EVALUATION AND PREDICTION OF THE TENSILE PROPERTIES OF LIME-TREATED MATERIALS

by

Walter S. Tulloch, II
W. Ronald Hudson
Thomas W. Kennedy

Research Report Number 98-5

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
Bureau of Public Roads

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

June 1970

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

PREFACE

This is the fifth in a series of reports dealing with the findings of a research project concerned with the evaluation of the tensile properties of stabilized subbase materials. This report provides a detailed investigation of the effects of five factors on the tensile properties of lime-treated materials. The report also presents the findings of two studies correlating indirect tensile test results for lime-treated materials with the results of the unconfined compression test and the cohesiometer test and the findings of a study of the effect of specimen size on the tensile strength of lime-treated materials.

The culmination of this report required the assistance of many individuals. The authors would like to acknowledge the work of the people who contributed to this report. Special thanks are extended to Dr. Gerald Wagner and Mr. Joseph A. Kozuh for their help in designing the statistical experiment and in providing guidance in the analysis of the data. Special appreciation is due Messrs. Pat Hardeman and James N. Anagnos for their assistance in the preparation and testing of the lime-treated materials. Thanks are also due to Messrs. James L. Brown and Harvey Treybig of the Texas Highway Department, who provided the technical liaison for the project.

Future reports will be concerned with a detailed investigation of the tensile characteristics of asphalt-treated and cement-treated materials. Reports will be written on such subjects as (1) factors affecting the tensile characteristics and behavior of these three materials when subjected to static loads and dynamic repeated loads, (2) correlation of indirect tensile test parameters with parameters from standard Texas Highway Department tests for asphalt-treated and cement-treated materials, (3) performance criteria for stabilized materials, (4) the feasibility of determining an effective modulus of elasticity and Poisson's ratio from results of indirect tensile tests, and (5) development of support value k for a layered system related to layer thickness, modulus, and the area of loading.

Walter S. Tulloch, II
W. Ronald Hudson
Thomas W. Kennedy

June 1970

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 lime-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, presents 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.

ABSTRACT, SUMMARY, AND IMPLEMENTATION STATEMENT

Abstract

This study was divided into four phases. Each phase consisted of a statistically designed experiment. An experiment was conducted to evaluate the effects of five factors on the tensile properties of lime-treated materials. The factors investigated were compactive effort, lime content, clay content, molding water content, and curing temperature. The indirect tensile strength, vertical failure deformation, and horizontal failure deformation were the parameters evaluated in this experiment. Tables of all main factors, interactions, and curvilinear effects significant at alpha levels of 1 and 5 percent are shown for each parameter. Those which had a significant effect ($\alpha = 0.05$) on indirect tensile strength are discussed in this report. Through regression analysis, an equation for indirect tensile strength was developed in terms of the five factors studied. Two experiments were conducted to correlate the indirect tensile test with the unconfined compression test and the cohesiometer test for lime-treated materials. In one of the correlation experiments the specimens were cured according to procedures established at the Center for Highway Research. In the other correlation experiment the specimens were cured according to standard Texas Highway Department procedures. Through regression analysis, equations for indirect tensile strength in terms of unconfined compressive strength and/or cohesiometer value were developed. The fourth phase of this study consisted of an experiment in which it was found that specimen size did not have a significant effect on the indirect tensile strength of lime-treated materials.

KEY WORDS: tensile strength, cohesiometer, unconfined compression, lime stabilization, test correlation, subbase.

Summary

The purpose of this report is to summarize the findings from a detailed investigation concerned with establishing the important factors affecting the tensile strength of lime-treated materials, determining the nature of these effects, and developing predictive equations for estimating the tensile strengths.

Five factors, compactive effort, lime content, clay content, molding water content, and curing temperature, were investigated at five levels in a statistically designed experiment to obtain detailed information on the effects produced by these factors and to compare the results from the indirect tensile test with the results from the unconfined compression test and cohesiometer test.

All five factors significantly affect the indirect tensile strength either directly or by significantly influencing the effect produced by one or more of the other factors. Generally it was found that tensile strength was increased by

(1) increasing the compactive effort,
(2) increasing the lime content,
(3) decreasing the molding water content, and
(4) increasing the curing temperature.

More important, however, was the fact that these five factors interact with each other so that the actual effect produced by changing one variable is dependent on the levels of the other involved variables. In addition, it was found that the effects of curing temperature and molding water content were nonlinear. The strength increase associated with increased curing temperature was greater in the higher temperature ranges and strength was maximum at an intermediate molding water content, indicating that there is an optimum molding water content for strength. Probably the most important factor affecting the indirect tensile strength was curing temperature. It produced a significant effect by itself and influenced the effect produced by three of the other factors.

In addition to the investigation of factors, an equation containing ten variables was developed for predicting indirect tensile strengths for any combination of given factor levels. This equation accounted for 94 percent of the observed variation and usually provided estimates within ±4.03 psi.

Predictive equations were also developed for estimating indirect tensile strengths in terms of unconfined compressive strength and/or cohesiometer value for both Center for Highway Research and Texas Highway Department curing procedures.

It was found that specimen size does not have a significant effect on the indirect tensile strength of lime-treated materials. This finding is in agreement with previous theoretical and experimental evaluations of size effects.

Implementation Statement

The results of these studies are part of a program to provide a better understanding of the behavior and performance of stabilized materials used as elements in a pavement structure. As indicated in the recommendations, the results will be used in the next phase of the study, repeated loading. They will also be compared to the findings for cement-treated and asphalt-treated materials to develop overall information for stabilized materials.

Furthermore, the detailed findings relating to the effect of individual factors on tensile strength can be used to develop design information for stabilized mixtures. This information provides for an immediate upgrading of approximate design techniques currently utilized and, until an improved design technique is available, the predictive equations can be used to estimate the tensile strength of lime-treated materials. In addition, the findings concerning the factors affecting tensile strength and the nature of these effects can be used as a guide to the design, placement, and curing of lime-treated materials in the field.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

The Center for Highway Research at The University of Texas at Austin is presently continuing a study of the tensile properties of stabilized subbase materials. Initially, Hudson and Kennedy (Refs 1 and 2), after reviewing the available literature and conducting laboratory tests, determined the indirect tensile test to be the most adequate for the study undertaken by the Center. Then, in three initial screening experiments (Refs 3, 4, 5, and 6), preliminary evaluations were made of the factors affecting the tensile characteristics of asphalt-treated, cement-treated, and lime-treated materials.

The purpose of this current report is twofold:

(1) to extend the study of the tensile properties of lime-treated materials and to clarify and reinforce the preliminary findings previously reported (Ref 6) and

(2) to compare the results of the indirect tensile test being developed in this project (Ref 1) to the results of the conventional Texas Highway Department tests for these materials, i.e., the unconfined compression test and the cohesiometer test.

In order to accomplish these objectives four experiments were conducted:

(1) the factor evaluation experiment, to extend the study of the factors affecting the tensile properties of lime-treated materials;

(2) the Center for Highway Research correlation, to compare the indirect tensile test results with the results of the unconfined compression test and the cohesiometer test for soil-lime specimens cured according to procedures established at the Center for Highway Research;

(3) the Texas Highway Department correlation, to compare the indirect tensile test results with the results of the unconfined compression test and the cohesiometer test for soil-lime specimens cured according to standard Texas Highway Department procedures; and

(4) the specimen size study, to determine the effect of specimen size on the indirect tensile strength of soil-lime specimens.

Chapter 2 is a review of the preliminary evaluation of lime-treated materials conducted prior to this study by Miller et al (Ref 6) and also a review of literature concerning lime stabilization and previous test correlations. The experimental program is described in Chapter 3. The results from the experiment evaluating the effects of various factors on the tensile properties of lime-treated materials and a method of predicting the tensile strength of a lime-treated material are presented in Chapter 4. Chapter 5 contains the results of correlation experiments and presents equations for predicting indirect tensile strength in terms of the unconfined compressive strength and/or the cohesiometer value for lime-treated materials and an analysis of the effect of specimen size on the tensile strength of lime-treated materials. Chapter 6 contains a summary of the findings of this report, recommendations for further soil-lime research, and suggestions for utilization of the findings of this report.

CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

A considerable amount of research concerning the characteristics of lime-treated materials has been accomplished. This chapter includes a brief summary of previous research related to the present study and a summary of the work accomplished by Miller, Kennedy, and Hudson (Ref 6). In addition, a review of the available literature dealing with test correlations for soil-lime specimens and with studies of the effect of specimen size on indirect tensile test results is included.

PREVIOUS SOIL-LIME RESEARCH

A review of the work by Herrin and Mitchell (Ref 7), Mateos (Ref 8), and Thompson (Refs 9 and 10) shows several specific changes in soil properties brought about by the addition of lime:

(1) reduced plasticity indices,
(2) increased plastic limits,
(3) increased effective grain sizes,
(4) increased strengths,
(5) increased durability,
(6) reduced volume changes,
(7) reduced maximum dry densities,
(8) increased optimum moisture contents, and
(9) increased shrinkage limits.

Diamond and Kinter (Ref 11), and Herrin and Mitchell (Ref 7) as well as several other authors (Refs 9, 12, and 13) attribute these changes to one or a combination of four mechanisms or reactions involving soil and lime:

(1) cation exchange,
(2) flocculation and agglomerations,
(3) carbonation, and
(4) pozzolanic reactions.

Although these mechanisms are generally accepted as the causes of the changes associated with lime stabilization, there is still a great deal to be learned about the subject and authorities are not in complete agreement. However, it is evident from these studies that the effect of adding lime to a soil is very complex and is affected by many factors.

From an extensive review of the available literature Miller et al (Ref 6) determined that the most significant factors affecting lime stabilization were

(1) compactive effort,
(2) lime content,
(3) clay content,
(4) molding water content,
(5) curing temperature,
(6) compaction type,
(7) curing procedure, and
(8) curing time.

Furthermore the literature seemed to indicate that the compressive strength of lime-treated materials was generally increased by

(1) increasing lime content,
(2) increasing curing time,
(3) increasing curing temperature,
(4) increasing density,
(5) providing better mixing and pulverization,
(6) increasing molding water content in the range below optimum,
(7) compacting immediately following mixing,
(8) using clay rather than an all granular material, and
(9) using clay with low organic carbon content.

RESULTS OF PRELIMINARY STUDY

On the basis of their study Miller et al (Ref 6) conducted a broad statistically designed screening experiment to study the effect of the eight factors listed above on the indirect tensile strength of soil-lime specimens. His experiment was designed to evaluate the significant effects of all eight main effects, all two-factor interactions, and selected higher order interactions.

The experiment was divided into three blocks of one fractional factorial each in order to reduce the number of specimens required to be produced in any one day and to study the effect of a wide range of clay contents. Indirect tensile strength was the only parameter evaluated in that experiment.

Through an analysis of variance all eight factors were found to be significant as main effects or as interactions. Included in the significant effects were several higher order interactions. It was found that the average strength was significantly increased by

(1) using impact compaction rather than gyratory shear compaction,
(2) using 100 percent clay rather than a mixture of clay and gravel,
(3) curing at a temperature of 100° F rather than 40° F,
(4) using a high compactive effort,
(5) increasing the lime content from 2 to 6 percent,
(6) using sealed rather than air-dried curing, and
(7) curing from six weeks rather than two weeks.

The only main effect which was not significant involved the molding water content. Although not significant as a main effect it was involved in a number of highly significant interaction effects. Thus, it was found that all eight factors chosen for evaluation on the basis of a literature review were important to the tensile strength of the lime-treated materials. Curing time, although significant, had very little practical effect, probably because the longer curing time was relatively short.

Eleven two-factor interactions produced highly significant effects on the indirect tensile strength at a probability level of 0.001. These interactions were

(1) compaction type × treatment type,
(2) curing procedure × curing temperature,
(3) compactive effort × treatment type,
(4) compactive effort × compaction type,
(5) compactive effort × curing procedure,
(6) compactive effort × lime content,
(7) lime content × curing time,
(8) compaction type × curing temperature,
(9) compaction type × curing procedure,

(10) compaction type × lime content, and

(11) curing procedure × treatment type.

In addition, 10 three-factor and 3 four-factor interactions were found to be significant, at a probability level of 0.001. The four-factor interactions were all confounded with another four-factor interaction and four of the three-factor interactions were confounded with other three-factor interactions; thus, the majority of the higher-order interactions could not be evaluated.

The significant effects appeared to be dominated by compactive effort, treatment type, and curing temperature, all of which appeared as main effects and occurred in many interaction effects. The most important of these factors was treatment type, which contained the confounded factors of water content and clay content.

Evaluation of treatment type indicated that both water content and clay content were important and that they also interacted to produce a significant effect.

The only factor which did not appear to be important was curing time, probably because the curing times used in this study were short and strength gain in lime-treated materials is a long-term process. Future investigations probably should include a much longer curing time.

It is also felt that all factors should be expanded to include additional levels. In addition, since all specimens were tested in an air-dried moisture condition, subsequent investigations should give consideration to testing at a higher moisture content, which would more closely resemble current practice and better simulate the worst condition.

By regression Miller also obtained a preliminary prediction equation for indirect tensile strength in terms of the eight factors studied. This equation contained 25 terms, had a multiple correlation coefficient of 0.90, and had a standard error of estimate equal to ±16.8 psi.

Because the experiment was not a full factorial design and because the specimens were arranged in blocks, not all possible interactions could 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 and in order to investigate the various factors at additional levels. The 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 Center experiments using the indirect tensile test can be related to past and future work involving other commonly used tests, correlations involving these tests were conducted.

TEST CORRELATIONS

Because the Texas Highway Department currently uses the unconfined compression test and the cohesiometer test to evaluate lime-treated soils, it 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-lime research at the Center for Highway Research has been conducted using specimens with 4-inch diameters, a study was also required 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 lime-treated materials have been accomplished. Townsend and Klym (Ref 14) and Thompson (Refs 10 and 15) have reported correlations between these two tests; however, little work has been conducted to correlate cohesiometer test results with indirect tensile test results for lime-treated materials.

Metcalf and Frydman (Ref 16) reported that the tensile strength is between one-twelfth and one-tenth of the unconfined compressive strength for stabilized soils. Thompson (Ref 15) reported (1) that indirect tensile strength S_t and compressive strength q_u vary in a similar manner, (2) that the ratio between them exhibits little variation, and (3) that for the specimens studied the overall average ratio of approximately 0.13 was appropriate (Refs 10 and 15). He qualified this average by saying that the ratio was affected by soil type (Ref 15). Mitchell (Ref 17) and several other authors (Ref 1) reported that, on the basis of theoretical and experimental considerations, specimen size had little effect on the indirect tensile strength of the specimen, although the average tensile strength and the dispersion of the test results was slightly less for larger specimens.

The results of correlations between indirect tensile strength, cohesiometer value, and unconfined compressive strength are presented in Chapter 5. Originally it was planned that all the specimens for the test correlations would be prepared and cured according to the procedures established at the

Center for Highway Research, but since the Texas Highway Department has its own standard curing procedure, part of the specimens used were cured according to Texas Highway Department standard curing procedures.

CHAPTER 3. EXPERIMENTAL PROGRAM

This chapter describes the overall program, including those portions which are common to all four phases:

(1) factor evaluation experiment (factor experiment),

(2) Center for Highway Research correlation (CFHR correlation),

(3) Texas Highway Department correlation (THD correlation), and

(4) specimen size study (size study).

Those details which pertain only to a particular part of the experiment are discussed in the appropriate sections of Chapter 4 or 5.

SELECTION OF FACTORS

In choosing a statistical design for the detailed investigation several objectives were kept in mind: (1) the number of specimens had to be a size which could be produced in one day, in order to maintain homogeneity, (2) it was desirable that all interactions be analyzed since this was not possible in the preliminary experiment on lime-treated materials and that experiment indicated that a more thorough investigation of the interactions was needed, (3) it was desirable that the curvilinear effects of all factors be measured.

As previously mentioned, Miller et al (Ref 6) found that each of the eight factors produced a significant effect, either a main effect or in an interaction. Thus, since the objective of the detailed investigation was to develop more detailed information, studying all eight factors would have required an extremely large number of specimens and it was therefore necessary to reduce the number of factors.

On the basis of judged practical significance in the design process, three of the original eight factors were eliminated. Curing time was eliminated as a variable by fixing it at 21 days, a reasonable length of time for curing in the field before the application of traffic. Some specimens were prepared and cured for six months prior to testing in order to determine the effects of extremely long curing times since strength gain in lime-treated materials is time-dependent and very slow. Nevertheless the results are not reported here but will be included in a later report. Type of compaction was eliminated as a variable by selecting gyratory shear compaction, which seemed to produce specimens with a more uniform density and a more uniform height than impact compaction and is the method of laboratory compaction commonly used by the Texas Highway Department. Curing procedure was made invariable by sealing all of the specimens with a single layer of PVC film to help retain moisture. Eliminating these three factors reduced the number of factors to be studied to five:

(1) compactive effort,
(2) lime content,
(3) clay content,
(4) molding water content, and
(5) curing temperature.

In all of the experiments except the THD correlation these five factors were variables. Standard Texas Highway Department compaction and curing procedures fixed the compactive effort and curing temperature in the THD correlation. The factors and factor levels studied are discussed below.

<u>Compactive Effort</u>

Two objectives were sought in choosing the range of compactive efforts for this report; 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 would be produced. Since the compactive effort for each type of compaction is 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 2.

<u>Lime Content</u>

Lime contents of 0 to 10 percent are of interest in the stabilization of pavement materials. Miller et al (Ref 6) studied three levels, 2, 4, and 6 percent, which covered the range of practical interest. In this study a 0 percent level was added to provide a comparison of the unstabilized soil with the stabilized soil. Thus, the range of lime contents varied from 0 to 6 percent.

Clay Content and Molding Water Content

It would have been desirable in this study to vary clay content from 0 to 100 percent. However, since molding water content was also a factor and also had to be varied over a significant range, a trade-off was required. When a small percentage of clay was mixed with a large percentage of water, the specimens were too wet and tended to slump. When a large percentage of clay was combined with a small percentage of water the specimens were too dry and would not hold together properly. After preliminary lab work, the wettest desirable combination of factors was found to be 25 percent clay and 18 percent water and the driest desirable combination was found to be 75 percent clay and 8 percent water. This effectively set the range of clay contents to be studied at 25 to 75 percent and the range of molding water contents at 8 to 18 percent.

Curing Temperature

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

Factors Held Constant

Throughout each of the four experiments several factors were held constant. A review of previous research showed that curing times selected by other researchers ranged from two days to ten years (Refs 8, 9, 10, 18, and 19). Curing time for the specimens in the THD correlation was fixed at approximately 18 days by the standard Texas Highway Department curing procedures. The curing time for the other experiments was established as 21 days, which was felt to be a reasonable time for curing lime-treated material in the field before loading it. A 21-day period does not allow a study of long term soil-lime strength gains, however, and a set of 16 companion specimens corresponding to a one-half fraction of the full-factorial described in the factor experiment was prepared. These specimens will cure for six months. The treatment combinations for the specimens to be cured six months are presented in Appendix 9. The results of this long-term curing experiment will be reported at a later date.

