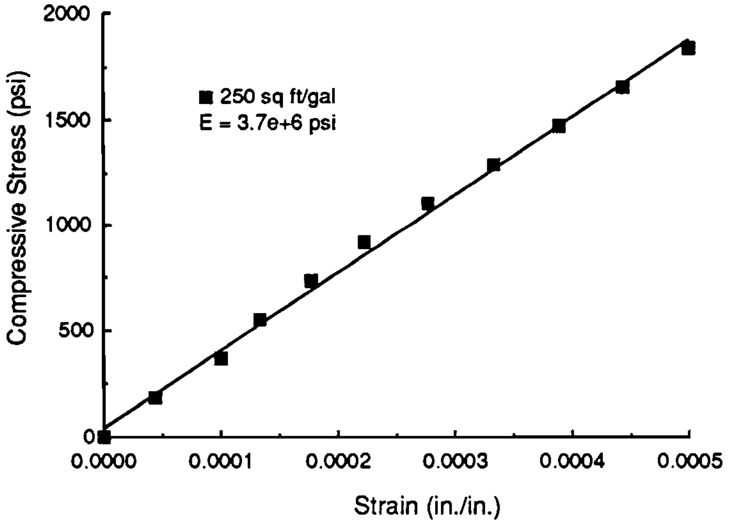

Fig 5.11. Modulus of elasticity on pavement cores, treated with 250 sq ft/gal of curing compound. Large strain method.

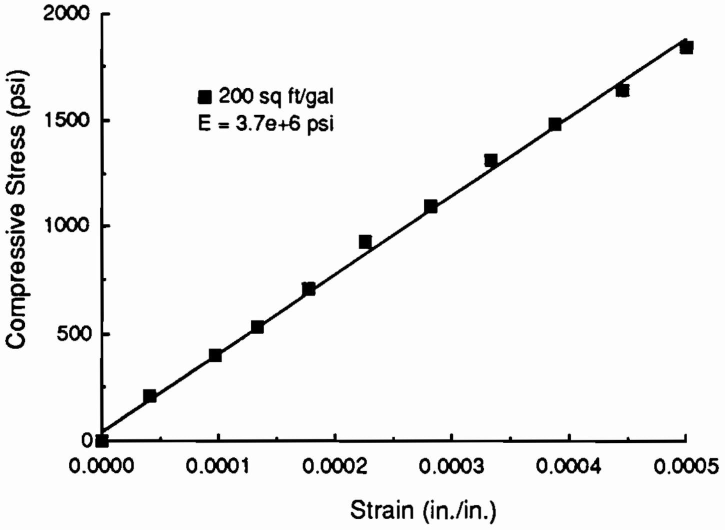

Fig 5.12. **Modulus of elasticity from pavement cores. Large strain method.**

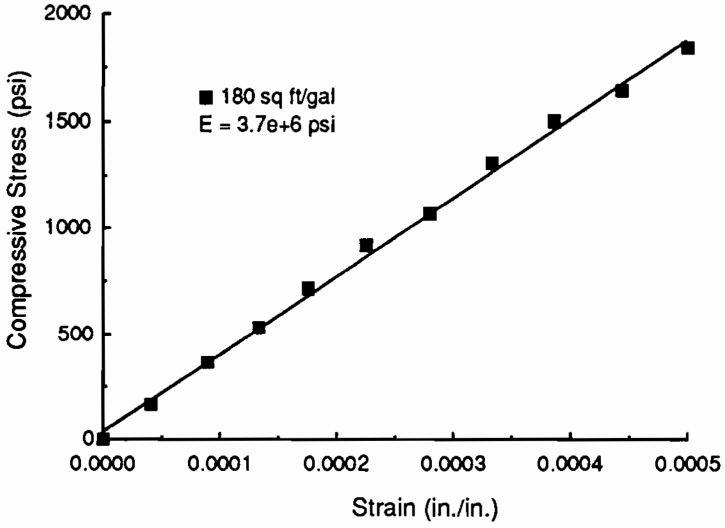

Fig 5.13. **Modulus of elasticity from pavement cores. Large strain method.**

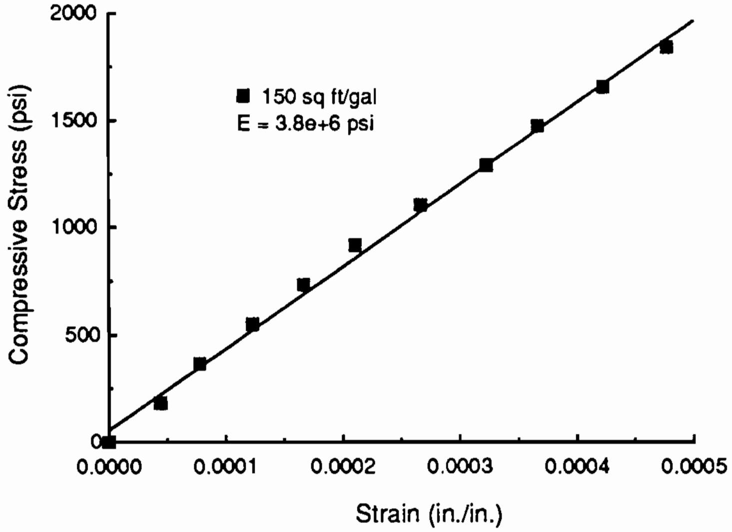

Fig 5.14. Application rate vs. tensile strength normalized as a percentage of the tensile strength of the control specimens. Field cylinders, mean values.

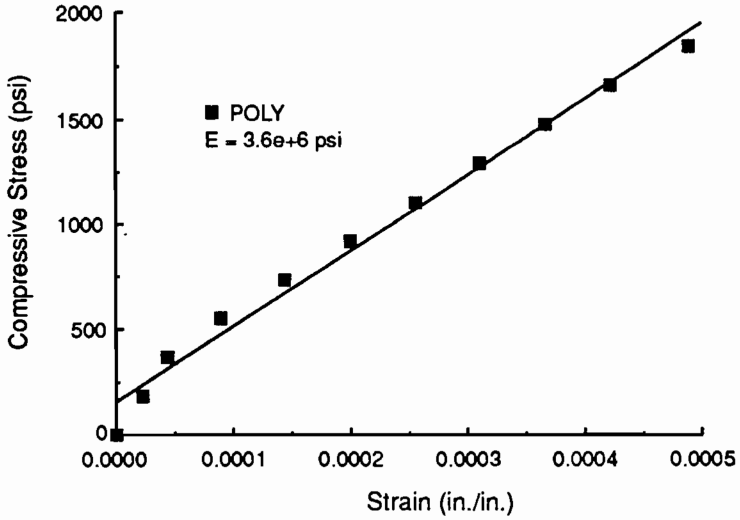

Fig 5.15. Modulus of elasticity on pavement cores, cured with polyethylene sheet. Large strain method.

higher than those of the previous graph by an average factor of 1.6. Second, the variation of values of the modulus between with each coverage rates is larger and no trend is apparent as was the case in the previous graph. This may be due to any one of several factors related to the novelty of the experiment and the limited number of available specimens that did not allow for familiarization with the testing procedures and any improvement upon them.

Spectral Analysis of Surface Waves (SASW)

The testing schedule for all SASW tests performed in District 24 over a period of six days is shown in Table C.1 in Appendix C. Panel one, which was left completely uncured, was used as the "control" panel. Because of equipment shortage one receiver set-up was left on this panel for the duration of the test and the second set-up had to be shuttled between all the other four panels. For this reason tests indicated in Table C.1 in Appendix C as #2 and #4 were not performed on panels two, three, four, and seven.

The results for each individual panel as plots of Young's modulus vs. time for wavelengths, L, of 0.25, 0.50, and 0.75 foot and a receiver spacing, R, of 1.00 foot are shown in Figs 5.18 to 5.22.

As a rule, shorter wavelengths represent the properties near the surface of the slab and longer wavelengths represent those at greater depth. Essentially, the measured stiffness is the average value over a depth equal to the wavelength, and can be considered under these condition to represent the stiffness at a depth half the wavelength. As can be seen from the graphs, for each panel, Young's modulus measured in test #8 is consistently lower near the surface, and higher near the bottom of the slab. The average value over all the slabs for a wavelength of 0.25 foot ("top" of slab) is 4.3 x 10^6 psi. For a wavelength of 0.50 foot ("middle" of slab) the value is 4.5 x 10^6 psi, which is 4 percent higher, and for a wavelength of 0.75 foot ("bottom" of slab) the average value is 4.7 x 10^6 psi which is 9 percent higher than the first. Nevertheless, a conclusion that the stiffness profile of a slab can be accurately predicted should be considered cautiously because the scatter of the data appears to be within the overall experimental error.

A receiver spacing of 0.50 foot was also used, but part of the data thus obtained appears to have been severely affected by body wave reflections and must be excluded from consideration for panels one, three, and seven. Figures 5.23 and 5.24 show the plots of Young's Modulus vs. Time for wavelengths of 0.25, 0.50, and 0.75 foot and receiver spacing of 0.50 foot for panels two and four. Figure 5.25 is an example of a plot such as the previous ones but which shows the effects of body wave reflections.

Tables C.2 and C.3 show moduli values averaged over all three wavelengths used for receiver spacings of 1.00 and

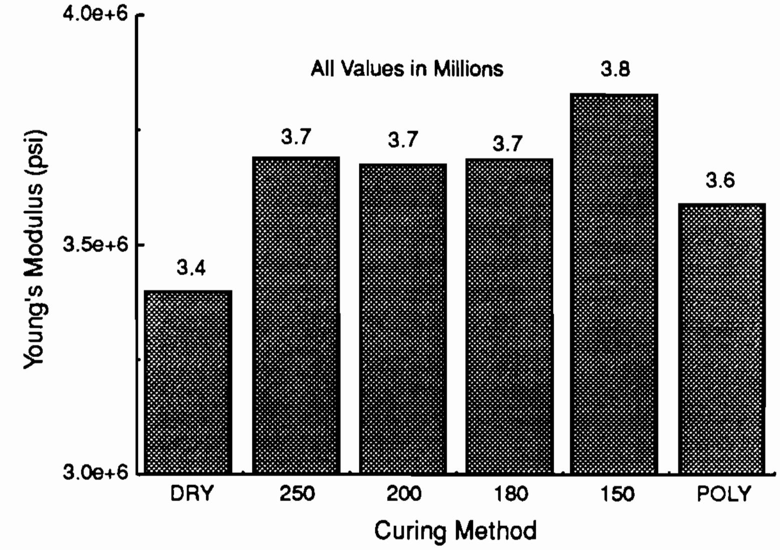

Fig 5.16. Curing method vs. Young's modulus at 28 days. Large strain method.

