EVALUATION AND PREDICTION OF TENSILE PROPERTIES OF CEMENT-TREATED MATERIALS

by

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Research Report Number 98-8

Evaluation of Tensile Properties of Subbases
for Use in New Rigid Pavement Design

Research Project 3-8-66-98

conducted for

The Texas Highway Department

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

October 1970

PREFACE

This is the eighth in a series of reports dealing with the findings of a research project concerned with the evaluation of properties of stabilized subbase materials. This report is intended to provide a detailed investigation of the effects of six factors on the tensile properties of cement-treated materials. Also, this report presents the findings of a correlation study between indirect tensile strengths for cement-treated materials and unconfined compressive strengths and cohesiometer values. In addition the findings of the effect of specimen size with regard to tensile strength is reported.

The culmination of this report required the assistance of many individuals whose efforts the authors would like to acknowledge. Special thanks are extended to Dr. Gerald Wagner, Messrs. Thomas A. Ohlendorf, Joseph A. Kozuh, Raymond K. Moore, and William O. Hadley for their help in designing the statistical experiment and providing guidance in the analysis of the data. Special appreciation is due Mr. Pat Hardeman for his assistance in the preparation and testing phase of the study. Thanks are also due to Messrs. James L. Brown and Larry J. Butler of the Texas Highway Department, who provided the technical liaison for the project.

Future reports will be concerned with:

(1) a detailed factor study involving asphalt-treated materials,

(2) a linkup analysis between the preliminary factor and detailed factor experiment of lime-treated materials,

(3) a linkup analysis between the preliminary factor and detailed factor evaluation experiment of cement-treated materials,

(4) a preliminary layered-system design method, and

(5) a correlation between the beam-flexural test and indirect tensile test for asphalt-treated materials.

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LIST OF REPORTS

Report No. 98-1, "An Indirect Tensile Test for Stabilized Materials," by W. Ronald Hudson and Thomas W. Kennedy, summarizes current knowledge of the indirect tensile test, reports findings of limited evaluation of the test, and describes the equipment and testing techniques developed.

Report No. 98-2, "An Evaluation of Factors Affecting the Tensile Properties of Asphalt-Treated Materials," by William O. Hadley, W. Ronald Hudson, and Thomas W. Kennedy, discusses factors important in determining the tensile strength of asphalt-treated materials and reports findings of an evaluation of eight of these factors.

Report No. 98-3, "Evaluation of Factors Affecting the Tensile Properties of Cement-Treated Materials," by Humberto J. Pendola, Thomas W. Kennedy, and W. Ronald Hudson, presents factors important in determining the strength of cement-treated materials and reports findings of an evaluation by indirect tensile test of nine factors thought to affect the tensile properties of cement-treated materials.

Report No. 98-4, "Evaluation of Factors Affecting the Tensile Properties of Lime-Treated Materials," by S. Paul Miller, Thomas W. Kennedy, and W. Ronald Hudson, presents factors important in determining the strength of cement-treated materials and reports findings of an evaluation by indirect tensile test of eight factors thought to affect the tensile properties of lime-treated materials.

Report No. 98-5, "Evaluation and Prediction of the Tensile Properties of Lime-Treated Materials," by Walter S. Tulloch, II, W. Ronald Hudson, and Thomas W. Kennedy, a detailed investigation by indirect tensile test of five factors thought to affect the tensile properties of lime-treated materials and reports findings of an investigation of the correlation between the indirect tensile test and standard Texas Highway Department tests for lime-treated materials.

Report No. 98-6, "Correlation of Tensile Properties with Stability and Cohesiometer Values for Asphalt-Treated Materials," by William O. Hadley, W. Ronald Hudson, and Thomas W. Kennedy, presents a detailed correlation of indirect tensile test parameters, i.e., strength, modulus of elasticity, Poisson's ratio, and failure strain, with stability and cohesiometer values for asphalt-treated materials.

Report No. 98-7, "A Method of Estimating Tensile Properties of Materials Tested in Indirect Tension," by William O. Hadley, W. Ronald Hudson, and Thomas W. Kennedy, presents the development of equations for estimating material properties such as modulus of elasticity, Poisson's ratio, and tensile strain based upon the theory of the indirect tensile test and reports verification of the equations for aluminum.

Report No. 98-8, "Evaluation and Prediction of Tensile Properties of Cement-Treated Materials," by James N. Anagnos, Thomas W. Kennedy, and W. Ronald Hudson, investigates, by indirect tensile test, six factors affecting the tensile properties of cement-treated materials, and reports the findings of an investigation of the correlation between indirect tensile strength and standard Texas Highway Department tests for cement-treated materials.

ABSTRACT

This report describes the continuation of an investigation of the indirect tensile properties of cement-treated materials and was accomplished with a statistically designed experiment. The six factors investigated were molding water content, aggregate gradation, curing temperature, compactive effort, cement content, and aggregate type. The indirect tensile strengths, vertical failure deformations, and horizontal failure deformations were the parameters measured. All main effects, interaction effects, and curvilinear effects on indirect tensile strength have been summarized. In addition, through regression analysis, a predictive equation for indirect tensile strengths was developed for the six factors evaluated.

Two additional experiments were performed in an attempt to develop correlation equations relating indirect tensile strengths with the unconfined compression strengths and the cohesiometer values for cement-treated materials. One of the correlation experiments compared the indirect tensile strengths with the unconfined compressive strengths and cohesiometer values of cement-treated materials compacted and cured in a manner other than that utilized by the Texas Highway Department. The other correlation experiment compared the indirect tensile strengths with the unconfined compressive strength and cohesiometer values of specimens prepared, compacted, and cured by Texas Highway Department procedures. Through regression analyses, prediction equations were developed from both experiments.

A third experiment was conducted to evaluate the effects of specimen size. The results indicated that specimen size had no effect on indirect tensile strength.

KEY WORDS: tensile strength, cohesiometer, unconfined compression, specimen size, cement-treated, test correlation.

SUMMARY

The purpose of this report is to summarize the findings of an expanded investigation to determine the factors affecting the tensile strengths of cement-treated materials, to correlate tensile strengths with the unconfined compressive strengths and cohesiometer values, to determine the effect of specimen size on tensile strength, and to develop predictive equations for determining tensile strengths.

Of the six factors investigated, molding water content, aggregate gradation, curing temperature, compactive effort, cement content, and aggregate type, it was determined that two of the factors, aggregate gradation and compactive effort, had little or no effect upon tensile strengths.

As expected, the tensile strengths were increased by:

(1) increasing the cement content;

(2) using crushed limestone aggregates rather than Seguin gravel;

(3) increasing the molding water content to some optimum value, above which increasing the water content decreased the strength; and

(4) increasing the curing temperature.

The magnitude of the effects produced by these factors was influenced by the level of other factors.

Two of the three interactions which were found to be important showed that cement-treated mixtures containing limestone not only had higher tensile strengths, but also exhibited larger strength gains due to increased cement or molding water contents than did mixtures containing gravel.

The third interaction which involved molding water content and cement content indicated that an adequate amount of water must be available for the proper hydration of the cement.

A predictive equation containing 20 terms was developed to estimate tensile strengths and accounts for 93 percent of the observed variations within an estimated error of ±29.0 psi.

Correlation equations were also developed which enable the tensile strengths to be estimated from the unconfined compressive strengths or the

cohesiometer values. The correlations between the indirect tensile strength and the cohesiometer value were very good; however, the correlations between the indirect tensile strength and the unconfined compressive strength were only fair. In both cases, however, relative large errors could be expected if tensile strengths were estimated utilizing these equations alone.

The Specimen Size Study, as previous theoretical and experimental findings have shown, indicated that size has essentially no effect on the tensile strengths of cement-treated materials.

IMPLEMENTATION STATEMENT

This study is a portion of a comprehensive program to provide a better understanding of the behavior and performance of stabilized materials as components of a pavement structure. The results will be used in a subsequent phase of the study on repeated loading. They will also be used in a comparison of cement-treated materials and the findings for asphalt-treated and lime-treated materials to develop overall information for stabilized materials.

Furthermore, the detailed findings concerning the effects of individual factors on tensile strengths can be used to develop design information for cement-stabilized mixtures. The ability to estimate tensile strengths from the unconfined compressive strengths and cohesiometer values by the use of the prediction equations can be used to assist the designer in evaluating cement pavement design techniques.

Texas Highway Department personnel can immediately apply the information in this report to improve their understanding and design of cement-treated materials. In addition, the results will be integrated into an overall stabilized pavement layer design method.

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CHAPTER 1. INTRODUCTION

The Center for Highway Research at The University of Texas at Austin is currently studying the tensile properties of subbase materials treated with asphalt, cement, or lime. The factors affecting the tensile properties of these treated materials were evaluated by three screening experiments and the results have been previously reported (Refs 1, 9, and 7).

This report is a continuation of the cement-treated materials investigation (Ref 9). The investigation of the indirect tensile properties of cement-treated materials was continued in an experiment called the Factor Evaluation Experiment and is described in Chapters 3 and 4.

In addition, the experiment compares the indirect tensile test as developed by the Center for Highway Research (Ref 3) to the standard Texas Highway Department tests (the unconfined compression test and the cohesiometer test) for cement-treated materials.

A comparison of the indirect tensile properties of cement-treated materials to the standard Texas Highway Department test for cement-treated materials was accomplished in two experiments. The first experiment, the General Correlation, compares the indirect tensile strengths with the unconfined compressive strengths and cohesiometer values of cement-treated materials compacted and cured in a manner other than that used by the Texas Highway Department. Chapters 3 and 5 describe this experiment in detail.

The second experiment, the Texas Highway Department Correlation, compares the indirect tensile strengths with the unconfined compressive strengths and cohesiometer values using specimens that were prepared, compacted, and cured by Texas Highway Department procedure and tested by standard procedures utilized by the Texas Highway Department and the Center for Highway Research. This experiment is also described in detail in Chapters 3 and 5.

In addition, a specimen size study comparing the indirect tensile strengths of 6-inch-diameter specimens and 4-inch-diameter specimens was made and is described in Chapters 3 and 5.

CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

A considerable amount of research on the characteristics of cement-treated materials has been accomplished. This chapter includes a brief summary of previous research which is related to the present study and a summary of the work reported by Pendola, Kennedy, and Hudson (Ref 9). In addition, a review of the available literature dealing with test correlations for cement-treated specimens and with studies of the effect of specimen size on indirect tensile test results is included.

PREVIOUS SOIL-CEMENT RESEARCH FINDINGS

The addition of portland cement to a soil usually results in a material with engineering characteristics which are significantly improved as compared to the properties of the unaltered soil. In general, cement-treated soils exhibit the following changes (Ref 9):

(1) reduced plasticity indices,
(2) increased plastic limits,
(3) reduced liquid limits (for soils with liquid limits greater than 40) or increased liquid limits (for soils with liquid limits less than 40),
(4) increased strengths,
(5) reduced permeabilities, and
(6) reduced volume changes.

These changes are generally attributed to one or to a combination of two or more of the four mechanisms or reactions involving soil and portland cement:

(1) hydration,
(2) cation exchange,
(3) carbonation, and
(4) pozzolanic reaction

with the latter two being of minor importance.

From a literature review Pendola et al (Ref 9) concluded that the more important factors affecting cement-treated materials were:

(1) water content at the time of mixing and compaction,
(2) cement content,
(3) type of soil
(4) gradation of the soil,
(5) type of curing,
(6) length of the curing period,
(7) temperature of curing,
(8) method of compaction,
(9) compactive effort, and
(10) density of the compacted mixture.

In addition, the literature review indicated that unconfined compressive strength was increased by:

(1) an increase in cement content,
(2) an increase in density,
(3) the use of coarse graded materials,
(4) the use of angular aggregates,
(5) an increase in molding moisture content in the range below optimum,
(6) a better retention of moisture during the curing period,
(7) an increase of curing time,
(8) an increase of curing temperature,
(9) the use of a low shear strain type of compaction at moisture contents above optimum,
(10) an increase in compactive effort,
(11) a decrease of mixing time,
(12) an increase in the degree of pulverization of the soil, and
(13) the use of high early-strength cement for curing periods of less than 28 days.

RESULTS OF PRELIMINARY STUDY

On the basis of their literature review Pendola et al (Ref 9) conducted a broad statistically designed screening experiment to study the effect of the first nine factors listed above on the indirect tensile strength of cement-treated specimens. The experiment was designed to evaluate the significance of all nine main effects, all two-factor interactions and selected higher order interactions. Table 1 summarizes the factors and levels selected for the experiment.

The analysis of the experimental data revealed that seven of the nine factors produced significant main effects on the indirect tensile strength at a probability level of 1 percent and that the average strength was significantly increased by:

(1) increasing the molding water content from 3 to 7 percent,
(2) using sealed rather than air-dried curing,
(3) increasing the cement content from 4 to 8 percent,
(4) using crushed limestone rather than rounded gravel aggregates,
(5) using a high compactive effort,
(6) curing for 21 days rather than 7 days, and
(7) using impact compaction rather than gyratory shear compaction.

Eleven of the 36 two-factor interactions evaluated produced significant effects on the indirect tensile strength at a probability level of 1 percent. These interactions were

(1) molding water content x cement content,
(2) molding water content x type of curing,
(3) type of curing x aggregate type,
(4) type of aggregate x cement content,
(5) molding water content x aggregate type,
(6) type of curing x cement content,
(7) molding water content x aggregate gradation,
(8) molding water content x type of compaction,
(9) curing temperature x aggregate type,
(10) molding water content x curing time, and
(11) curing time x compactive effort.

Two three-factor and one four-factor interactions were found to be significant at a probability level of 1 percent. The four-factor interaction was confounded with another four-factor interaction and therefore could not be evaluated. The three-factor interactions were

(1) molding water content x type of curing x cement content and
(2) aggregate type x type of curing x cement content.

TABLE 1. FACTORS AND LEVELS SELECTED FOR THE EXPERIMENT

Factor	Level: Low	Level: Medium	Level: High	Variable Type
A. Molding water content, %	3	5	7	Quantitative
B. Curing time, days	7	14	21	Quantitative
C. Aggregate gradation*	Fine	Medium	Coarse	Qualitative
D. Type of curing	Air-dried	--	Sealed	Qualitative
E. Aggregate type	Gravel	--	Limestone	Qualitative
F. Curing temperature, °F	40	75	110	Quantitative
G. Compactive effort	Low	--	High	Qualitative
H. Type of compaction	Impact	--	Gyratory shear	Qualitative
J. Cement content, %	4	6	8	

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* See Appendix 2.

In addition to the highly significant effects summarized above, one main effect, four two-factor interaction effects, seven three-factor interaction effects, and two four-factor interaction effects were found to be significant at a probability level of 5 percent.

Curing temperature was the only factor which did not produce a significant main effect at a level of 5 percent. However, there was evidence that moisture needed for hydration was driven from the specimens cured at 110° F. Thus, the benefits of increased temperature may have been offset by the loss of moisture.

Molding water content was the most important factor affecting the strength of the cement-treated materials since it was a highly significant main effect and was involved in 6 of the 11 highly significant two-factor interaction effects.

By regression Pendola also obtained a preliminary prediction equation for indirect tensile strength in terms of the nine factors studied. This equation contained ten terms, and a multiple correlation coefficient of 95 percent, and had a standard error of estimate of ± 32.02 psi.

Because the experiment was not a full-factorial design and the specimens were arranged in blocks, all possible interactions could not be evaluated. Furthermore, the complexity of the findings with so many significant effects indicated that a more complete experiment was needed in order to understand the problem. Also, more and more attention has been given to strain failure as a critical design factor. Thus, specimen deformations involved in tensile failure also needed to be investigated as did the relationship of the indirect tensile strength to the results of other tests. In order that research such as the experiments conducted at the Center for Highway Research using the indirect tensile test can be related to past and future work involving other more commonly used tests, correlations involving these tests were also conducted.

TEST CORRELATIONS

The Texas Highway Department currently uses the unconfined compression test and the cohesiometer test to evaluate cement-treated materials, and therefore, has some experience with these tests. It thus seemed desirable that the relationship between these test results and the indirect tensile strength be investigated. Since standard Texas Highway Department specimens have 6-inch diameters and since all previous soil-cement research at the Center for Highway Research has been conducted using 4-inch-diameter specimens, a study was also performed to determine the effect of specimen diameter on the indirect tensile test results.

A considerable amount of work using the unconfined compression test and a lesser amount using the indirect tensile test to study cement-treated materials has been accomplished; however, little work has been conducted to correlate cohesiometer or unconfined compression test results with indirect tensile test results for cement-treated materials.

Metcalf and Frydman (Ref 5) reported that the tensile strength is between one-twelfth and one-tenth of the unconfined compressive strength for stabilized soils. Mitchell (Ref 8) and several other authors (Ref 3) reported that on the basis of theoretical and experimental considerations specimen size has little effect on the indirect tensile strength of the specimen although the average tensile strength and the dispersion of the test results should be slightly less for larger specimens.

The experimental program used to investigate the properties of cement-treated materials and for the correlations and specimen size studies is given in Chapter 3.

CHAPTER 3. EXPERIMENTAL PROGRAM

This chapter describes the overall experimental program which includes:

(1) Factor Evaluation Experiment,
(2) General Correlation,
(3) Texas Highway Department Correlation, and
(4) Specimen Size Study.

The test results and those details which pertain only to a particular part of the experiment are discussed in Chapter 4 for the Factor Evaluation Experiment and Chapter 5 for the Correlation and Specimen Size Study.

SELECTION OF FACTORS

In choosing a statistical design for the detailed investigation, several objectives had to be kept in mind. The number of specimens had to be small enough to be produced in one day in order to maintain homogeneity. It was desirable that all interactions be analyzed since this was not possible in the preliminary experiment on cement-treated materials and since the preliminary experiment indicated that a more thorough investigation of the interactions was needed. It was also desirable that the curvilinear effects of all factors be measured.

As previously mentioned, Pendola et al (Ref 9) found that all nine factors produced a significant effect, either as main effects or as interactions. Since the objective of the detailed investigation was to develop more detailed information, it was not possible to study all nine factors without requiring an extremely large number of specimens. Thus, the number of factors had to be reduced.

On the basis of their judged practical significance in the design process, three of the original nine factors were eliminated, curing time, type of compaction, and curing type. The remaining six were

(1) molding water content,
(2) aggregate gradation,

(3) curing temperature,
(4) compactive effort,
(5) cement content, and
(6) aggregate type.

In the Factor Evaluation Experiment, these six factors were allowed to vary; however, in the correlation experiments compactive effort, curing temperature, and aggregate gradation were held constant. The factors and factor levels studied are discussed below.

Compactive Effort

A significant range of densities over which to study the effect of compactive effort was desired, and the range of compactive efforts had to be such that testable specimens could be produced. Since each type of compaction had its compactive effort controlled in a different manner, a range of compactive efforts had to be chosen for each compaction type. The low end of the range was the compactive effort below which a specimen would not hold together and the high end was the compactive effort above which insignificant increases in density were obtained. The compaction procedures associated with the various levels are presented in Appendix 4.