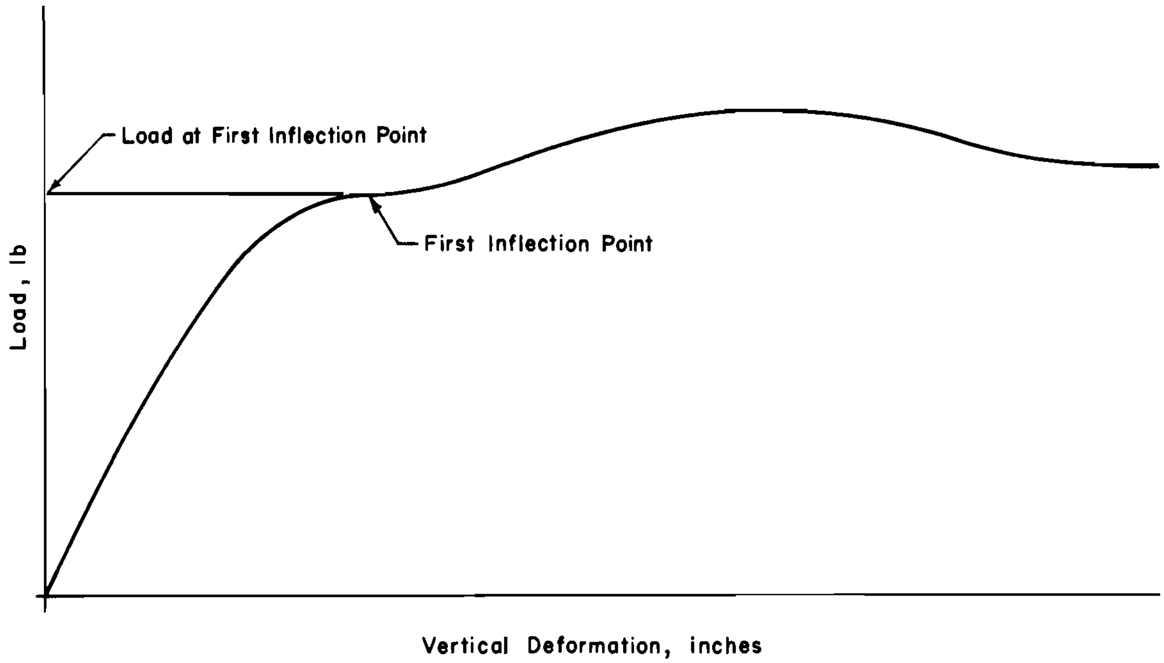
Impact compaction, which is the standard type used by the Texas Highway Department, was used for the THD correlation. Gyratory shear compaction was selected for the factor experiment and the size study because it produced a specimen more uniform in density and height than impact compaction.

Ideally, gyratory shear compaction would have been used in the CFHR correlation, but each 6-inch-diameter by 8-inch-high specimen compacted by gyratory shear compaction failed in the mold or during extrusion from the mold, possibly because of excessive pore pressure. A complete discussion of this problem is presented in Appendix 11. In the absence of gyratory shear compaction the logical method remaining for the CFHR correlation was impact compaction.

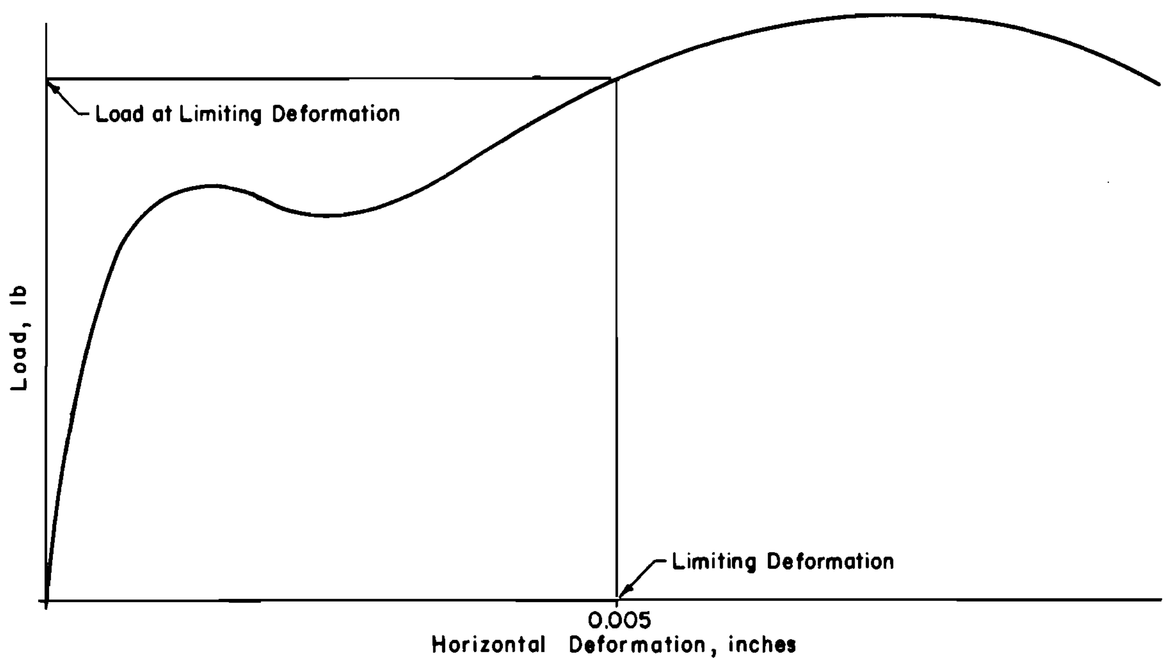
For the THD correlation, standard Texas Highway Department curing procedures required that the specimens be cured in triaxial cells. The specimens in the other three experiments were wrapped or sealed with a single layer of PVC film to help retain moisture, just as protective coating or sprinkling in the field does. The soil was Seguin gravel mixed with Taylor Marl clay (Ref 6), both of which are native to the central Texas area. Their properties are described in Appendix 7. The gradations of the Seguin gravel used for the various levels of clay content are presented in Appendix 10. All loading was static. A high-calcium lime, available locally, was chosen for this study; its properties are presented in Appendix 7.

PARAMETERS EVALUATED

Tensile stress at failure is the most important 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. For most specimens, failure was defined as the first noticeable inflection point on the plot of load versus vertical deflection (Fig 1). For several of the specimens, however, the lateral deformation corresponding to this definition of failure was extremely large, which could not be tolerated in a pavement system; and, therefore, a limiting deformation or strain was also established as a failure criterion. Thompson (Ref 15) reported that strain may be important in determining the tensile strength of brittle materials such as lime-treated materials.



(a) Specimen failure criterion for load - vertical deformation curves.



(b) Specimen failure criterion for load - horizontal deformation curves.

Fig 1. Load-deformation curves for indirect tension testing.

Thompson (Ref 18) reported an average compressive failure strain of 1.02 percent for soil-lime specimens which he had tested in unconfined compression. Assuming that these specimens actually failed in tension and that the material had a Poisson's ratio of 0.25, the horizontal or tensile failure strain corresponding to a vertical strain of 1.0 percent would be 0.25 percent. Hadley et al (Ref 20) determined that for specimens tested in indirect tension the horizontal deformation is twice the horizontal strain at the center of the specimen or the zone of failure, and a limiting horizontal deformation of 0.005 inch was established. Thus the tensile strength at failure is determined from the first inflection point on the plot of load versus vertical deflection or from the load at the horizontal deformation of 0.005 inch, whichever is the smaller. The indirect tensile strength is determined by use of the following equation:

$$S_t = \frac{2P}{\pi a t} (\sin 2\alpha - \alpha)$$

where

S_t = indirect tensile strength,

P = total vertical load on specimen at failure,

a = width of loading strip,

t = height of specimen at beginning of test.

For α see Fig 2. Vertical failure deformation is the vertical deformation of a specimen at the load defined as failure. This deformation is recorded on the plot of load versus vertical deformation and is 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 the LVDT. Horizontal failure deformation is the horizontal deformation of the specimen at the load defined as failure and is recorded on the plot at load versus horizontal deformation. Horizontal deformation is measured by a lateral deflection device (see Fig 21 in Appendix 4).

The unconfined compressive strength at failure was the parameter evaluated for the unconfined compression test. Failure was defined in Texas Highway Department Test Method Tex-117-E (Ref 21) as the maximum load resisted or the load at a limiting vertical deformation of 0.6 inch. The following equation was used to obtain this parameter:

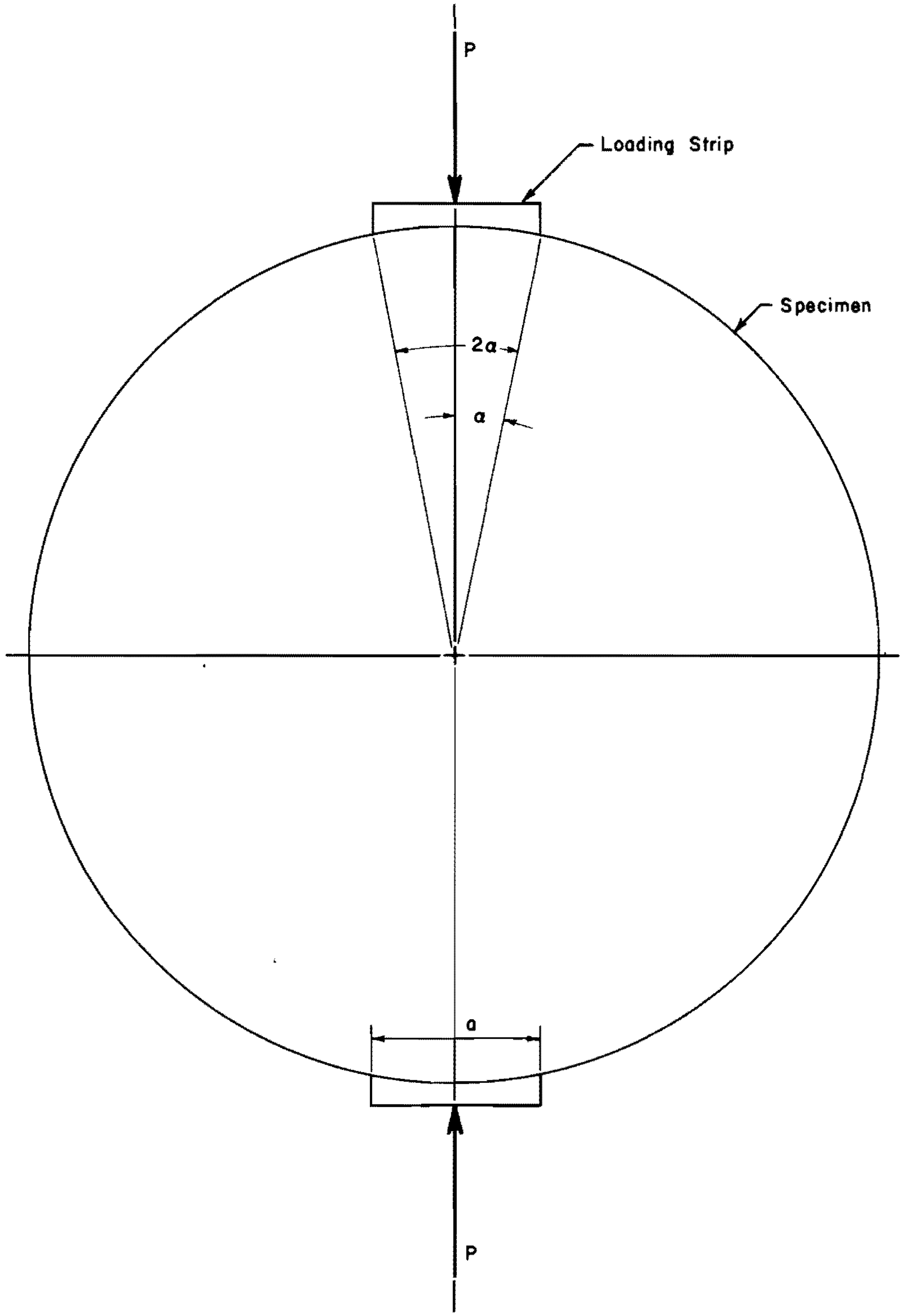


Fig 2. Notation for indirect tensile test.

$$p = \frac{P}{A}(1 - d/t)$$

where

p = corrected vertical unit stress, psi;

P = total vertical load on specimen at failure, pounds;

A = end area of cylindrical specimen at beginning of test, in^2;

d = total vertical deformation at failure, inches;

t = height of specimen at beginning of test, inches.

The cohesiometer value, the parameter evaluated for the cohesiometer test, is defined in Ref 21 as the value, weight in grams, required to break a test specimen 3-inches high and 1-inch wide and is obtained by using the following equation:

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

where

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

P = total load at failure, grams;

W = diameter or width of specimen, inches;

t = height of specimen at beginning of test, inches.

SPECIMEN PREPARATION

Specimen preparation was divided into three phases: (1) mixing, (2) compaction, and (3) curing. The procedure for mixing is presented in Appendix 1. The specimens in the factor experiment were compacted on the THD gyratory shear compactor for 4-inch-diameter specimens. The specimens in the CFHR correlation and the THD correlation were compacted according to standard THD impact compaction procedures. The 6-inch-diameter specimens in the size study were compacted on a gyratory shear compactor for 6-inch-diameter specimens. The three compaction procedures are presented in Appendix 2. The THD correlation specimens were cured according to standard Texas Highway Department curing procedures. All other specimens were cured according to procedures established at the Center for Highway Research. Both curing procedures are described in Appendix 3.

STANDARD TEST PROCEDURES

The procedure followed for the indirect tension testing of soil-lime specimens was the same as that originally recommended by Hudson and Kennedy (Ref 1) and later modified slightly (Ref 3) and was the same as that used in the previous study of lime-treated materials as reported by Miller et al (Ref 6). 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 loading strip with a curved portion with a radius of 3 inches was used to test the 6-inch-diameter specimens and one with a curved portion 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 4.

The unconfined compression tests were run according to the standard THD procedure (Ref 21), which is described in Appendix 5. The specimens had a nominal diameter of 6 inches and a nominal height of 8 inches.

All cohesiometer specimens were tested at the laboratories of the Materials and Tests Division of the Texas Highway Department. The procedure followed was the standard THD procedure (Ref 21), which is described in Appendix 6. The specimens had a nominal diameter of 6 inches and a nominal height of 2 inches.

CHAPTER 4. FACTOR EVALUATION EXPERIMENT

Preliminary experimental work by Miller et al (Ref 6) reported a broad investigation of the effects of compactive effort, lime content, clay content, molding water content, curing temperature, type of compaction, curing time, and type of curing on the tensile strength of lime-treated materials. The statistical design of the experiment allowed the analysis of all main effects, all two-factor interactions, and selected higher order interactions. This chapter presents the results of a more detailed evaluation of lime-treated materials.

EXPERIMENTAL DESIGN

After considering several possible statistical designs it was decided that a central composite rotatable design would realize the objectives of the detailed investigation of the factor experiment. Basically, a composite design provided an economical means of studying the curvilinear, interaction, and main effects of a number of factors with a minimum of observations. This design consisted of a 2^5 full factorial with 32 cells, 10 star points, and 6 center points. There were two star points per factor and they consisted of the extreme high level and the extreme low level of that factor in combination with the middle levels of the other factors. The center points were replicated or repeated specimens which were produced by combining the middle levels of all of the factors. The full factorial in this design allowed the analysis of the main effects and all interactions. The star points and center points allowed the analysis of the curvilinear effects. The replicated center points also provided a measure of experimental error. The factors and levels selected for the factor experiment are presented in Table 1. The treatment combinations are presented in Table 21, Appendix 9.

EXPERIMENTAL RESULTS

The indirect tensile strengths for the factor evaluation experiment are presented in Table 2. The horizontal and vertical failure deformations are

TABLE 1. FACTORS AND LEVELS IN THE FACTOR EVALUATION EXPERIMENT

	Level				
Factor	-2	-1	0	+1	+2
A - Compactive effort*	75	100	125	150	175
D - Molding water content, %	8.0	10.5	13.0	15.5	18.0
E - Lime content, %	0.0	1.5	3.0	4.5	6.0
F - Curing temperature, °F	50	75	100	125	150
H - Clay content, %	25.0	37.5	50.0	62.5	75.0

* See Appendix 2 for explanation of compactive effort.

TABLE 2. INDIRECT TENSILE STRENGTHS FOR THE FACTOR EVALUATION EXPERIMENT

Specimen No.	Indirect Tensile Strength, psi	Specimen No.	Indirect Tensile Strength, psi
1	42.7	25	20.1
2	30.8	26	19.1
3	35.2	27	22.0
4	22.6	28	15.8
5	33.3	29	12.5
6	17.8	30	11.6
7	53.8	31	27.7
8	27.1	32	17.5
9	22.8	33	24.2
10	23.3	34	38.2
11	24.6	35	22.6
12	19.7	36	23.4
13	17.5	37	18.7
14	15.8	38	28.1
15	40.5	39	23.2
16	18.8	40	20.8
17	26.9	41	25.6
18	31.4	42	45.5
19	27.4	43	22.0
20	17.4	44	29.3
21	37.1	45	28.9
22	15.4	46	27.9
23	53.7	47	26.0
24	23.6	48	30.4

Note: Specimens 1 through 32, cells
Specimens 33 through 42, star points
Specimens 43 through 48, center points

presented in Table 3. The results from this experiment cannot be compared directly to the preliminary investigation (Ref 6) since all of these specimens were allowed to air dry to a constant moisture content before testing whereas the specimens in this experiment were tested as soon as they were removed from curing. The differences in results will be thoroughly evaluated in a later report.

An analysis of variance for the vertical failure deformations and for the horizontal failure deformations are presented in Tables 4 and 5, respectively, but no detailed interpretation of these results will be made at this time because a theoretical study of the use of these deformations to establish elastic moduli is presently in progress. A subsequent report will discuss these results in detail.

Table 6 presents the effects which were found to have a significant effect on indirect tensile strengths at the 1 percent and 5 percent levels. The mean square for residual is the sum of squares for all terms not found to be significant at 1 percent or 5 percent, divided by 37, the number of degrees of freedom for these terms. To obtain an F value for each effect, the mean squares for the various effects were divided by the error mean squares obtained from the repeated specimens. The repeated specimens are the center points from the composite design and the variation among them was used as an estimate of experimental error. No interaction above a two-factor interaction was found to be significant. The relationships of the significant curvilinear effects, interactions, and main effects are presented in Figs 3 through 12.

The data points presented in the figures representing main factors and interactions are average values of the tensile strengths for all of 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, and, therefore, each value plotted is the mean for the data from eight different specimens. In the figures representing the curvilinear effects, the high and low level points are the values of the two star points corresponding to the factor represented and the middle level point is the mean of the six center points.

In the following sections, those curvilinear effects, interactions, and main effects which were shown to be significant in Table 6 are discussed.