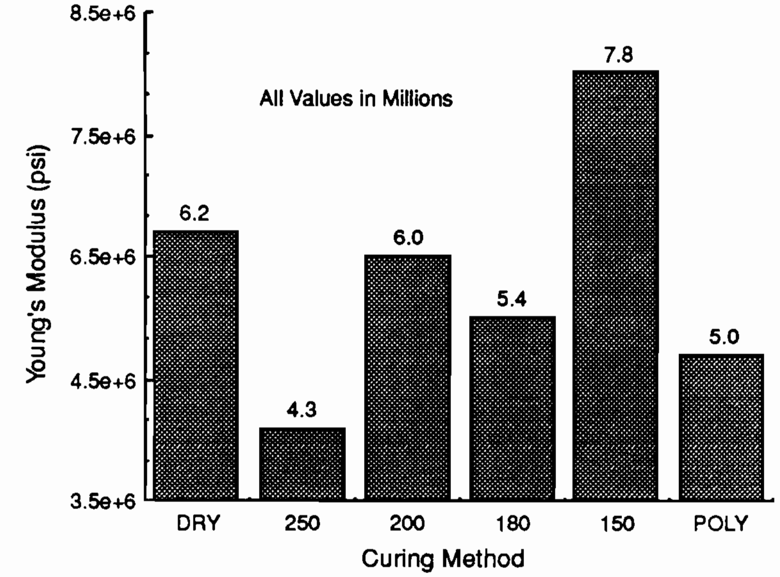

Fig 5.17. Curing method vs. Young's modulus at 28 days. P-Wave method (small strains).

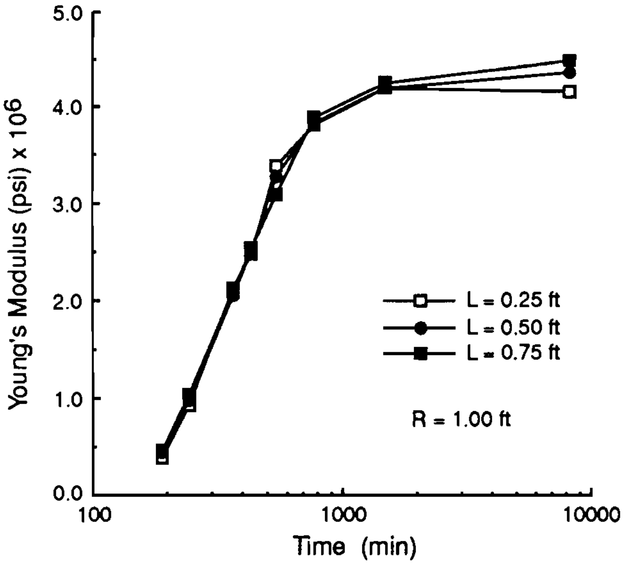

Fig 5.18. Young's modulus by the SASW method. Panel #1 (DRY).

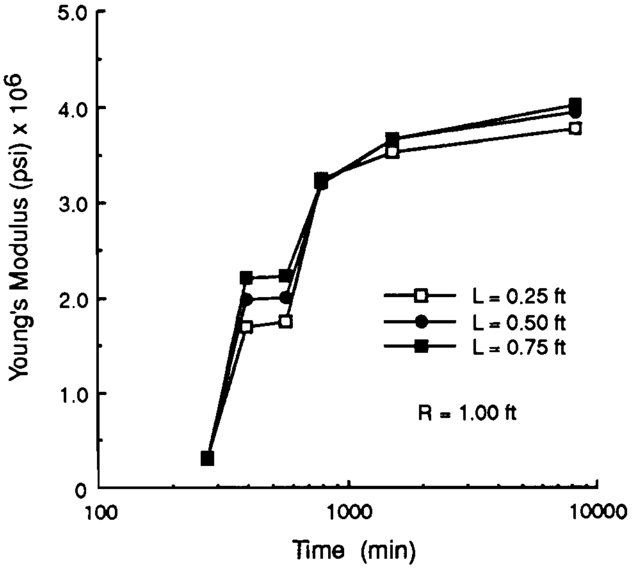

Fig 5.19. Young's modulus by the SASW method. Panel #2 (150 sq ft/gal).

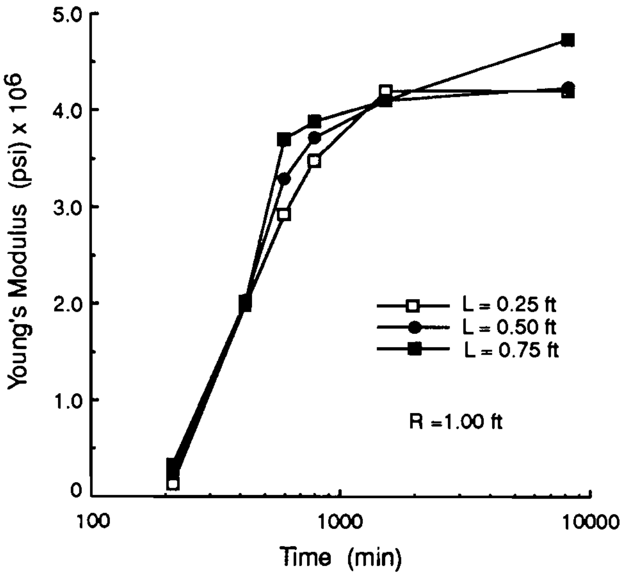

Fig 5.20. Young's modulus by the SASW method. Panel #3 (250 sq ft/gal).

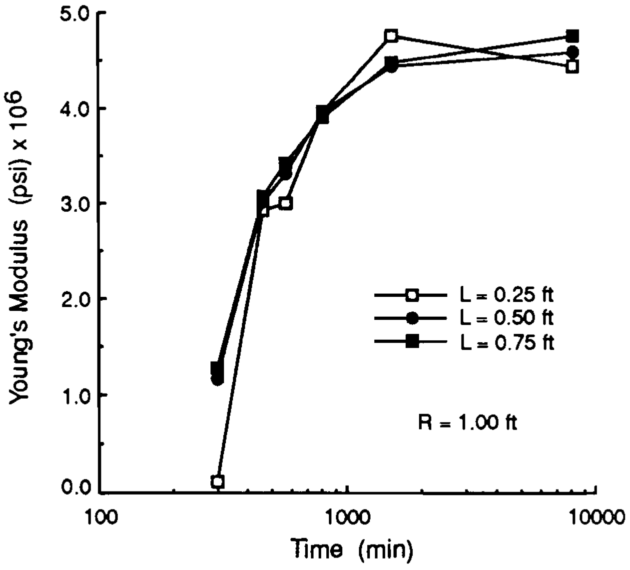

Fig 5.21. Young's modulus by the SASW method. Panel #4 (180 sq ft/gal).

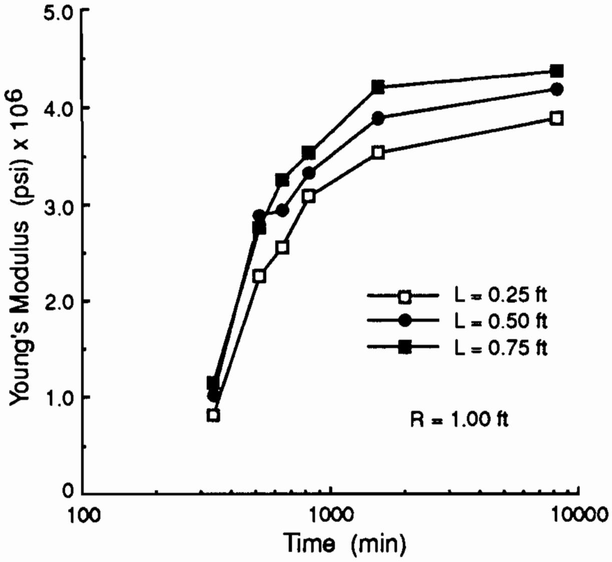

Fig 5.22. Young's modulus by the SASW method. Panel #7 (200 sq ft/gal).

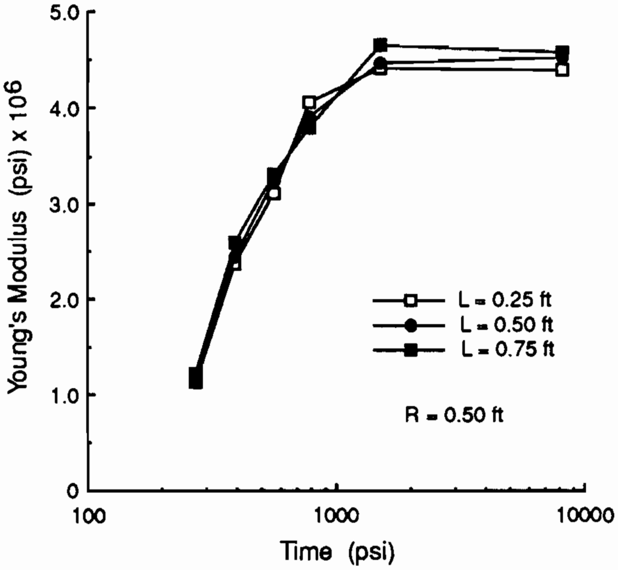

Fig 5.23. Young's modulus by the SASW method. Panel #2 (150 sq ft/gal).