Cement Content

Cement contents up to 10 percent are of interest in the stabilization of pavement materials. Pendola et al (Ref 9) studied three levels, 4, 6, and 8 percent, which covered the range of practical interest. For this study, however, the range was extended to include cement contents from 2 to 10 percent. A portland cement, available locally, was chosen for this study.

Molding Water Content

Molding water contents were varied from 4 to 9 percent. It was felt that in the preliminary experiment, the high level of molding moisture, 7 percent, was too low, particularly when curvilinear effects were anticipated. Furthermore, this range enabled specimens to be compacted with a small probability that too little water was present and that the specimens would fail as they were extruded from the compaction mold.

Curing Temperature

A range of curing temperatures from 50° F to 150° F was chosen for this study. Previous studies have indicated that little cement reaction occurs at temperatures below 40° F. The upper end of the curing temperature range was fixed at 150° F since this was the maximum expected in the field.

Factors Held Constant

Throughout each of the four experiments, several factors were held constant. Curing time was fixed at seven days since the Texas Highway Department procedures specify this time and since it was felt that this was a reasonable length of time for curing in the field before the cement-treated material would be loaded. Impact compaction was used for the Texas Highway Department Correlation since this is the standard type of compaction currently used by the Texas Highway Department for cement-treated materials. Gyratory shear compaction was selected as the type of compaction for the Factor Evaluation Experiment, General Correlation, and the Specimen Size Study since it seemed to produce a specimen more uniform in density and height than could be produced by impact compaction.

The curing procedure for the Texas Highway Department Correlation was in accordance with Texas Highway Department standard procedures which require the specimens to be stored in a damp room with top and bottom porous stones in place. The specimens in the other three experiments were wrapped or sealed with a single layer of PVC film. Wrapping the specimens helped retain moisture as it is attempted in the field through the use of protective coatings or sprinkling.

SPECIMEN PREPARATION

Specimen preparation was divided into three phases: (1) batching and mixing, (2) compaction, and (3) curing. The procedures used for batching and mixing are summarized in Appendix 3. The specimens in the Factor Evaluation Experiment were compacted on a Texas Highway Department gyratory shear compactor for 4-inch-diameter specimens.

Those specimens used in the General Correlation were 6 inches in diameter and were compacted on a gyratory shear compactor and were cured in the same manner as in the main experiment.

The Texas Highway Department Correlation specimens were 6 inches in diameter and were compacted in accordance with standard Texas Highway Department procedures on an automatic drop-hammer compactor. These specimens were cured according to standard Texas Highway Department curing procedures.

The Specimen Size Study specimens were 6 inches and 4 inches in diameter and were taken from the General Correlation and Factor Evaluation Experiment, respectively.

The compaction procedure and curing procedure used in all of the experiments are described in Appendices 4 and 5, respectively.

STANDARD TEST PROCEDURES

The procedure followed for the indirect tension testing of soil-cement specimens was the same as that originally recommended by Hudson and Kennedy (Ref 3) and later modified slightly (Ref 1) and was the same as that used in the previous study of cement-treated materials as reported by Pendola et al (Ref 9). Testing was conducted at 75° F at a loading rate of 2 inches per minute. The specimens had a nominal diameter of 4 or 6 inches and a nominal height of 2 inches. A 1/2-inch-wide loading strip with a curved face with a radius of 3 inches was used to test the 6-inch-diameter specimens, and a strip with a curved face with a radius of 2 inches was used to test the 4-inch-diameter specimens. The procedure for this test is described in detail in Appendix 6.

The unconfined compression tests were performed according to standard Texas Highway Department procedures, Test Method Tex-120-E (Ref 4). This procedure is described in Appendix 6. The specimens had a nominal diameter of 6 inches and a nominal height of 8 inches.

All cohesiometer specimens were tested in accordance with the procedures utilized by the Texas Highway Department, Test Method Tex-122-E (Ref 4). This procedure is described in Appendix 6. The specimens had a nominal diameter of 6 inches and a nominal height of 2 inches.

PARAMETER EVALUATED

Tensile stress at failure was the primary parameter evaluated for those specimens tested in indirect tension. In addition, the vertical failure deformations and the horizontal failure deformations were recorded for the specimens in the factor experiment. Failure was defined as the maximum load applied to the specimen. Typical load-vertical deformation and load-horizontal deformation curves for cement-treated materials are shown in Fig 1. The indirect tensile strength was determined by the use of the following equation (see Fig 2 for notation):

$$\hat{S}_t = \frac{2P}{\pi at} (\sin 2\alpha - \alpha) \qquad (3.1)$$

where

$\hat{S}_t$ = indirect tensile strength;

P = the total vertical load on the specimen at failure;

a = the width of the loading strip, 0.5 inches; and

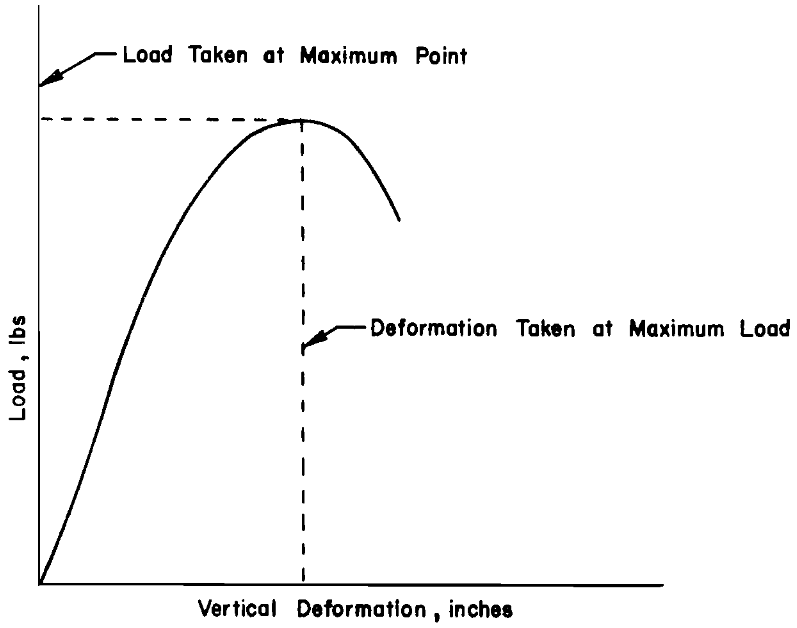
t = height of the specimen.

α is defined in Fig 2.

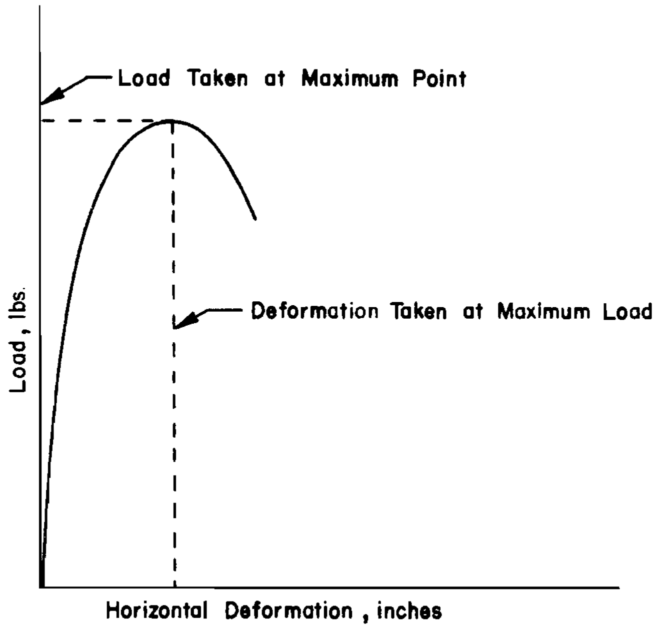
Vertical failure deformation was the vertical deformation of a specimen at the failure load. This deformation was recorded on the load-vertical deformation plot and was assumed to be equal to the movement of the upper platen from the point of initial load application to the point of failure load as measured by a DC differential transformer. Horizontal failure deformation was the horizontal deformation of the specimen at the failure load and was recorded on the load-horizontal deformation plot. Horizontal deformations were measured by a lateral deflection device shown in Appendix 6, Fig A5.

The unconfined compressive strength at failure was the parameter evaluated for the unconfined compression test. Failure is defined in Texas Highway Department Test Method Tex-120-E (Ref 4) as the maximum load sustained by the specimen. The following equation was used to obtain this parameter:

$$p = \frac{P}{A} \qquad (3.2)$$



(a) Load-vertical deformation curve.



(b) Load-horizontal deformation curve.

Fig 1. Typical load-deformation curves for indirect tensile testing or cement-treated materials.

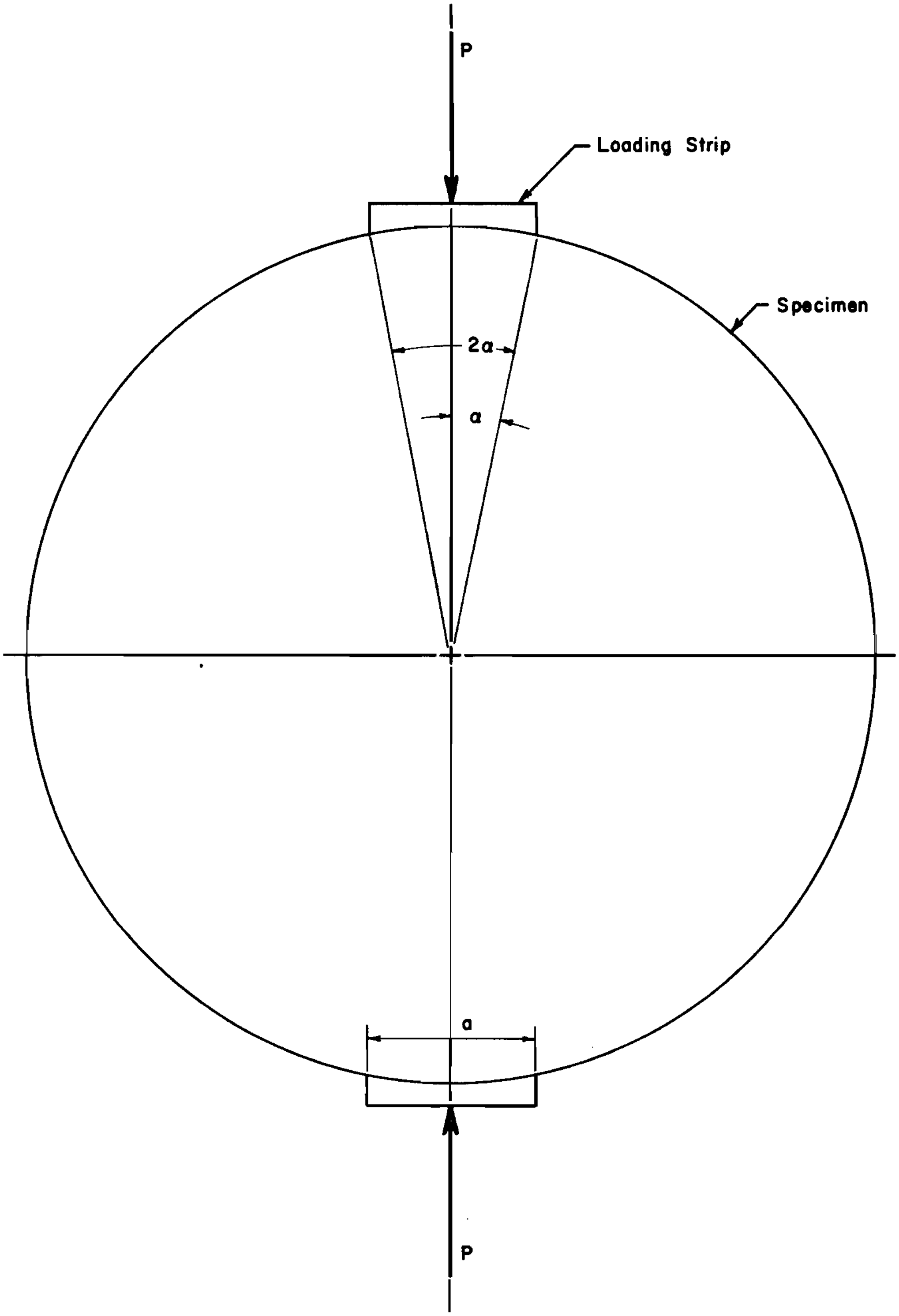


Fig 2. Notation for indirect tensile test.

where

p = vertical unit stress in psi,

P = total vertical load on specimen at failure, and

A = end area of the cylindrical specimen at beginning of test.

The cohesiometer value, the parameter evaluated for the cohesiometer test, is defined in Texas Highway Department Test Method Tex-122-E (Ref 4) as the load in grams required to break a test specimen 3 inches in height and 1 inch wide and was obtained by using the following equations:

$$C = \frac{P}{W(0.2t + 0.044t^2)} \tag{3.3}$$

where

C = cohesiometer value (grams per inch width corrected to a 3-inch height);

P = load of shot, grams;

W = diameter of specimen, inches; and

t = height of specimen, inches.

CHAPTER 4. FACTOR EVALUATION EXPERIMENT

Preliminary experimental work by Pendola et al (Ref 9) provided a broad investigation of the effects of compactive effort, cement content, aggregate type, aggregate gradation, molding water content, curing temperature, type of compaction, curing time, and type of curing on the tensile strength of cement-treated materials.

The selection of an appropriate experiment design for a more detailed study of cement-treated materials was based on the following criteria. A full factorial was included in the statistical design to analyze all main effects and interactions of the six factors studied, and the levels were expanded to five rather than two or three as used by Pendola. Unless the number of factors was reduced, these modifications would require that a large number of specimens be prepared, tested, and analyzed.

The Center for Highway Research laboratory facilities are capable of producing approximately 100 specimens in a given day; these specimens are 2 inches high by 4 inches in diameter and compacted by the small Texas Highway Department gyratory shear compactor. It was desirable to compact a complete set of specimens in one day to preclude any day-to-day variation. Consequently, this experiment was designed so that the number of specimens did not exceed the one-day compaction capabilities of the available laboratory facilities.

EXPERIMENTAL DESIGN

A central, composite, rotatable full-factorial statistical design was selected for use in this experiment. This economical and efficient design allowed curvilinear, interaction, and main effects to be studied with a minimum number of observations. The design consisted of a 2^6 full factorial of 64 specimens, 20 star-point specimens, and 12 center-point specimens. A total of 96 specimens was compacted, tested, and analyzed. The star points assigned to each factor consisted of the extreme high and extreme low levels of that factor combined with the middle levels of the remaining factors. The center points were repeated specimens using the middle levels of all the factors. The full factorial design enabled all main effects and interactions to be analyzed while the star and center points provided data on the curvilinear effects. In addition, the experimental error was estimated by the replicated center points. The factors and their levels for the Factor Evaluation Experiment are presented in Table 2.

EXPERIMENTAL RESULTS

The indirect tensile strengths for the Factor Evaluation Experiment are presented in Table 3. The horizontal and vertical failure deformation, along with densities and water contents at the time of testing, are shown in Appendix 7, Table A5. The results from this experiment cannot be compared directly to the preliminary investigation (Ref 9) since the factors and levels are different and since all of the specimens in the preliminary experiment were allowed to air dry to a constant moisture content before testing whereas the specimens in this experiment were tested immediately after being removed from curing.

Table 4 presents those effects which were found to have a significant effect on the indirect tensile strength at a probability level of 5 percent or better. The mean squares for residual is the sum of squares for all the terms, which were not significant at the 5 percent level, divided by 75, the number of degrees of freedom for these terms. The mean squares for the various effects were divided by the error mean square obtained from the repeated center point specimens to obtain an F value for each effect. Only the effects found to be significant at the 1 percent level are discussed. No interactions above a two-factor interaction were found to be significant at this level. The relationships for the highly significant main effects, two-factor interactions, and quadratic effects are illustrated by the use of bar graphs.

The data points representing main factors and interactions are average values of the tensile strengths for all the specimens containing a given level or combination of levels. Each plotted point for a main factor is the mean value obtained from the 16 specimens which included that particular level of the factor. There are four possible combinations of factors for a two-factor interaction; therefore, each value plotted is the mean for the data from eight different specimens.

TABLE 2. EXPERIMENTAL FACTORS AND LEVELS

	Level					
Factor	-2	-1	0	+1	+2	Variable Type
A. Molding water content, %	4.0	5.25	6.5	7.75	9.0	Quantitative
B. Aggregate gradation**	Fine	Fine +	Medium	Medium +	Coarse	Qualitative
C. Curing temp., °F	50	75	100	125	150	Quantitative
D. Compactive effort**	60	85	110	135	160	Quantitative
E. Cement content, %	2	4	6	8	10	Quantitative
F. Aggregate type		Seguin Gravel		Crushed Limestone		Qualitative

---

* See Appendix 2.

** See Appendix 4, Gyratory Compaction of 4-Inch-Diameter Specimens.

TABLE 3. EXPERIMENTAL RESULTS - MAIN EXPERIMENT

Specimen Number	Tensile Strengths, psi
1	110
2	93
3	117
4	76
5	114
6	115
7	133
8	123
9	112
10	94
11	142
12	85
13	128
14	108
15	129
16	126
17	159
18	147
19	189
20	220
21	202
22	269
23	195
24	274
25	230
26	227
27	215
28	240
29	194
30	267
31	213
32	216
33	102
34	163
35	242
36	207
37	193
38	199
39	238
40	227
41	98
42	229
43	134
44	221
45	203
46	230
47	206
48	245
49	123
50	130
51	107
52	150
53	125
54	144
55	126
56	198
57	115
58	165
59	92
60	181
61	165
62	216
63	175
64	161
65	217
66	454
67	279
68	432
69	245
70	420
71	272
72	484
73	243
74	318
75	270
76	350
77	272
78	447
79	328
80	428
81	112
82	229
83	257
84	387
85	251
86	416
87	257
88	272
89	98
90	475
91	248
92	266
93	268
94	280
95	276
96	254

TABLE 4. ANALYSIS OF VARIANCE FOR TENSILE STRENGTH - FACTOR EVALUATION EXPERIMENT

Source of Variation	Degrees of Freedom	Mean Squares	F Value	Significance Level, %
E	1	413926	496	1
F	1	148799	178	1
A	1	48897	59	1
EF	1	46298	55	1
A^2	1	43400	52	1
AF	1	29602	35	1
AE	1	27291	33	1
C	1	20240	24	1
CDF	1	5965	7	5
E^2	1	4555	5	5
Residual	75	1118		
Within Treatments Treated Alike	10	835		

Legend of Factors

A - Molding Water Content
B - Aggregate Gradation
C - Curing Temperature
D - Compactive Effort
E - Cement Content
F - Aggregate Type

Critical F Values

F(1, 10, 1%) = 10.00
F(1, 10, 5%) = 4.96

In the following sections, those two-factor interactions and main effects which were found to be significant at the 1-percent level are discussed. Although it is not possible from this experiment to explain the observed effect, postulations are suggested regarding their possible causes.