TABLE 3. HORIZONTAL AND VERTICAL DEFORMATIONS AT FAILURE FOR THE FACTOR EVALUATION EXPERIMENT

Specimen No.	Horizontal Failure Deformation, inches ($\times 10^{-3}$)	Vertical Failure Deformation, inches ($\times 10^{-3}$)
1	5.00	16.7
2	3.52	17.6
3	5.00	15.1
4	4.99	15.3
5	2.40	15.0
6	2.46	12.9
7	2.94	16.5
8	1.57	10.0
9	4.60	15.7
10	2.31	15.0
11	5.00	16.0
12	5.00	16.5
13	5.00	19.9
14	4.90	17.4
15	2.36	11.4
16	2.40	15.0
17	2.15	15.2
18	3.30	16.8
19	5.00	18.3
20	4.09	15.3
21	2.44	13.3
22	1.74	16.6
23	2.24	13.2
24	1.50	11.9

(Continued)

TABLE 3. (CONTINUED)

Specimen No.	Horizontal Failure Deformation, inches ($\times 10^{-3}$)	Vertical Failure Deformation, inches ($\times 10^{-3}$)
25	5.00	18.6
26	4.34	15.6
27	5.00	18.2
28	5.00	17.4
29	3.68	16.0
30	3.91	16.8
31	5.00	17.5
32	2.30	15.5
33	3.35	18.2
34	5.00	15.6
35	2.00	21.7
36	0.46	8.1
37	2.10	11.6
38	4.00	15.4
39	5.00	15.5
40	5.00	34.3
41	1.66	14.8
42	5.00	18.2
43	5.00	17.2
44	5.00	16.6
45	5.00	18.0
46	2.90	14.0
47	3.00	12.4
48	4.50	15.0

TABLE 4. ANALYSIS OF VARIANCE FOR VERTICAL FAILURE DEFORMATIONS FOR THE FACTOR EVALUATION EXPERIMENT

Source of Variation	Degree of Freedom	Mean Squares	F Value*	Significance Level, %
D^2	1	111.2	24.7	1
D	1	71.8	16.0	5
E	1	62.5	13.9	5
H^2	1	32.5	7.2	5
Residual	43	8.2		
Within treatments treated alike	5	4.5		

* Critical F values: $F_{(1,\ 5,\ .01)} = 16.3$; $F_{(1,\ 5,\ .05)} = 6.6$.

<u>Legend</u>

D - Molding water content

E - Lime content

H - Clay content

TABLE 5. ANALYSIS OF VARIANCE FOR HORIZONTAL FAILURE DEFORMATIONS FOR THE FACTOR EVALUATION EXPERIMENT

Source of Variation	Degree of Freedom	Mean Squares	F Value*	Significance Level, %
H	1	17.2	16.7	1
E^2	1	12.8	12.4	5
E	1	8.6	8.3	5
DH	1	7.1	6.9	5
Residual	43	0.9		
Within treatments treated alike	5	1.0		

* Critical F values: $F_{(1,\ 5,\ .01)} = 16.3$; $F_{(1,\ 5,\ .05)} = 6.6$.

Legend

D - Molding water content

E - Lime content

H - Clay content

TABLE 6. ANALYSIS OF VARIANCE FOR TENSILE STRENGTH FOR THE FACTOR EVALUATION EXPERIMENT

Source of Variation	Degree of Freedom	Mean Squares	F Value*	Significance Level, %
F	1	1105.2	119.4	1
E	1	709.8	76.6	1
DH	1	558.4	60.3	1
FH	1	235.6	25.4	1
A	1	225.6	24.4	1
EF	1	189.2	20.4	1
DF	1	174.8	18.9	1
D	1	136.4	14.7	5
F^2	1	97.2	10.5	5
D^2	1	77.3	8.4	5
Residual	37	20.3		
Within treatments treated alike	5	9.3		

* Critical F values: $F_{(1, 5, .01)} = 16.3$; $F_{(1, 5, .05)} = 6.6$.

Legend

A - Compactive effort

D - Molding water content

E - Lime content

F - Curing temperature

H - Clay content

Although it is not possible from this experiment to explain the observed effects, postulations are put forward regarding their possible causes.

Curvilinear Effects

In this study the possible curvilinear effects of all five factors were studied. It was determined, as is shown in Table 6, that only curing temperature and molding water content had significant curvilinear effects on the indirect tensile strength of lime-treated materials. These two curvilinear effects which were significant at a probability level of 0.05 are illustrated in Figs 3 and 4, respectively, and are discussed below.

Curing Temperature (F^2 - Fig 3). Tensile strength increased with an increased curing temperature; however, the increase associated with raising the temperature from 100° F to 150° F was much greater than that associated with raising the temperature from 50° F to 100° F. This observation is supported by Ruff and Ho (Ref 19) who reported a greater rate of strength increase associated with a temperature increase in the higher temperature ranges.

Molding Water Content (D^2 - Fig 4). The average indirect tensile strength increased when the molding water content was increased from 8 percent to 13 percent but decreased when it was raised from 13 percent to 18 percent. Thus, it would appear that there was an optimum water content for the materials tested.

Interactions

The two-factor, three-factor, four-factor, and five-factor interactions, listed in Table 7, were analyzed in this experiment. Of these interactions, only 4 two-factor interactions were found to be significant at the 1 percent and 5 percent levels. These two-factor interactions are illustrated in Figs 5 through 8 and are discussed below.

Curing Temperature × Clay Content (Interaction F × H - Fig 5). For a curing temperature of 75° F a change in clay content from 37.5 percent to 62.5 percent caused a slight increase in indirect tensile strength. However, for a curing temperature of 125° F, the same change in clay content caused a considerable decrease in the indirect tensile strength. It is possible that this loss in strength was due to cracking of the high clay content specimens when cured at elevated temperatures. Another possible explanation for this

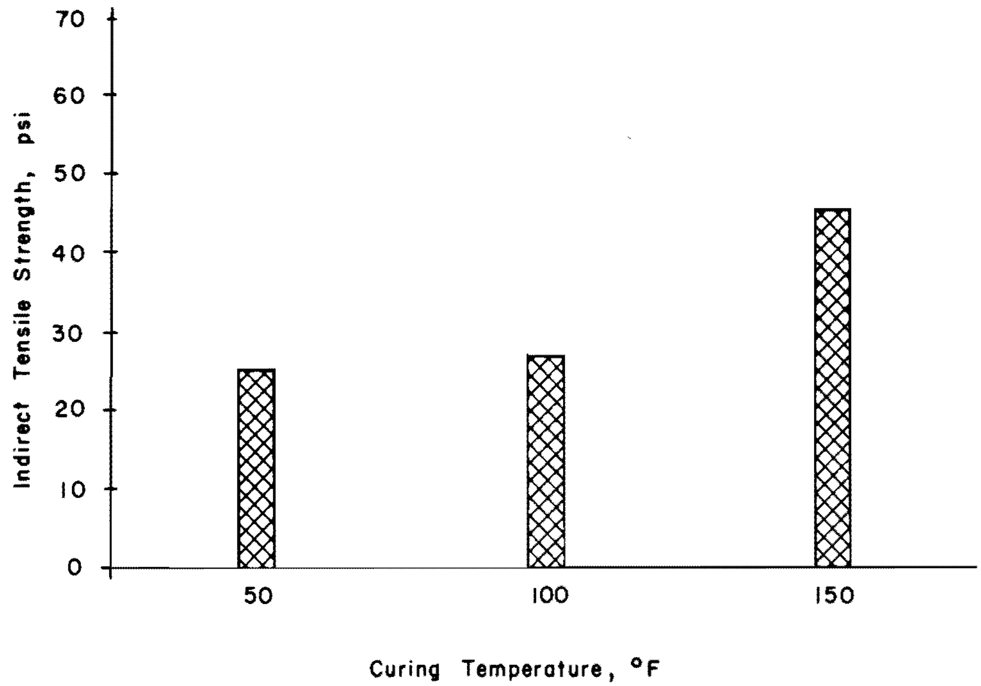


Fig 3. Quadratic effect of curing temperature on tensile strength (Quadratic Effect F^2).

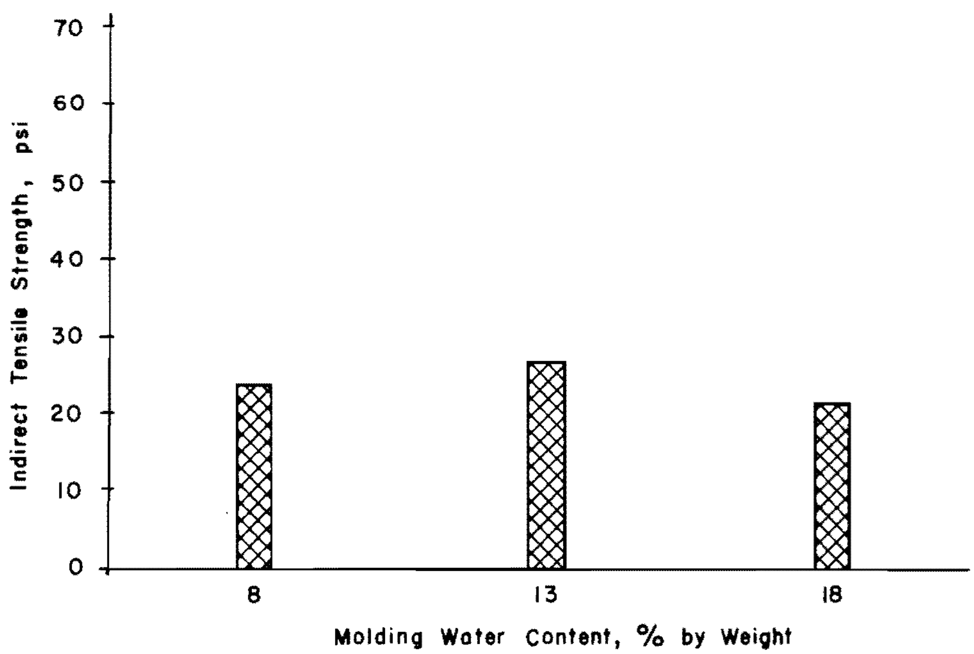


Fig 4. Quadratic effect of molding water content on tensile strength (Quadratic Effect D^2).

TABLE 7. EFFECTS EXAMINED IN THE EXPERIMENTAL DESIGN OF THE FACTOR EVALUATION EXPERIMENT

Main Factors	Two-Factor Interactions	Three-Factor Interactions
A	AD	ADE
D	AE	ADF
E	AF	ADH
F	AH	AEF
H	DE	AEH
	DF	AFH
	DH	DEF
	EF	DEH
	EH	DFH
	FH	EFH

Four-Factor Interactions	Five-Factor Interactions	Quadratic Effects
ADEF	ADEFH	A^2
ADEH		D^2
ADFH		E^2
AEFH		F^2
DEFH		H^2

<u>Legend</u>

A - Compactive effort

D - Molding water content

E - Lime content

F - Curing temperature

H - Clay content

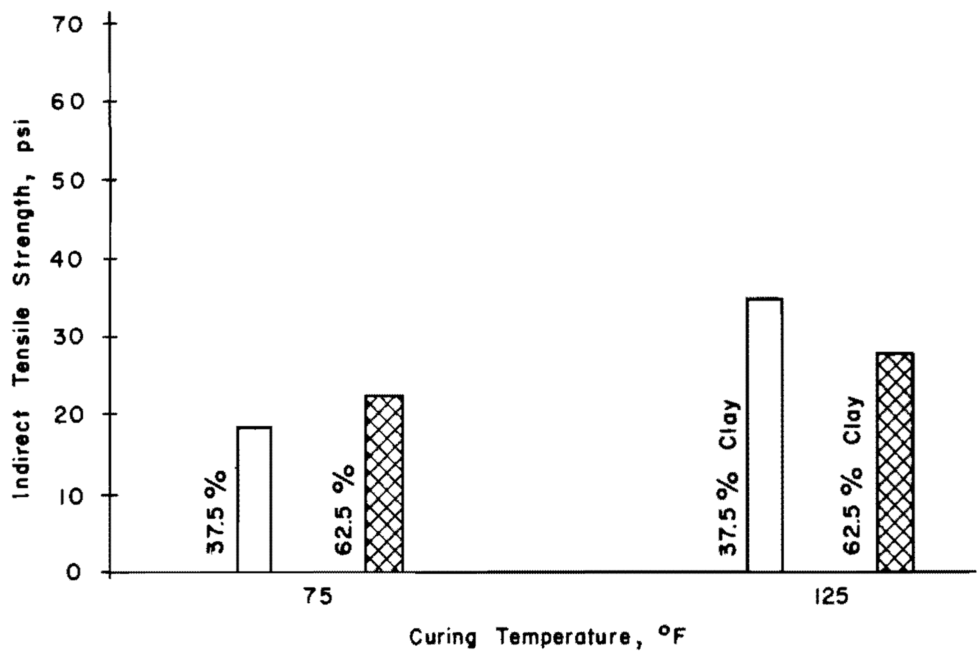


Fig 5. Effect of interaction between curing temperature and clay content on tensile strength.

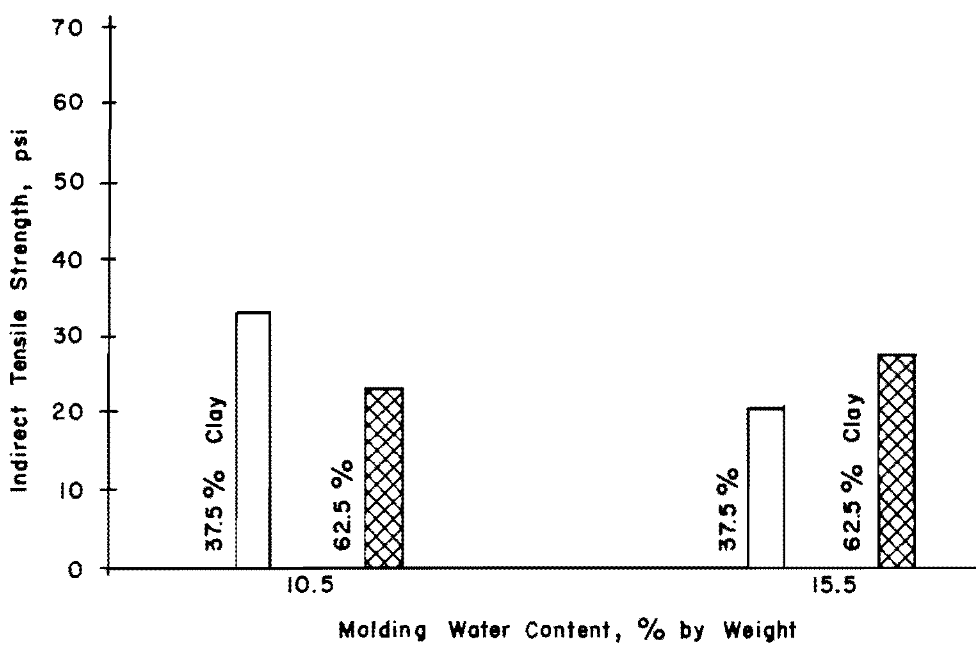


Fig 6. Effect of interaction between molding water content and clay content on tensile strength.

interaction is that at the low curing temperature, 75° F, the increase in clay content did not have a significant effect on the indirect tensile strength. However, at the high curing temperature, 125° F, the increase in clay content caused most of the lime to be adsorbed by the increased number of clay particles. This resulted in insufficient lime for the strength gain reactions causing a significant decrease in the specimen strength.

Molding Water Content × Clay Content (Interaction D × H - Fig 6). For a low molding water content of 10.5 percent, an increase in clay content from 37.5 to 62.5 percent caused a considerable decrease in the indirect tensile strength, whereas, for a high molding water content of 15.5 percent, the same increase in clay content caused an increase in the strength of the soil-lime specimens. A possible explanation of this interaction is that when a low water content is combined with a low clay content, there is sufficient water for the reactions which produce strength gains to take place. However, with the low water content and an increased clay content it is possible that so much of the water was adsorbed by the clay particles that there was an insufficient amount left for the complete soil-lime reactions to take place. This possibility is supported by the fact that when the water content in combination with the high clay content was increased from 10.5 to 15.5 percent, there was an accompanying strength increase. However, when the water content in combination with the low clay content was increased from 10.5 to 15.5 percent, there was a sharp decrease in tensile strength. It is probable that 15.5 percent molding water was on the wet side of optimum and that any soil-lime strength gaining reactions were overshadowed by a decrease in the cohesive strength of the low clay content soil due to the excessive water content.

Molding Water Content × Curing Temperature (Interaction D × F - Fig 7). At the molding water content of 10.5 percent, an increase in curing temperature from 75° F to 125° F caused a marked increase in indirect tensile strength. However, for the specimens molded with a molding water content of 15.5 percent, the strength increase was much less for the same increase in curing temperature. It appears that a water content of 15.5 percent was on the wet side of optimum and that excessive water caused a reduction in the strength of the clay matrix of the specimens, making the strength increase due to an increase in curing temperature less apparent than in the low water content specimens, which were relatively dry and hard.

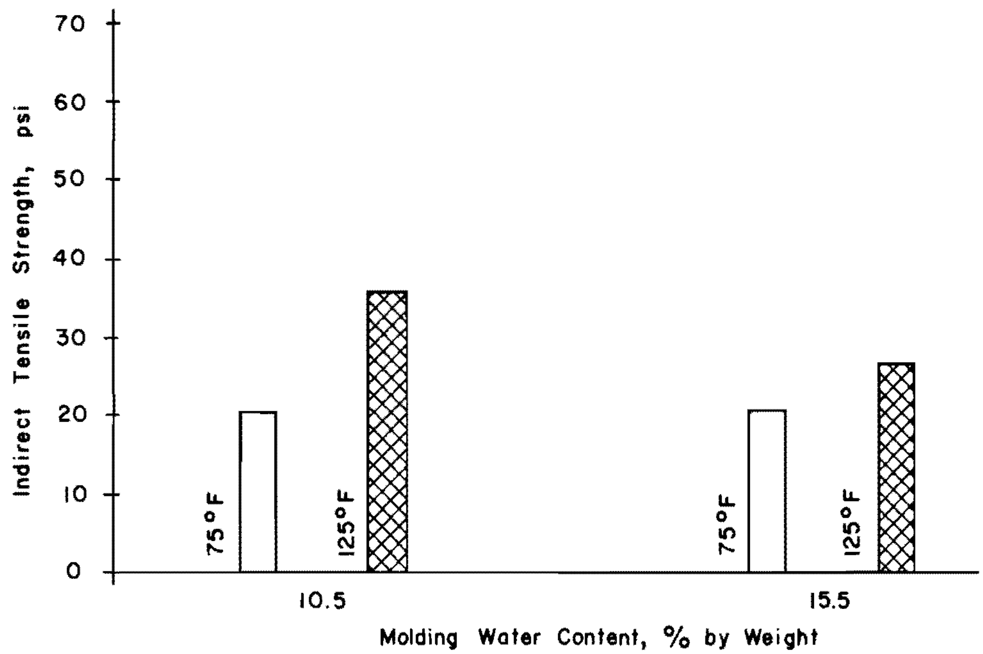


Fig 7. Effect of interaction between molding water content and curing temperature on tensile strength.