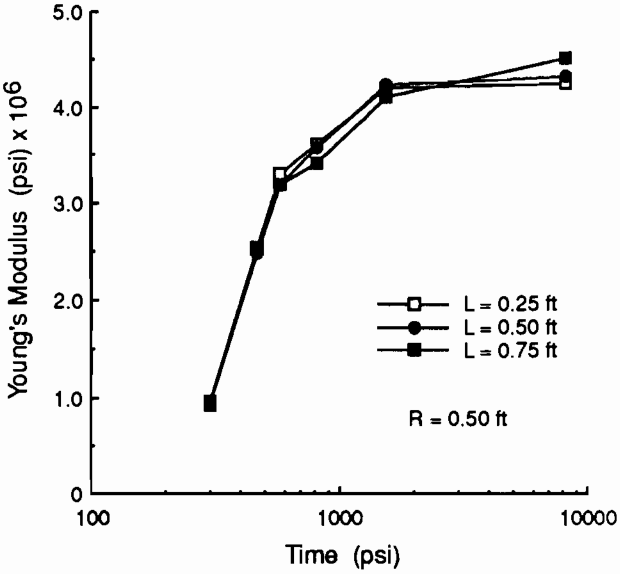

Fig 5.24. Young's modulus by the SASW method. Panel #4 (180 sq ft/gal).

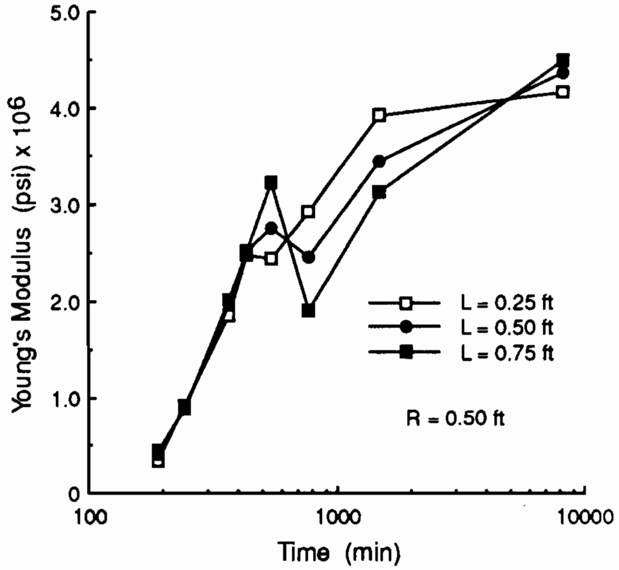

Fig 5.25. Young's modulus by the SASW method. Panel (DRY).

0.50 feet, respectively. Figures 5.26 and 5.27 present the same information schematically for comparison purposes. In both cases, and in particular in the case of the 1.00-foot receiver spacing where more data are available, a slight trend of increasing modulus values with increasing application rates can be detected. It is uncertain at this point, based on the amount of testing performed, whether this is a real trend, or normal data scatter.

These values should be compared with those obtained from the direct measurement of Young's modulus by the ASTM method, as described in the previous section.

Since the values obtained by the SASW method are six-day values and the others are 28-day values, it would appear that an adjustment in respect with time is necessary. It has been reported (Mindess, 1981)[28] that the compressive strength of air-cured concrete at three days is about 65 percent of that of 28-day concrete. If this adjustment factor is used for the modulus of elasticity as well, the results by the SASW test would be about 90 percent higher than the mean of the values obtained by the ASTM test. This approach would clearly be unrealistic. Hence a theory is needed which would explain this discrepancy. A closer look at the SASW modulus of elasticity vs. time graphs shows that at six days the rate of change of the modulus in all panels had reached or was very close to reaching zero, indicating that the material had reached its stiffness limit. This may be related to the size of the hydrated cement grains which are smaller at an early age, or to the quality or quantity of bonding between cement grains which may change with age. Since both tests actually test the same material the long term moduli should be closer.

Under this assumption, it is reasonable to compare the six-day SASW results with the 28-day ASTM results directly. This comparison can be found in graphical form in Fig 5.28. The mean modulus value obtained by the ASTM method is 3.6 x 10^6 psi, and the mean value obtained by the SASW method is 4.5 x 10^6 psi which is about 24 percent higher.

A new set of modulus of elasticity readings that were obtained after the completion of this project (approximately four months after placement) has verified that the rate of change of the modulus is essentially minimal, and that the above assumption is a good approximation.

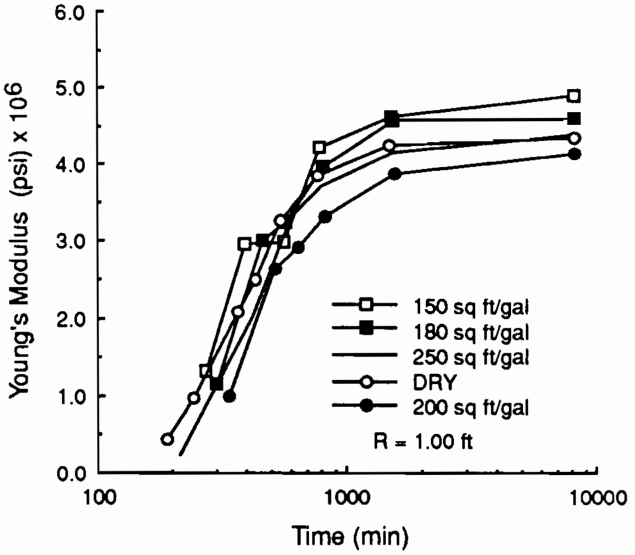

Fig 5.26. Young's modulus vs. time for a receiver spacing of 1.00 feet and averaged over wavelengths of 0.25, 0.50, and 0.75 feet.

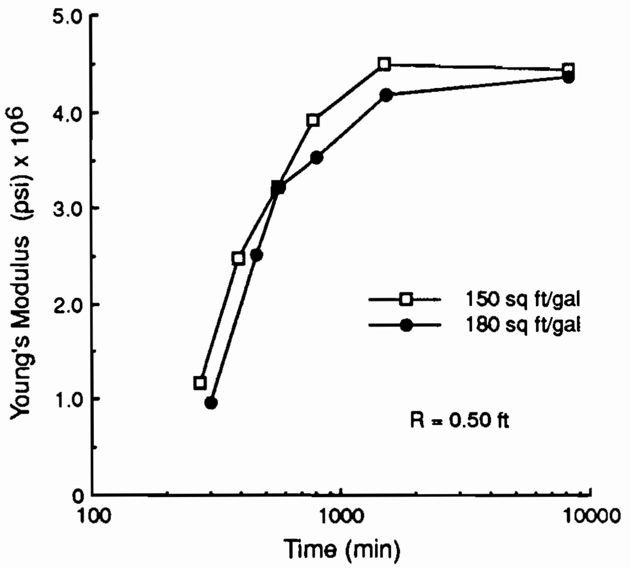

Fig 5.27. Average Young's modulus values for receiver spacing of 0.50 feet and wavelengths of 0.25, 0.50, and 0.75 feet.

LABORATORY EXPERIMENT

As mentioned before, the prevailing MCC coverage rate is 180 square feet/gallon. Therefore, most tests were performed using this rate under various environmental conditions and concrete temperatures with the assumption that any trends in tensile or flexural strength dependent on such conditions would also apply for application rates other than 180 square feet/gallon.

Two tests were also performed using 200 and 150 square feet/gallon rates under medium ambient temperature, relative humidity, and concrete temperature with the assumption that any trends in tensile or flexural strength dependent on MCC application rates would also apply for temperature and humidity conditions other than medium.

For each batch, one specimen was designated at random as the control specimen, and was cured under controlled conditions according to the ASTM Standard Procedure

C192-81, "Curing Concrete Specimens in the Laboratory"[29].

All tensile and flexural strength values were normalized in order to exclude the effects of the concrete mix design from the analysis of the effects of the other variables on the strength properties of the treated specimens. The normalized strength for a specimen, NSTR, expressed as a percentage of the strength of the control specimen of each batch, was calculated by the formula:

$$NSTR = (STRG_s/STRG_N) * 100$$

where

$STRG_s$ = tensile or flexural strength obtained from each cylinder or beam respectively, in psi; and,

$STRG_N$ = tensile or flexural strength obtained from the control cylinder or beam respectively, of each batch, in psi.

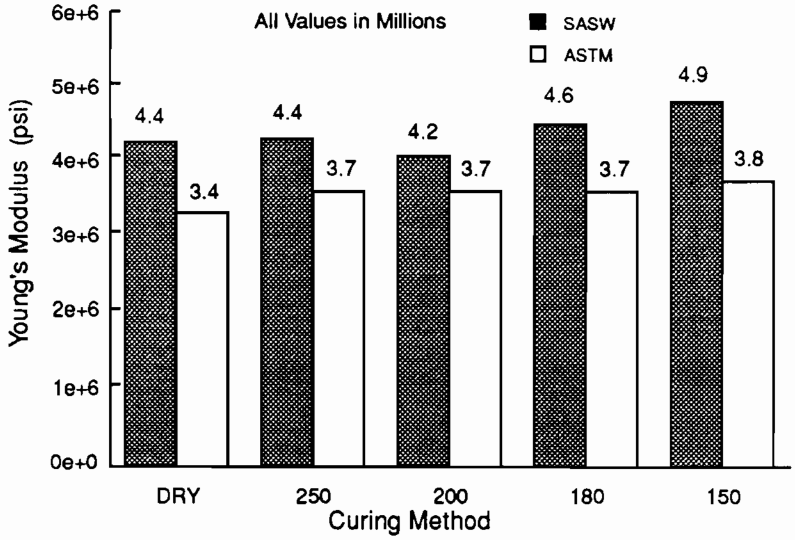

Fig 5.28. Comparison of Young's modulus values obtained by the ASTM large-strain method on cores, with values obtained by the SASW small-strain method on pavement panels.

The effects of the ambient temperature, concrete temperature, and relative humidity on the flexural or tensile strength of beams or cylinders respectively, for an MCC application rate of 180 square feet/gallon, were analyzed by using model 5A. The following table describes the treatments and levels in this model:

Variable	Treatment	Designation	Levels	Designation
Fixed	Ambient Temperature	AT	2	High, Medium
Fixed	Concrete Temperature	CT	3	High, Medium, Low
Fixed	Relative Humidity	RH	3	High, Medium, Low

Finally, this model included Duncan's multiple range test which was performed for the variable NSTR to find which means are significantly different in regards to the variables CT, RH, and the interaction CT*RH.