Interactions

All two-factor, three-factor, four-factor, and five-factor interactions were analyzed in this experiment. Of these interactions, only 3 two-factor interactions were found to be significant at the 1-percent level. The two-factor interactions are illustrated in Figs 3 through 5 and are discussed below.

Cement Content x Aggregate Type (Interaction E x F). The cement content x aggregate type interaction illustrated in Fig 3 shows that increasing the cement content from 4 percent to 8 percent produced increased tensile strengths for both Seguin gravel and crushed limestone aggregates. However, the effect of the increased cement content was larger for the limestone aggregate than for the Seguin gravel. It is thought that the angular, coarse-textured crushed limestone provides a better bonding of particles, thereby producing a stronger specimen. Thus, the specimens containing limestone aggregates were capable of benefiting more from the improved matrix than were the specimens containing the rounded gravel.

Molding Water Content x Aggregate Type (Interaction A x F). As shown in Fig 4, the increase of molding water content from 5.25 percent to 7.75 percent produced very little change in tensile strengths for specimens composed of Seguin gravel. However, when crushed limestone was utilized, the increased molding water content resulted in an average increase in tensile strengths of approximately 95 psi. The limestone aggregate has more surface porosity than the Seguin gravel aggregate thereby enabling the limestone to absorb more moisture than the gravel. At low moisture contents the absorption of the molding water by the limestone limits the amount of moisture available for hydration of the cement. When the higher level of moisture content was used in conjunction with the limestone, adequate water was available to satisfy both the absorption potential of the aggregate and the water requirements for proper cement hydration. Therefore, the average tensile strengths for the crushed limestone specimen was substantially increased as the molding water content was increased.

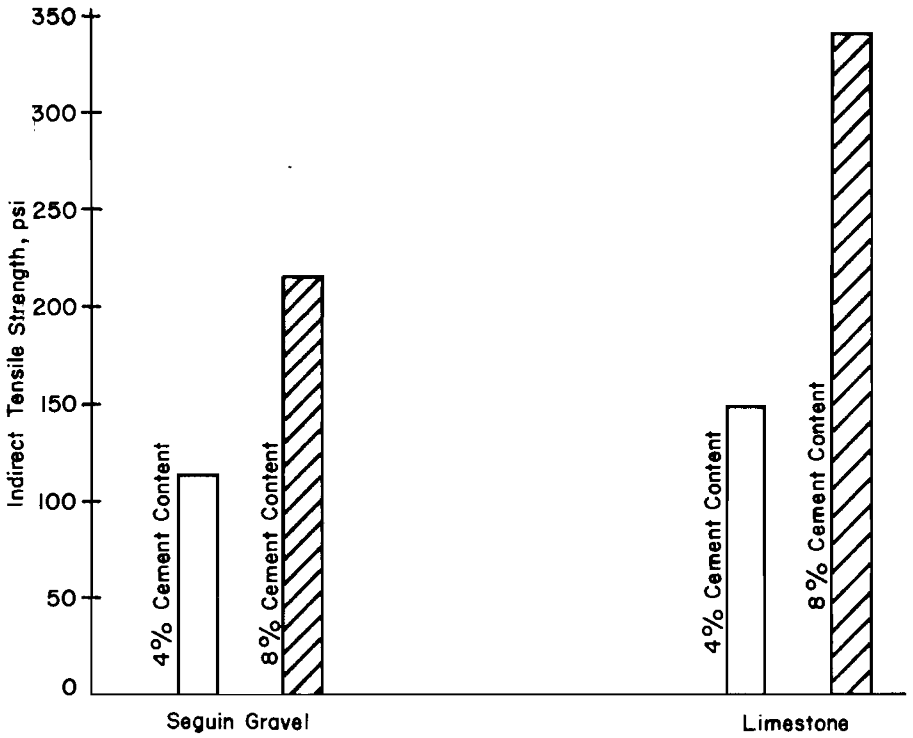


Fig 3. Effect of interaction between cement content and aggregate type (interaction E × F).

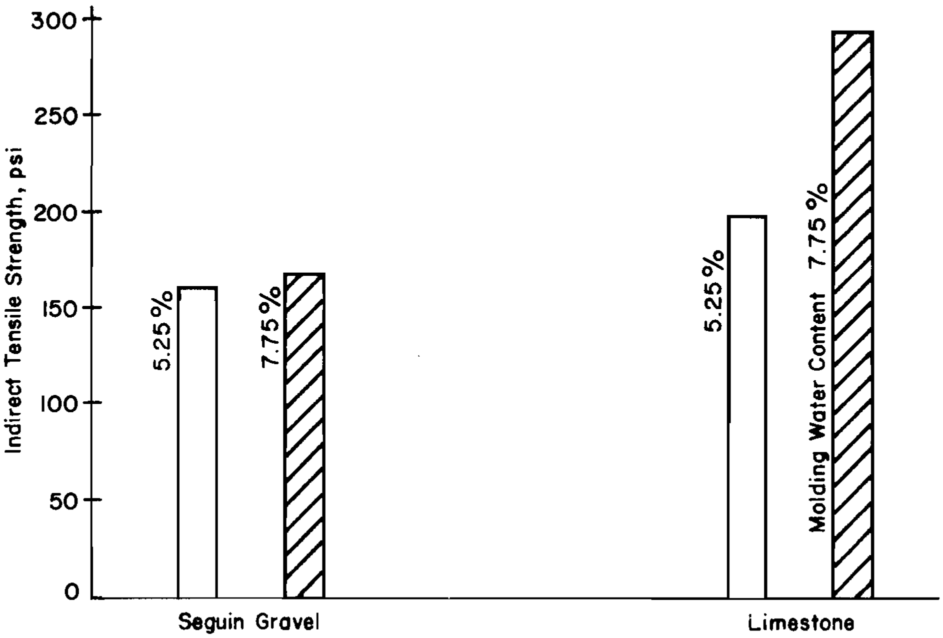


Fig 4. Effect of interaction between molding water content and aggregate type (interaction A × F).

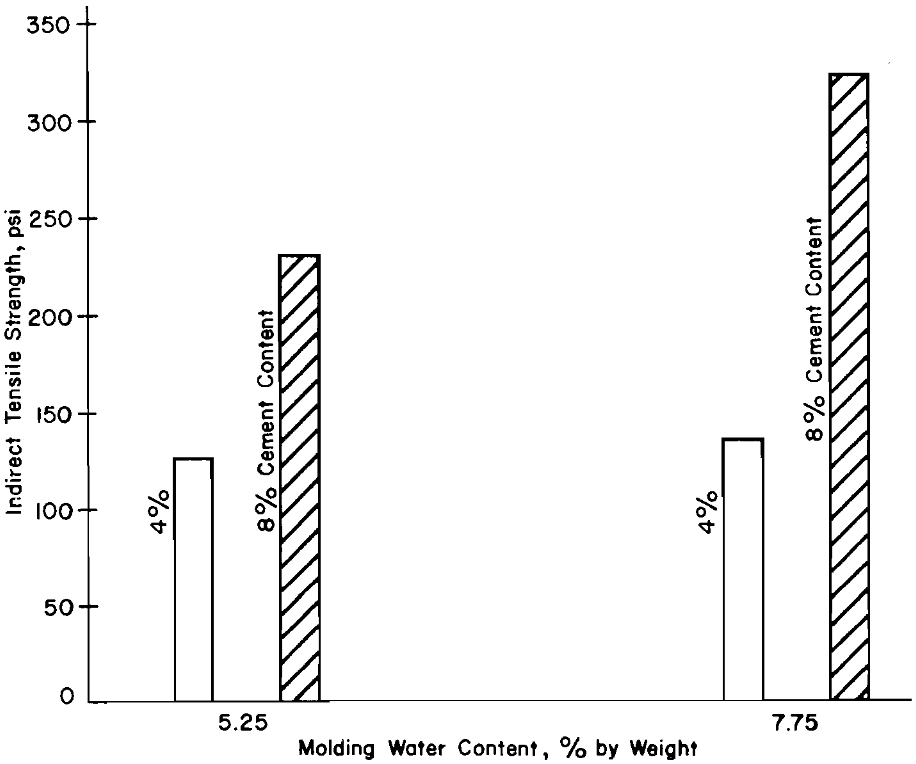


Fig 5. Effect of interaction between molding water content and cement content (interaction A x E).

The Seguin gravel has a lower absorption potential and at the low level of moisture content sufficient water was present to satisfy the absorption potential and the requirements of the cement for hydration. Only a small increase in average tensile strengths for the Seguin gravel is noted as the molding moisture was increased since the additional water was not needed for the adequate hydration of the portland cement.

In addition, a stronger structural soil-cement matrix is developed at the higher water content and the coarse-textured limestone benefits by providing a better bond resulting in higher tensile strengths.

Molding Water Content x Cement Content (Interaction A x E). Figure 5 illustrates that as the cement content was increased from 4 percent to 8 percent, tensile strengths increased, but the magnitude of the increase was larger when the molding water content was at 7.75 percent. In addition, it should be noted that strength increased with an increase in molding water content but that the increase was only 10 psi when 4 percent cement was used, while the strength increase with 8 percent cement was 92 psi. Thus it would appear that in order for maximum benefits to be obtained from high cement percentages an adequate amount of water must be present for proper hydration of the portland cement.

Main Effects

The analysis of variance showed that four of the main effects were significant at the 1 percent level with one of the factors being significant as a quadratic effect. Aggregate gradation and compactive effort were not significant at this probability level. Figures 6 through 9 show the effects of these four factors. From these figures it can be seen that the average indirect tensile strength was increased by

1. increasing cement content from 4 to 8 percent (Fig 6),
2. using crushed limestone aggregate rather than Seguin gravel (Fig 7),
3. increasing the molding water content from 5.25 percent to 7.75 percent (Fig 8), and
4. increasing the curing temperature from 75° F to 125° F (Fig 9).

In addition to the main effect, a significant quadratic effect was detected for the molding water content as shown in Fig 10. The average indirect tensile strength increased when the molding water content was increased from 4 percent

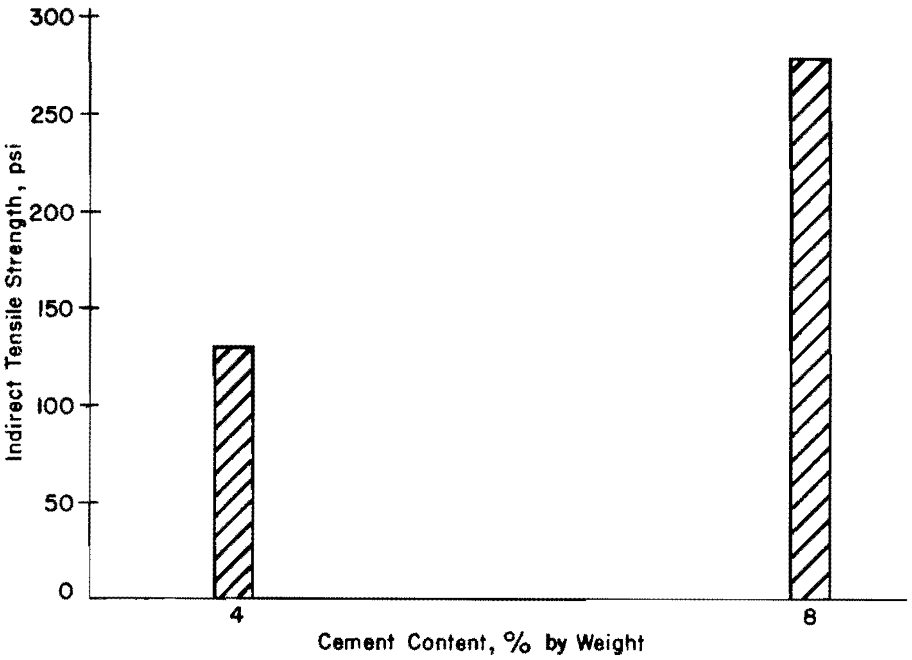


Fig 6. Effect of cement content on the indirect tensile strength (factor E).

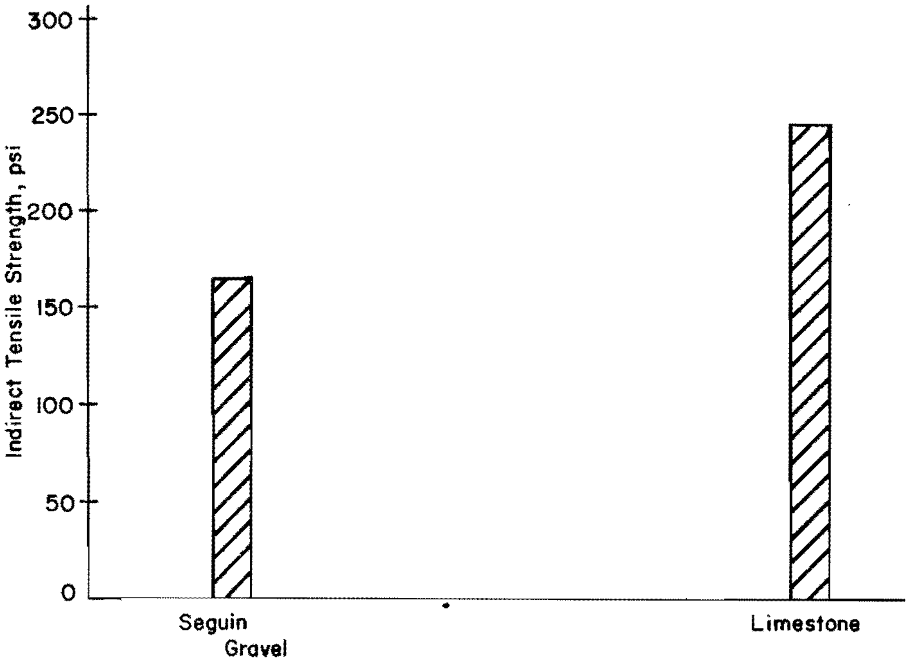


Fig 7. Effect of aggregate type on the indirect tensile strength (factor F).

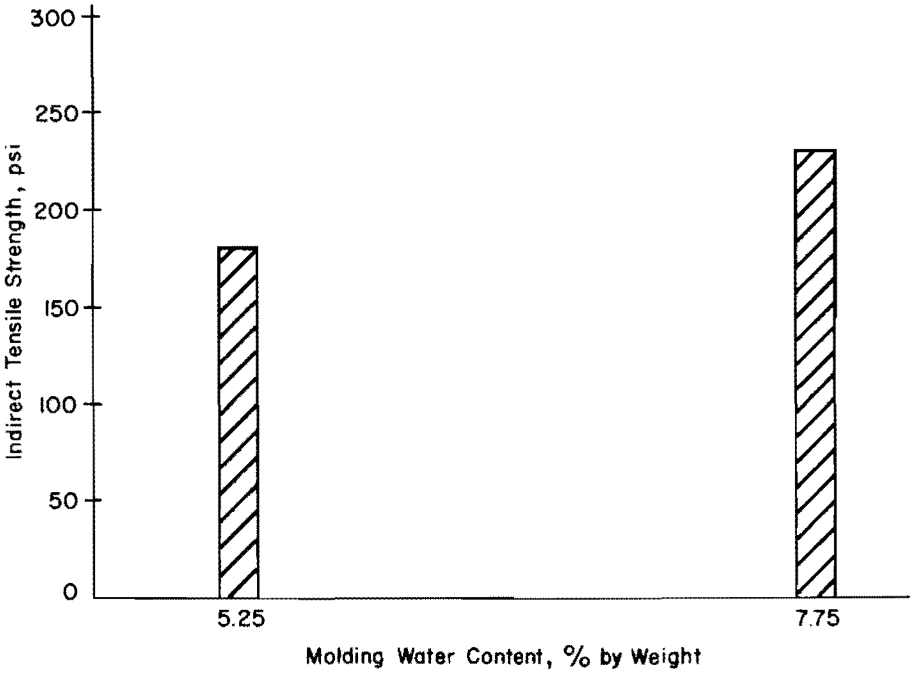


Fig 8. Effect of molding water content on the indirect tensile strength (factor A).

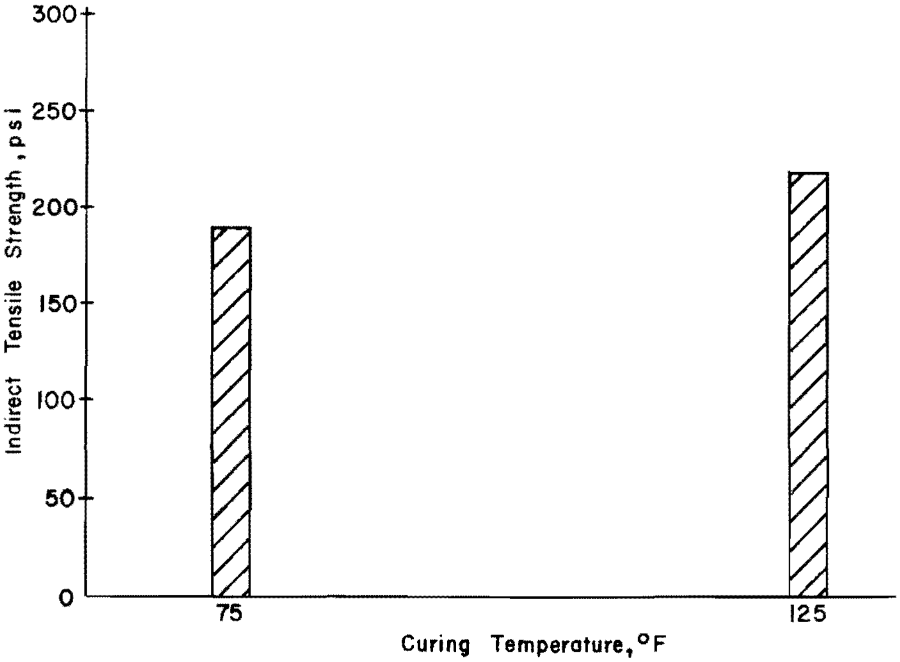


Fig 9. Effect of curing temperature on the indirect tensile strength (factor C).