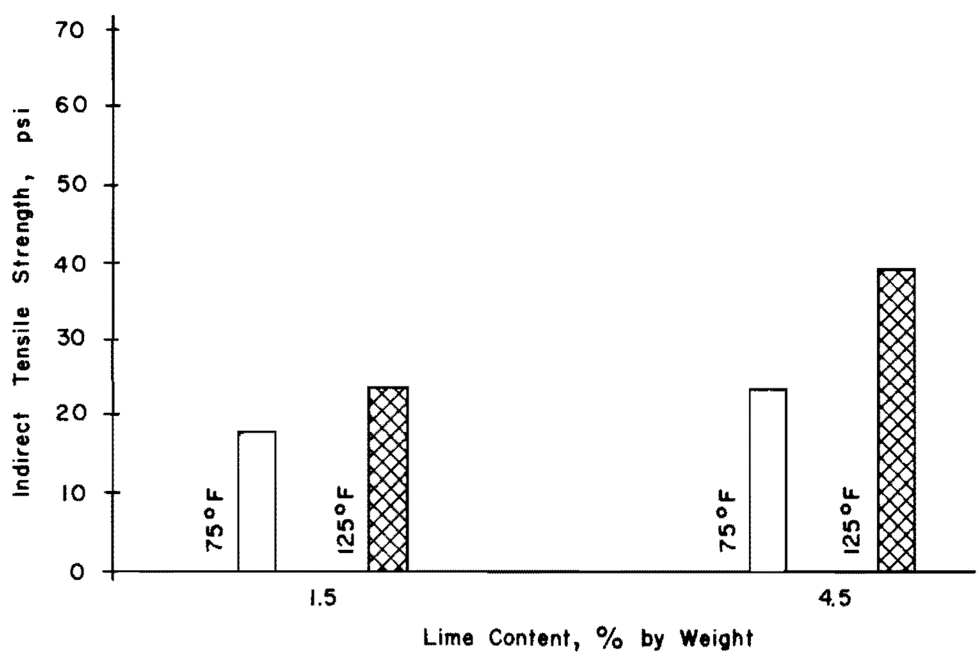


Fig 8. Effect of interaction between lime content and curing temperature on tensile strength.

Lime Content × Curing Temperature (Interaction E × F - Fig 8). For specimens with a lime content of 1.5 percent, an increase in curing temperature from 75° F to 125° F caused an increase in the indirect tensile strength of the specimens, but for specimens with a lime content of 4.5 percent, the same increase in curing temperature caused a much greater increase in specimen strength. In analyzing curing temperature as a curvilinear effect, it was seen that increased curing temperatures cause increased specimen strengths. However, it is probable that at the low lime content there was insufficient lime for the increased curing temperature to have much effect.

Main Effects

The analysis of variance showed that four of the main effects were significant at the 5 percent level with three significant at the 1 percent level. Clay content was the only factor which did not appear to be a significant main effect. The effects of the four significant factors are shown in Figs 9 through 12, in which it can be seen that the average indirect tensile strength was increased by

(1) increasing the compactive effort (Fig 9),
(2) increasing the lime content (Fig 10),
(3) decreasing the molding water content (Fig 11), and
(4) increasing the curing temperature (Fig 12).

The effects, reported above, of compactive effort, lime content, and curing temperature on the indirect tensile strength of lime-treated materials are supported by the review of literature presented in Chapter 2. The analysis of the curvilinear effects shows that analyzing only the linear main effects of curing temperature and molding water content is misleading. If the curvilinear effects of these two factors had not been measured, the observations of a greater rate of strength increase at the higher temperatures and of an optimum molding water content would not have been made.

Prediction Equation

A regression analysis was conducted in order to obtain an equation with which to predict the indirect tensile strength of lime-treated materials. It must be remembered that the use of this prediction equation is valid only for the range of levels of the factors considered in this experiment and when the

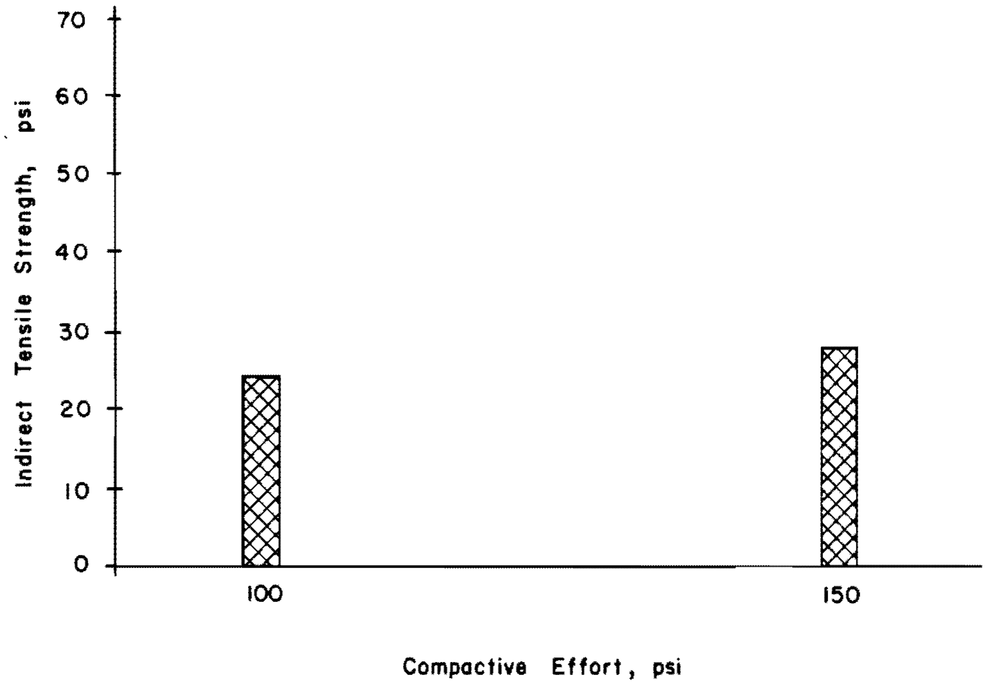


Fig 9. Effect of compactive effort on tensile strength.

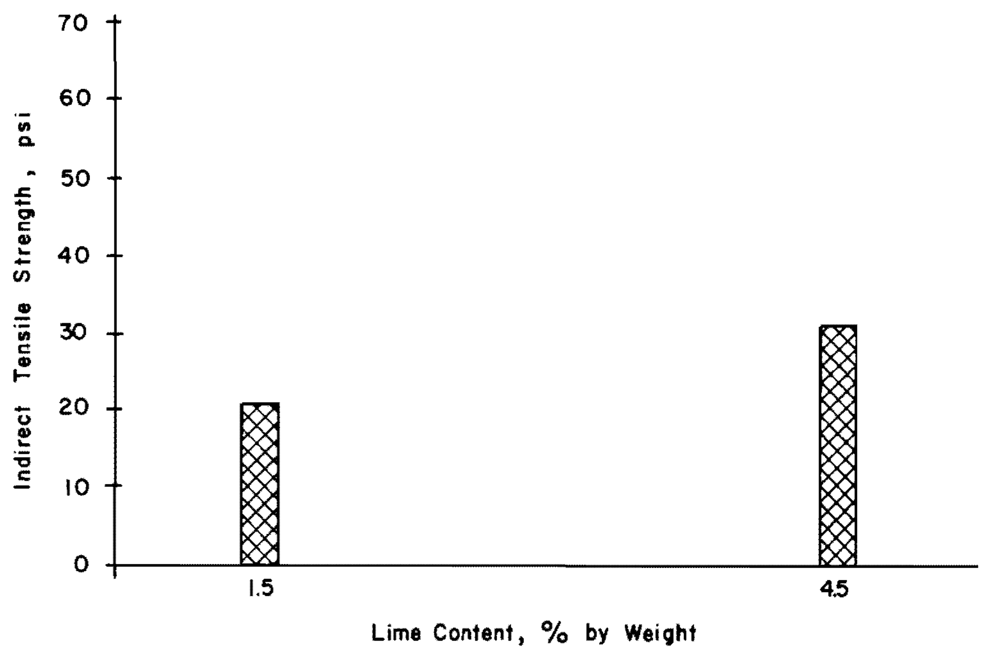


Fig 10. Effect of lime content on tensile strength.

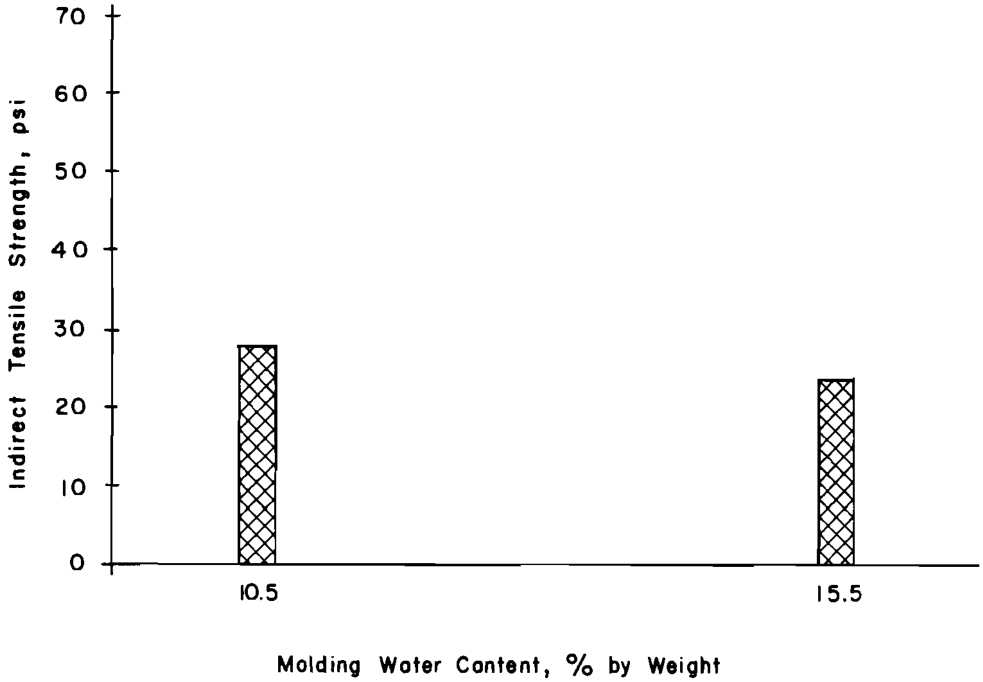


Fig 11. Effect of molding water content on tensile strength.

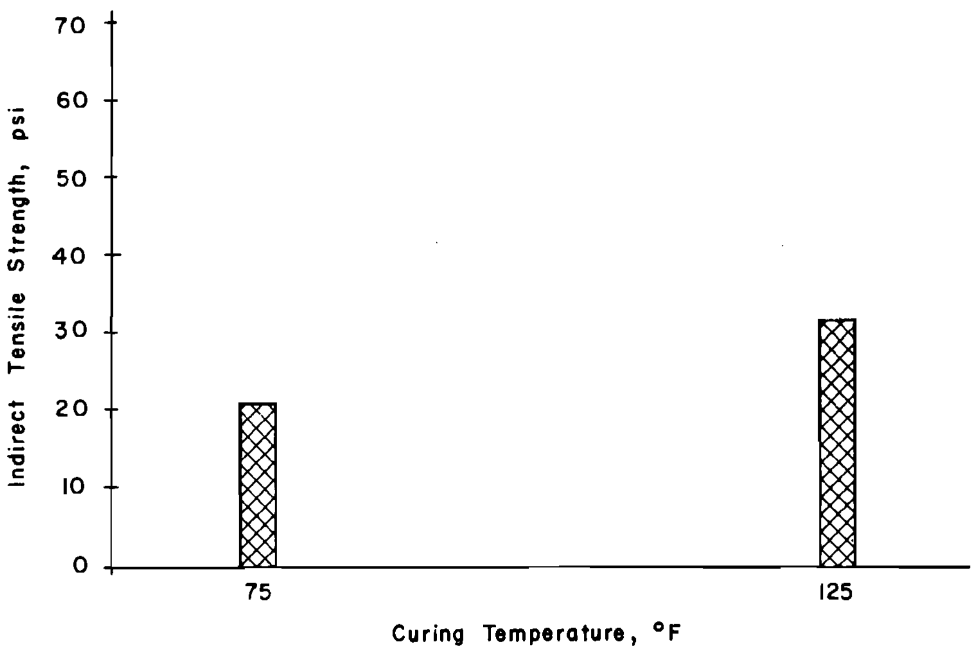


Fig 12. Effect of curing temperature on tensile strength.

values of the factors held constant, such as type of lime and type of clay, are the same.

The levels of the factors used to obtain the following prediction equation are presented in Table 1:

$$
\begin{aligned}
\hat{S}_t = {} & 228.18 - 1.647A + 3.100D - 86.375E - 2.218F \\
& - 5.234H + .017AF + .035AH + .581AE + .043FH \\
& + .137DH + 1.727EH - .037DF + .929EF - .261D^2 \\
& - .611E^2 + .0028F^2 - .008H^2 - .0116AEH - .0058AEF \\
& - .000348AFH - .0173EFH + .000116AEFH
\end{aligned} \quad (4.1)
$$

where

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

A, D, E, F, H = factors considered for prediction;

The multiple correlation coefficient for the predictive equation was .94 and the standard error of estimate was ±4.03 psi.

CHAPTER 5. DISCUSSION OF THE CORRELATION EXPERIMENTS

This chapter discusses the experimental designs and the test results for the Center for Highway Research correlation, the Texas Highway Department correlation, and the specimen size study.

CENTER FOR HIGHWAY RESEARCH CORRELATION

The CFHR correlation was run to compare the results of the indirect tensile test with the results of the unconfined compression test and the cohesiometer test for soil-lime specimens cured according to procedures established at the Center for Highway Research.

Experimental Design

The experimental design consisted of a half fraction of a 2^5 factorial, or 16 observations, plus three center points, a total of 19 observations, for each of the three tests. The five factors were the same as those in the factor evaluation experiment: compactive effort, lime content, clay content, molding water content, and curing temperature. The factors and levels are presented in Table 8. The fractional factorial was chosen for this experiment since it provided an adequate range of test results over which to make the correlations. The center points provided a measure of experimental error. For each treatment combination in the experimental design, three companion specimens were prepared: a 2-inch-high by 6-inch-diameter specimen tested in indirect tension, a 2-inch-high by 6-inch-diameter specimen tested in the cohesiometer, and an 8-inch-high by 6-inch-diameter specimen tested in unconfined compression. The exact treatment combinations are presented in Table 22 in Appendix 9. The treatment combinations in the fractional factorial were determined by the statistical identity (Ref 22)

$$I = ABCDE$$

TABLE 8. FACTORS AND LEVELS IN THE CFHR CORRELATION

Factor	Level		
	-1	0	+1
A - Compactive effort, blows/layer*	50.0	75.0	100.0
D - Molding water content, %	10.5	13.0	15.5
E - Lime content, %	1.5	3.0	4.5
F - Curing temperature, ^{o} F	75.0	100.0	125.0
H - Clay content, %	37.5	50.0	62.5

* For explanation of compactive effort see Appendix 2.

This identity is a statistical algorithm used to select the appropriate treatment combinations for the specimens in this experiment and allows the analysis of all main effects and two-factor interactions if desired.

Experimental Results

The parameters evaluated were indirect tensile strength, unconfined compressive strength, and cohesiometer value. The results of these tests are presented in Table 9. 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 CFHR correlation was the development of predictive equations with which the indirect tensile strength of the lime-treated material could be predicted if the unconfined compressive strength and/or the cohesiometer value were known. It must be kept in mind that the use of these prediction equations is valid only for the range of levels of the factors considered in this experiment and when the values of the factors held constant, such as curing procedure and type of clay, are the same.

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

$$\hat{S}_t = 16.46 + 36.7q_u \tag{5.1}$$

for which the multiple correlation coefficient was 0.89 and the standard error of estimate was ±5.9;

$$\hat{S}_t = 7.46 + 2.19(C/100) \tag{5.2}$$

for which the multiple correlation coefficient was 0.93 and the standard error of estimate was ±4.8; and

$$\hat{S}_t = 9.27 + 14.8q_u + 1.46(C/100) \tag{5.3}$$

for which the multiple correlation coefficient was 0.94 and the standard error of estimate was ±4.4

TABLE 9. EXPERIMENTAL RESULTS FOR THE CFHR CORRELATION

Specimen No.	Unconfined Compressive Strength, psi	Specimen No.	Cohesiometer Value, grams/inch width	Specimen No.	Indirect Tensile Strength, psi
65	1012	84	1871	103	54.5
66	345	85	1134	104	40.1
67	63	86	677	105	16.1
68	1187	87	2645	106	65.3
69	186	88	669	107	24.4
70	684	89	1022	108	36.4
71	179	90	431	109	14.8
72	221	91	949	110	29.5
73	207	92	1238	111	33.4
74	469	93	1489	112	32.7
75	451	94	1624	113	34.9
76	247	95	956	114	33.3
77	361	96	791	115	23.7
78	270	97	811	116	25.1
79	53	98	464	117	14.6
80	597	99	1557	118	40.8
81	608	100	1315	119	30.4
82	571	101	1131	120	35.3
83	626	102	1057	121	33.7

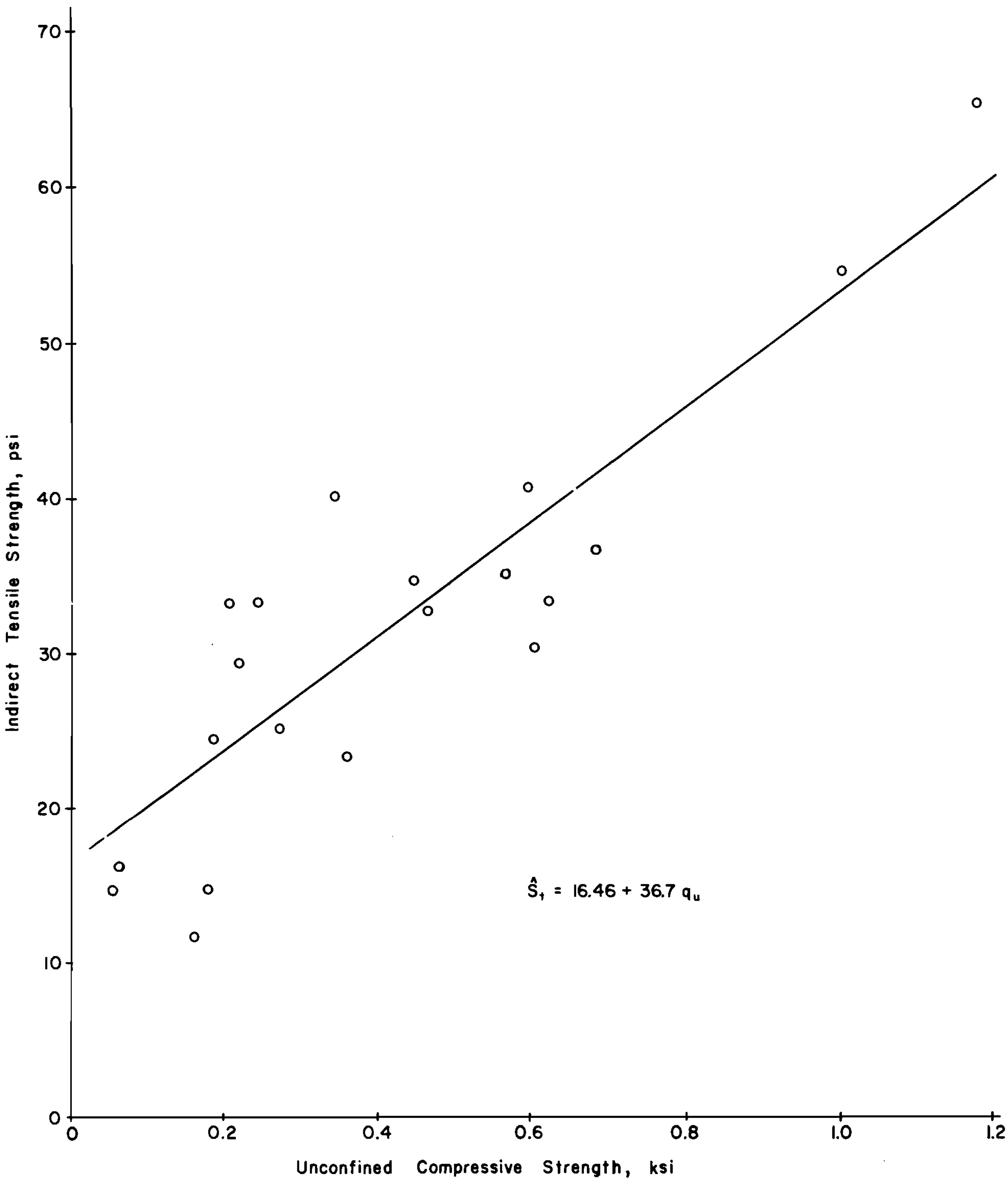


Fig 13. Relationship of indirect tensile strength and unconfined compressive strength for CFHR correlation.