It should be noted here that equipment limitations did not allow the performance of any tests that required a combination of high ambient temperature and medium or low relative humidity, as well as the combination of medium ambient temperature and low relative humidity. The effect of this was that the combinations of CT and RH performed at high ambient temperature were not repeated for medium ambient temperature. As a result, the means at high ambient temperature cannot be statistically compared with the means at medium ambient temperature except if both the variables CT and RH, as well as their interaction CT*RH were to be found statistically non-significant. This would allow all data taken at high or medium ambient temperature to be considered as random repeats at each temperature regardless of the concrete temperature and the relative humidity, which, in turn, would allow an inference to be made in respect to the ambient temperature.

The effect of the MCC application rate on the flexural or tensile strength of beams or cylinders respectively was analyzed by model 5B. This model has only one fixed treatment, application rate, designated as RATE, with three levels designated as 200, 180, and 150. A point of interest in this model is that the error term mean square (error variance) used is that of model 5A instead of that which normally results from model 5B. The reason for this operation is the fact that model 5A describes a larger number of observations of the same nature than model 5B. It was therefore judged correct to perform this substitution in order to obtain more accurate results.

In this model as well, Duncan's multiple range test was performed for the variable NSTR to find which means are pairwise significantly different in regards to the variable RATE.

Splitting Tensile Strength Test

The results of the Splitting Tensile Strength Test are presented in Table D.1 in Appendix D. Table D.2 contains the same data, but normalized as described in the previous section. Table E.1 in Appendix E presents the results of the statistical analysis as regards to the ambient temperature, concrete temperature, and relative humidity. As can be seen the variable CT as well as the interaction of CT with RH are significant. Therefore it is not possible to make any judgments on AT for the reasons discussed in the previous section. Nevertheless, the comparison of the means for high and medium ambient temperature is given in Fig 5.29 for the sake of completeness.

The variable CT (concrete temperature) was significant as shown in Table E.1. In order to find the significant differences among the three levels of CT (high, medium, or low temperature) the Duncan's test[31] for multiple comparisons. When comparing more than two means the analysis of variance only specifies that there are significant differences among the levels but it does not tell which means differ from which other means. Duncan's test is one of various tests that can be used to compare the means when variables are found significant. In the particular case the test showed that the three means for high, medium, and low temperature are different, and that the tensile strength is highest at high temperature and lowest at medium temperature. These results are also shown graphically in Fig 5.30.

The variable RH (relative humidity) was found to be non-significant in the analysis of variance. Despite non-significant statistical differences among the three humidity levels, Fig 5.31 indicates increasing tensile strength with increasing relative humidity levels.

It would be misleading to consider these results as complete for either CT or for RH because the interaction of these two main effects, CT*RH, was also found to be significant. In cases such as this, one is usually interested in the interaction rather than the main effects[30]. Therefore the interaction is used, along with Duncan's test for this interaction, to obtain the complete picture. This latter test showed that mean tensile strengths are equal for high and medium humidity at low concrete temperature, that they are equal for any humidity at medium concrete temperature, and that they are equal for medium and low humidity at high temperature. This can also be seen graphically in Fig 5.32.

From the above observations it can therefore be said that

(1) at low concrete temperatures lower mean tensile values can be expected for concrete cured at low humidity than for concrete cured at medium or high humidity;

(2) at medium concrete temperatures no difference in mean tensile strength should be expected for any level of humidity; and

(3) at high concrete temperatures lower mean tensile strengths should be expected for concrete cured at either low or medium humidity than for concrete treated at high humidity.

The investigation about the effect of application rates on the tensile strength of concrete showed that RATE is significant, as shown in Table E.2. Duncan's test showed that higher mean tensile strengths should be expected at an application rate of 200 square feet/gallon than at rates of either 150 or 180 square feet/gallon. This relationship is presented graphically in Fig 5.33.

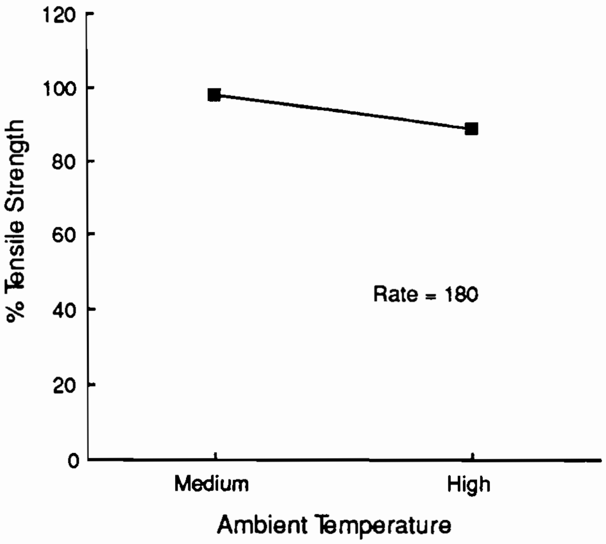

Fig 5.29. Ambient temperature vs. tensile strength normalized as a percentage of the tensile strength of the control specimen. Laboratory cylinders, mean values.

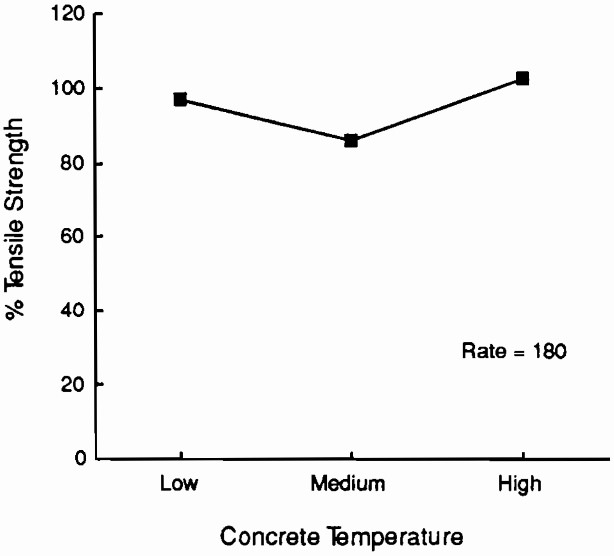

Fig 5.30. Concrete temperature vs. tensile strength normalized as a percentage of the tensile strength of the control specimen. Laboratory cylinders, mean values.

Flexure Test

The results of the flexure test are presented in Table D.3. Table D.4 contains the same data, but normalized as described previously. Table E.3 presents the results of the statistical analysis as regards to the ambient temperature, concrete temperature, and relative humidity.

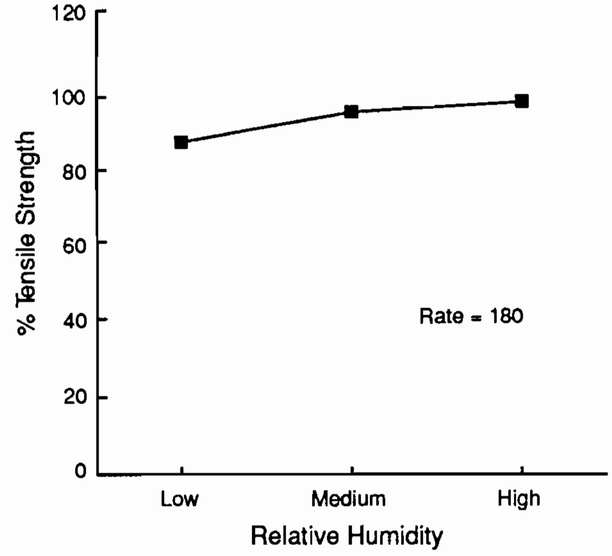

Fig 5.31. Relative humidity vs. tensile strength normalized as a percentage of the tensile strength of the control specimen. Laboratory cylinders, mean values.

Again, in this test no inference can be made about AT because both RH and the interaction of RH with CT, RH*CT, are found to be significant. Figures 5.34, 5.35, and 5.36 are graphical representations of the mean flexural strength as a function of ambient temperature, concrete temperature, and relative humidity, respectively.

Here again, as in the previous section, it is necessary to consider the interaction of CT with RH to establish what relationship exists between relative humidity, concrete temperature, and flexural strength. Duncan's test showed that that mean flexural strengths are equal for high and low humidity at low concrete temperature, that they are also equal for high and low humidity at medium concrete temperature, and that they are equal for medium and low humidity at high temperature. This can also be seen graphically in Fig 5.37.

From the above observations it can therefore be said that

(1) at low concrete temperatures lower mean flexural strength values can be expected for concrete cured at medium humidity than for concrete cured at low or high humidity;

(2) at medium concrete temperatures higher mean flexure values can be expected for concrete cured at medium humidity than for concrete cured at low or high humidity; and

(3) at high concrete temperatures lower mean flexural strengths should be expected for concrete cured at either low or medium humidity than for concrete treated at high humidity.

The investigation about the effect of application rates on the flexural strength of concrete showed that RATE is not significant, as shown in Table E.4. This indicates that mean flexural strengths at all three application rates of 200,150 or 180 square feet/gallon are statistically equal. This result is presented graphically in Fig 5.38.

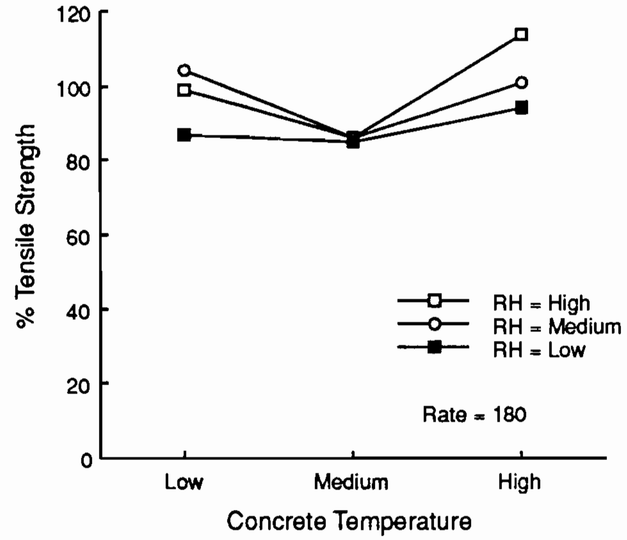

Fig 5.32. Interaction of concrete temperature vs. tensile strength normalized as a percentage of the tensile strength of the control specimen. Laboratory cylinders, mean values. Points connected with vertical lines were shown to be statistically equal by Duncan's test.