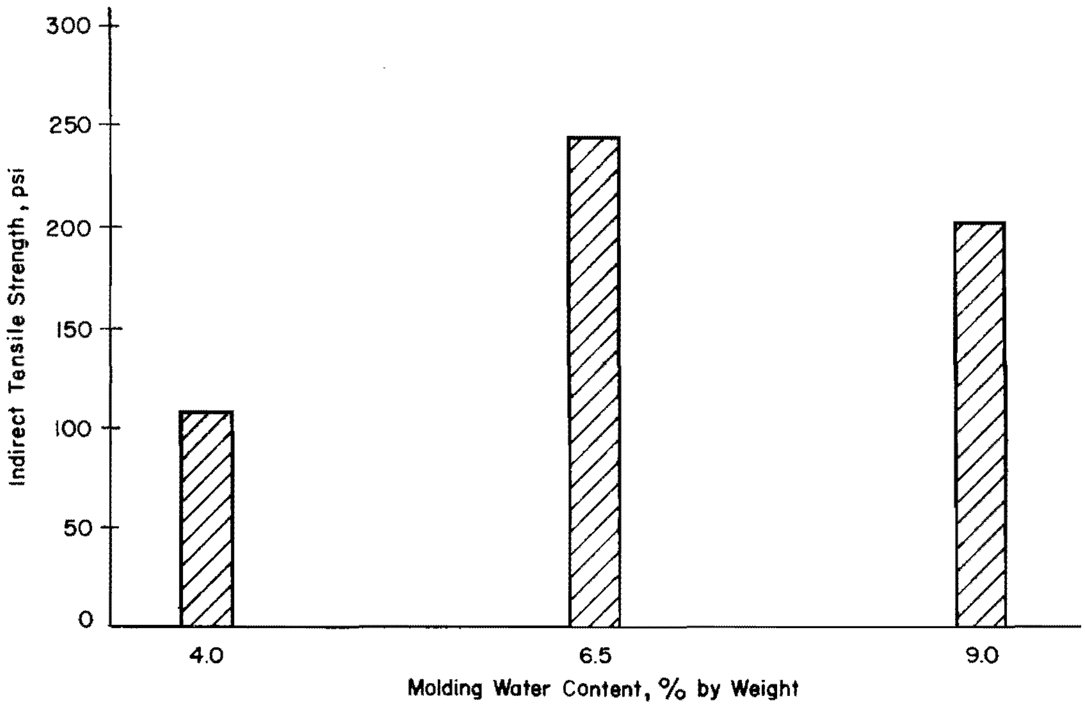


Fig 10. Quadratic effect of molding water content on indirect tensile strength (factor A).

to 6.5 percent but decreased when it was raised from 6.5 percent to 9 percent. Thus, it would appear that there was an optimum water content for strength for the materials tested.

The effects as reported above were supported by previous findings (Ref 9), and similar trends have been reported by others in the literature concerned with compression tests of cement-treated materials.

Prediction Equation

A regression analysis was conducted to obtain an equation which would satisfactorily predict the indirect tensile strengths of the cement-treated materials tested in this experiment. Since this equation is based on the results of this experiment, its use is only valid for the factors, factor levels, and conditions of this experiment.

The prediction equation, which follows, utilizes all factors and interactions which produced significant effects at a probability level of 10 percent. These factors and their levels are presented in Table 2.

$$\begin{aligned}\hat{S} = {} & -344.7 + 147.9A + 6.799B + 0.6362C - 2.766D \\ & - 66.83E + 36.70F + 0.4255AD + 19.80AE - 1.956AF \\ & - 1.426CF + 0.6817DE - 0.7649DF + 7.535EF \\ & - 17.26A^2 - 2.157E^2 - 0.1049ADE + 2.891AEF \\ & + 0.01545CDF - 0.1300DEF \end{aligned} \tag{4.1}$$

where

$\hat{S}_t$ = predicted value of indirect tensile strength, in psi;

A, B, C, D, E, F = factors considered for prediction.

Factors B and F, aggregate gradation and aggregate type, are coded; therefore, a value of from -2 to +2 must be substituted depending on the level selected. The remaining factors, A, C, D, and E, in the equation are uncoded, and the actual value may be substituted in the prediction equation.

The coefficient of determination R^2 for this equation was 0.93 and the standard error of the estimate was ±29.0 psi. As indicated by the coefficient, this equation accounted for 93 percent of the observed variations; however, the standard error of the estimate was relatively large and some error could be associated with the predicted strength values. Nevertheless, this error is essentially equal to the error associated with repeated specimens.

CHAPTER 5. THE CORRELATION EXPERIMENTS

This chapter discusses the experimental designs and the results for the General Correlation, the Texas Highway Department Correlation, and the Specimen Size Study.

GENERAL CORRELATION

The General Correlation was conducted to compare the results of the indirect tensile test with the results of the cohesiometer test and the unconfined compression test for cement-treated specimens. These specimens were prepared, cured, and tested according to the same procedures used in the main experiment, except that the specimen was 6 inches in diameter for the correlation study rather than 4 inches in diameter.

Experimental Design

The same six factors used in the main experiment, molding water content, cement content, aggregate type, aggregate gradation, curing temperature, and compactive effort, were used in General Correlation with the first three being variable and the last three held constant at a level corresponding to a level used in the main experiment. The factors and levels are presented in Table 5.

For each type of aggregate five specimens were prepared at varying molding water content and cement content in order to produce an adequate range of strength for each test. Thus, a total of 30 specimens were tested; 10 by indirect tension, 10 by the cohesiometer, and 10 by unconfined compression. The treatment combinations are presented in Appendix 1, Table A2.

All specimens were compacted in a gyratory shear compactor capable of producing 6-inch-diameter specimens of the desired height of 2 inches for the indirect tension test and the cohesiometer test and 8 inches for the unconfined compression test.

The sample preparation and curing procedure was the same as used in the main experiment and is summarized in Appendices 3 and 5. The compaction procedure for the 6-inch-diameter gyratory shear compactor is shown in Appendix 4.

TABLE 5. FACTORS AND LEVELS - GENERAL CORRELATION

Variable Factors	Level Low	Level Medium	Level High
A. Molding water content, %	4	6.5	9
E. Cement content, %	2	6	10
F. Aggregate type	Seguin gravel		Crushed limestone
Constant Factors			
B. Aggregate gradation (1)		Medium	
C. Curing temperature, ° F (2)		100	
D. Compactive effort, psi (3)		175	

(1) See Appendix 2.

(2) See Appendix 5.

(3) See Appendix 4, Gyratory Compaction of 6-Inch-Diameter Specimens.

TABLE 6. EXPERIMENTAL RESULTS - GENERAL CORRELATION

Spec. No.	Tensile Strength, psi	Cohesiometer Value Spec. No.	Cohesiometer Value	Unconfined Compression Spec. No.	Unconfined Compressive Strength, psi
97	77	117	3,106	137	518
98	97	118	2,895	138	819
101	103	121	2,952	141	605
102	62	122	2,335	142	805
105	198	125	5,323	145	675
106	255	126	8,131	146	2,049
109	330	129	10,656	149	1,474
110	327	130	10,370	150	1,784
113	224	133	7,408	153	1,500
114	288	134	6,629	154	1,252

The test procedures for the indirect tensile test, the cohesiometer test, and the unconfined compression test are detailed in Appendix 6.

Experimental Results

The parameters evaluated were the indirect tensile strength, the unconfined compressive strength, and the cohesiometer value. The results of these tests are presented in Table 6. Additional experimental test data are shown in Appendix 7, Tables A6, A7, and A8. Plots of indirect tensile strength-unconfined compressive strength and indirect tensile strength-cohesiometer value are presented in Figs 11 and 12, respectively. The ultimate objective of the General Correlation was the development of predictive equations with which the indirect tensile strength of the cement-treated material could be estimated if the unconfined compressive strength or the cohesiometer value were known. It should be noted that the use of these predicted equations is valid only for the factors and levels considered in this experiment and for the conditions associated with the experiment.

A regression analysis was conducted on the data and the following equations were obtained:

$$\hat{S}_t = 18.45 + .1548q_u \tag{5.1}$$

for which the coefficient of determination R^2 was 0.63 and the standard error of estimate s was ±67.2 psi, and

$$\hat{S}_t = 4.85 + .0320C \tag{5.2}$$

for which the coefficient of determination R^2 was 0.93 and the standard error of estimate s was ±30.4 psi,

where

$\hat{S}_t$ = predicted value of indirect tensile strength, in psi;

q_u = measured value of unconfined compressive strength, in psi; and

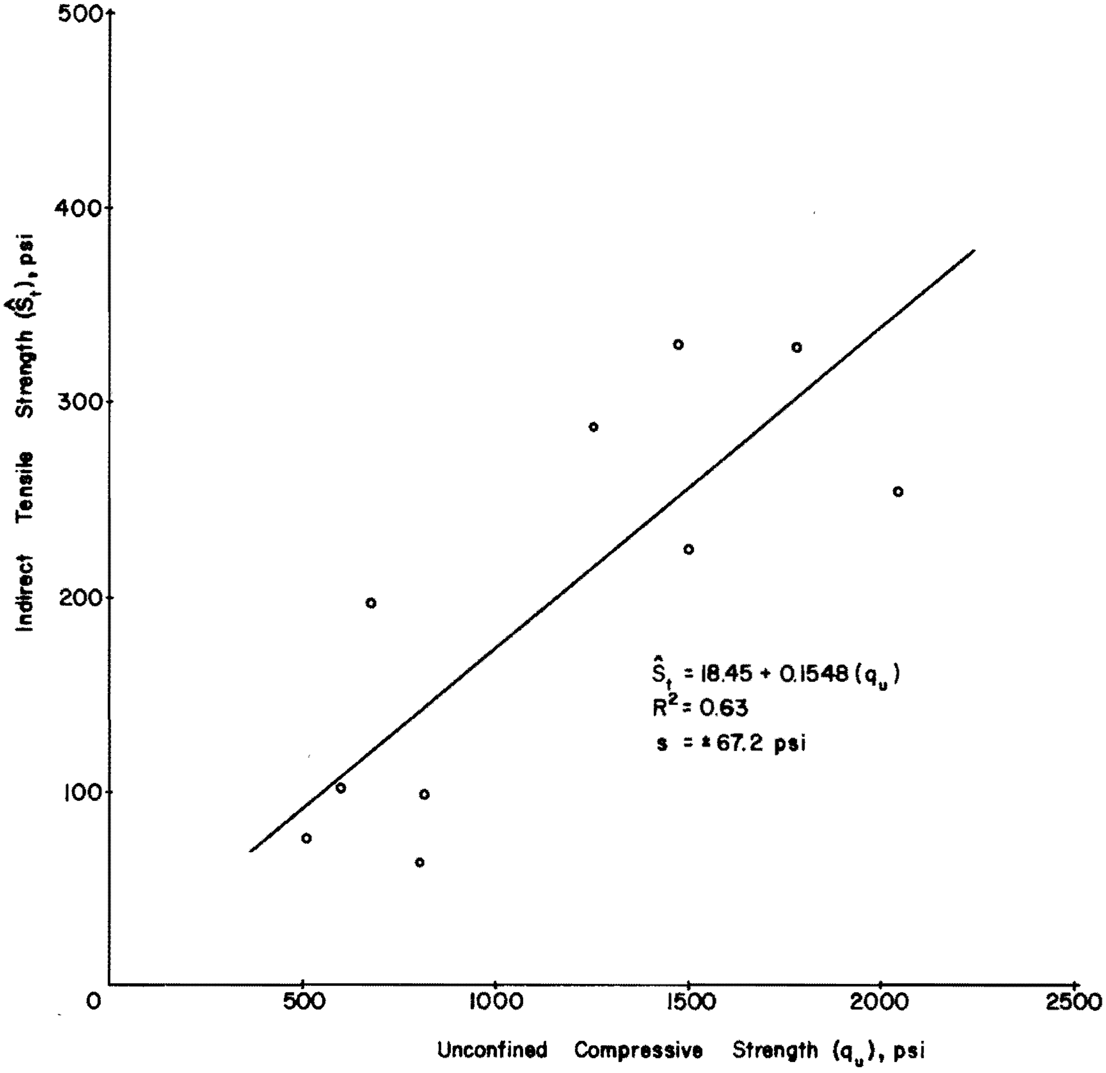


Fig 11. Indirect tensile strength-unconfined compressive strength relationship for General Correlation.

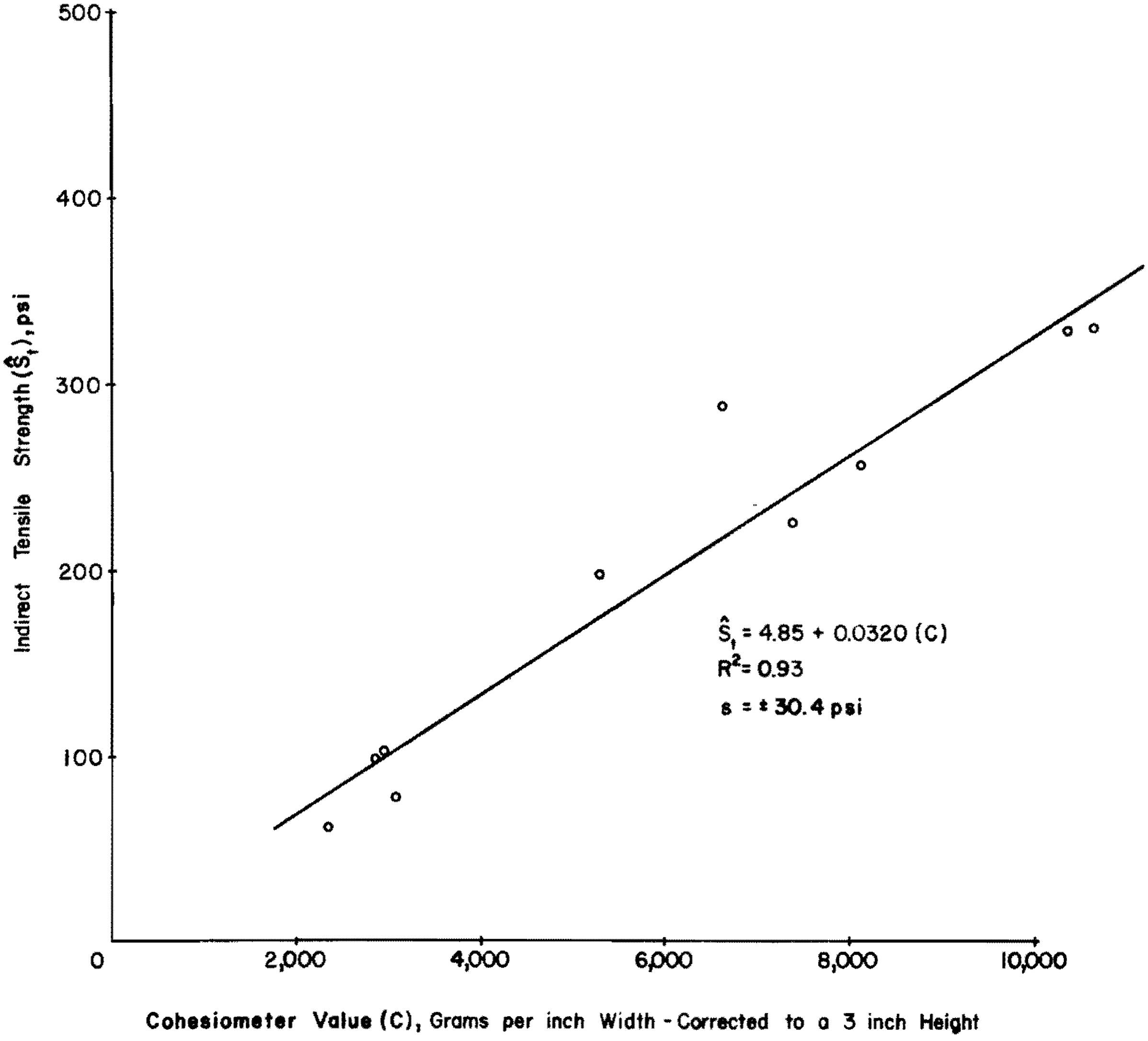


Fig 12. Indirect tensile strength-cohesiometer value relationship for General Correlation.

C = measured cohesiometer value, in grams per inch of width, corrected to a 3-inch height.

In an attempt to establish a qualitative feel for the precision associated with these various correlations, it has been assumed that a coefficient of determination R^2 of 0.90 to 1.00 was excellent, 0.80 to 0.90 was good, 0.70 to 0.80 was fair, and 0.60 to 0.70 was poor. Thus, it was concluded that the correlation between the unconfined compressive strength and the indirect tensile strength was poor, but that the correlation between the cohesiometer value and the indirect tensile strength was excellent. Nevertheless, both correlations had a high standard error of the estimate; therefore, errors would be expected if either the unconfined compressive strength or the cohesiometer value were used to estimate indirect tensile strength.

TEXAS HIGHWAY DEPARTMENT CORRELATION

The Texas Highway Department Correlation was conducted to compare the results of the indirect tensile test with the results of the unconfined compression test and the cohesiometer test for cement-treated specimens compacted and cured according to Texas Highway Department procedures (Ref 4).

Experimental Design

Texas Highway Department procedures designated the compactive effort and the curing temperature; therefore, only three of the factors studied in the Factor Evaluation Experiment could be varied in the Texas Highway Department Correlation. The treatment combinations were chosen to provide an adequate range of strengths over which to make the correlations. The factors and levels involved in the various treatment combinations are presented in Table 7. For each treatment combination in the experimental design, three companion specimens were prepared, a 2-inch-high by 6-inch-diameter specimen to be tested in indirect tension, a 2-inch-high by 6-inch-diameter specimen to be tested in the cohesiometer, and an 8-inch-high by 6-inch-diameter specimen to be tested in unconfined compression.

Experimental Results

The parameters evaluated were the indirect tensile strength, the unconfined compressive strength, and the cohesiometer value. The results of these

TABLE 7. FACTORS AND LEVELS - TEXAS HIGHWAY DEPARTMENT CORRELATION

Variable Factors	Level Low	 Medium	 High
A. Molding water content, %	4	6.5	9
E. Cement content, %	2	6	10
F. Aggregate type	Seguin gravel		Crushed limestone
Constant Factors			
B. Aggregate gradation (1)		Medium	
C. Curing temperature, °F (2)		Moisture room	
D. Compactive effort (3)		25 blows per layer	

(1) See Appendix 2.

(2) See Appendix 5.

(3) See Appendix 4, Impact Compaction of 6-Inch-Diameter Specimens.

TABLE 8. EXPERIMENTAL RESULTS - TEXAS HIGHWAY DEPARTMENT CORRELATION

Spec. No.	Tensile Strength, psi	Cohesiometer Value Spec. No.	Cohesiometer Value	Unconfined Compression Spec. No.	Unconfined Compressive Strength, psi
99	30	119	1,244	139	451
100	78	120	1,418	140	651
103	84	123	2,418	143	527
104	39	124	1,703	144	622
107	119	127	4,327	147	776
108	246	128	7,133	148	1,755
111	351	131	6,757	151	1,822
122	273	132	7,040	152	1,892
115	233	135	5,663	155	1,311
116	149	136	6,040	156	1,492

tests are presented in Table 8. Additional experimental test data are shown in Appendix 7, Tables A6, A7, and A8. Plots of indirect tensile strength versus unconfined compressive strength and indirect tensile strength versus cohesiometer value are presented in Figs 13 and 14, respectively. The ultimate objective of the Texas Highway Department Correlation was the development of predictive equations with which the indirect tensile strength of the cement-treated material could be estimated if the unconfined compressive strength or the cohesiometer value were known. A regression analysis was conducted and the following prediction equations were obtained:

$$\hat{S}_t = -38.34 + 0.1752q_u \tag{5.3}$$

for which the coefficient of determination R^2 was 0.86 and the standard error of estimate s was ±43.8 psi, and

$$\hat{S}_t = -16.14 + 0.0403C \tag{5.4}$$

for which the coefficient of determination R^2 was 0.82 and the standard error of estimate s was ±49.3 psi,

where

$\hat{S}_t$ = predicted value of indirect tensile strength, in psi;

q_u = measured value of unconfined compressive strength, in psi; and

C = measured cohesiometer value, in grams per inch of width, corrected to a 3-inch height.