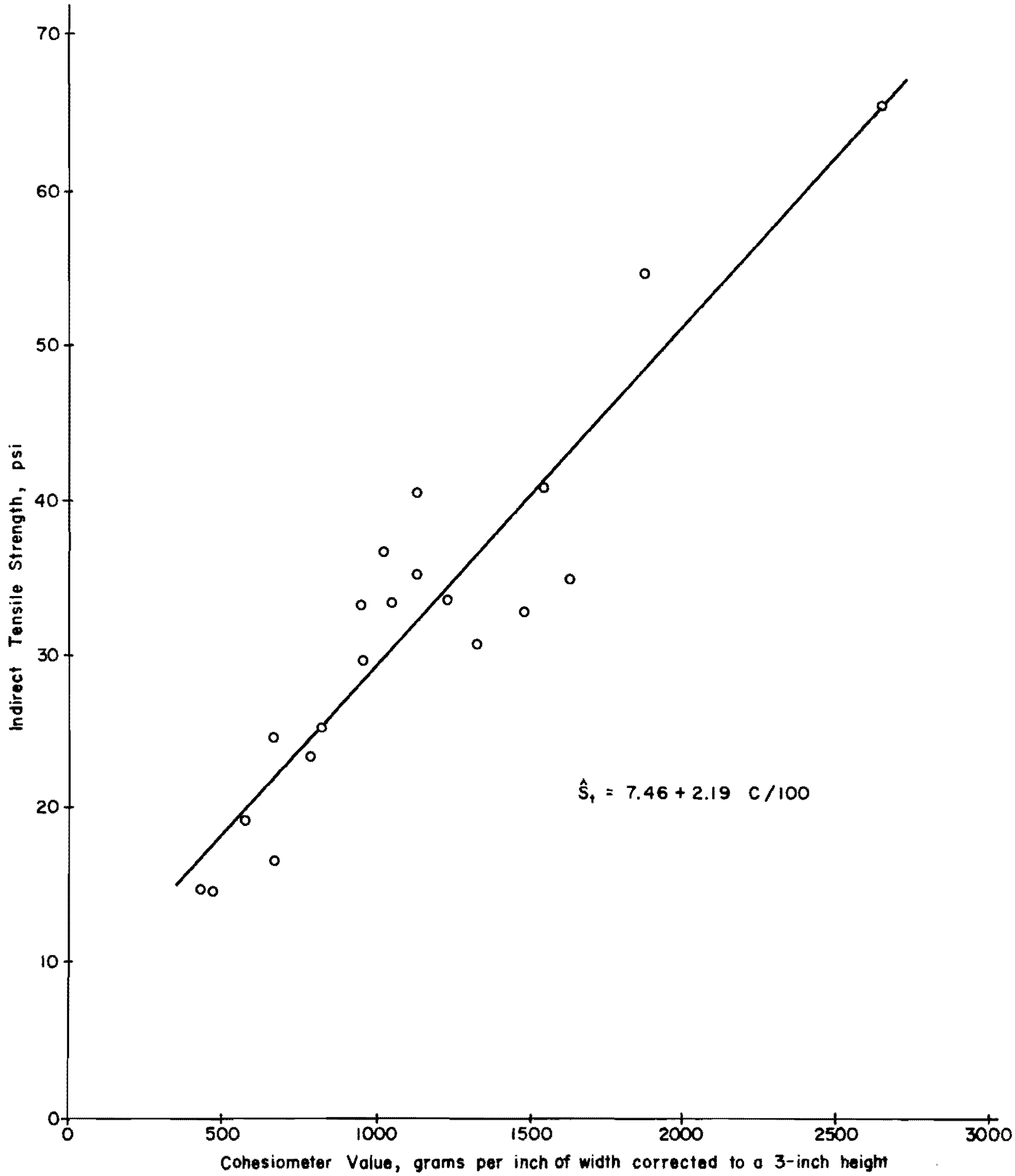


Fig 14. Relationship of indirect tensile strength and cohesiometer value for CFHR correlation.

where

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

q_u = measured value of unconfined compressive strength, in ksi;

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

Since this experiment was designed as a half fraction of a 2^5 factorial with center points, it was possible to perform analyses of variance and regression analyses to obtain an analysis of variance and predictive equations, in terms of the five factors analyzed, for each of the parameters. This information is presented in Appendix 8.

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 lime-treated specimens cured according to standard Texas Highway Department procedures (Ref 21).

Experimental Design

Since the standard THD procedures fixed the compactive effort and the curing temperature, only three of the factors studied in the factor evaluation experiment could be varied in the THD correlation. The statistical experiment used was chosen to provide an adequate range of strengths over which to make the correlations. This design consisted of a 2^3 full factorial with eight cells, six star points, and six center points, for a total of 20 specimens per test. The factors and levels are presented in Table 10. 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. The treatment combinations are presented in Table 23 (Appendix 9). Statistically this experiment is called a central composite rotatable design and allows the analysis of all main effects, two-factor interactions, and curvilinear effects, if desired.

TABLE 10. FACTORS AND LEVELS IN THE THD CORRELATION

Factor	Level				
	-1.682	-1	0	+1	+1.682
D - Molding water content, %	8.8	10.5	13.0	15.5	17.2
E - Lime content, %	0.477	1.5	3.0	4.5	5.523
H - Clay content, %	29.0	37.5	50.0	62.5	71.0

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 11. Plots of indirect tensile strength versus unconfined compressive strength and indirect tensile strength versus cohesiometer value are presented in Figs 15 and 16, respectively. The ultimate objective of the THD correlation was the development of predictive equations with which the indirect tensile strength of the lime-treated material could be predicted if the unconfined compressive strength and/or the cohesiometer value were known. A regression analysis was conducted and the following prediction equations were obtained:

$$\hat{S}_t = -1.43 + 96.5q_u \qquad (5.4)$$

for which the multiple correlation coefficient was 0.85 and the standard error of estimate was ±2.4;

$$\hat{S}_t = 1.52 + 4.59(C/100) \qquad (5.5)$$

for which the multiple correlation coefficient was 0.75 and the standard error of estimate was ±3.0; and

$$\hat{S}_t = -1.68 + 74.4q_u + 1.6(C/100) \qquad (5.6)$$

for which the multiple correlation coefficient was 0.87 and the standard error of estimate was ±2.3

where

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

q_u = measured value of unconfined compressive strength, in ksi;

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

Because this experiment was set up as a central composite rotatable design, it was possible, through analysis of variance and regression analysis,

TABLE 11. EXPERIMENTAL RESULTS FOR THE THD CORRELATION

Specimen No.	Unconfined Compressive Strength, psi	Specimen No.	Cohesiometer Value, grams/inch width	Specimen No.	Indirect Tensile Strength, psi
122	134	142	184	162	15.6
123	109	143	87	163	7.0
124	85	144	96	164	4.4
125	44	145	84	165	3.4
126	51	146	70	166	4.6
127	115	147	148	167	7.6
128	150	148	265	168	18.3
129	117	149	192	169	10.2
130	34	150	37	170	2.8
131	148	151	211	171	11.7
132	54	152	111	172	6.5
133	143	153	142	173	10.7
134	97	154	151	174	3.9
135	83	155	182	175	5.1
136	149	156	163	176	12.8
137	143	157	196	177	13.3
138	156	158	272	178	14.0
139	138	159	261	179	10.3
140	126	160	178	180	9.6
141	112	161	298	181	11.3

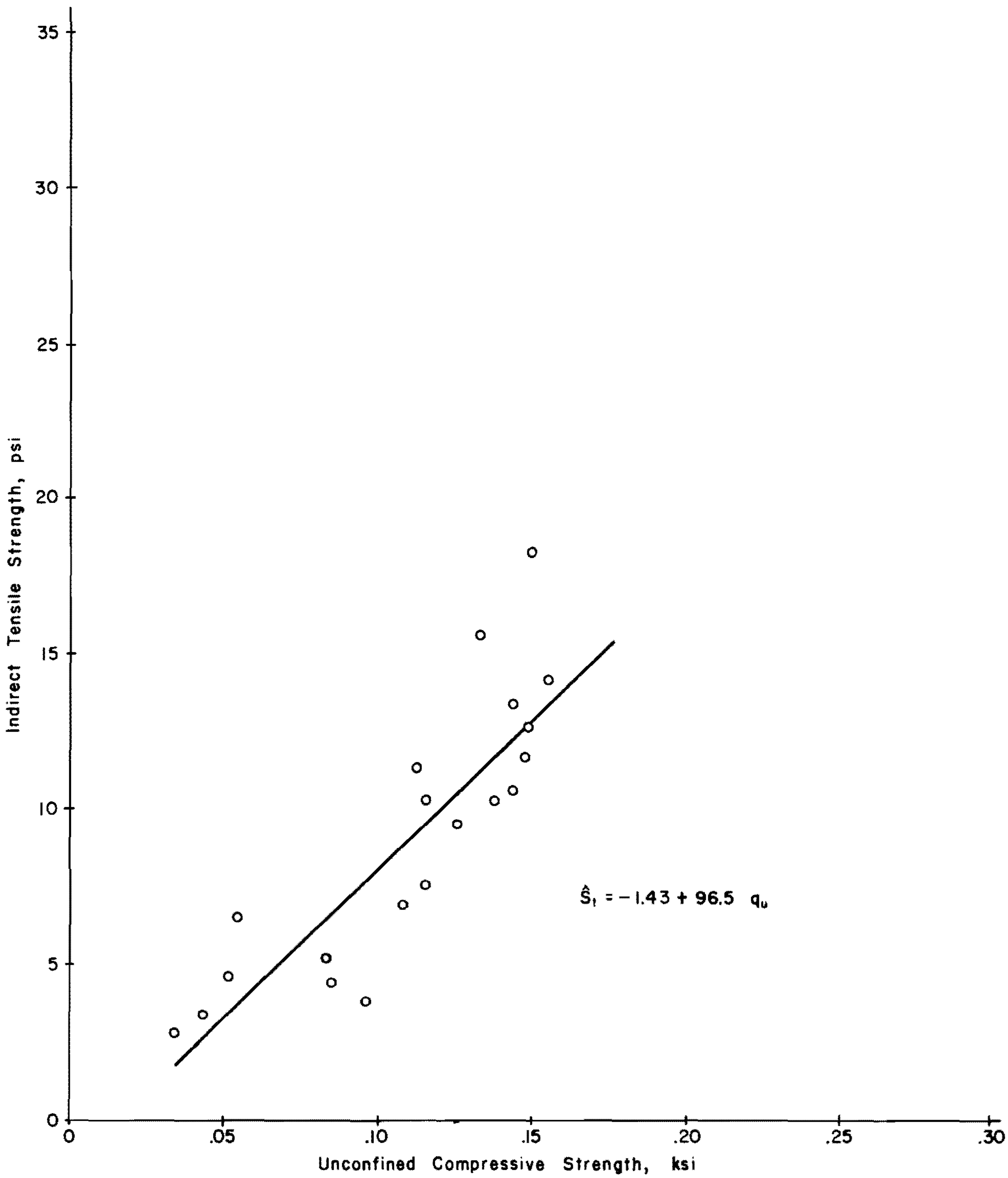


Fig 15. Relationship of indirect tensile strength and unconfined compressive strength for THD correlation.

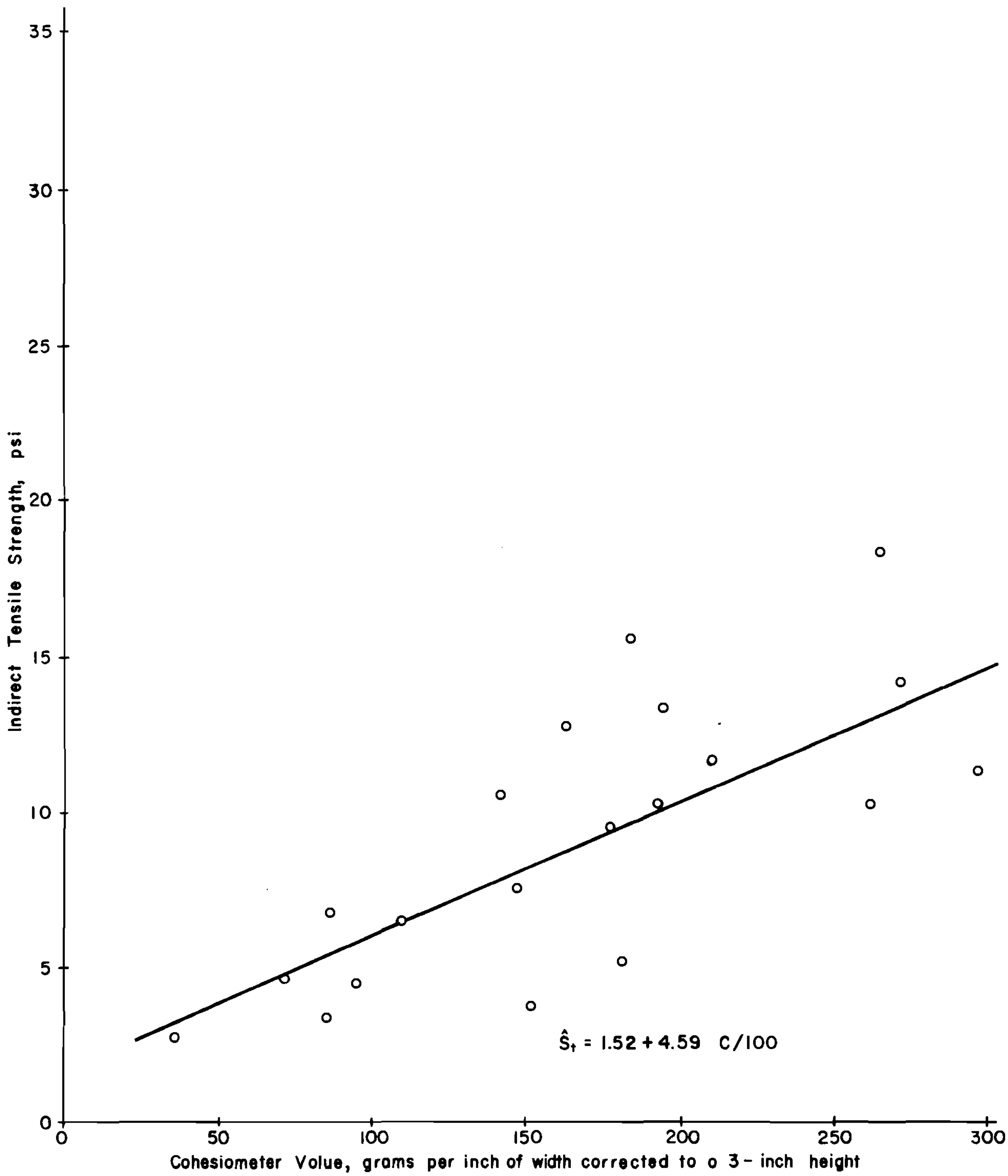


Fig 16. Relationship of indirect tensile strength and cohesiometer value for THD correlation.

to obtain an analysis of variance for each of the three parameters and predictive equations for the three parameters in terms of the three factors studied. This information is presented in Appendix 8.