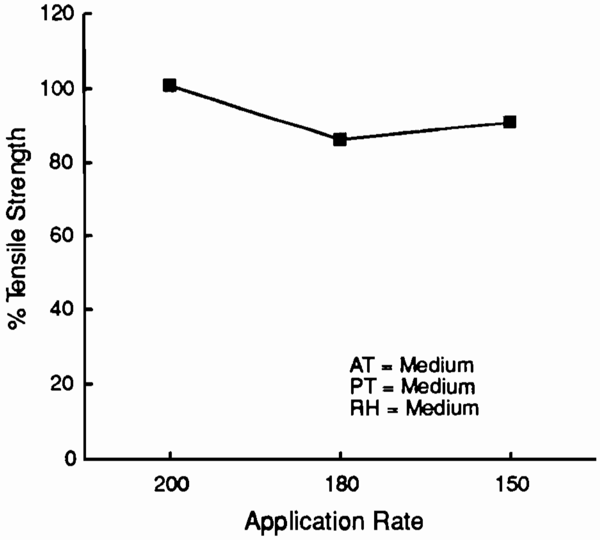

Fig 5.33. Application rate vs. tensile strength normalized as a percentage of the tensile strength of the control specimen. Laboratory cylinders, mean values.

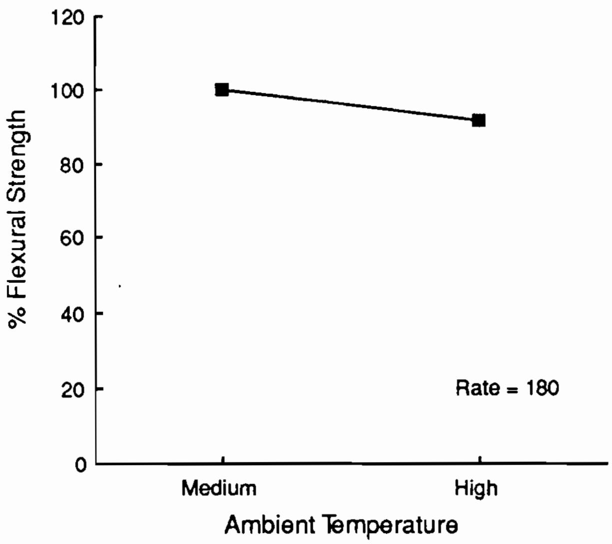

Fig 5.34. Relative temperature vs. flexural strength normalized as a percentage of the tensile strength of the control specimen. Laboratory cylinders, mean values.

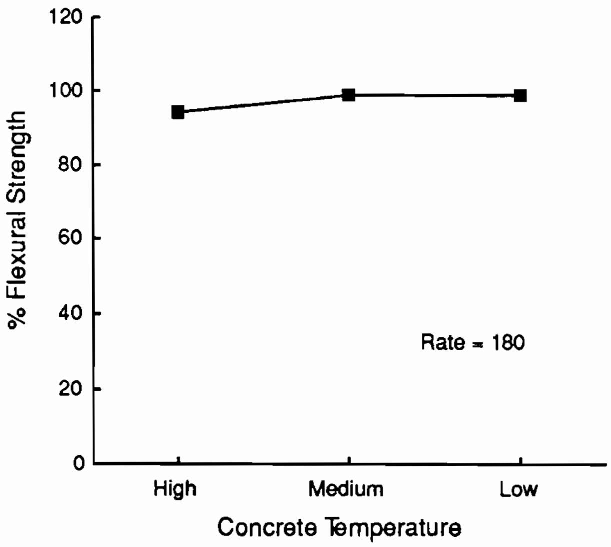

Fig 5.35. Concrete temperature vs. flexural strength normalized as a percentage of the tensile strength of the control specimen. Laboratory cylinders, mean values.

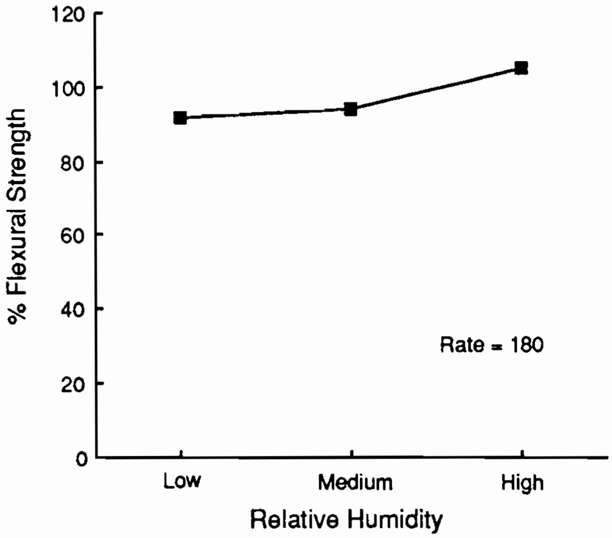

Fig 5.36. Relative humidity vs. flexural strength normalized as a percentage of the tensile strength of the control specimen. Laboratory cylinders, mean values.

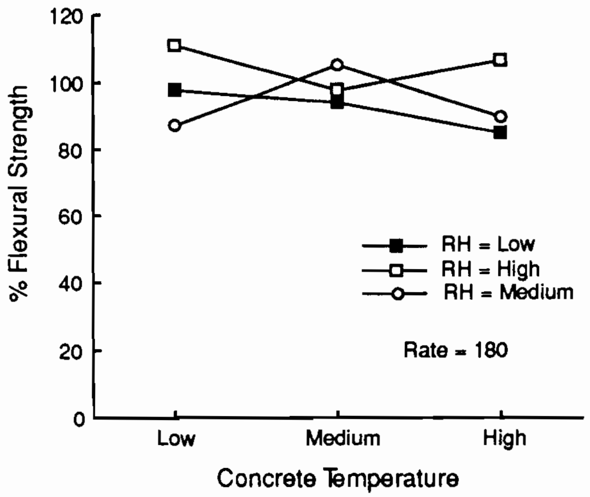

Fig 5.37. Interaction of concrete temperature and relative humidity vs. flexural strength normalized as a percentage of the tensile strength of the control specimen. Laboratory cylinders, mean values. Points connected with lines were shown to be statistically equal by Duncan's test.

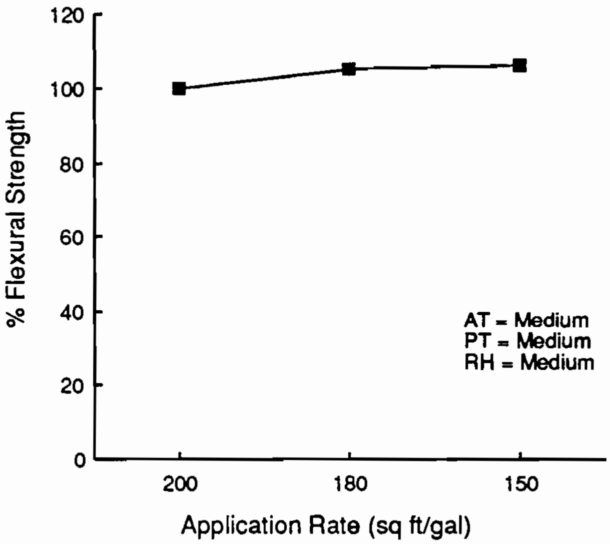

Fig 5.38. Application rate vs. flexural strength normalized as a percentage of the tensile strength of the control specimen. Laboratory cylinders, mean values.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Based upon the experimental results the following conclusions can be made:

(1) For application rates of the membrane curing compound between 150 to 200 square feet per gallon it can be concluded that

  (a) the application rate does not have a significant effect on the tensile strength of pavement concrete as measured by the splitting tensile strength test performed on cores extracted from pavement slabs. This applies for the full depth of the pavement, and for temperature, humidity, and wind conditions resulting in evaporation rates of 0.03 to 0.28 lbs per hour per square foot as defined by the Portland Cement Association;

  (b) the application rate does not have a significant effect on the surface durability of pavement concrete as measured by the sandblast abrasion test;

  (c) the application rate does not have a significant effect on the density of the pavement concrete. This applies for the full depth of the pavement; and

  (d) the application rate does not have a significant effect on the flexural or the tensile strength of specimens prepared in the field under casting and curing conditions similar to those of the actual pavement.

(2) Spectral Analysis of Surface Waves (SASW) is a feasible in-situ, non-destructive method that can be used to monitor the stiffness gain of fresh concrete with an accuracy that may be favorably compared to that of the traditional large-strain method of measuring the modulus of elasticity. Both these methods showed that an increase in the membrane curing compound application rate may result in an increase in the stiffness of pavement concrete.

(3) The P-wave method for the measurement of the modulus of elasticity, when used on cores extracted from concrete pavement, did not offer any conclusive results.

(4) Laboratory tests gave conflicting and inconclusive results in regards to the effects of the membrane curing compound application rate and of temperature and humidity curing conditions on the flexural and tensile strength of beams and cylinders, respectively. Therefore no correlation of laboratory and field test is possible.

RECOMMENDATIONS

Based upon the experimental results, the following recommendations can be made:

(1) The membrane curing compound application rate of 180 square feet per gallon specified for highway pavements was found to be slightly conservative. It would therefore be possible to decrease it to 200 square feet per gallon without any significant loss on tensile or flexural strength, surface durability, and density regardless of environmental conditions.

(2) Spectral Analysis of Surface Waves (SASW) method should be further investigated and developed as an in-situ, non-destructive method for quality control of both fresh and cured concrete, as well as a method to be used in studying the material properties of concrete in general.

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APPENDIX A. FIELD EXPERIMENT RESULTS

TABLE A.1. SPLIT TENSILE TEST RESULTS ON 2-INCH SLICES OF CORES OBTAINED IN THE FIELD. SITE #1, TULIA, TEXAS. ALL VALUES IN PSI.

				CORE	
CONTR	SECT	RATE	POS	1	2
N1	S1	EX	B	434	556
			T	431	442
		POLY	B	467	399
			T	520	475
		150	B	595	460
			T	542	555
		200	B	355	496
			T	417	550
		180	B	443	492
			T	525	488
	S2	180	B	555	407
			T	585	503
		200	B	*	460
			T	494	535

* Damaged specimen

TABLE A.2. SPLIT TENSILE TEST RESULTS ON 2-INCH SLIDES OF CORES OBTAINED IN THE FIELD. SITE #2, TULIA, TEXAS. ALL VALUES IN PSI.