Utilizing the previously defined criteria it was concluded that both correlations were good but that the large errors associated with both would make it very difficult to establish an accurate estimate of indirect tensile strength from the unconfined compressive strength or the cohesiometer value.

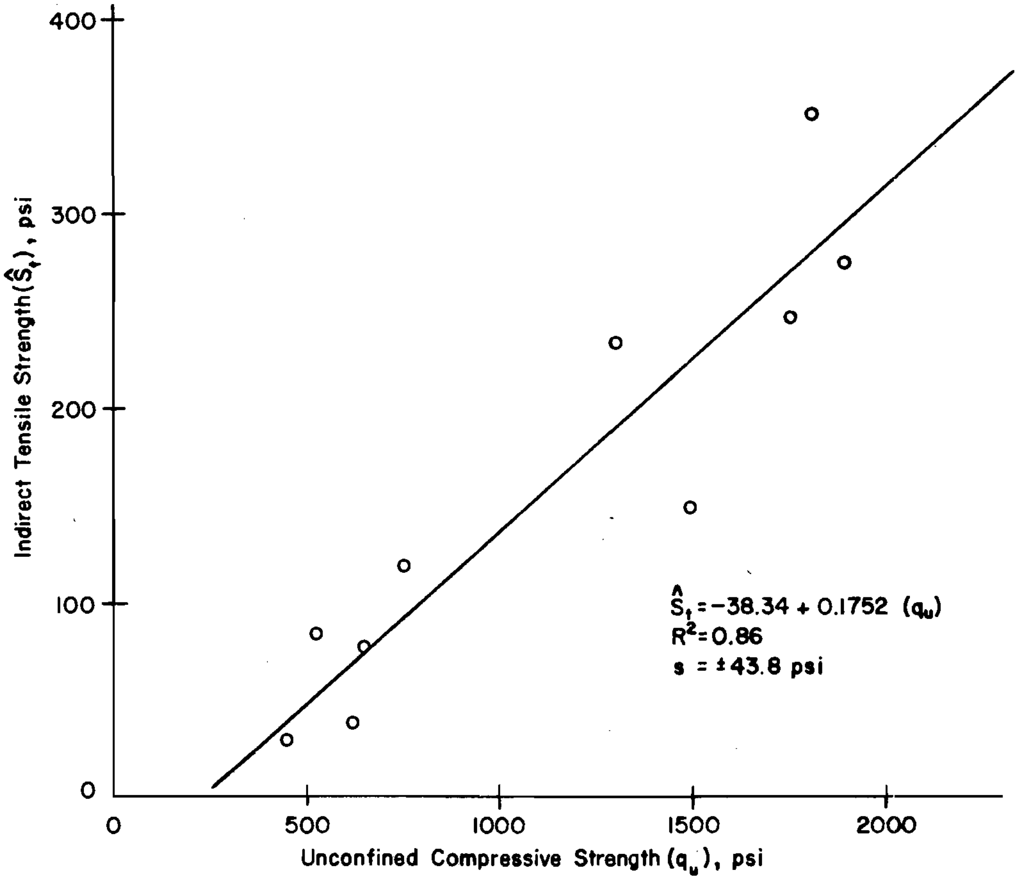


Fig 13. Indirect tensile strength-unconfined compressive strength relationship for Texas Highway Department Correlation.

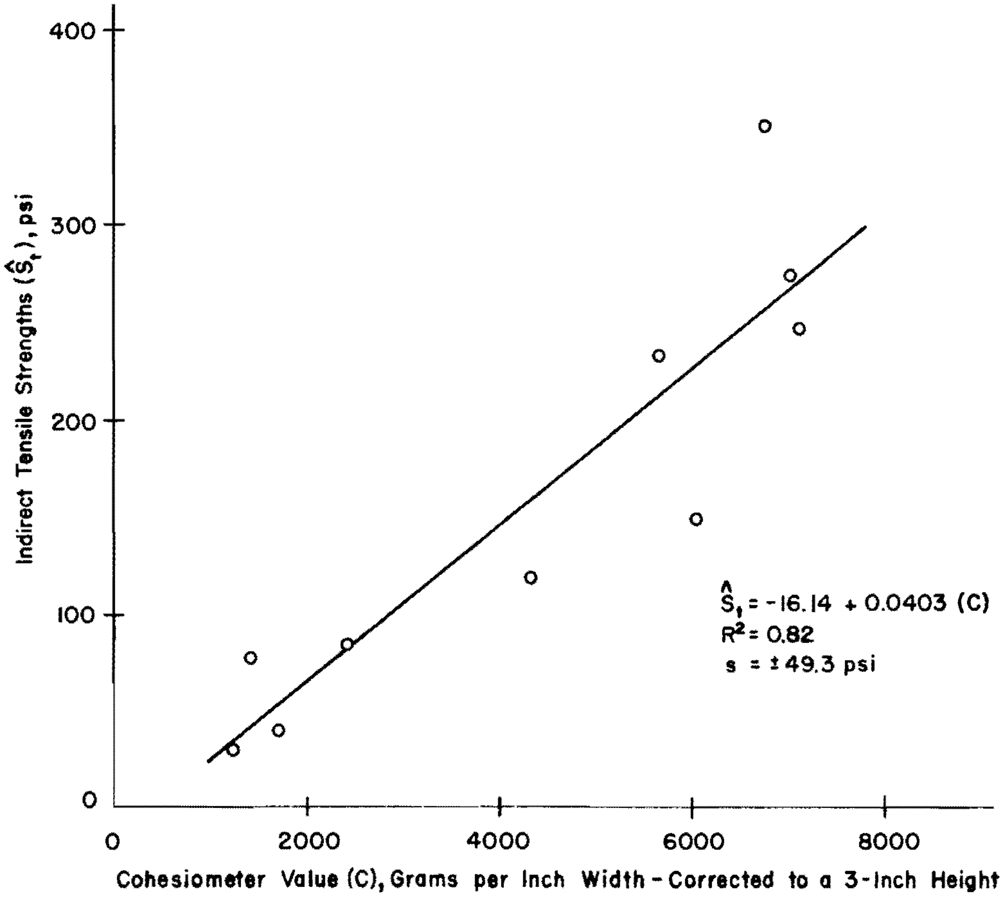


Fig 14. Indirect tensile strength-cohesiometer value relationship for Texas Highway Department Correlation.

COMBINED CORRELATION RESULTS

The strengths obtained for the Texas Highway Department Correlation were generally less than the strength obtained from the General Correlation. The moisture contents at test time were generally higher in the Texas Highway Department Correlation than in the General Correlation which probably accounts for the lower strengths. Since the ranges of strength for the two correlations were quite different, the data from the experiments were combined to determine whether there was a relationship between indirect tensile test results and the results of the unconfined compression test and the cohesiometer test over the entire range of strengths. Figures 15 and 16 show the combined data. A regression analysis was conducted on these combined data and the following prediction equations were obtained:

$$\hat{S}_t = -11.38 + .1662q_u \tag{5.5}$$

for which the coefficient of determination R^2 was 0.73 and the standard error of estimate s was ±56.6 psi, and

$$\hat{S}_t = 1.68 + .0341C \tag{5.6}$$

for which the coefficient of determination R^2 was 0.85 and the standard error of estimate s was ±41.6 psi,

where

$\hat{S}_t$ = predicted value of indirect tensile strength, in psi;

q_u = measured value of unconfined compressive strength, in psi; and

C = measured cohesiometer value, in grams per inch of width, corrected to a 3-inch height.

For these combined results, the correlation was good between the indirect tensile strength and the cohesiometer value, but the correlation between the indirect tensile strength and the unconfined compressive strength could only

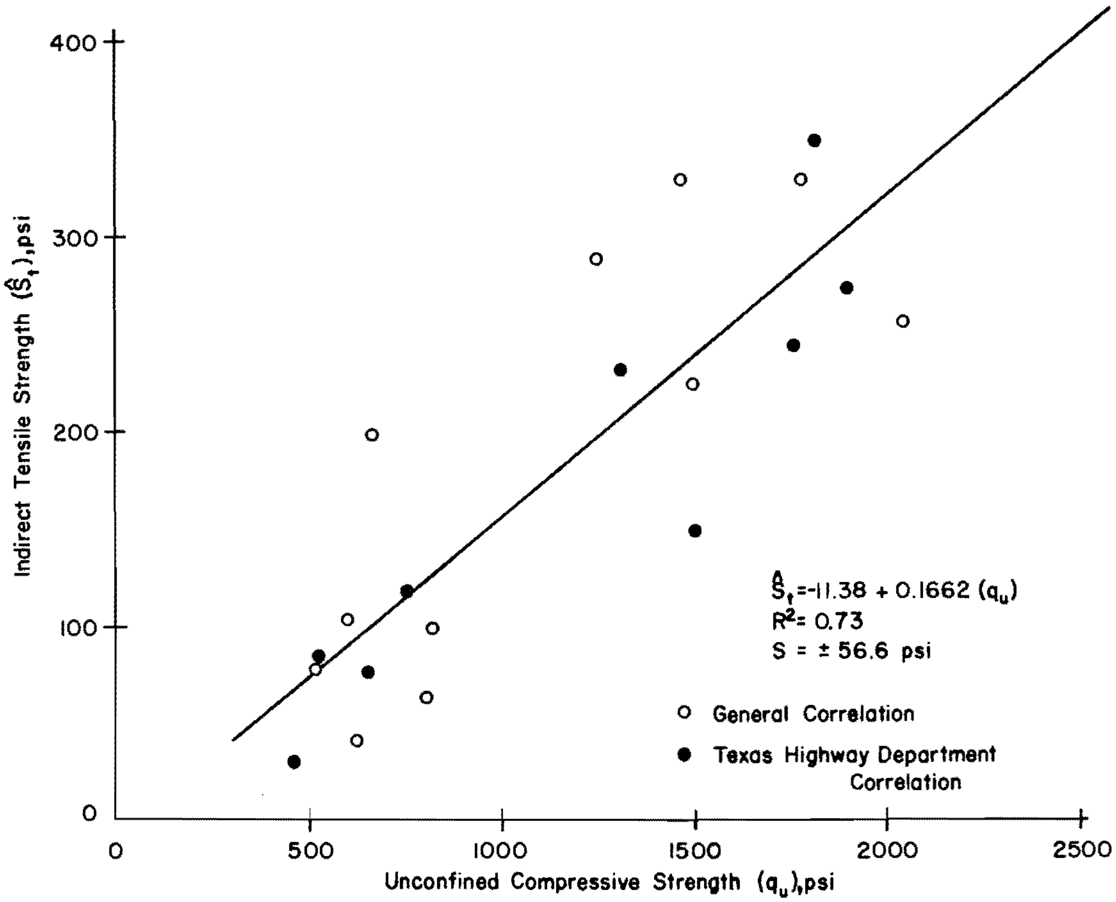


Fig 15. Indirect tensile strength-unconfined compressive strength for combined data.

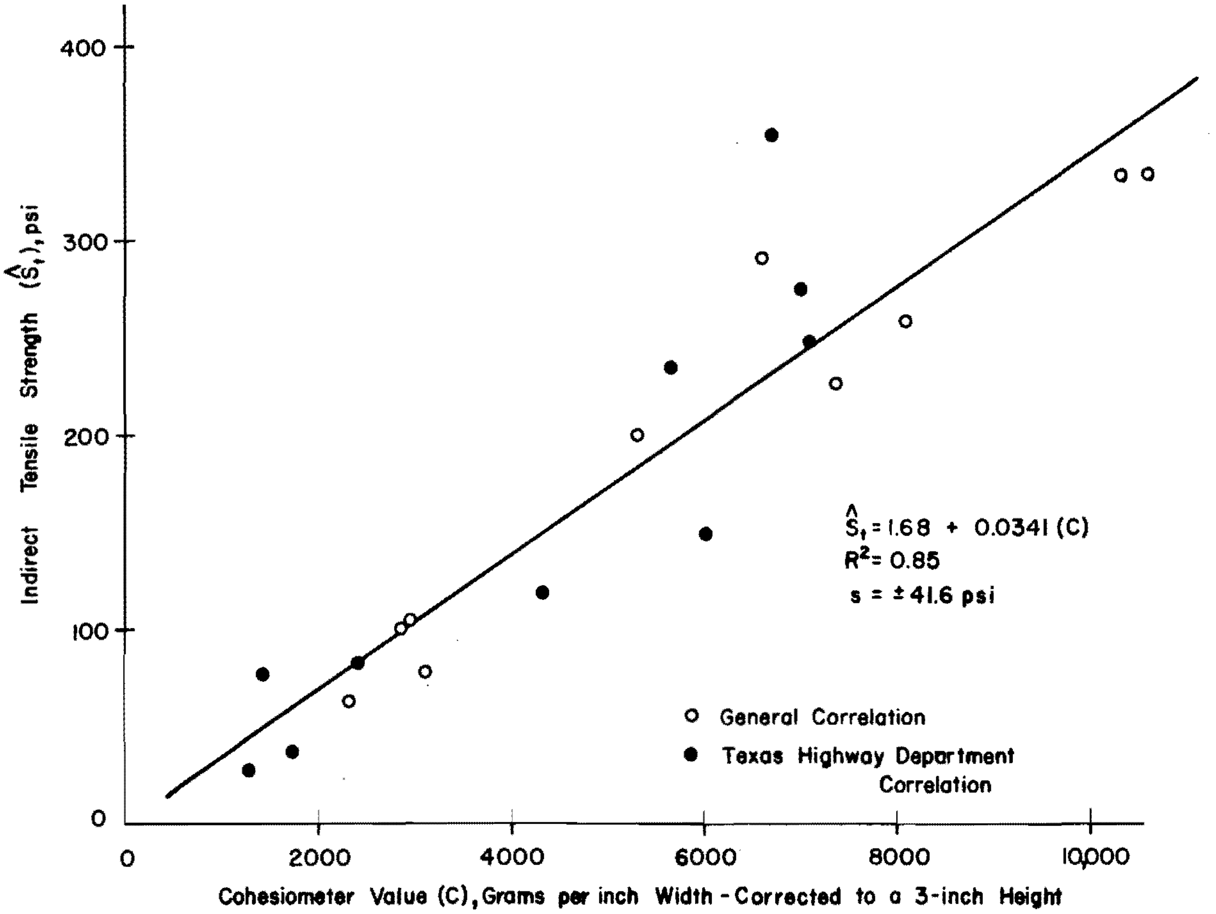


Fig 16. Indirect tensile strength-cohesiometer value for combined data.

be classified as fair. As with the previous correlations, large errors would be expected if the indirect tensile strength was estimated on the basis of these correlations alone.

SPECIMEN SIZE STUDY

The Specimen Size Study was conducted to determine the effect of specimen size on the indirect tensile strength of cement-treated materials.

Experimental Design

The specimens used for the size study were obtained from the Main Experiment and the General Correlation Experiment since the factors and levels used in both were the same. The only difference was specimen size; 4-inch-diameter specimens were used in the Main Experiment and 6-inch-diameter in the General Correlation.

Ten specimens from the General Correlation Experiment, five containing Seguin gravel and five containing crushed limestone, were compared with duplicate specimens in the Main Experiment. The factors and levels are shown in Table 9.

Experimental Results

The results of the Specimen Size Study are presented in Table 10 and a plot of the indirect tensile strength of 4-inch-diameter specimens versus 6-inch-diameter specimens is shown in Fig 17.

It is apparent that specimen size did not seriously affect the indirect tensile strength; this observation was supported by a statistical analysis, involving a paired "t" test, which showed no significant difference. Previous research (Ref 3) also supports this observation.

TABLE 9. FACTORS AND LEVELS - SPECIMEN SIZE STUDY

	Level		
Variable Factors	Low	Medium	High
A. Molding water content, %	4	6.5	9
E. Cement content, %	2	6	10
F. Aggregate type	Seguin gravel		Crushed limestone
Constant Factors			
B. Aggregate gradation (1)		Medium	
C. Curing temperature, °F (2)		100	
D. Compactive effort, psi (3)		175*	

* Equivalent to 110 psi gage pressure on 4-inch-diameter Texas Highway Department gyratory shear compactor.

(1) See Appendix 2.

(2) See Appendix 5.

(3) See Appendix 4, Gyratory Compaction of 6-Inch-Diameter Specimens.