COMBINED CORRELATION RESULTS

The strengths of the specimens tested for the THD correlation were generally less than the strength of those tested for the CFHR correlation. The THD correlation specimens were cured in capillarity for 10 days before testing, which probably accounts for their lower strengths. Since the ranges of strength for the two correlations were quite different, the data from the experiments were combined to check for 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, from low to high. Figures 17 and 18 show the combined data. A regression analysis was run on these combined data and the following prediction equations were obtained:

$$\hat{S}_t = 6.89 + 50.6q_u \tag{5.7}$$

for which the multiple correlation coefficient was 0.91 and the standard error of estimate was ±6.4;

$$\hat{S}_t = 5.52 + 2.33(C/100) \tag{5.8}$$

for which the multiple correlation coefficient was 0.96 and the standard error of estimate was ±4.1; and

$$\hat{S}_t = 3.61 + 16.5q_u + 2.3(C/100) - 0.03(C/100)^2 \tag{5.9}$$

for which the multiple correlation coefficient was 0.97 and the standard error of estimate was ±3.7

where

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

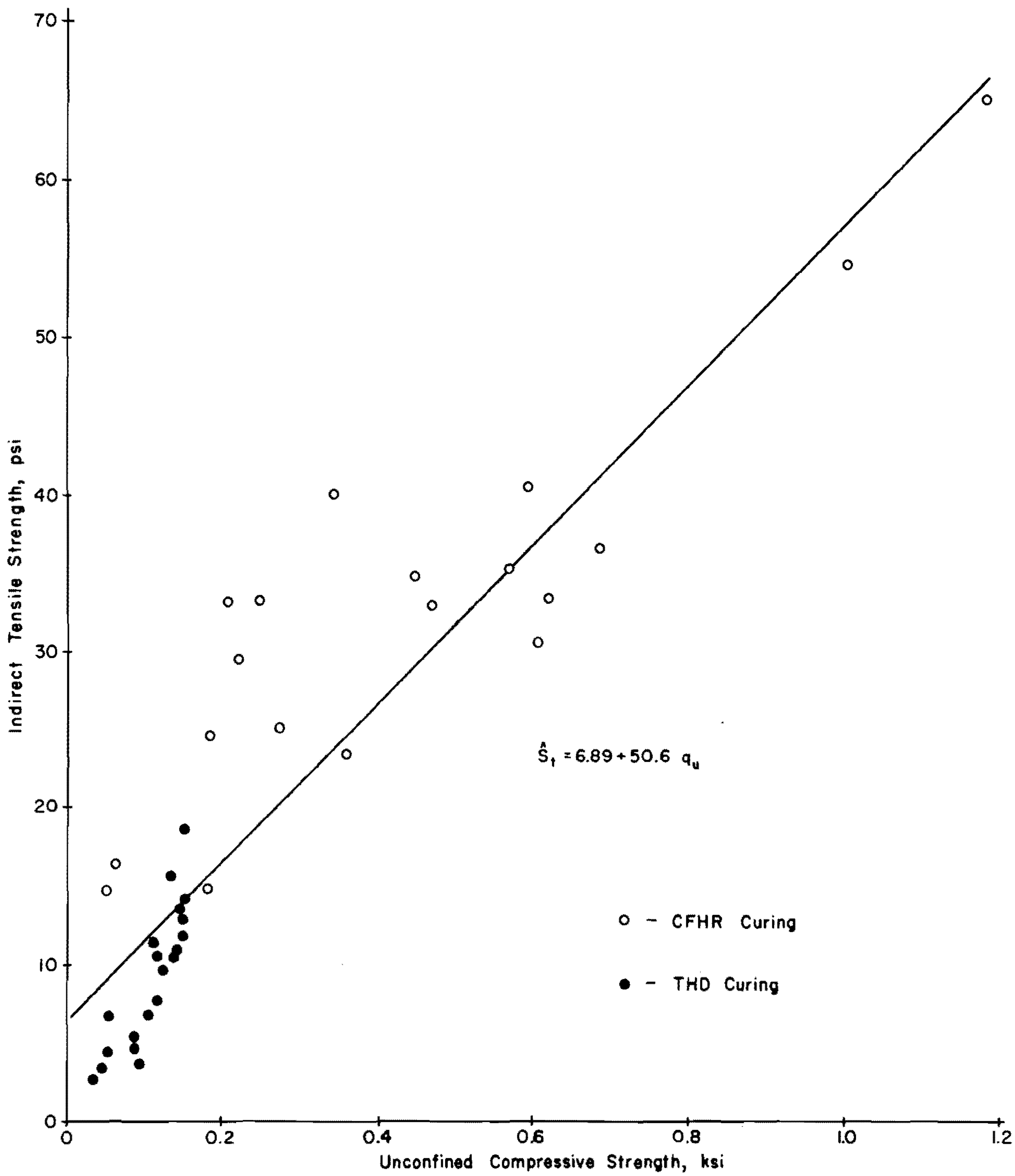


Fig 17. Relationship of indirect tensile strength and unconfined compressive strength for combined correlation data.

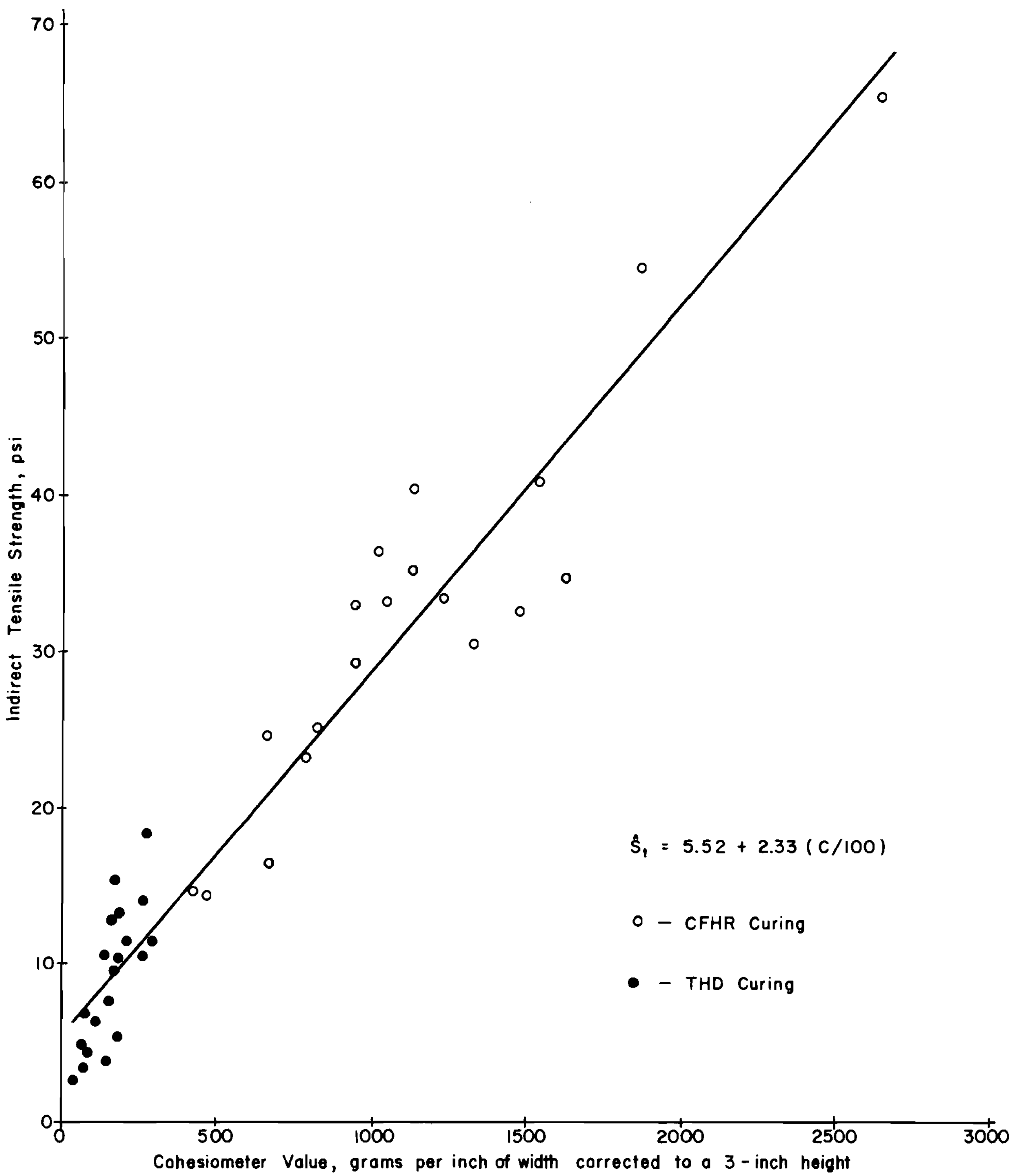


Fig 18. Relationship of indirect tensile strength and cohesiometer value for combined correlation data.

q_u = measured value of unconfined compressive strength, in ksi;

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

SPECIMEN SIZE STUDY

The specimen size study was conducted to determine the effect of specimen size on the indirect tensile strength of lime-treated materials.

Experimental Design

Since 48 specimens with a 2-inch height and a 4-inch diameter had been analyzed in the factor evaluation experiment, half of the full factorial in that experiment was chosen and corresponding 2-inch-high by 6-inch-diameter specimens were prepared. Three center point specimens were also prepared, to provide a measure of experimental error. However, there were six center points in the factor evaluation experiment, and three were chosen at random for the specimen size study. The problem, mentioned in the CFHR correlation, of being unable to produce 8-inch-high by 6-inch-diameter specimens by gyratory shear compaction did not occur when 2-inch-high by 6-inch-diameter specimens were compacted. The factors and levels studied in this experiment are presented in Table 12, and the treatment combinations are presented in Table 24 (Appendix 9). The fractional factorial was described by the statistical identity

$$I = ABCDE$$

Experimental Results

The results of the specimen size study are presented in Table 13. An analysis of variance was conducted and it was found that specimen size does not have a significant effect on tensile strength at the 5 percent level. This observation was supported by the review of previous research discussed in Chapter 2. It appears, therefore, that the conclusions and observations arrived at in experiments conducted using 4-inch-diameter specimens can be applied with confidence to 6-inch-diameter specimens.

TABLE 12. FACTORS AND LEVELS IN THE SPECIMEN SIZE STUDY

Factor	Level		
	-1	0	+1
A - Compactive effort, blows/layer*	150.0	200.0	250.0
D - Molding water content, %	10.5	13.0	15.5
E - Lime content, %	1.5	3.0	4.5
F - Curing temperature, °F	75.0	100.0	125.0
H - Clay content, %	37.5	50.0	62.5

* See Appendix 2 for explanation of compactive effort.

TABLE 13. EXPERIMENTAL RESULTS FOR THE SPECIMEN SIZE STUDY

2 by 4-Inch Specimens		2 by 6-Inch Specimens	
Specimen No.	Indirect Tensile Strength, psi	Specimen No.	Indirect Tensile Strength, psi
1	42.7	182	39.5
4	22.6	183	54.9
6	17.8	184	12.2
7	53.8	185	53.3
10	23.3	186	23.3
11	24.6	187	42.8
13	17.5	188	12.0
16	18.8	189	24.2
18	31.4	190	34.0
19	27.4	191	28.7
21	37.1	192	21.0
24	23.6	193	29.5
25	20.1	194	19.6
28	15.8	195	35.2
30	11.6	196	11.2
31	27.7	197	28.5
45*	28.9	198*	28.2
47*	26.0	199*	27.4
48*	30.4	200*	32.6

* Center points

CHAPTER 6. CONCLUSIONS, RECOMMENDATIONS, AND UTILIZATION OF RESULTS

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

On the basis of the data and the analysis described the following conclusions and recommendations were made.

CONCLUSIONS

All five factors included in this study had a significant effect on the indirect tensile strength, either as a main effect or an interaction. Those quadratic effects, interactions, and main factors which affected the tensile strength of the lime-treated materials were

Quadratic effects

Curing temperature
Molding water content

Interactions

Curing temperature × clay content
Molding water content × clay content
Molding water content × curing temperature
Lime content × curing temperature

Main effects

Curing temperature
Lime content
Compactive effort
Molding water content

As previously observed, the indirect tensile strength was increased by

(1) increasing the curing temperature,

(2) increasing the lime content, and

(3) increasing the compactive effort

In addition, it was found that the strength increase associated with increased curing temperatures was greater in the higher temperature ranges. It was also observed that strength was maximum at an intermediate molding water content and that, therefore, there appears to be an optimum molding water content for strength, as expected.

Probably the most important factor affecting the indirect tensile strength was curing temperature. It produced the largest main effect, as shown by the analysis of variance. In addition, it was found to produce a significant quadratic effect and appeared in three out of the four significant two-factor interactions.

An equation containing ten variables that predicts the indirect tensile strength for any combination of the levels of the independent variables has been developed from the regression analysis (see page 37). This regression equation has a multiple correlation coefficient of .90 and a standard error of estimate of ±4.03 psi.

Predictive equations (see Eqs 5.1 through 5.6) are provided for indirect tensile strength in terms of unconfined compressive strength and/or cohesiometer value for both Center for Highway Research and Texas Highway Department curing procedures. High correlation exists for both types of curing and the data can be combined to cover a larger strength range as shown in Eqs 5.7 through 5.9.

It was found that specimen size does not have a significant effect on the indirect tensile strength of lime-treated materials. This finding is in agreement with previous theoretical and experimental evaluations of size effects.

The factors and interactions which produced highly significant effects on the vertical failure deformations of lime-treated materials were

Quadratic effects

- Molding water content
- Clay content

Main effects

- Molding water content
- Lime content

No interaction effects were found to be significant and only three of the five factors studied (lime content, clay content, and molding water content) had a significant effect as either a main or quadratic effect.

The factors and interactions which produced highly significant effects on the horizontal failure deformations of lime-treated materials were

Quadratic effects

Lime content

Interactions

Clay content × molding water content

Main effects

Clay content
Lime content

Only three of the factors considered (lime content, clay content, and molding water content) had a significant effect on the horizontal failure deformations of lime-treated materials. These three factors were the same as those having significant effects on the vertical failure deformations.

RECOMMENDATIONS

This is the second in a series of studies of the tensile strength of lime-treated materials. The next step in the investigation is to look at the data from both studies to make common inferences and ascertain the effects which predominate through both experiments. These factors can then be considered in future design procedures.

In addition to strength effects, work is needed on deformation data, including a study of material properties, among which are moduli of deformation and Poisson's ratio. This work is presently under way and will be reported at a later date.

Upon completion of these two phases of the study it would be profitable to study the behavior of lime-treated materials in fatigue or repeated loading. Such studies are ultimately needed if the performance of these materials under the repeated loadings of normal traffic is to be evaluated.

UTILIZATION OF RESULTS

The results of these studies are part of a program to provide a better understanding of the behavior and performance of stabilized materials used as elements in a pavement structure. As indicated in the recommendations, the results will be used in the next phase of the study, repeated loading.

They will also be compared to the findings for cement-treated and asphalt-treated materials to develop overall information for stabilized materials.

Furthermore, the detailed findings with reference to the effect of individual factors on tensile strength can be used to develop design information for stabilized mixtures for immediate upgrading of approximate design techniques.

REFERENCES

1. Hudson, W. Ronald, and Thomas W. Kennedy, "An Indirect Tensile Test for Stabilized Materials," Research Report No. 98-1, Center for Highway Research, The University of Texas at Austin, January 1968.

2. Kennedy, Thomas W., and W. Ronald Hudson, "Application of the Indirect Tensile Test to Stabilized Materials," Highway Research Record No. 235, Highway Research Board, January 1968, pp 36-48.

3. Hadley, William O., W. Ronald Hudson, and Thomas W. Kennedy, "An Evaluation of Factors Affecting the Tensile Properties of Asphalt-Treated Materials," Research Report No. 98-2, Center for Highway Research, The University of Texas at Austin, March 1969.

4. Hadley, William O., W. Ronald Hudson, and Thomas W. Kennedy, "An Evaluation of the Factors Affecting the Tensile Characteristics of Asphalt-Treated Materials," a paper presented at the 1969 Annual Meeting of the American Association of Asphalt Paving Technologists, February 1969.

5. Pendola, Humberto J., Thomas W. Kennedy, and W. Ronald Hudson, "Evaluation of Factors Affecting the Tensile Properties of Cement-Treated Materials," Research Report No. 98-3, Center for Highway Research, The University of Texas at Austin, September 1969.

6. Miller, Samuel Paul, Thomas W. Kennedy, and W. Ronald Hudson, "Evaluation of Factors Affecting the Tensile Properties of Lime-Treated Materials," Research Report No. 98-4, Center for Highway Research, The University of Texas at Austin, March 1970.

7. Herrin, Moreland, and Henry Mitchell, "Lime-Soil Mixtures," Bulletin 304, Highway Research Board, 1961, pp 99-138.

8. Mateos, Manual, "Soil Lime Research at Iowa State University," Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, March 1964.

9. Thompson, Marshall R., "Lime Reactivity of Illinois Soils," Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, September 1966.

10. Thompson, Marshall R., "Lime-Treated Soils for Pavement Construction," Journal of the Highway Division, Proceedings of the American Society of Civil Engineers, November 1968.

11. Diamond, Sidney, and Earl B. Kinter, "Mechanisms of Soil-Lime Stabilization," Highway Research Record No. 92, Highway Research Board, 1965, pp 83-95.

12. Eades, James L., F. P. Nichols, Jr., and Ralph E. Grim, "Formation of New Minerals With Lime Stabilization as Proven by Field Experiments in Virginia," Bulletin 335, Highway Research Board, 1963, pp 31-39.

13. Clare, K. E., and A. E. Cruchley, "Laboratory Experiments in the Stabilization of Clays with Hydrated Lime," Geotechnique, Vol VII, The International Journal of Soil Mechanics, The Institution of Civil Engineers, London SW1, March 1957.

14. Townsend, David L., and Tony W. Klym, "Durability of Lime-Stabilized Soils," Highway Research Record No. 139, Highway Research Board, 1966, pp 25-41.

15. Thompson, Marshall R., "The Split-Tensile Strength of Lime-Stabilized Soils," A Report of the Investigation of Lime Stabilization of Soils for Highway Purposes, Project IHR-76, Illinois Cooperative Highway Research Program, Engineering Experiment Station, University of Illinois, Urbana, December 1964.

16. Metcalf, J. B., and S. Frydman, "A Preliminary Study of the Tensile Stresses in Stabilized Soil Pavements," Proceedings of the Australian Road Research Board, Vol 1, Pt 2, 1962.

17. Mitchell, Neal B., "The Indirect Tension Test for Concrete," Materials Research and Standards, Vol 1, No. 10, American Society for Testing and Materials, October 1961.

18. Thompson, Marshall R., "Shear Strength and Elastic Properties of Lime-Soil Mixtures," Highway Research Record No. 139, Highway Research Board, 1966, pp 1-14.

19. Ruff, C. G., and Clara Ho, "Time-Temperature Strength-Reaction Product Relationships in Lime-Bentonite-Water Mixtures," Highway Research Record No. 139, Highway Research Board, 1966, pp 42-60.

20. Hadley, William O., W. Ronald Hudson, and Thomas W. Kennedy, "A Method of Estimating the Tensile Properties of Materials Tested in Indirect Tension," Research Report No. 98-7, Center for Highway Research, The University of Texas at Austin, July 1970.

21. Texas Highway Department, Manual of Testing Procedures, Vol 1, Test Method Tex-206-F, September 1966.

22. Davies, Owen L., The Design and Analysis of Industrial Experiments, Hafner Publishing Company, New York, 1967.

23. Milberger, Lionel J., and Wayne A. Dunlap, "A Gyratory Compactor for Molding Large Diameter Triaxial Specimens of Granular Material," Research Report No. 99-2, Texas Transportation Institute, Texas A&M University, October 1966.

APPENDICES

APPENDIX 1

BATCHING AND MIXING PROCEDURE

APPENDIX 1. BATCHING AND MIXING PROCEDURE

(1) Select the clay content and gradation to be used. Batch the material by weight in the following way:

   (a) Weigh the portion of aggregate retained on No. 10 sieve and store in a container.

   (b) Weigh the appropriate portion of clay and the portion of aggregate passing No. 10 sieve and store in a different container.

(2) Add the appropriate amount of lime to the portion of aggregate passing No. 10 sieve.

(3) Mix the fine aggregate and clay with the lime by hand.

(4) Add half of the appropriate mixing water to the coarse portion of the aggregate and hand mix until the surfaces of all the coarse aggregate are wet.

(5) Add the fines and lime to the wet coarse aggregate and spread the fines over the coarser aggregate; then, add the remaining water.