				CORE	
CONTR	SECT	RATE	POS	1	2
N2	S1	EX	B	480	463
			T	377	479
		POLY	B	454	387
			T	419	419
		150	B	544	457
			T	557	*
		180	B	526	423
			T	462	547
		200	B	554	493
			T	467	481
	S2	180	B	509	403
			T	503	400
		200	B	463	430
			T	429	458

* Damaged specimen

TABLE A.3. SPLIT TENSILE TEST RESULTS ON 2-INCH SLICES OF CORES OBTAINED IN THE FIELD. SITE #3, FORT WORTH, TEXAS. ALL VALUES IN PSI.

				CORE			
CONTR	SECT	RATE	POS	1	2	3	4
N3	S1	EX	B	-	-	-	608
			T	414	633	452	538
		POLY	B	657	560	693	-
			T	710	589	409	557
		150	B	-	643	611	-
			T	662	480	735	542
		180	B	-	557	530	625
			T	711	526	681	628
		200	B	-	-	567	506
			T	540	618	701	623
	S2	Ex	B	-	440	547	-
			T	465	536	474	*
		150	B	650	693	521	584
			T	*	650	626	367
		180	B	-	805	-	761
			T	*	480	559	382
		200	B	518	-	557	530
			T	503	*	477	*

* Damaged specimen

\- Specimen severely honeycombed possibly due to undervibration. Not tested

TABLE A.4(A). SPLIT TENSILE TEST RESULTS ON 2-INCH SLICES OF CORES OBTAINED IN THE FIELD. SITE #4 AND 5, HOUSTON, TEXAS. ALL VALUES IN PSI.

				CORE
CONTR	SECT	RATE	POS	1
N4	S1	DRY	B	728
			M1	661
			M2	810
			T	683
		EX	B	*
			M1	615
			M2	763
			T	658
		POLY	B	*
			M1	552
			M2	793
			T	771
		150	B	693
			M1	645
			M2	580
			T	703
			B	859
			M1	771
			M2	767
			T	686
		200	B	783
			M1	804
			M2	854
			T	800
	S2	180	B	679
			M1	767
			M2	778
			T	812

* Damaged specimen

TABLE A.4(B). SPLIT TENSILE TEST RESULTS ON 2-INCH SLICES OF CORES OBTAINED IN THE FIELD. SITE #4 AND 5, HOUSTON, TEXAS. ALL VALUES IN PSI.

				CORE
CONTR	SECT	RATE	POS	1
N5	S1	DRY	B	633
			M1	674
			M2	777
			T	695
		EX	B	678
			M1	680
			M2	*
			T	699
		POLY	B	649
			M1	699
			M2	768
			T	698
		150	B	727
			M1	726
			M2	745
			T	688
		180	B	674
			M1	730
			M2	573
			T	657
		200	B	722
			M1	678
			M2	707
			T	872
	S2	Dry	B	754
			M1	730
			M2	793
			T	757
		Ex	B	738
			M1	763
			M2	718
			T	852
		150	B	727
			M1	739
			M2	745
			T	797
		180	B	773
			M1	794
			M2	833
			T	688
		200	B	661
			M1	709
			M2	808
			T	741

* Damaged specimen

TABLE A.5. SPLIT TENSILE TEST RESULTS ON 2-INCH SLICES OF CORES OBTAINED IN THE FIELD. SITE #6, EL PASO, TEXAS. ALL VALUES IN PSI.

				CORE
CONTR	SECT	RATE	POS	1
N6	S1	Dry	B	561
			M1	503
			M2	553
			T	383
		Ex	B	375
			M1	453
			M2	485
			T	523
		Poly	B	511
			M1	510
			M2	491
			T	507
		150	B	571
			M1	415
			M2	567
			T	693
		180	B	597
			M1	438
			M2	597
			T	380
		200	B	578
			M1	514
			M2	481
			T	383
		250	B	504
			M1	413
			M2	481
			T	432

TABLE A.6. SPLITTING TENSILE STRENGTH OF 6-INCH X 12-INCH CYLINDERS PREPARED AND CURED IN THE FIELD (PSI)

	Contractor						
	1	2	3		4	5	6
Application Rate, sq ft/gal	Sect 1	Sect 2	Sect 3	Sect 4	Sect 5	Sect 6	Sect 7
Dry					624	626	442
200	469 488	460 491	513 460	465	590	607	436
180	497 518	394 450	504 462	466 470	651 566	617 660	453 504
150	485 720	403 445	505 460	488	671	589	460

TABLE A.7. FLEXURAL STRENGTH OF 6-INCH X 21-INCH BEAMS PREPARED AND CURED IN THE FIELD (PSI)

	Contractor						
	1	2	3		4	5	6
Application Rate, sq ft/gal	**Sect 1**	**Sect 2**	**Sect 3**	**Sect 4**	**Sect 5**	**Sect 6**	**Sect 7**
Dry					865	865	620
200	743 655	625 690	560 510	590	1005 1005	920 920	680 680
180	670 715	610 620	675 710	625 470	890 1095	900 810	695 660
150	710 720	685 650	720 615	635	860	750	665

TABLE A.8. RESULTS FROM SURFACE DURABILITY TEST PERFORMED ON 4-INCH CORES (TOP SURFACE AREA 10.9 SQ IN.) (GRAMS)

	Contractor		
Application Rate, sq ft/gal	**4**	**5**	**6**
Dry	3.12	3.27 5.38*	4.40
250			4.50
200	3	3.21 2.70*	5.40
180	3.41	4.42 2.99*	4.50
Ex	2.96	3.13 2.84*	4.40
150		4.31 2.92*	3.20
Poly	3.94	3.56	4.00

* Values from the repeat section from contractor #5.

TABLE A.9. DENSITY AT TOP AND BOTTOM 2 INCHES OF CORES EXTRACTED FROM SITES #1 AND #2 (SEE TABLE 2.2) (LBS/CU FT)

			Contractor			
			1		2	
			Location		Location	
Application Rate, sq ft/gal	**SECT**	**CORES**	**Top**	**Bottom**	**Top**	**Bottom**
180	1	1	144.89	140.15	144.46	144.27
	1	2	147.08	141.52	141.02	141.59
	2	1	143.83	143.89	148.02	139.59
	2	2	144.21	142.77	140.40	142.40
200	1	1	146.52	139.78	143.46	142.96
	1	2	141.90	148.64	145.83	145.20
	2	1	143.02	157.50	140.34	143.15
	2	2	145.27	140.09	142.27	143.08
150	1	1	146.95	141.34	143.96	141.90
	1	2	146.14	142.96	138.22	142.58
EX	1	1	143.58	142.02	143.83	143.58
	1	2	142.46	141.46	145.45	146.27
POLY	1	1	145.20	140.46	144.64	142.33
	1	2	145.77	140.77	140.84	143.83

APPENDIX B. ANALYSIS OF VARIANCE RESULTS FOR FIELD EXPERIMENT

TABLE B.1. SUMMARY OF ANOVA OF SPLITTING TENSILE TEST RESULTS ON 2-INCH SLICES FROM CORES OBTAINED FROM THE FIELD (MODEL 1A)

Classification of Variables		
Class	Level	Values
CONTR	6	N1 N2 N3 N4 N5 N6
RATE	7	DRY EX POLY 150 180 200 250
SECT	2	S1 S2
POS	4	T M1 M2 B
CORE	4	1 2 3 4

Source	DF	F Value	Pr*	Significance a = 0.10
CONTR	5	32.4	< 0.01	Yes
SECT(CONTR)	5	1.76	0.18	No
δ	0	-	-	-
RATE	6	1.32	0.25 +	No
CONTR*RATE	22	1.45	0.25 +	No
RATEe*SECT(CONTR)	9	0.75	0.25 +	No
CORE(CONTR*RATE*SECT)	38	1.04	0.25 +	No
ω	0	-	-	-
POS	3	1.07	0.25 +	No
CONTR*POS	9	1.16	0.25 +	No
SECTt*POS(CONTR)	9	1.24	0.25 +	No
RATE*POS	18	0.84	0.25 +	No
CONTR*RATE*POS	40	0.88	0.25 +	No
RATE*SECT*POS(CONTR)	16	1.11	0.25 +	No
ERROR	23	-	-	-

* Probability of rejection value associated with the F value

TABLE B.2. SUMMARY OF ANOVA OF SPLITTING TENSILE TEST RESULTS ON 2-INCH SLICES FROM CORES OBTAINED FROM THE FIELD (MODEL 1B)

Classification of Variables		
Class	**Level**	**Values**
CONTR	3	N4 N5 N6
RATE	7	DRY EX POLY 150 180 200 250
SECT	2	S1 S2
POS	4	T M1 M2 B
CORE	1	1

Source	DF	F Value	Pr*	Significance a = 0.10
CONTR	2	25.76	0.05	Yes
SECT(CONTR)	2	-	-	-
δ		-	-	-
RATE	6	0.56	0.25 +	No
CONTR*RATE	10	1.32	0.25 +	No
RATE*SECT(CONTR)	4	-	-	-
CORE(CONTR*RATE*SECT)	-	-	-	-
ω	0	-	-	-
POS	3	1.93	0.24	No
CONTR*POS	6	1.02	0.25 +	No
SECT*POS(CONTR)	6	1.57	-	-
RATE*POS	18	0.10	0.25 +	No
CONTR*RATE*POS	29	1.58	0.23	No
RATE*SECT*POS(CONTR)	11	1.62	-	-
POS*CORE(CONTR*RATE*SECT)	0	-	-	-

* Probability of rejection value associated with the F value

TABLE B.3. SUMMARY OF ANOVA OF SPLITTING TENSILE TEST RESULTS ON 2-INCH SLICES FROM CORES OBTAINED FROM THE FIELD (MODEL 1C)

Classification of Variables		
Class	**Level**	**Values**
CONTR	3	N4 N5 N6
RATE	7	DRY EX POLY 150 180 200 250
SECT	2	S1 S2
POS	4	T M1 M2 B
CORE	1	1