TABLE 10. EXPERIMENTAL RESULTS - SPECIMEN SIZE STUDY

2" x 6" Size		2" x 4" Size	
Spec. No.	Tensile Strength, psi	Spec. No.	Tensile Strength, psi
97	77	33	102
98	97	81	112
101	103	41	98
102	62	89	98
105	198	34	163
106	255	82	229
109	330	42	228
110	327	90	475
113	224	48	245
114	288	93	268

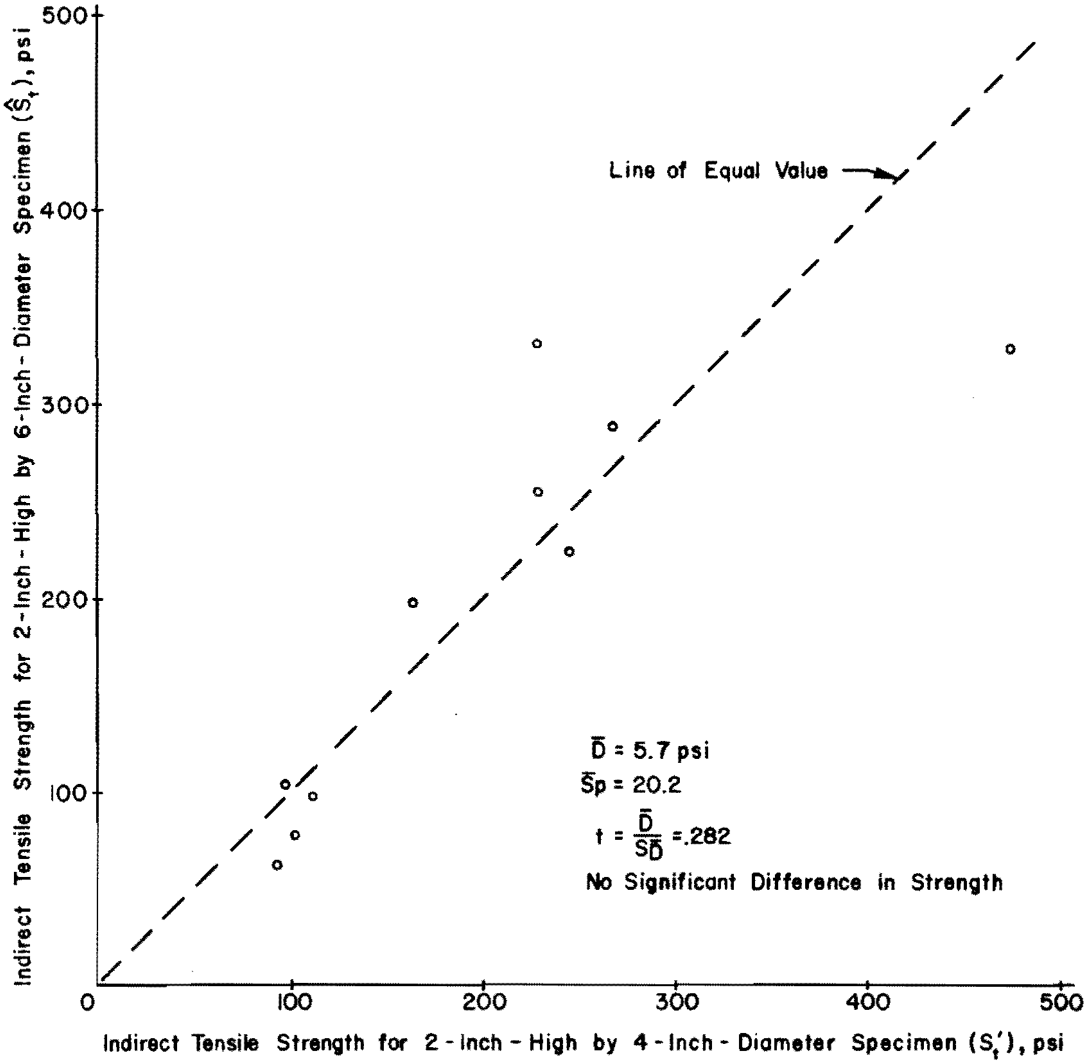


Fig 17. Indirect tensile strength relationships for Specimen Size Study.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

As in any controlled experimentation, the findings, conclusions, and recommendations resulting from this study are limited to the range of variables and conditions of the study. Any attempt to extend the results or to apply them outside of the factor space defined by the investigation should be done with caution.

On the basis of the data and analyses described herein, the following conclusions and recommendations can be made.

CONCLUSIONS

Factor Evaluation Experiment

Four of the factors investigated, cement content, aggregate type, molding water content, and curing temperature, had a significant effect on the indirect tensile strength either as a main effect or an interaction effect. The factors which did not significantly affect the indirect tensile strength were aggregate gradation and compactive effort.

The indirect tensile strength was increased by

(1) increasing the cement content;
(2) using crushed limestone aggregate;
(3) increasing the molding water content to some optimum value, above which increasing the water content decreased the strength; and
(4) increasing the curing temperature.

The magnitude of the changes in strength produced by these factors was influenced by the level of other factors. Thus, three two-factor interactions were found to have a significant effect on strength. These three interactions were

(1) cement content X aggregate type,
(2) molding water content X aggregate type, and
(3) molding water content X cement content.

Correlation Studies

The correlation analyses indicated that a good correlation existed between the indirect tensile strength and the cohesiometer value but that the correlation between the indirect tensile strength and the unconfined compressive strength was only fair. Based on these analyses, correlation equations were developed which can be used to obtain rough estimates of the indirect tensile strength from either the cohesiometer value or the unconfined compressive strength. These equations have a relatively large standard error of estimate; thus, large errors can be expected if the indirect tensile strength is estimated on the basis of these correlation equations alone.

Specimen Size Study

Based on a comparison of the indirect tensile strengths obtained from 4-inch and 6-inch diameter specimens, it was concluded that the diameter of the specimen did not affect the tensile strength obtained from indirect tensile testing.

RECOMMENDATIONS

This is the second of two studies investigating the indirect tensile strength of cement-treated materials. The next logical step is to analyze and interpret the data from both studies and from previous studies utilizing other test methods and to make definite recommendations for the design and construction of cement-treated bases and the need of additional studies.

In addition to the strength effects, additional work is needed on deformation data including an expanded study of material properties which include moduli of deformation and Poisson's ratio.

It would also be desirable to undertake an investigation of the behavior of cement-treated materials in fatigue or repeated loading using the indirect tensile test. Such studies are ultimately needed if the performance of these materials under the repeated loadings of simulated traffic is to be evaluated.

UTILIZATION OF RESULTS

The results of these studies are a segment of a comprehensive program to provide a better understanding of the behavior and performance of stabilized materials when used as components in a pavement structure. As indicated in the recommendation, the results will be used in the next phase of the study, repeated loading. They will also be used in comparison to the findings for lime-treated and asphalt-treated materials to develop overall information for stabilized materials.

Furthermore, the detailed findings concerning the effects of individual factors on tensile strength can be used to develop design information for stabilized mixtures for immediate upgrading of approximate and empirical design techniques. The correlations which were developed provide a means of making rough estimates of the tensile strength of cement-treated materials which have been previously used in pavements for which unconfined compressive strengths or cohesiometer values are known. In order to obtain accurate estimates, an indirect tensile test should be conducted.

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APPENDIX 1

TREATMENT COMBINATIONS

APPENDIX 1. TREATMENT COMBINATIONS

TABLE A1. FACTOR EVALUATION EXPERIMENT (FULL FACTORIAL)

Spec. No.	Molding Water Content, % A	Aggregate Gradation* B	Curing Temp., ° F** C	Compactive Effort*** D	Cement Content, % E	Aggregate Type F
1	-1	-1	-1	-1	-1	-1
	5.25	Fine +	75	85	4	Gravel
2	+1	-1	-1	-1	-1	-1
	7.75	Fine +	75	85	4	Gravel
3	-1	+1	-1	-1	-1	-1
	5.25	Medium +	75	85	4	Gravel
4	+1	+1	-1	-1	-1	-1
	7.75	Medium +	75	85	4	Gravel
5	-1	-1	+1	-1	-1	-1
	5.25	Fine +	125	85	4	Gravel
6	+1	-1	+1	-1	-1	-1
	7.75	Fine +	125	85	4	Gravel
7	-1	+1	+1	-1	-1	-1
	5.25	Medium +	125	85	4	Gravel
8	+1	+1	+1	-1	-1	-1
	7.75	Medium +	125	85	4	Gravel
9	-1	-1	-1	+1	-1	-1
	5.25	Fine +	75	135	4	Gravel
10	+1	-1	-1	+1	-1	-1
	7.75	Fine +	75	135	4	Gravel
11	-1	+1	-1	+1	-1	-1
	5.25	Medium +	75	135	4	Gravel
12	+1	+1	-1	+1	-1	-1
	7.75	Medium +	75	135	4	Gravel
13	-1	-1	+1	+1	-1	-1
	5.25	Fine +	125	135	4	Gravel

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* See Appendix 2.

** See Appendix 5.

*** See Appendix 4, Gyratory Compaction of 4-Inch-Diameter Specimens.

(Continued)

TABLE A1. (Continued)

Spec. No.	Molding Water Content, % A	Aggregate Gradation B	Curing Temp., ° F C	Compactive Effort D	Cement Content, % E	Aggregate Type F
14	+1 7.75	-1 Fine +	+1 125	+1 135	-1 4	-1 Gravel
15	-1 5.25	+1 Medium +	+1 125	+1 135	-1 4	-1 Gravel
16	+1 7.75	+1 Medium +	+1 125	+1 135	-1 4	-1 Gravel
17	-1 5.25	-1 Fine +	-1 75	-1 85	+1 8	-1 Gravel
18	+1 7.75	-1 Fine +	-1 75	-1 85	+1 8	-1 Gravel
19	-1 5.25	+1 Medium +	-1 75	-1 85	+1 8	-1 Gravel
20	+1 7.75	+1 Medium +	-1 75	-1 85	+1 8	-1 Gravel
21	-1 5.25	-1 Fine +	+1 125	-1 85	+1 8	-1 Gravel
22	+1 7.75	-1 Fine +	+1 125	-1 85	+1 8	-1 Gravel
23	-1 5.25	+1 Medium +	+1 125	-1 85	+1 8	-1 Gravel
24	+1 7.75	+1 Medium +	+1 125	-1 85	+1 8	-1 Gravel
25	-1 5.25	-1 Fine +	-1 75	+1 135	+1 8	-1 Gravel
26	+1 7.75	-1 Fine +	-1 75	+1 135	+1 8	-1 Gravel
27	-1 5.25	+1 Medium +	-1 75	+1 135	+1 8	-1 Gravel

(Continued)

TABLE A1. (Continued)

Spec. No.	Molding Water Content, % A	Aggregate Gradation B	Curing Temp., ° F C	Compactive Effort D	Cement Content, % E	Aggregate Type F	Note
28	+1	+1	-1	+1	+1	-1	
	7.75	Medium +	75	135	8	Gravel	
29	-1	-1	+1	+1	+1	-1	
	5.25	Fine +	125	135	8	Gravel	
30	+1	-1	+1	+1	+1	-1	
	7.75	Fine +	125	135	8	Gravel	
31	-1	+1	+1	+1	+1	-1	
	5.25	Medium +	125	135	8	Gravel	
32	+1	+1	+1	+1	+1	-1	
	7.75	Medium +	125	135	8	Gravel	
33	-2	0	0	0	0	-1	Star Points
	4.0	Medium	100	110	6	Gravel	
34	+2	0	0	0	0	-1	
	9.0	Medium	100	110	6	Gravel	"
35	0	-2	0	0	0	-1	
	6.5	Fine	100	110	6	Gravel	"
36	0	+2	0	0	0	-1	
	6.5	Coarse	100	110	6	Gravel	"
37	0	0	-2	0	0	-1	
	6.5	Medium	50	110	6	Gravel	"
38	0	0	+2	0	0	-1	
	6.5	Medium	150	110	6	Gravel	"
39	0	0	0	-2	0	-1	
	6.5	Medium	100	60	6	Gravel	"
40	0	0	0	+2	0	-1	
	6.5	Medium	100	160	6	Gravel	"
41	0	0	0	0	-2	-1	
	6.5	Medium	100	110	2	Gravel	"

(Continued)

TABLE A1. (Continued)

Spec. No.	Molding Water Content, % A	Aggregate Gradation B	Curing Temp., ° F C	Compactive Effort D	Cement Content, % E	Aggregate Type F	Note
42	0 6.5	0 Medium	0 100	0 110	+2 10	-1 Gravel	Star Points
43	0 6.5	0 Medium	0 100	0 110	0 6	-1 Gravel	Center Points
44	0 6.5	0 Medium	0 100	0 110	0 6	-1 Gravel	"
45	0 6.5	0 Medium	0 100	0 110	0 6	-1 Gravel	"
46	0 6.5	0 Medium	0 100	0 110	0 6	-1 Gravel	"
47	0 6.5	0 Medium	0 100	0 110	0 6	-1 Gravel	"
48	0 6.5	0 Medium	0 100	0 110	0 6	-1 Gravel	"
49	-1 5.25	-1 Fine +	-1 75	-1 85	-1 4	+1 Limestone	
50	+1 7.75	-1 Fine +	-1 75	-1 85	-1 4	+1 Limestone	
51	-1 5.25	+1 Medium +	-1 75	-1 85	-1 4	+1 Limestone	
52	+1 7.75	+1 Medium +	-1 75	-1 85	-1 4	+1 Limestone	
53	-1 5.25	-1 Fine +	+1 125	-1 85	-1 4	+1 Limestone	
54	+1 7.75	-1 Fine +	+1 125	-1 85	-1 4	+1 Limestone	
55	-1 5.25	+1 Medium +	+1 125	-1 85	-1 4	+1 Limestone	

(Continued)

TABLE A1. (Continued)

Spec. No.	Molding Water Content, % A	Aggregate Gradation B	Curing Temp., ° F C	Compactive Effort D	Cement Content, % E	Aggregate Type F
56	+1	+1	+1	-1	-1	+1
	7.75	Medium +	125	85	4	Limestone
57	-1	-1	-1	+1	-1	+1
	5.25	Fine +	75	135	4	Limestone
58	+1	-1	-1	+1	-1	+1
	7.75	Fine +	75	135	4	Limestone
59	-1	+1	-1	+1	-1	+1
	5.25	Medium +	75	135	4	Limestone
60	+1	+1	-1	+1	-1	+1
	7.75	Medium +	75	135	4	Limestone
61	-1	-1	+1	+1	-1	+1
	5.25	Fine +	125	135	4	Limestone
62	+1	-1	+1	+1	-1	+1
	7.75	Fine +	125	135	4	Limestone
63	-1	+1	+1	+1	-1	+1
	5.25	Medium +	125	135	4	Limestone
64	+1	+1	+1	+1	-1	+1
	7.75	Medium +	125	135	4	Limestone
65	-1	-1	-1	-1	+1	+1
	5.25	Fine +	75	85	8	Limestone
66	+1	-1	-1	-1	+1	+1
	7.75	Fine +	75	85	8	Limestone
67	-1	+1	-1	-1	+1	+1
	5.25	Medium +	75	85	8	Limestone
68	+1	+1	-1	-1	+1	+1
	7.75	Medium +	75	85	8	Limestone
69	-1	-1	+1	-1	+1	+1
	5.25	Fine +	125	85	8	Limestone

(Continued)

TABLE A1. (Continued)

Spec. No.	Molding Water Content, % A	Aggregate Gradation B	Curing Temp., ° F C	Compactive Effort D	Cement Content, % E	Aggregate Type F	Note
70	+1 7.75	-1 Fine +	+1 125	-1 85	+1 8	+1 Limestone	
71	-1 5.25	+1 Medium +	+1 125	-1 85	+1 8	+1 Limestone	
72	+1 7.75	+1 Medium +	+1 125	-1 85	+1 8	+1 Limestone	
73	-1 5.25	-1 Fine +	-1 75	+1 135	+1 8	+1 Limestone	
74	+1 7.75	-1 Fine +	-1 75	+1 135	+1 8	+1 Limestone	
75	-1 5.25	+1 Medium +	-1 75	+1 135	+1 8	+1 Limestone	
76	+1 7.75	+1 Medium +	-1 75	+1 135	+1 8	+1 Limestone	
77	-1 5.25	-1 Fine +	+1 125	+1 135	+1 8	+1 Limestone	
78	+1 7.75	-1 Fine +	+1 125	+1 135	+1 8	+1 Limestone	
79	-1 5.25	+1 Medium +	+1 125	+1 135	+1 8	+1 Limestone	
80	+1 7.75	+1 Medium +	+1 125	+1 135	+1 8	+1 Limestone	
81	-2 4.0	0 Medium	0 100	0 110	0 6	+1 Limestone	Star Points
82	+2 9.0	0 Medium	0 100	0 110	0 6	+1 Limestone	"
83	0 6.5	-2 Fine	0 100	0 110	0 6	+1 Limestone	"

(Continued)

TABLE A1. (Continued)

Spec. No.	Molding Water Content, % A	Aggregate Gradation B	Curing Temp., ° F C	Compactive Effort D	Cement Content, % E	Aggregate Type F	Note
84	0 6.5	+2 Coarse	0 100	0 110	0 6	+1 Limestone	Star Points
85	0 6.5	0 Medium	-2 50	0 110	0 6	+1 Limestone	"
86	0 6.5	0 Medium	+2 150	0 110	0 6	+1 Limestone	"
87	0 6.5	0 Medium	0 100	-2 60	0 6	+1 Limestone	"
88	0 6.5	0 Medium	0 100	+2 160	0 6	+1 Limestone	"
89	0 6.5	0 Medium	0 100	0 110	-2 2	+1 Limestone	"
90	0 6.5	0 Medium	0 100	0 110	+2 10	+1 Limestone	"
91	0 6.5	0 Medium	0 100	0 110	0 6	+1 Limestone	Center Points
92	0 6.5	0 Medium	0 100	0 110	0 6	+1 Limestone	"
93	0 6.5	0 Medium	0 100	0 110	0 6	+1 Limestone	"
94	0 6.5	0 Medium	0 100	0 110	0 6	+1 Limestone	"
95	0 6.5	0 Medium	0 100	0 110	0 6	+1 Limestone	"
96	0 6.5	0 Medium	0 100	0 110	0 6	+1 Limestone	"

TABLE A2. GENERAL CORRELATION

Indirect Tension Spec. No.	Cohesiometer Spec. No.	Unconfined Compression Spec. No.	Molding Water Content, %	Cement Content, %	Aggregate Type
97	117	137	4	6	Seguin gravel
98	118	138	4	6	Crushed limestone
101	121	141	6.5	2	Seguin gravel
102	122	142	6.5	2	Crushed limestone
105	125	145	9	6	Seguin gravel
106	126	146	9	6	Crushed limestone
109	129	149	6.5	10	Seguin gravel
110	130	150	6.5	10	Crushed limestone
113	133	153	6.5	6	Seguin gravel
114	134	154	6.5	6	Crushed limestone

TABLE A3. TEXAS HIGHWAY DEPARTMENT CORRELATION

Indirect Tension Spec. No.	Cohesiometer Spec. No.	Unconfined Compression Spec. No.	Molding Water Content, %	Cement Content, %	Aggregate Type
99	119	139	4	6	Seguin gravel
100	120	140	4	6	Crushed limestone
103	123	143	6.5	2	Seguin gravel
104	124	144	6.5	2	Crushed limestone
107	127	147	9	6	Seguin gravel
108	128	148	9	6	Crushed limestone
111	131	151	6.5	10	Seguin gravel
112	132	152	6.5	10	Crushed limestone
115	135	155	6.5	6	Seguin gravel
116	136	156	6.5	6	Crushed limestone

TABLE A4. SPECIMEN SIZE STUDY

2" x 4" Size Spec. No.	2" x 6" Size Spec. No.	Molding Water Content, %	Cement Content, %	Aggregate Type
33	97	4	6	Seguin gravel
81	98	4	6	Crushed limestone
41	101	6.5	2	Seguin gravel
89	102	6.5	2	Crushed limestone
34	105	9	6	Seguin gravel
82	106	9	6	Crushed limestone
42	109	6.5	10	Seguin gravel
90	110	6.5	10	Crushed limestone
48	113	6.5	6	Seguin gravel
93	114	6.5	6	Crushed limestone

APPENDIX 2

GRADATIONS

APPENDIX 2. GRADATIONS

	Fine, % by Weight	Fine +, % by Weight	Medium, % by Weight	Medium +, % by Weight	Coarse, % by Weight
Passing 7/8" sieve, retained on 1/2" sieve	2	1	-	-	-
Passing 1/2" sieve, retained on 3/8" sieve	3	11.5	-	-	-
Passing 7/8" sieve, retained on 3/8" sieve	5	12.5	20	23	26
Passing 3/8" sieve, retained on No. 4 sieve	20	19	18	19.5	21
Passing No. 4 sieve, retained on No. 10 sieve	15	14	13	14	15
Total retained on No. 10 sieve	40	45.5	51	56.5	62
Passing No. 10 sieve, retained on No. 40 sieve	30	26	22	18.5	15
Passing No. 40 sieve, retained on No. 80 sieve	10	8.5	7	6	5
Passing No. 80 sieve, retained on No. 200 sieve	10	10	10	9	8
Passing No. 200 sieve	10	10	10	10	10

APPENDIX 3

BATCHING AND MIXING PROCEDURE

APPENDIX 3. BATCHING AND MIXING PROCEDURE

(1) Select the cement content, moisture content, and gradation from the mix designs in experimental treatment combinations. Batch the material by dry weight as follows:

- (a) Weigh and store that portion of aggregate retained on the No. 10 sieve.
- (b) Weigh and store in a separate container that portion of material passing the No. 10 sieve.