(6) For 2-inch by 4-inch and 2-inch by 6-inch specimens, machine mix in a bowl for one minute; remove the fines stuck to the bottom and mix an additional minute. The mixing procedure for the two smaller sized specimens was performed with a model AS-200 machine manufactured by the Hobart Company.

(7) For 6-inch by 8-inch specimens, hand mix the materials in a large rectangular mixing pan until they are mixed thoroughly and the texture is uniform.

APPENDIX 2

COMPACTION PROCEDURES

APPENDIX 2. COMPACTION PROCEDURES

IMPACT COMPACTION PROCEDURE (Ref 21)

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

(2) After the materials are thoroughly mixed, separate a small amount of fines. Place the remaining material in the mold in 2-inch layers. Rod the material several times insuring that the coarser aggregate is towards the center of the mold.

(3) Compact each layer with the desired number of blows, using a 10-pound ram with an 18-inch drop. (The Texas Highway Department uses 50 blows per layer for lime-treated materials.) If there is more than one layer, scarify the top of the preceding layer before placing the material for the next layer in the mold.

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

(5) Use the fines retained in Step 2 to level the surface of the specimen.

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

(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 Compactor was used in this study.

GYRATORY SHEAR COMPACTION PROCEDURE FOR 4-INCH-DIAMETER SPECIMENS (Ref 21)

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

(2) With a bent spoon, transfer the laboratory mixture into the mold, in three approximately equal layers. Press each layer down lightly with the spoon, and move the larger particles away from the mold wall with a small spatula. Place a circular piece of paper on top of the mixture.

(3) Place a small amount of oil in the center of the motorized press platen, on the surface of the lower bearing, and around the periphery of the mold on the top surface of the hardened steel ring.

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

(5) Pump the ram into the center of the mold until the low pressure gage registers 40 psi.

(6) Pull the handle on the cam lever down to the horizontal position, cocking the mold to the proper angle for gyration.

(7) Push the reset button and then the start button.

(8) As soon as the last gyration is completed, raise the cam lever handle into a vertical position, leveling the mold.

(9) Repeat Steps 5 through 8 until one smooth full stroke of the pump handle will cause the low pressure gage to indicate the desired full stroke pressure for that specimen. During molding, when one stroke of the pump handle causes the gage to come to rest between 40 psi and the desired full stroke pressure, drop the pressure below 40 psi and then pump the pressure back up to 40 psi.

(10) When the desired full stroke pressure is reached, at approximately one stroke per second, pump the pressure up to 200 psi, as measured on the high pressure gage.

(11) Release the pressure and pump the ram up and out of the mold.

(12) Slide the mold out of the press.

(13) Extrude the specimen. Weigh and measure the height and diameter of the specimen.

(14) A Texas Highway Department gyratory shear compactor for 4-inch-diameter specimens was used in this study.

GYRATORY SHEAR COMPACTION PROCEDURE FOR 6-INCH-DIAMETER SPECIMENS (Ref 23)

(1) Before starting the compaction procedure, set the following compaction variables:

  (a) Set the gyratory angle at 3°.

  (b) Set the counter so that the compactor will cut off after 28 gyrations.

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

  (d) Set the micrometer at 0.1562, so that when the gyrating angle has reached 0° the counter will have reached 28 gyrations.

  (e) Set the desired molding pressure.

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

(3) Spread a thin layer of fines in the bottom of the mold and put the remaining material in the mold. After each placement, spread the large aggregates 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 sample. Place a circular piece of filter

paper on top of the sample. Insert the top bearing plate and grease lightly.

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

(5) Allow pressure head to apply load to specimen. When vertical movement has stopped, release load and remove split rings from beneath mold.

(6) Allow pressure head to apply load to specimen. When vertical movement stops, open valve to apply angle.

(7) Start gyration.

(8) When gyration has ended, roll counter to zero and retract pressure head.

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

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

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

(12) Figure 19 shows the gyratory compactor used for this type of compaction.

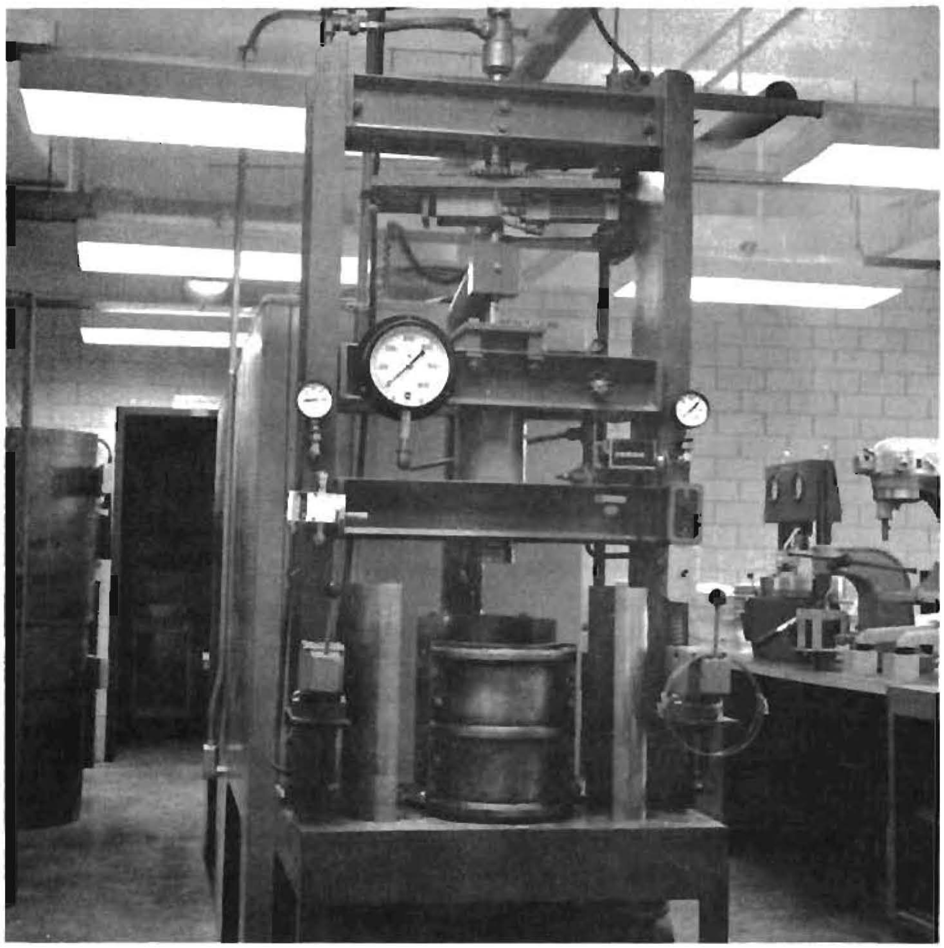


Fig 19. Gyratory shear compactor for 6-inch-diameter specimens.

APPENDIX 3

CURING PROCEDURES

APPENDIX 3. CURING PROCEDURES

CENTER FOR HIGHWAY RESEARCH CURING PROCEDURE

(1) After compaction weigh and measure the height and diameter or circumference of the specimen.

(2) Wrap the specimen with one layer of PVC film and secure the film with rubber bands.

(3) Place the specimen in the appropriate temperature environment, i.e., oven, air-conditioned laboratory, or environmental chamber.

(4) Allow the specimen to cure for three weeks.

TEXAS HIGHWAY DEPARTMENT CURING PROCEDURE (Ref 21)

(1) The test specimens with top and bottom porous stone in place are covered with a triaxial cell immediately after extruding from the forming mold and stored at room temperature for a period of seven days.

(2) After this curing period, remove the cells and place the specimens in an air drier and dry at a temperature not to exceed 140° F for about six hours or until one-third to one-half of the molding moisture has been removed. All lime-treated soils are dried this way even though a considerable amount of cracking may occur. Allow the specimen to cool for at least eight hours before continuing test.

(3) Weigh, measure, and enclose the specimens in triaxial cells and subject them to capillarity for ten days. Use a constant lateral pressure of 1 psi and a surcharge weight of 15 pounds.

APPENDIX 4

INDIRECT TENSILE TEST PROCEDURE

APPENDIX 4. INDIRECT TENSILE TEST PROCEDURE

The indirect tensile test and its application to stabilized materials were considered and discussed in detail by Hudson and Kennedy (Refs 1 and 2). Essentially the test involves loading a cylindrical specimen with compressive loads distributed along two opposite generators. This results in a relatively uniform tensile stress perpendicular to and along the diametral plan containing the applied load. The failure usually occurs by splitting along this loaded plane. The procedure followed for the testing of the lime-treated specimens is essentially the same as that recommended by Hudson and Kennedy.

Testing was conducted at room temperature at a loading rate of 2 inches per minute. Stainless steel loading strips were used to apply the load to the specimens. The overall width of the strip was one-half inch. The loading strip was curved, with a 2-inch radius for 4-inch-diameter specimens and a 3-inch radius for 6-inch-diameter specimens.

The basic testing equipment was the same as previously used in other studies at The University of Texas at Austin (Refs 1 through 6) and 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.

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

The steps in the procedure to test soil-lime specimens in indirect tension are as follows:

(1) Weigh and measure the height and diameter or circumference of the specimen.

(2) Center the specimen on the lower loading strip.

(3) Zero the x-y plotter which measures load versus vertical deflection.

(4) Load the specimen to 25 pounds.

(5) Position the device for measuring transverse deformation.

(6) Bring the pointer on the x-y plotter measuring load versus lateral deflection to a position relative to the pointer on the x-y plotter measuring load versus vertical deflection.

(7) Engage the pen points on the x-y plotters and test the specimens at a rate of 2 inches per minute.

(8) Figure 20 shows the apparatus used in the indirect tensile testing of soil-lime specimens and Fig 21 shows the lateral deflection device.

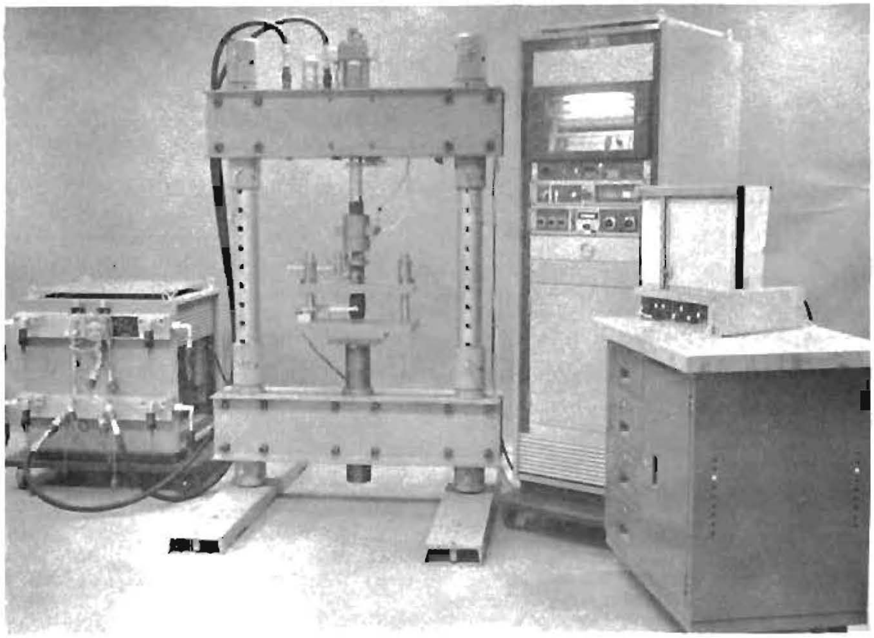


Fig 20. Basic indirect tensile testing equipment.

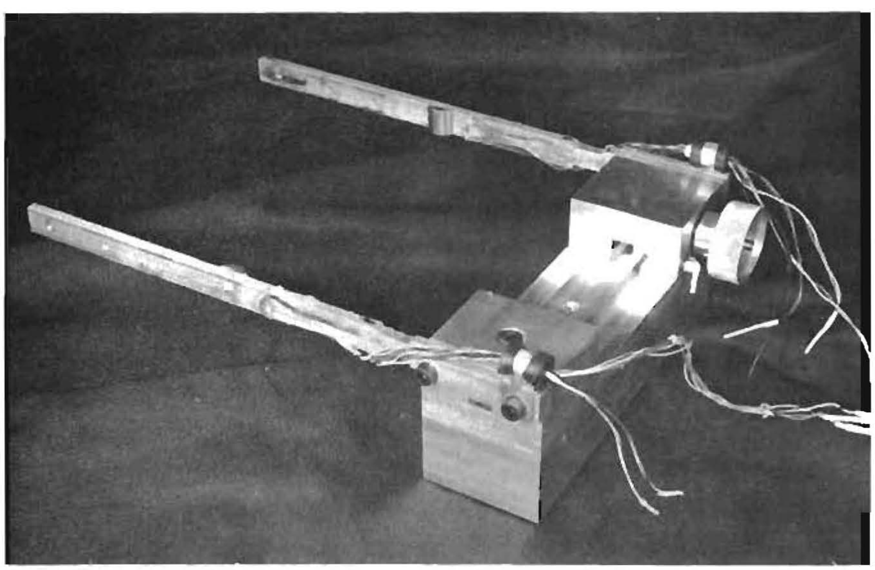


Fig 21. Lateral deflection device.

APPENDIX 5

UNCONFINED COMPRESSION TEST PROCEDURE

APPENDIX 5. UNCONFINED COMPRESSION TEST PROCEDURE (Ref 21)

(1) Remove the specimen from the curing environment. Weigh and measure height and circumference of the specimen.

(2) Center the specimen with top and bottom porous stones in place on the lower platen of the test rig.

(3) Zero the x-y plotter.

(4) Preload the specimen to approximately 50 pounds and rezero the x-coordinate of the x-y plotter.

(5) Test the specimen to failure at a loading rate of 0.14 inch per minute.

(6) Load and vertical deformation are recorded on the x-y plotter.

APPENDIX 6

COHESIOMETER TEST PROCEDURE

APPENDIX 6. COHESIOMETER TEST PROCEDURE (Ref 21)

All cohesiometer specimens for this study were tested at the Materials and Test Division laboratory of the Texas Highway Department, as follows:

(1) Remove test specimen from curing room. Weigh and measure the height and diameter of the specimen.

(2) Place the specimen with topside, as molded, up on platform of cohesiometer. Center the test specimen on lower platen 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 for firm soil-lime specimens.

(3) Release the shot to test the specimen. The flow of shot is stopped automatically when the specimen breaks.

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

APPENDIX 7

PROPERTIES OF MATERIALS

APPENDIX 7. PROPERTIES OF MATERIALS

LIME

Lime used in the experiments was a hydrated calcitic lime manufactured by the Austin White Lime Company, Austin, Texas. The following chemical compositions were determined by Texas Highway Department laboratories:

Chemical Composition	Percent by Weight
$Ca(OH)_2$	93.67
CaO	0.0
"Free Water" content, H_2O	1.38
$CaCO_3$	3.75
"Inert Matter" (SiO_2, etc.)	1.20
Residue retained on No. 30 (590 micron) sieve	0.0

GRAVEL

The aggregate used in the experiments was a rounded, pit-run gravel known locally as Seguin gravel. It was quarried near Seguin, Texas, and used as a base material. Its properties are described in the following items:

Texas triaxial classification	3.0
Unified classification	GM_d
Texas Highway Department classification	Type B Grade 3
Specific gravity	2.64
Unit weight (dry)	113.9 lb/ft^3
Wet ball mill	37.2
Los Angeles abrasion	(100 revolutions) 7.2 (50 revolutions) 27.3
50-blow optimum moisture	7.3

Plasticity tests conducted on material passing the No. 30 sieve yielded the following results:

Liquid limit	21.3 percent
Plastic index	7.4 percent
Linear shrinkage	5.6 percent

CLAY

Clay used in the experiments is common to the local area and is known as Taylor Marl clay. Its properties are described below and in Fig 22.

Liquid limit	59 percent
Plastic limit	18 percent
Plastic index	41 percent

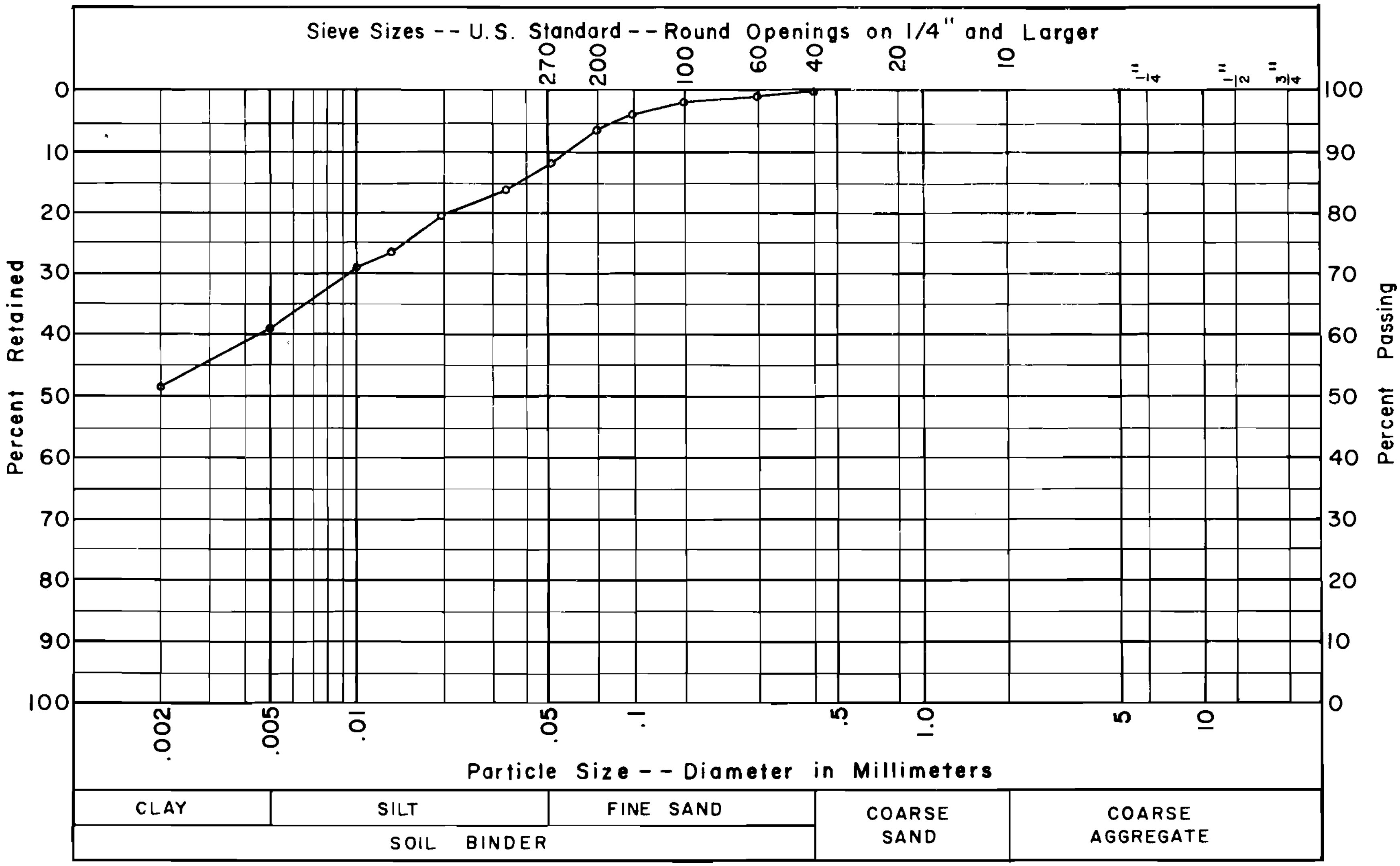


Fig 22. Grain size distribution curve for Taylor Marl clay.