Source	DF	F Value	Pr*	Significance a = 0.10
CONTR	2	25.76	0.05	Yes
SECT(CONTR)	2	-	-	-
δ		-	-	-
RATE	6	0.56	0.25 +	No
CONTR*RATE	10	1.32	0.25 +	No
RATE*SECT(CONTR)	4	-	-	-
CORE(CONTR*RATE*SECT)	-	-	-	-
ω	0	-	-	-
POS	3	1.93	0.24	No
CONTR*POS	6	1.02	0.25 +	No
SECT*POS(CONTR)	6	1.57	-	-
RATE*POS	18	0.10	0.25 +	No
CONTR*RATE*POS	29	1.58	0.23	No
RATE*SECT*POS(CONTR)	11	1.62	-	-
POS*CORE(CONTR*RATE*SECT)	0	-	-	-

* Probability of rejection value associated with the F value

TABLE B.4. SUMMARY OF ANOVA OF SPLITTING TENSILE TEST RESULTS ON 2-INCH SLICES FROM CORES OBTAINED FROM THE FIELD (MODEL 1D)

Classification of Variables		
Class	**Level**	**Values**
CONTR	6	N1 N2 N3 N4 N5 N6
RATE	7	DRY EX POLY 150 180 200 250
SECT	2	S1 S2
POS	4	T M1 M2 B
CORE	4	1 2 3 4

Source	DF	F Value	Pr*	Significance a = 0.10
CONTR	5	12.26	0.01	Yes
SECT(CONTR)	5	1.16	0.25 +	No
δ	0	-	-	-
RATE	6	1.56	0.22	No
CONTR*RATE	22	1.92	0.18	No
RATE*SECT(CONTR)	9	0.50	0.25 +	No
CORE(CONR*RATE*SECT)	38	1.04	0.25 +	No
ω	0	-	-	-
POS	3	0.91	0.25 +	No
CONTR*POS	9	1.46	0.25 +	No
SECT*POS(CONTR)	9	0.94	0.25 +	No
RATE*POS	18	0.73	0.25 +	No
CONTR*RATE*POS	40	1.24	0.25 +	No
RATE*SECT*POS(CONTR)	16	0.88	0.25 +	No
ERROR	23	-	-	-

* Probability of rejection value associated with the F value

TABLE B.5. SUMMARY OF ANOVA OF SPLITTING TENSILE TEST RESULTS ON 2-INCH SLICES FROM CORES OBTAINED FROM THE FIELD. NORMALIZED DATA. ENVIRONMENTAL EFFECTS INCLUDED. (MODEL 1E)

Classification of Variables		
Class	**Level**	**Values**
CONTR	5	N1 N2 N3 N4 N5
RATE	6	DRY EX POLY 150 180 200 250
SECT	2	S1 S2
POS	4	T M1 M2 B
CORE	4	1 2 3 4
EVAP	7	0.3 0.03 0.14 0.22 0.23 0.25 0.28

Source	DF	F Value	Pr*	Significance a = 0.10
CONTR	4	3.20	0.13	No
SECT(CONTR)	5	1.34	0.25 +	No
δ	0	-	-	-
EVAP(CONTR*SECT)	0	-	-	-
RATE	5	1.23	0.25 +	No
CONTR*RATE	17	2.11	0.14	No
RATE*EVAP(CONTR*SECT)	9	0.42	0.25 +	No
ω	0	-	-	-
POS	3	0.40	0.25 +	No
CONTR*POS	6	1.17	0.25 +	No
POS*EVAP(CONTR*SECT)	9	1.16	0.25 +	No
RATE*POS	15	0.98	0.25 +	No
CONTR*RATE*POS	25	0.50	0.25 +	No
ERROR	77	-	-	-

* Probability of rejection value associated with the F value

TABLE B.6. SUMMARY OF ANOVA OF SPLITTING TENSILE TEST RESULTS ON 2-INCH SLICES FROM CORES OBTAINED FROM THE FIELD (MODEL 2A)

Classification of Variables		
Class	Level	Values
CONTR	6	N1 N2 N3 N4 N5 N6
RATE	7	DRY EX POLY 150 180 200 250
SECT	2	S1 S2
POS	4	T M1 M2 B

Source	DF	F Value	Pr*	Significance a = 0.10
CONTR	5	26.78	< 0.01	Yes
SECT(CONTR)	5	1.21	0.25 +	No
δ	0	-	-	-
RATE	6	1.39	0.25 +	No
CONTR*RATE	22	1.21	0.25 +	No
RATE*SECT(CONTR)	9	0.79	0.25 +	No
ω	0	-	-	-
POS	3	0.96	0.25 +	No
CONTR*POS	9	1.30	0.25 +	No
SECT*POS(CONTR)	9	1.20	0.25 +	No
RATE*POS	18	1.81	0.25 +	No
CONTR*RATE*POS	40	0.77	0.25 +	No
RATE*SECT*POS(CONTR)	16	1.20	0.25 +	No
ERROR	61	-	-	-

* Probability of rejection value associated with the F value

TABLE B.7. SUMMARY OF ANOVA OF SPLITTING TENSILE TEST RESULTS ON 2-INCH SLICES FROM CORES OBTAINED IN THE FIELD (MODEL 2B)

Classification of Variables		
Class	Level	Values
CONTR	3	N4 N5 N6
RATE	7	DRY EX POLY 150 180 200 250
SECT	2	S1 S2
POS	4	T M1 M2 B

Source	DF	F Value	Pr*	Significance a = 0.10
CONTR	2	25.03	0.05	Yes
SECT(CONTR)	2	-	-	-
RATE	6	1.67	0.24	No
CONTR*RATE	10	1.31	0.25 +	No
RATE*SECT(CONTR)	4	-	-	-
POS	3	1.76	0.25 +	-
CONTR*POS	6	1.11	0.25 +	No
SECT*POS(CONTR)	6	1.57	0.25	No
RATE*POS	18	1.03	0.25 +	No
CONTR*RATE*POS	28	1.58	0.23	No
RATE*SECT*POS(CONTR)	11	-	-	-

* Probability of rejection value associated with the F value

TABLE B.8. SUMMARY OF ANOVA OF SPLITTING TENSILE TEST RESULTS ON 2-INCH SLICES FROM CORES OBTAINED FROM THE FIELD (MODEL 2C)

Classification of Variables

Class	Level	Values
CONTR	6	N1 N2 N3 N4 N5 N6
RATE	7	DRY EX POLY 150 180 200 250
SECT	2	S1 S2
POS	2	T B

Source	DF	F Value	Pr*	Significance a = 0.10
CONTR	5	32.2	< 0.01	Yes
SECT(CONTR)	5	2.03	0.08	Yes
δ	0	-	-	-
RATE	6	1.83	0.16	No
CONTR*RATE	22	0.98	0.25 +	No
RATE*SECT(CONTR)	9	0.86	0.25 +	No
ω	0	-	-	-
POS	1	-	-	-
CONTR*POS	5	1.27	0.25 +	No
SECT*POS(CONTR)	5	1.94	0.09	Yes
RATE*POS	6	1.13	0.25 +	No
CONTR*RATE*POS	20	0.64	0.25 +	No
RATE*SECT*POS(CONTR)	9	1.62	0.12	No
ERROR	61	-	-	-

* Probability of rejection value associated with the F value

TABLE B.9. SUMMARY OF ANOVA OF SPLIT CYLINDER TEST RESULTS ON 6-INCH X 12-INCH CYLINDERS OBTAINED FROM THE FIELD

Classification of Variables

Class	Level	Values
CONTR	6	N1 N2 N3 N4 N5 N6
RATE	4	DRY 150 180 200
SECT	2	S1 S2

Source	DF	F value	Pr*	Significance a = 0.10
CONTR	5	127	< 0.01	Yes
SECT(CONTR)	1	-	-	-
δ	0	-	-	-
RATE	3	0.34	0.25 +	No
CONTR*RATE	12	7.82	0.14	No
SECT*RATE(CONTR)	2	0.11	0.25 +	No
ERROR	12	-	-	-

* Probability of rejection value associated with the F value

TABLE B.10. SUMMARY OF ANOVA OF SPLIT CYLINDER TEST RESULTS ON 6-INCH X 12-INCH CYLINDERS OBTAINED FROM THE FIELD. NORMALIZED VALUES.

Classification of Variables

Class	Level	Values
CONTR	6	N1 N2 N3 N4 N5 N6
RATE	4	DRY 150 180 200
SECT	2	S1 S2

Source	DF	F Value	Pr*	Significance a = 0.10
CONTR	5	57	< 0.01	Yes
SECT(CONTR)	1	0.20	0.25 +	No
δ	0	-	-	-
RATE	3	0.29	0.25 +	No
CONTR*RATE	12	7.38	0.16	No
SECT*RATE(CONTR)	2	0.12	0.25 +	No
ERROR	-	-	-	-

* Probability of rejection value associated with the F value

TABLE B.11. SUMMARY OF ANOVA OF FLEXURE TEST RESULTS ON 6-INCH X 12-INCH BEAMS OBTAINED FROM THE FIELD

Classification of Variables

Class	Level	Values
CONTR	6	N1 N2 N3 N4 N5 N6
RATE	4	DRY 150 180 200
SECT	2	S1 S2

Source	DF	F Value	Pr*	Significance a = 0.10
CONTR	5	400	< 0.01	Yes
SECT(CONTR)	1	-	-	-
δ	0	-	-	-
RATE	3	0.46	0.25 +	No
CONTR*RATE	12	1.61	0.25 +	No
SECT*RATE(CONTR)	2	0.92	0.25 +	No
ERROR	-	-	-	-

* Probability of rejection value associated with the F value

TABLE B.12. SUMMARY OF ANOVA OF FLEXURE TEST RESULTS ON 6-INCH X 21-INCH BEAMS OBTAINED FROM THE FIELD. NORMALIZED VALUES.