(2) To the portion of material retained on the No. 10 sieve add all of the weighed quantity of water and stir the mixture thoroughly.

(3) Add the appropriate quantity of cement to the portion of material passing the No. 10 sieve and mix by hand.

(4) Add the cement and fines to the wet coarse aggregate (plus No. 10).

(5) Mix as follows:

- (a) Two x 4-inch and 2 x 6-inch specimens - machine mix for one minute, remove the fines adhering to the bottom of the mixing bowl, and continue to mix for an additional minute. The mixer used for this procedure was a Model AS-200 Hobard Company (Ohio) mixer.
- (b) Six x 8-inch specimens - hand mix the materials in a large rectangular mixing pan. Continue mixing until all materials are mixed thoroughly and uniformly.

APPENDIX 4

COMPACTION PROCEDURES

APPENDIX 4. COMPACTION PROCEDURES

FACTOR EVALUATION EXPERIMENT: GYRATORY SHEAR COMPACTION FOR 4-INCH-DIAMETER SPECIMENS*

A Texas Highway Department gyratory shear compactor (Fig A1) for 4-inch-diameter specimens was used in this study with the same general operating procedures utilized by the Texas Highway Department.

(1) Coat the mold and base plate with a thin layer of kerosene, and place a circular-shaped piece of filter paper at the bottom of the mold.

(2) Transfer the laboratory mixes into the mold in approximately three equal layers. Rod each layer and use a small spatula to remove the larger particles away from the mold wall. Place a circular-shaped piece of filter paper on top of the mixture.

(3) Slide mold onto the platen and center it in molding position beneath the ram.

(4) Apply pressure to the specimen until 30 psi is reached on the low pressure gage. Gyrate the specimen three times and stop. Repeat the three gyrations until the desired compactive effort (60, 85, 110, 135, or 160) is registered on the low-pressure gage.

(5) At approximately one stroke per second, increase the pressure to 1,000 psi, as measured on the high-pressure gage. Then release the pressure and pump the ram up and out of the mold.

(6) Extract the 2-inch-high by 4-inch-diameter specimen from the mold.

(7) Weigh and measure the height and diameter of the specimen.

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* Ref 4

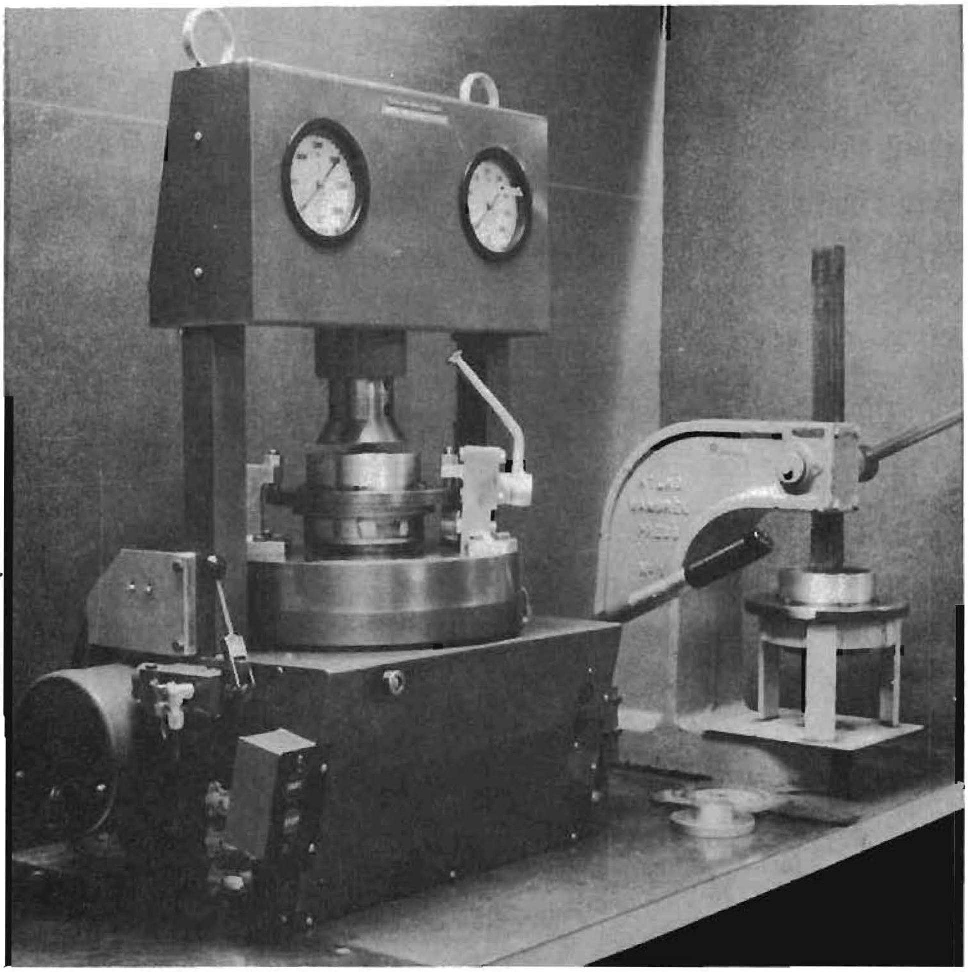

Fig A1. Gyratory shear compactor for 4-inch-diameter specimens and mechanical extruding apparatus.

GENERAL CORRELATION: GYRATORY SHEAR COMPACTION PROCEDURE FOR 6-INCH-DIAMETER SPECIMENS

A gyratory shear compactor (Fig A2), capable of producing 6-inch-diameter specimens, which was developed by the Texas Transportation Institute, Texas A&M University, was used in this study (Ref 6).

The compaction procedure used is as follows:

(1) Prior to starting compaction, the following compactor variables were fixed:

  (a) Set the gyratory angle at 3°.

  (b) Set the counter so that all gyrations will cease after 28 revolutions.

  (c) Set the speed of gyration at 10 rpm.

  (d) Set the micrometer pressure regulator at 0.1562 so that the gyrating angle has reached 0° at the completion of 28 revolutions.

  (e) Set the desired molding pressure (175 psi gage pressure).

(2) Coat the mold with a thin layer of kerosene and place slip ring spacers on base plate, tighten circumferential bands around the compaction mold, place the mold on the base plate, and place a circular-shaped piece of filter paper at the bottom of the mold.

(3) Spread a small layer of fines in the bottom of the mold, and place the remaining material in the mold. After each placement, spread the large aggregate evenly over the top of the soil layer and spade the periphery of the soil with a spatula. Leave a small amount of fines for the top of the specimen. Place a circular-shaped piece of filter paper on top of the specimen. Insert the top bearing plate and grease lightly.

(4) Slide mold and base plate into place, fitting the proper spacer in its groove on the pressure head. Fasten the base plate into place. Install front of mold chuck and tighten bolts.

(5) Allow pressure head to apply load to specimen. Upon completion of vertical movement, release load and remove slip ring spacers from beneath compaction mold.

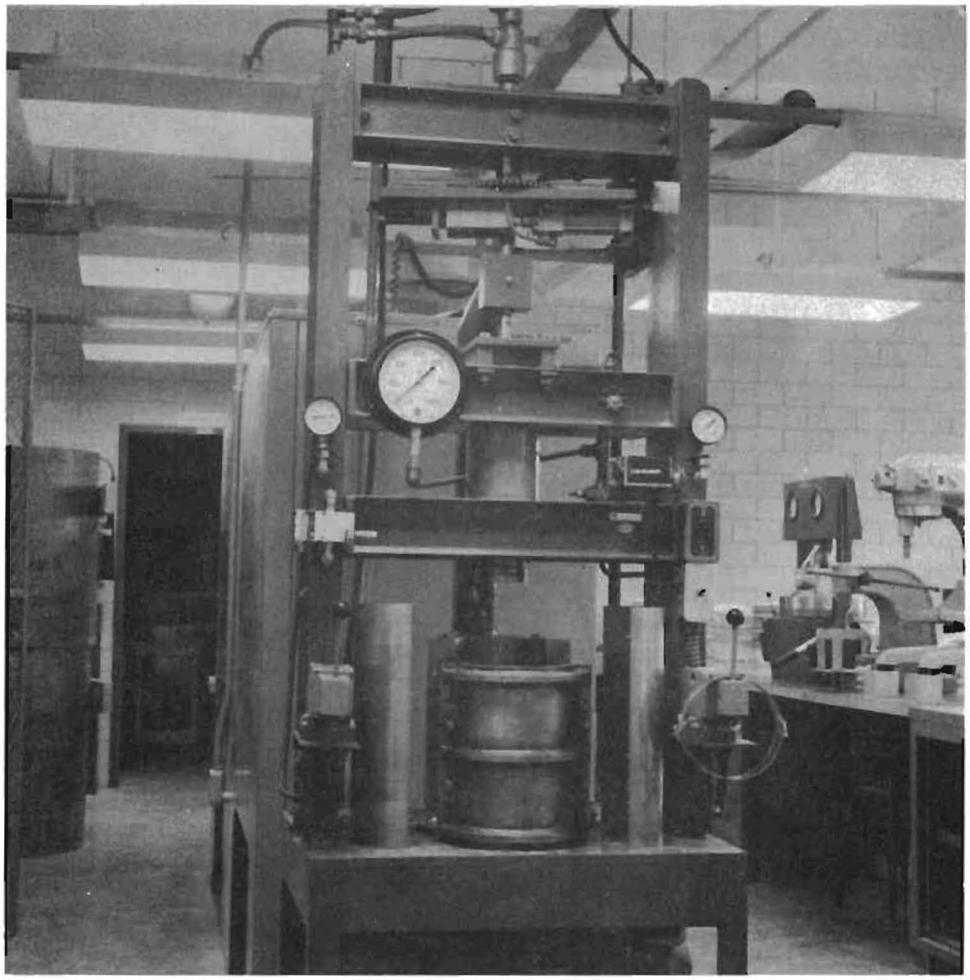

Fig A2. Gyratory shear compactor for 6-inch-diameter specimens.

(6) Reapply load to specimen. When vertical movement ceases, open valve to apply gyrating angle.

(7) Start gyration.

(8) When gyration has ended, retract pressure head.

(9) Remove mold chuck and loosen the base plate.

(10) Remove mold from base plate and loosen circumferential bands slightly.

(11) Extrude specimen. Weigh and measure height and diameter of specimen.

TEXAS HIGHWAY DEPARTMENT CORRELATION: IMPACT COMPACTION*

(1) Coat the mold and base plate with a thin layer of kerosene.

(2) After the materials are thoroughly mixed, set aside a small amount of fines. Place the remaining material into the 6-inch-diameter mold in 2-inch layers. Rod the material several times to insure that the coarser aggregate is towards the center of the mold.

(3) Compact each layer with a compactive effort of 6.63 foot-pounds per cubic inch (25 blows per 2-inch layer using a 10-pound ram with 18-inch drop). If there is more than one layer, scarify the top of the preceding layer prior to placing the material for the next layer into the mold.

(4) After the material is compacted, remove the compaction mold and base plate from the compactor.

(5) Use the small amount of fines set aside in Step 2 to level the surface of the specimen.

(6) To achieve a flat, level surface apply five to ten light and five firm blows to the specimen using a flat-faced finishing tool and a 1 to 2-pound plastic-faced hammer and a 4 to 5-pound rawhide-faced hammer. Use a small level to check the surface.

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* Ref 4

(7) Remove the mold from the base plate and extrude the specimen. Weigh and measure the height and circumference of the specimen.

(8) A Rainhart Automatic Tamper was used in this study (Fig A3).

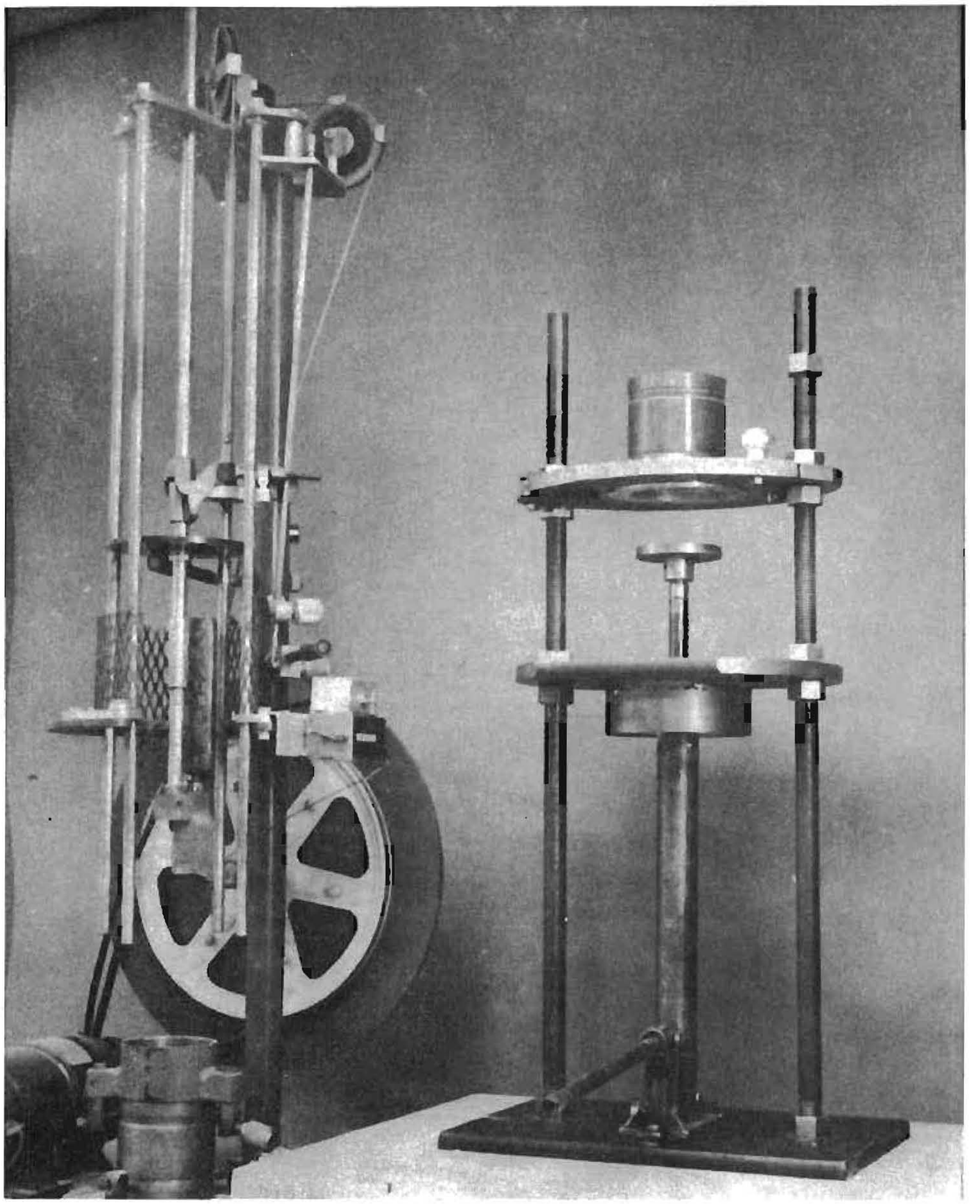

Fig A3. Rainhart Automatic Tamper and mechanical extruding apparatus.

APPENDIX 5

CURING PROCEDURES

APPENDIX 5. CURING PROCEDURES

FACTOR EVALUATION EXPERIMENT, GENERAL CORRELATION, AND SPECIMEN SIZE STUDY

The curing procedures utilized for the Factor Evaluation Experiment, the General Correlation, and the Specimen Size Study were identical as follows:

(1) Immediately after compaction and weighing and measuring the height and diameter, wrap the specimen with one layer of PVC film and secure the film with rubber bands.

(2) Place the specimen in the appropriate temperature environment as required in the experiment (50^{o} F, 75^{o} F, 100^{o} F, 125^{o} F, or 150^{o} F) for seven days.

(3) At the end of seven days take the specimen from its environmental chamber, remove the PVC film; weigh and measure the height and diameter of specimen.

(4) Test specimen.

TEXAS HIGHWAY DEPARTMENT CORRELATION

For this experiment the standard Texas Highway Department curing procedures (Ref 9) were utilized as follows:

(1) Immediately after compaction and weighing and measuring the height and diameter, place the test specimen with top and bottom porous stones in place in a damp room for a period of seven days.

(2) At the end of seven days remove the test specimen from damp room and remove any free water on surface of specimen.

(3) Weigh and measure the height and diameter of the specimen.

(4) Test specimen.

APPENDIX 6

TEST PROCEDURES

APPENDIX 6. TEST PROCEDURES

INDIRECT TENSILE TEST PROCEDURE

The basic testing equipment was the same as previously used in other studies at The University of Texas (Refs 1, 2, 3, 7, and 9) and which consists of an adjustable loading frame, a closed loop, electrohydraulic loading system, and a loading head which is a modified, commercially available shoe-die with upper and lower platens constrained to remain parallel during testing.

Testing was conducted at room temperature at a constant loading rate of 2 inches per minute. Upper and lower curved stainless steel loading strips of 1/2-inch width were used to apply the load to the specimens. The curved loading strips had a radius of 2 inches for 4-inch-diameter specimens and 3 inches for 6-inch-diameter specimens.

Horizontal deformation of the specimen was measured by a device consisting of two cantilevered arms with attached strain gages. Vertical deformations were measured by a DC linear-variable-differential transducer which also was used to control the rate of load application by providing an electrical signal related to the relative movements of the upper and lower platens to the control module. All measurements were recorded on two x-y plotters.

The following steps were used to test the cement-treated specimens in indirect tension:

(1) Center the specimen on the lower loading strip.
(2) Zero the x-y plotter recording load versus vertical deformation.
(3) Preload the specimen to 25 pounds.
(4) Position the device for measuring horizontal deformations.
(5) Bring the marking pen on the x-y plotter recording load versus horizontal deformation to a position relative to the marking pen on the x-y plotter recording load versus vertical deformation.
(6) Engage both marking pens and initiate test.