APPENDIX 8

ADDITIONAL STATISTICAL INFORMATION

APPENDIX 8. ADDITIONAL STATISTICAL INFORMATION

Primarily, the Center for Highway Research correlation and the Texas Highway Department correlation were run to compare indirect tensile test results with unconfined compression test results and cohesiometer test results for lime-treated materials, but since the experiments were statistically designed, additional statistical information was gained. As a result, analyses of variance for indirect tensile strength, unconfined compressive strength, and cohesiometer value are presented in Tables 14, 15, and 16 for soil-lime specimens cured according to procedures established at the Center for Highway Research and in Tables 17, 18, and 19 for specimens cured according to standard Texas Highway Department procedures. In addition, the following prediction equations were obtained from the regression analysis.

CENTER FOR HIGHWAY RESEARCH CORRELATION

$$\hat{q}_u = 1594 - 14.6A - 290.3E - 53.0D - 6.1F + 2.1AF + 0.11AF + 1.9EF + 0.31DH \qquad (A8.1)$$

for which the multiple correlation coefficient was .91 and the standard error of estimate was ±170;

$$\hat{C} = 1666 - 479.5E - 223.7D + 24.3F + 3.1AE - 0.65AD + 4.5EF + 4.1DH - 0.53FH \qquad (A8.2)$$

for which the multiple correlation coefficient was .96 and the standard error of estimate was ±194; and

TABLE 14. ANALYSIS OF VARIANCE FOR INDIRECT TENSILE STRENGTH FOR CFHR CURING

Source of Variation	Degree of Freedom	Mean Squares	F Value*	Significance Level, %
E	1	1274.1	206.5	1
DH	1	1015.7	164.6	1
D	1	943.5	152.9	1
F	1	935.3	151.6	1
A	1	227.3	36.8	5
EF	1	225.8	36.6	5
AE	1	207.7	33.7	5
AH	1	183.4	29.7	5
FH	1	179.7	29.1	5
AD	1	164.5	26.7	5
AF	1	155.4	25.2	5
Residual	7	21.5		
Within treatments treated alike	2	6.2		

* Critical F values: $F_{(1, 2, .01)} = 98.5$; $F_{(1, 2, .05)} = 18.5$.

Legend

A - Compactive effort

D - Molding water content

E - Lime content

F - Curing temperature

H - Clay content

TABLE 15. ANALYSIS OF VARIANCE FOR UNCONFINED COMPRESSIVE STRENGTH FOR CFHR CURING

Source of Variation	Degree of Freedom	Mean Squares	F Value*	Significance Level, %
F	1	1400577.3	1752.2	1
D	1	284284.4	355.7	1
DH	1	281771.5	352.5	1
E	1	256030.9	320.3	1
AE	1	193395.4	242.0	1
A	1	186889.7	233.8	1
EF	1	170081.5	212.8	1
AF	1	164327.8	205.6	1
AH	1	47526.0	59.5	5
H	1	35870.5	44.9	5
AD	1	29479.6	36.9	5
DE	1	28540.2	35.7	5
EH	1	16708.8	20.9	5
DF	1	16154.1	20.2	5
Residual	4	51156.9		
Within treatments treated alike	2	799.3		

* Critical F values: $F_{(1, 2, .01)} = 98.5$; $F_{(1, 2, .05)} = 18.5$.

Legend

A - Compactive effort

D - Molding water content

E - Lime content

F - Curing temperature

H - Clay content

TABLE 16. ANALYSIS OF VARIANCE FOR COHESIOMETER VALUE FOR CFHR CURING

Source of Variation	Degree of Freedom	Mean Squares	F Value*	Significance Level, %
E	1	3051709.8	172.2	1
F	1	2565973.3	144.8	1
DH	1	1142799.9	64.5	5
D	1	977929.1	55.2	5
EF	1	922041.3	52.0	5
FH	1	447136.4	25.2	5
Residual	12	88467.4		
Within treatments treated alike	2	17724.2		

* Critical F values: $F_{(1, 2, .01)} = 98.5$; $F_{(1, 2, .05)} = 18.5$.

<u>Legend</u>

D - Molding water content

E - Lime content

F - Curing temperature

H - Clay content

TABLE 17. ANALYSIS OF VARIANCE FOR INDIRECT TENSILE STRENGTH FOR THD CURING

Source of Variation	Degree of Freedom	Mean Squares	F Value*	Significance Level, %
DH	1	130.2	41.0	1
E	1	64.9	20.4	1
D^2	1	63.8	20.0	1
Residual	16	6.9		
Within treatments treated alike	5	3.2		

* Critical F values: $F_{(1, 5, .01)} = 16.3$; $F_{(1, 5, .05)} = 6.6$.

Legend

D - Molding water content

E - Lime content

H - Clay content

TABLE 18. ANALYSIS OF VARIANCE FOR UNCONFINED COMPRESSIVE STRENGTH FOR THD CURING

Source of Variation	Degree of Freedom	Mean Squares	F Value*	Significance Level, %
DH	1	6483.8	24.6	1
H	1	5168.3	19.6	1
E	1	3763.4	14.3	5
D^2	1	3086.2	11.7	5
E^2	1	2914.6	11.0	5
Residual	14	540.2		
Within treatments treated alike	5	264.0		

* Critical F values: $F_{(1, 5, .01)} = 16.3$; $F_{(1, 5, .05)} = 6.6$.

Legend

D - Molding water content

E - Lime content

H - Clay content

TABLE 19. ANALYSIS OF VARIANCE FOR COHESIOMETER VALUE FOR THD CURING

Source of Variation	Degree of Freedom	Mean Squares	F Value*	Significance Level, %
DH	1	25651.1	8.2	5
Residual	18	4112.4		
Within treatments treated alike	5	3131.2		

* Critical F values: $F_{(1,\ 5,\ .01)} = 16.3$; $F_{(1,\ 5,\ .05)} = 6.6$.

Legend

D - Molding water content

H - Clay content

$$\hat{S}_t = 19.74 + 0.22A - 8.0E - 4.4D + 0.69F$$

$$+ 0.07AE + 0.003AH - 0.04AD + 0.07EF$$

$$+ 0.1DH - 0.01FH \qquad (A8.3)$$

for which the multiple correlation coefficient was .94 and the standard error of estimate was ±6.36

where

$\hat{q}_u$ = predicted unconfined compressive strength, psi;

$\hat{C}$ = predicted cohesiometer value, grams per inch;

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

A, D, E, F, H = factors considered for prediction (see Table 8, p 40).

TEXAS HIGHWAY DEPARTMENT CORRELATION

$$\hat{q}_u = 48 + 40.2E - 2.9H + 12.2D - 6.3E^2 - 0.007H^2$$

$$+ 0.009DH - 2.5D^2 + 0.05DEH \qquad (A8.4)$$

for which the multiple correlation coefficient was .89 and the standard error of estimate was ±23;

$$\hat{C} = 128 + 48.7E - 15.8E^2 + 0.91EH - 0.24H^2$$

$$+ 1.7DH - 3.5D^2 + 0.11DEH \qquad (A8.5)$$

for which the multiple correlation coefficient was .88 and the standard error of estimate was ±44; and

$$\hat{S}_t = 39.3 + 0.4E - 1.2H - 0.54E^2 + 0.33DE$$

$$- 0.005H^2 + 0.14DH - 0.3D^2 \quad \text{(A8.6)}$$

for which the multiple correlation coefficient was .91 and the standard error of estimate was ±2.37

where

$\hat{q}_u$ = predicted unconfined compressive strength, psi;

$\hat{C}$ = predicted cohesiometer value, grams per inch;

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

D, E, H = factors considered for prediction (see Table 10, p 46).

APPENDIX 9

TREATMENT COMBINATIONS

TABLE 20. TREATMENT COMBINATIONS FOR SPECIMENS TO BE CURED FOR SIX MONTHS

	Level of Factor*				
Specimen No.	A	E	H	D	F
49	+1	+1	+1	+1	+1
50	+1	+1	+1	-1	-1
51	+1	+1	-1	+1	-1
52	+1	+1	-1	-1	+1
53	+1	-1	+1	+1	-1
54	+1	-1	+1	-1	+1
55	+1	-1	-1	+1	+1
56	+1	-1	-1	-1	-1
57	-1	+1	+1	+1	-1
58	-1	+1	+1	-1	+1
59	-1	+1	-1	+1	+1
60	-1	+1	-1	-1	-1
61	-1	-1	+1	+1	+1
62	-1	-1	+1	-1	-1
63	-1	-1	-1	+1	-1
64	-1	-1	-1	-1	+1

* For explanation of level of factor see Table 1, p 20.

TABLE 21. TREATMENT COMBINATIONS FOR FACTOR EVALUATION EXPERIMENT (FULL FACTORIAL)

	Level of Factor				
Specimen No.	A	E	H	D	F
1	+1	+1	+1	+1	+1
2	+1	+1	+1	+1	-1
3	+1	+1	+1	-1	+1
4	+1	+1	+1	-1	-1
5	+1	+1	-1	+1	+1
6	+1	+1	-1	+1	-1
7	+1	+1	-1	-1	+1
8	+1	+1	-1	-1	-1
9	+1	-1	+1	+1	+1
10	+1	-1	+1	+1	-1
11	+1	-1	+1	-1	+1
12	+1	-1	+1	-1	-1
13	+1	-1	-1	+1	+1
14	+1	-1	-1	+1	-1
15	+1	-1	-1	-1	+1
16	+1	-1	-1	-1	-1
17	-1	+1	+1	+1	+1
18	-1	+1	+1	+1	-1
19	-1	+1	+1	-1	+1
20	-1	+1	+1	-1	-1
21	-1	+1	-1	+1	+1
22	-1	+1	-1	+1	-1
23	-1	+1	-1	-1	+1
24	-1	+1	-1	-1	-1
25	-1	-1	+1	+1	+1
26	-1	-1	+1	+1	-1

(Continued)

TABLE 21. (CONTINUED)

	Level of Factor				
Specimen No.	A	E	H	D	F
27	-1	-1	+1	-1	+1
28	-1	-1	+1	-1	-1
29	-1	-1	-1	+1	+1
30	-1	-1	-1	+1	-1
31	-1	-1	-1	-1	+1
32	-1	-1	-1	-1	-1
	Star Points				
33	-2	0	0	0	0
34	+2	0	0	0	0
35	0	-2	0	0	0
36	0	+2	0	0	0
37	0	0	-2	0	0
38	0	0	+2	0	0
39	0	0	0	-2	0
40	0	0	0	+2	0
41	0	0	0	0	-2
42	0	0	0	0	+2
	Center Points				
43	0	0	0	0	0
44	0	0	0	0	0
45	0	0	0	0	0
46	0	0	0	0	0
47	0	0	0	0	0
48	0	0	0	0	0

TABLE 22. TREATMENT COMBINATIONS FOR CFHR CORRELATION

Specimen No.			Level of Factor*				
Unconfined Compression	Cohesiometer	Indirect Tension	A	E	H	D	F
65	84	103	+1	+1	+1	+1	+1
66	85	104	+1	+1	+1	-1	-1
67	86	105	+1	+1	-1	+1	-1
68	87	106	+1	+1	-1	-1	+1
69	88	107	+1	-1	+1	+1	-1
70	89	108	+1	-1	+1	-1	+1
71	90	109	+1	-1	-1	+1	+1
72	91	110	+1	-1	-1	-1	-1
73	92	111	-1	+1	+1	+1	-1
74	93	112	-1	+1	+1	-1	+1
75	94	113	-1	+1	-1	+1	+1
76	95	114	-1	+1	-1	-1	-1
77	96	115	-1	-1	+1	+1]	+1
78	97	116	-1	-1	+1	-1	-1
79	98	117	-1	-1	-1	+1	-1
80	99	118	-1	-1	-1	-1	+1
81**	100**	119**	0	0	0	0	0
82**	101**	120**	0	0	0	0	0
83**	102**	121**	0	0	0	0	0

* For explanation of level of factor see Table 4, p 25.

** Center points.

TABLE 23. TREATMENT COMBINATIONS FOR THD CORRELATION

Specimen No.			Level of Factor*		
Unconfined Compression	Cohesiometer	Indirect Tension	E	H	D
122**	142**	162**	+1	-1	-1
123**	143**	163**	-1	+1	-1
124***	144***	164***	+1	+1	-1
125**	145**	165**	-1	-1	+1
126***	146***	166***	+1	-1	+1
127***	147***	167***	-1	+1	+1
128**	148**	168**	+1	+1	+1
129***	149***	169***	-1	-1	-1
130**	150**	170**	-1.682	0	0
131**	151**	171**	+1.682	0	0
132**	152**	172**	0	-1.682	0
133**	153**	173**	0	+1.682	0
134**	154**	174**	0	0	-1.682
135**	155**	175**	0	0	+1.682
136**	156**	176**	0	0	0
137**	157**	177**	0	0	0
138**	158**	178**	0	0	0
139***	159***	179***	0	0	0
140***	160***	180***	0	0	0
141***	161***	181***	0	0	0

* For explanation of level of factor see Table 4, p 25.

** Block 1.

*** Block 2.

Note: Specimens 122-129, 142-149, and 162-169 = Full factorial

Specimens 130-135, 150-155, and 170-175 = Star points

Specimens 136-141, 156-161, and 176-181 = Center points

TABLE 24. TREATMENT COMBINATIONS FOR SPECIMEN SIZE STUDY

Specimen No.		Level of Factor*				
2 by 4-Inch	2 by 6-Inch	A	E	H	D	F
1	182	+1	+1	+1	+1	+1
4	183	+1	+1	+1	-1	-1
6	184	+1	+1	-1	+1	-1
7	185	+1	+1	-1	-1	+1
10	186	+1	-1	+1	+1	-1
11	187	+1	-1	+1	-1	+1
13	188	+1	-1	-1	+1	+1
16	189	+1	-1	-1	-1	-1
18	190	-1	+1	+1	+1	-1
19	191	-1	+1	+1	-1	+1
21	192	-1	+1	-1	+1	+1
24	193	-1	+1	-1	-1	-1
25	194	-1	-1	+1	+1	+1
28	195	-1	-1	+1	-1	-1
30	196	-1	-1	-1	+1	-1
31	197	-1	-1	-1	-1	+1
45**	198**	0	0	0	0	0
47**	199**	0	0	0	0	0
48**	200**	0	0	0	0	0

* For explanation of level of factor see Table 1, p 20.

** Center points.

APPENDIX 10

AGGREGATE GRADATIONS

TABLE 25. GRAVEL GRADATIONS FOR THE VARIOUS CLAY CONTENTS

	Clay Content, Percent by Weight						
	25.0	29.0	37.5	50.0	62.5	71.0	75.0
Passing 7/8" Sieve	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Retained on 1/2" Sieve	13.0	12.0	11.0	9.0	6.5	5.0	4.0
Retained on 3/8" Sieve	9.0	9.0	7.5	6.0	4.5	3.0	3.0
Retained on No. 4 Sieve	14.0	13.0	11.5	9.0	7.0	6.0	5.0
Retained on No. 10 Sieve	13.0	12.0	11.0	9.0	6.5	5.0	4.0
Retained on No. 40 Sieve	13.0	12.0	11.0	9.0	6.5	5.0	4.0
Retained on No. 80 Sieve	5.0	5.0	5.0	3.0	2.5	2.0	2.0
Retained on No. 200 Sieve	8.0	8.0	5.5	5.0	4.0	3.0	3.0
Passing No. 200 Sieve	0.0	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX 11

GYRATORY SHEAR COMPACTION OF 6 BY 8-INCH SOIL-LIME SPECIMENS

APPENDIX 11. GYRATORY SHEAR COMPACTION OF 6 BY 8-INCH SOIL-LIME SPECIMENS

In compacting 6-inch-diameter by 8-inch-high soil-lime specimens by gyratory shear compaction, it was found that the specimens exhibited cracks on the circumference upon extrusion, and the cracks indicated the location of one or more failure planes which extended longitudinally through the specimen. The specimen in which cracks were first noticed consisted of 37.5 percent Seguin gravel and 62.5 percent fat clay. The molding water content was 15.5 percent and the lime content was 1.5 percent. The gyrating or molding pressure was 250 psi. The properties of the materials are presented in Appendix 7.

Several preliminary suggestions were made as to the possible causes of the cracking: that pore pressure buildup in the specimens which contained a large amount of clay sizes was responsible for the failure, that failure occurred during extrusion, that the molding pressure was too great during compaction, and that the particular compaction machine used was not functioning properly.

The molding pressure was reduced in increments of 50 psi from 250 to 100 psi. With a molding pressure of 100 psi, the specimens were still failing and the density was reduced to approximately 125 lb/cu ft. In order to ascertain whether failure occurred during extrusion, the split mold was opened before the specimen had been extruded. This split the specimen longitudinally with half of the specimen remaining in each half of the mold. Investigation of the two halves of the specimen showed that the failure plane was present in the specimen before extrusion. To determine if failure was due to a machine malfunction, an identical specimen was prepared on the large gyratory shear compaction machine at the Materials and Test Division laboratory of the Texas Highway Department, and this specimen also failed during compaction.

It was thought that the water content of the clay might be enough that with the addition of molding water the water content would become excessive. The water content of the clay was determined to be 2.22 percent, and an additional specimen was prepared using a molding water content of 13.0 percent. This specimen also failed.

All of the above mentioned specimens contained 62.5 percent clay and 15.5 or 13.0 percent molding water. It is possible that by decreasing the clay content or by further decreasing the molding pressure or the molding water content, specimens could be produced which would not fail during compaction. However, in order to use gyratory shear compaction for this particular study it was necessary to be able to produce specimens with 62.5 percent clay, 15.5 percent water, and densities which fell within the range of 128 to 132 lb/cu ft, and therefore, it was decided to use impact compaction.

ABOUT THE AUTHORS

Walter S. Tulloch, II

First Lieutenant, U.S. Army Corps of Engineers, Germany; formerly Graduate Assistant, Center for Highway Research, The University of Texas at Austin.

W. Ronald Hudson

Research Engineer, Center for Highway Research; Associate Professor of Civil Engineering; and Associate Dean of Engineering, The University of Texas at Austin.

Thomas W. Kennedy

Research Engineer, Center for Highway Research; Associate Professor of Civil Engineering, The University of Texas at Austin.