Classification of Variables		
Class	Level	Values
CONTR	6	N1 N2 N3 N4 N5 N6
RATE	4	DRY 150 180 200
SECT	2	S1 S2

Source	DF	F Value	Pr*	Significance a = 0.10
CONTR	5	219	<0.01	Yes
SECT(CONTR)	1	0.08	0.25 +	No
δ	0	-	-	-
RATE	3	0.41	0.25 +	No
CONTR*RATE	12	1.17	0.25 +	No
SECT*RATE(CONTR)	2	1.23	0.25 +	No
ERROR	-	-	-	-

* Probability of rejection value associated with the F value

TABLE B.13. SUMMARY OF ANOVA OF SURFACE DURABILITY TEST RESULTS ON 2-INCH SLICES FROM CORES OBTAINED FROM THE FIELD (MODEL D4)

Classification of Variables		
Class	Level	Values
CONTR	3	N4 N5 N6
RATE	7	DRY EX POLY 150 180 200 250
SECT	2	S1 S2

Source	DF	F Value	Pr*	Significance a = 0.10
CONTR 2	5.54	0.25 +	No	
SECT(CONTR)	1	-	-	-
δ	-	-	-	-
RATE	6	0.52	0.25 +	No
CONTR*RATE	8	0.49	0.25 +	No
RATE*SECT(CONTR)	-	-	-	-

* Probability of rejection value associated with the F value

TABLE B.14. SUMMARY OF ANOVA OF DENSITY TEST RESULTS ON 2-INCH SLICES FROM CORES OBTAINED FROM THE FIELD (MODEL D5)

Classification of Variables		
Class	Level	Values
CONTR	2	N1 N2
RATE	5	EX POLY 150 180 200
SECT	2	S1 S2
POS	2	T B
CORE	2	1 2

Source	DF	F Value	Pr*	Significance a = 0.10
CONTR	1	4.55	0.200	No
SECT(CONTR)	2	-	-	-
δ	-	-	-	-
RATE	4	0.52	0.25 +	No
CONTR*RATE	4	1.15		
RATE*SECT(CONTR)	2	0.87	-	-
CORE(CONTR*RATE*SECT)	14	-	-	-
ω	-	-	-	-
POS	1	1.10	0.25 +	No
CONTR*POS	1	0.33	0.25 +	No
SECT*POS(CONTR)	2	1.09	0.25 +	No
RATE*POS	4	2.83	0.128	No
CONTR*RATE*POS	4	0.74	0.25 +	No
RATE*SECT*POS(CONTR)	2	0.33	0.25 +	No
POS*CORE(CONTR*RATE*SECT)	14	-	-	-

* Probability of rejection value associated with the F value

APPENDIX C. SPECTRAL ANALYSIS OF SEISMIC WAVES (SASW) RESULTS

TABLE C.1. SASW TESTING SCHEDULE. ALL TIMES IN MINUTES AFTER CONCRETE MIXING.

Panel	Rate	Test #1	Test #2	Test #3	Test #4	Test #5	Test #6	Test #7	Test #8
1	DRY	190	245	369	434	544	770	1486	8160
2	150	272	-	393	-	560	775	1508	8221
3	250	214	-	420	-	600	790	1530	8230
4	180	299	-	464	-	573	806	1542	8240
7	200	340	-	519	-	639	827	1563	8250

TABLE C.2. YOUNG'S MODULUS. AVERAGE VALUES FOR RECEIVER SPACINGS OF 1.00 FT AND WAVELENGTHS OF 0.25, 0.50, AND 0.75 FOOT. ALL VALUES IN PSI X 10^6.

Panel	Rate	Test #1	Test #2	Test #3	Test #4	Test #5	Test #6	Test #7	Test #8
1	DRY	0.43	0.98	2.09	2.51	3.26	3.84	4.23	4.35
2	150	1.31	-	2.96	-	2.98	4.21	4.60	4.90
3	250	0.23	-	2.01	-	3.31	3.70	4.14	4.40
4	180	1.16	-	3.00	-	3.25	3.95	4.56	4.60
7	200	1.00	-	2.63	-	2.92	3.32	3.88	4.15

TABLE C.3. YOUNG'S MODULUS. AVERAGE VALUES FOR RECEIVER SPACINGS OF 0.50 FT AND WAVELENGTHS OF 0.25, 0.50, AND 0.75 FOOT. ALL VALUES IN PSI X 10^6.

Panel	Rate	Test #1	Test #2	Test #3	Test #4	Test #5	Test #6	Test #7	Test #8
1	DRY	*	*	*	*	*	*	*	*
2	150	1.17	-	2.47	-	3.22	3.92	4.51	4.49
3	250	*	-	*	-	*	*	*	*
4	180	0.96	-	2.51	-	3.22	3.53	4.19	4.37
7	200	*	-	*	-	*	*	*	*

APPENDIX D. LABORATORY EXPERIMENT RESULTS

TABLE D.1. LABORATORY EXPERIMENT. SPLIT TENSILE TEST, 6-INCH X 12-INCH CYLINDERS. ALL VALUES IN PSI. CYLINDER "A" IS THE CONTROL SPECIMEN.

			Rate											
			200				180				150			
			Cylinder				Cylinder				Cylinder			
AT	**CT**	**RH**	**#1**	**#2**	**#3**	**N**	**#1**	**#2**	**#3**	**N**	**#1**	**#2**	**#3**	**N**
High	**High**	**High**												
		Med												
		Low					426	494	461	490				
	Med	**High**												
		Med												
		Low					382	426	397	475				
	Low	**High**												
		Med												
		Low					382	359	375	428				
Med	**High**	**High**					477	498	427	411				
		Med					439	386	404	407				
		Low												
	Med	**High**					476	413	431	513				
		Med	433	468	408	431	406	409	404	470	361	373	402	417
		Low												
	Low	**High**					448	416	387	421				
		Med					446	448	393	413				
		Low												

TABLE D.2. LABORATORY RESULTS, 6-INCH X 12-INCH CYLINDERS. NORMALIZED DATA. ALL VALUES REPRESENT PERCENTAGES OF THE SPLIT TENSILE STRENGTH OF THE CONTROL CYLINDER OF EACH BATCH. (DESIGNATED AS SPECIMEN "N")

			Rate											
			200				180				150			
			Cylinder				Cylinder				Cylinder			
AT	CT	RH	#1	#2	#3	N	#1	#2	#3	N	#1	#2	#3	N
High	High	High												
		Med												
		Low					87	101	94	100				
	Med	High												
		Med												
		Low					80	90	84	100				
	Low	High												
		Med												
		Low					89	84	88	100				
Med	High	High					116	121	104	100				
		Med					108	95	99	100				
		Low												
	Med	High					93	82	84	100				
		Med	100	109	95	100	86	87	86	100	87	89	96	100
		Low												
	Low	High					106	99	92	100				
		Med					108	108	95	100				
		Low												

TABLE D.3. LABORATORY RESULTS. FLEXURE TEST, 6-INCH X 12-INCH BEAMS. ALL VALUES IN PSI. BEAM "N" IS THE CONTROL SPECIMEN.

			Rate											
			200				180				150			
			Cylinder				Cylinder				Cylinder			
AT	CT	RH	#1	#2	#3	N	#1	#2	#3	N	#1	#2	#3	N
High	High	High												
		Med												
		Low					587	570	540	670				
	Med	High												
		Med												
		Low					567	590	610	630				
	Low	High												
		Med												
		Low					587	695	585	633				
Med	High	High					680	690	650	630				
		Med					655	600	510	650				
		Low												
	Med	High					655	665	690	685				
		Med												
		Low												
	Low	High					773	640	660	625				
		Med					590	600	535	660				
		Low												

TABLE D.4. LABORATORY RESULTS. 6-INCH X 21-INCH BEAMS. NORMALIZED DATA. ALL VALUES ARE PERCENTAGES OF THE FLEXURAL STRENGTH OF THE CONTROL BEAM OF EACH BATCH. (DESIGNATED AS SPECIMEN)

			Rate											
			200				180				150			
			Cylinder				Cylinder				Cylinder			
AT	CT	RH	#1	#2	#3	N	#1	#2	#3	N	#1	#2	#3	N
High	High	High												
		Med												
		Low					88	85	81	100				
	Med	High												
		Med												
		Low					90	94	97	100				
	Low	High												
		Med												
		Low					93	110	92	100				
Med	High	High					108	110	103	100				
		Med					101	92	78	100				
		Low												
	Med	High					96	97	101	100				
		Med	101	96	104	100	104	111	100	100	107	103	108	100
		Low												
	Low	High					124	102	106	100				
		Med					89	91	81	100				
		Low												

APPENDIX E. ANALYSIS OF VARIANCE RESULTS FOR THE LABORATORY EXPERIMENT

TABLE E.1. SUMMARY OF ANOVA OF FLEXURAL STRENGTH TEST RESULTS ON 6-INCH X 21-INCH CYLINDERS PREPARED IN THE LABORATORY (MODEL 5A)

Classification of Variables		
Class	Levels	Values
AT	2	H M
CT	3	H M L
RH	2	H M L

Source	DF	F Value	Pr*	Significance a = 0.10
AT	0	-	-	-
CT	2	17.5	< 0.01	Yes
RH	1	0.91	0.25 +	No
CT*RH	4	2.94	0.05	Yes
Error	18	-	-	-

* Probability of rejection value associated with the F value

TABLE E.2. SUMMARY OF ANOVA OF FLEXURAL STRENGTH TEST RESULTS ON 6-INCH X 21-INCH CYLINDERS PREPARED IN THE LABORATORY (MODEL 5B)

Classification of Variables		
Class	Levels	Values
RATE	3	200 180 150

Source	DF	F Value	Pr*	Significance a = 0.10
RATE	2	4.70	0.05	Yes
ERROR	6	-	-	-

* Probability of rejection value associated with the F value

TABLE E.3. SUMMARY OF ANOVA OF FLEXURAL STRENGTH TEST RESULTS ON 6-INCH X 21-INCH BEAMS PREPARED IN THE LABORATORY (MODEL 5A)

Classification of Variables

Class	Levels	Values
AT	2	H M
CT	3	H M L
RH	2	H M L

Source	DF	F Value	Pr*	Significance $\alpha = 0.10$
AT	0	-	-	-
CT	2	1.29	0.25 +	No
RH	1	10.5	< 0.01	Yes
CT*RH	4	4.51	0.01	Yes
ERROR	18	-	-	-

* Probability of rejection value associated with the F value

TABLE E.4. SUMMARY OF ANOVA OF FLEXURAL STRENGTH TEST RESULTS ON 6-INCH X 21-INCH BEAMS PREPARED IN THE LABORATORY (MODEL 5B)

Classification of Variables

Class	Levels	Values
RATE	3	200 180 150

Source	DF	F Value	Pr*	Significance $\alpha = 0.10$
RATE	2	0.52	0.25 +	No
ERROR	6	-	-	-

* Probability of rejection value associated with the F value