The basic test equipment is shown in Fig A4 and the lateral deflection device is shown in Fig A5.

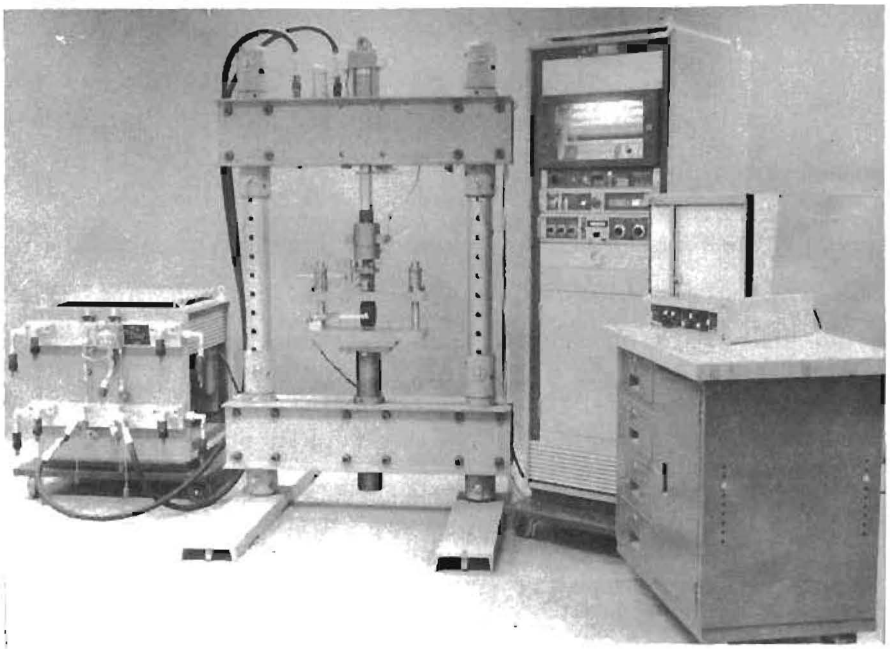

Fig A4. Basic indirect tensile testing equipment.

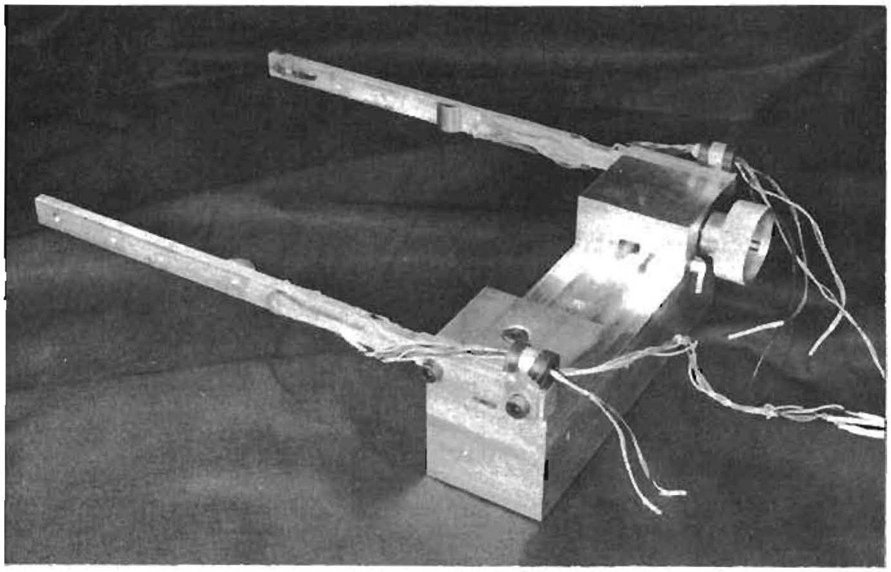

Fig A5. Lateral deflection device.

UNCONFINED COMPRESSION TEST PROCEDURE

A compression testing machine was used for this test procedure which complies with A.S.T.M. Designation D 1633-59T. The procedure used for testing cement-treated specimens was the same as required by the Texas Highway Department (Ref 4) and are tested at room temperature as follows:

(1) Place and center specimen between upper and lower platens.
(2) Apply load to the specimen at the rate of 20 ± 10 psi per second.
(3) Record ultimate load at failure.

COHESIOMETER TEST PROCEDURE

The same basic test procedures were used as those utilized by the Texas Highway Department (Ref 4) and are tested at room temperature as follows:

(1) Place the cement-treated specimen (with top side, as molded, up) on platform of cohesiometer. Center the test specimen on lower plates and clamp the specimen firmly in testing machine making certain that the top plates are parallel with the surface of the specimen. Use torque wrench to tighten clamp screws sufficiently to prevent slippage but not so tight that the specimen is damaged. Use approximately 24 inch-pounds pressure for soil-cement specimens.

(2) Release the shot to test the specimen at the flow rate of 1800 ± 20 grams of shot per minute until the specimen breaks.

(3) Weigh the shot in the receiver and record to the nearest gram.

APPENDIX 7

EXPERIMENTAL DATA

APPENDIX 7. EXPERIMENTAL DATA

TABLE A5. MAIN EXPERIMENT

Specimen Number	Height, Inches	Diameter, Inches	Water Content at Compaction, %	Water Content at Test, %	Dry Density, pcf	Horizontal Deflection, Inches ($\times 10^{-4}$)	Vertical Deflection, Inches ($\times 10^{-4}$)	Failure Load, Pounds
1	1.932	4.008	5.25	4.1	133.0	5.8	71	1,406
2	1.994	4.015	7.75	6.3	131.4	6.0	160	1,190
3	1.964	4.007	5.25	3.9	134.3	17.0	90	1,470
4	1.989	4.018	7.75	6.0	133.7	3.3	188	970
5	1.967	4.006	5.25	1.3	134.0	12.5	115	1,440
6	1.993	4.008	7.75	2.0	132.1	8.0	164	1,470
7	1.963	4.005	5.25	1.0	134.8	8.0	120	1,675
8	1.964	4.013	7.75	1.8	133.1	5.5	88	1,550
9	1.959	4.009	5.25	4.1	134.5	8.0	110	1,405
10	1.991	4.013	7.75	6.3	132.5	6.0	95	1,210
11	1.936	4.009	5.25	3.8	136.1	7.0	80	1,763
12	1.956	4.018	7.75	6.3	133.2	5.2	135	1,075
13	1.959	4.003	5.25	1.3	134.8	8.3	100	1,615
14	1.984	4.015	7.75	2.0	132.6	5.0	100	1,375
15	1.945	4.006	5.25	1.2	135.3	17.0	105	1,613
16	1.966	4.012	7.75	1.6	134.4	10.5	90	1,588
17	2.059	4.008	5.25	3.6	133.9	7.8	142	2,100
18	2.056	4.017	7.75	5.7	133.4	3.0	150	1,950
19	2.035	4.008	5.25	3.7	135.1	7.5	141	2,470
20	2.046	4.015	7.75	5.6	134.3	6.0	155	2,900
21	2.060	4.006	5.25	1.0	133.6	7.0	86	2,675
22	2.064	4.010	7.75	1.7	132.9	5.2	110	3,570
23	2.051	4.006	5.25	0.9	134.3	9.0	75	2,575
24	2.055	4.014	7.75	1.9	134.4	5.6	185	3,620

(Continued)

TABLE A5. (Continued)

Specimen Number	Height, Inches	Diameter, Inches	Water Content at Compaction, %	Water Content at Test, %	Dry Density, pcf	Horizontal Deflection, Inches ($\times 10^{-4}$)	Vertical Deflection, Inches ($\times 10^{-4}$)	Failure Load, Pounds
25	2.036	4.007	5.25	3.6	135.3	7.5	96	3,010
26	2.069	4.012	7.75	5.8	132.3	6.5	140	3,025
27	2.003	4.008	5.25	3.6	137.5	6.4	85	2,765
28	2.054	4.012	7.75	5.5	133.6	6.6	123	3,175
29	2.047	4.004	5.25	1.3	134.4	6.5	80	2,550
30	2.072	4.012	7.75	1.8	132.3	6.5	98	3,565
31	2.012	4.007	5.25	1.3	136.2	7.8	92	2,751
32	2.044	4.018	7.75	1.9	133.6	4.8	265	2,840
33	2.005	4.004	4.0	1.8	134.2	7.5	90	1,312
34	2.058	4.021	9.0	5.0	132.6	7.3	93	2,157
35	2.009	4.008	6.5	3.7	134.1	7.0	88	3,130
36	1.979	4.010	6.5	2.9	135.8	5.3	80	2,640
37	1.995	4.012	6.5	5.6	134.1	6.2	120	2,475
38	1.990	4.006	6.5	0.5	135.1	7.5	85	2,550
39	1.991	4.007	6.5	3.5	135.5	7.0	88	3,040
40	1.979	4.007	6.5	3.6	136.1	7.3	156	2,890
41	1.909	4.010	6.5	3.9	134.9	5.7	132	1,208
42	2.056	4.008	6.5	3.6	136.4	8.3	160	3,025
43	1.975	4.008	6.5	3.4	136.3	4.3	87	1,700
44	1.979	4.008	6.5	3.4	136.2	6.0	70	2,810
45	1.973	4.012	6.5	3.5	136.4	5.7	120	2,580
46	1.985	4.008	6.5	3.4	135.8	12.5	129	2,930
47	1.991	4.008	6.5	3.4	135.5	5.5	78	2,640
48	1.990	4.009	6.5	3.6	135.3	7.0	80	3,145

(Continued)

TABLE A5. (Continued)

Specimen Number	Height, Inches	Diameter, Inches	Water Content at Compaction, %	Water Content at Test, %	Dry Density, pcf	Horizontal Deflection, Inches ($\times 10^{-4}$)	Vertical Deflection, Inches ($\times 10^{-4}$)	Failure Load, Pounds
49	2.037	4.006	5.25	3.4	130.2	6.7	94	1,608
50	1.992	4.011	7.75	5.7	131.2	7.2	170	1,665
51	2.009	4.009	5.25	3.8	131.6	6.5	132	1,388
52	1.967	4.020	7.75	5.5	134.0	12.5	212	1,906
53	2.024	4.008	5.25	0.3	130.4	7.0	145	1,630
54	1.992	4.014	7.75	1.3	132.7	7.0	195	1,845
55	2.024	4.006	5.25	0.3	131.0	7.4	120	1,638
56	1.974	4.016	7.75	1.0	134.2	13.0	143	2,513
57	2.009	4.009	5.25	3.6	131.3	10.3	83	1,490
58	1.980	4.014	7.75	5.7	133.1	6.8	130	2,100
59	1.987	4.010	5.25	3.6	132.9	8.5	105	1,170
60	1.950	4.009	7.75	5.7	135.3	6.5	155	2,275
61	2.023	4.008	5.25	0.2	130.6	5.9	110	2,150
62	1.994	4.016	7.75	1.0	132.7	7.9	91	2,770
63	1.994	4.005	5.25	0.3	132.6	5.6	82	2,235
64	1.963	4.022	7.75	1.5	133.5	10.0	245	2,039
65	2.113	4.010	5.25	2.9	130.4	8.9	95	2,945
66	2.067	4.017	7.75	5.0	133.9	7.5	150	6,050
67	2.072	4.008	5.25	3.3	132.2	9.0	100	3,720
68	2.047	4.020	7.75	5.3	134.3	5.3	120	5,700
69	2.099	4.007	5.25	0.5	131.6	8.5	100	3,300
70	2.089	4.047	7.75	1.1	133.0	5.4	102	5,650
71	2.091	4.008	5.25	0.6	131.9	7.5	100	3,650
72	2.086	4.013	7.75	1.5	134.3	5.3	113	6,500

(Continued)

TABLE A5. (Continued)

Specimen Number	Height, Inches	Diameter, Inches	Water Content at Compaction, %	Water Content at Test, %	Dry Density, pcf	Horizontal Deflection, Inches ($\times 10^{-4}$)	Vertical Deflection, Inches ($\times 10^{-4}$)	Failure Load, Pounds
73	2.075	4.007	5.25	3.1	133.1	9.5	90	3,240
74	2.051	4.018	7.75	5.3	128.5	5.0	174	4,200
75	2.072	4.008	5.25	3.3	132.9	6.8	130	3,590
76	2.042	4.016	7.75	5.2	134.6	3.7	150	4,600
77	2.051	4.008	5.25	0.6	134.7	8.0	139	3,590
78	2.071	4.018	7.75	1.5	133.8	6.0	100	5,970
79	2.087	4.010	5.25	0.6	131.8	5.3	105	4,400
80	2.055	4.026	7.75	1.3	134.1	6.5	112	5,680
81	2.049	4.008	4.0	0.9	132.0	8.8	160	1,480
82	2.020	4.027	9.0	4.8	132.5	5.2	189	2,990
83	2.041	4.008	6.5	3.1	132.9	6.5	101	3,375
84	2.019	4.010	6.5	2.5	134.4	6.5	113	5,025
85	2.014	4.010	6.5	5.2	134.4	8.0	135	3,250
86	2.025	4.009	6.5	0.2	133.7	8.0	125	5,420
87	2.048	4.010	6.5	2.8	132.4	8.0	123	3,380
88	2.007	4.007	6.5	2.9	135.1	8.0	140	3,510
89	1.953	4.010	6.5	3.0	133.6	6.5	80	1,225
90	2.123	4.008	6.5	2.5	133.3	6.8	122	6,480
91	2.022	4.008	6.5	2.8	134.0	7.5	117	3,220
92	2.207	4.009	6.5	2.7	134.1	7.2	119	3,460
93	2.017	4.008	6.5	3.2	134.1	6.3	125	3,480
94	2.039	4.008	6.5	3.1	133.8	8.5	124	3,675
95	2.009	4.011	6.5	3.0	134.9	8.5	120	3,570
96	2.025	4.008	6.5	3.0	133.9	10.7	94	3,310

TABLE A6. INDIRECT TENSION TEST

Spec. No.	Height, In.	Diam., In.	Failure Load, Pounds	Horiz. Defl., In.	Vert. Defl., In.	Water Content, % Compaction	Water Content, % Testing	Dry Density, pcf
GENERAL CORRELATION								
97	1.953	5.994	1,423	.00110	.0160	4	2.5	131.6
98	1.998	5.994	1,850	.00050	.0080	4	1.2	129.6
101	1.830	5.997	1,800	.00025	.0160	6.5	5.0	134.2
102	1.899	5.984	1,120	.00065	.0160	6.5	4.2	130.1
105	1.854	6.006	3,500	.00050	.0220	9	4.5	135.3
106	1.878	6.003	4,550	.00225	.0475	9	4.4	134.4
109	1.975	5.997	6,200	.00058	.0217	6.5	3.9	135.8
110	2.032	5.991	6,320	.000585	.0208	6.5	3.2	132.4
113	1.908	6.000	4,060	.00040	.0118	6.5	4.4	134.1
114	1.962	6.013	5,380	.00059	.0180	6.5	3.3	130.8
TEXAS HIGHWAY DEPARTMENT CORRELATION								
99	2.044	5.991	5,840	.00120	.0080	4	0.5	131.5
100	2.030	5.997	1,510	.00095	.0080	4	2.9	125.9
103	1.854	6.000	1,490	.00050	.0140	6.5	6.0	133.5
104	1.961	5.997	720	.00100	.0170	6.5	5.5	126.4
107	1.980	5.949	2,230	.00017	.0335	9	7.7	130.2
108	1.939	5.968	4,505	.00050	.0276	9	1.9	137.9
111	2.011	6.000	6,720	.000595	.0115	6.5	5.1	133.7
112	2.082	5.991	5,400	.000750	.0118	6.5	4.5	128.9
115	1.932	5.994	4,150	.00038	.0110	6.5	5.4	134.4
116	2.022	5.994	2,860	.00055	.0105	6.5	4.9	128.3

TABLE A7. UNCONFINED COMPRESSION TEST

Spec. No.	Height, Inches	Diameter, Inches	Failure Load, Pounds	Water Content, %		Dry Density, pcf
				Compaction	Testing	
			GENERAL CORRELATION			
137	7.938	5.991	14,600	4	2.8	130.9
138	8.105	5.994	23,100	4	2.1	128.8
141	7.380	5.997	17,100	6.5	5.3	134.9
142	7.578	5.991	22,700	6.5	4.5	132.0
145	7.817	6.032	19,300	9	6.2	131.4
146	7.689	6.035	58,600	9	5.1	134.1
149	8.180	5.994	41,600	6.5	3.8	133.8
150	8.346	6.003	50,500	6.5	3.8	130.2
153	7.703	6.000	42,400	6.5	4.8	135.1
154	8.026	6.000	35,400	6.5	3.9	129.7
			TEXAS HIGHWAY DEPARTMENT CORRELATION			
139	8.161	5.991	12,700	4	3.9	127.4
140	8.281	6.000	18,400	4	2.8	125.2
143	7.459	5.997	15,900	6.5	5.9	133.7
144	7.795	5.987	17,500	6.5	5.1	128.6
147	7.836	6.077	22,500	9	7.5	129.4
148	7.707	6.089	51,100	9	7.1	131.4
151	8.240	5.981	51,200	6.5	4.9	132.4
152	8.485	5.994	53,400	6.5	4.1	128.4
155	7.884	5.987	36,900	6.5	5.3	132.5
156	8.138	5.987	42,000	6.5	4.6	128.9

TABLE A8. COHESIOMETER TEST

Spec. No.	Height, Inches	Diameter, Inches	Weight of Shot, gms	Water Content, %		Dry Density, pcf
				Compaction	Testing	
			GENERAL CORRELATION			
117	1.935	5.996	10,276	4	2.4	132.8
118	2.000	5.994	9,994	4	1.6	129.3
121	1.815	6.001	8,997	6.5	4.8	135.5
122	1.916	5.996	7,626	6.5	4.0	129.5
125	1.873	6.019	16,946	9	4.7	135.0
126	1.913	6.017	26,595	9	4.2	132.5
129	1.962	5.998	35,907	6.5	3.8	136.9
130	2.055	5.994	37,097	6.5	3.2	131.7
133	1.894	5.998	23,843	6.5	4.2	136.0
134	1.994	5.997	22,808	6.5	3.2	129.9
			TEXAS HIGHWAY DEPARTMENT CORRELATION			
119	2.023	5.996	4,360	4	4.4	128.0
120	2.047	5.998	5,050	4	2.8	126.0
123	1.860	5.995	7,600	6.5	6.1	132.9
124	1.949	5.994	5,685	6.5	5.3	127.3
127	1.993	5.976	14,828	9	7.6	130.4
128	1.938	6.012	23,709	9	4.6	135.7
131	2.042	5.999	23,991	6.5	5.0	132.0
132	2.101	5.995	25,933	6.5	4.4	128.4
135	1.941	5.997	18,815	6.5	5.4	133.4
136	2.005	5.995	20,925	6.5	5.3	129.5

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