EVALUATION OF FACTORS AFFECTING THE TENSILE PROPERTIES OF LIME-TREATED MATERIALS

by

S. Paul Miller
Thomas W. Kennedy
W. Ronald Hudson

Research Report Number 98-4

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

Research Project 3-8-66-98

conducted for

The Texas Highway Department

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

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

March 1970

PREFACE

This is the fourth in a series of reports dealing with the findings of Research Project No. 3-8-66-98, which is concerned with the evaluation of the tensile properties of stabilized subbase materials. This report presents some of the factors which are important in determining the strength of lime-treated materials, reports the findings of an evaluation by indirect tensile test of eight factors thought to affect the tensile properties of lime-treated materials, and summarizes the effects of these eight factors and their interactions on tensile strength.

Future reports will be concerned with detailed investigation of the tensile characteristics of asphalt-treated, cement-treated, and lime-treated materials. Reports will be written on such subjects as (1) factors affecting the tensile characteristics and behavior of the materials when subjected to static and dynamic repeated loads, (2) correlation of indirect tensile test parameters with parameters from standard Texas Highway Department tests, (3) performance criteria for stabilized materials, (4) 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.

This report required the assistance of many individuals and the authors would like to acknowledge the work of all those who contributed to it. Special thanks are extended to Dr. Virgil L. Anderson, Dr. Gerald R. Wagner, Mr. Raymond K. Moore, and Mr. Joseph A. Kozuh for their help in designing the statistical experiment and in providing guidance in the analysis and interpretation of the data. Special appreciation is also due Messrs. Pat S. Hardeman and James N. Anagnos for their assistance in the preparation and testing of the lime-treated materials, and to Messrs. James L. Brown and Harvey J. Treybig of the Texas Highway Department, who provided the technical liaison for the project.

S. Paul Miller
Thomas W. Kennedy
W. Ronald Hudson

March 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 cement-treated materials and reports findings of an evaluation by indirect tensile test of eight factors thought to affect the tensile properties of lime-treated materials.

Report No. 98-5, "Evaluation and Prediction of the Tensile Properties of Lime-Treated Materials," by Walter S. Tulloch, II, W. Ronald Hudson, and Thomas W. Kennedy, 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.

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

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

ABSTRACT

The indirect tensile test was used to study the tensile properties of lime-treated materials. Factors indicated to be important by a literature review were included in a fractional factorial experiment consisting of three experimental blocks.

An analysis of variance was run for indirect tensile strength to determine those factors and their interactions which significantly affected strength at probability levels of 0.05 or lower. Those effects and interactions which were felt to be significant in practical application of the results are presented in graphs and discussed. In addition, all of the data from the three experimental blocks were pooled for a large regression which produced a predictive equation for indirect tensile strength in terms of the significant factors and interaction. This equation can be used to estimate the tensile strength of lime-treated materials and to aid in the design of lime-treated mixtures.

KEY WORDS: indirect tensile test, tensile strength, lime stabilization, subbases, experiment design, regression analysis, lime stabilized clay, split cylinder test.

SUMMARY

This report details the results of a preliminary factor screening experiment which investigated some of the more important variables that affect the indirect tensile strength of lime-treated materials. After a comprehensive literature review, which is summarized in the report and represents a state-of-the-art statement concerning lime-treated materials, the factors to be studied were selected. These variables included compactive effort, compaction type, curing procedure, lime content, curing temperature, curing time, moisture content, and clay content.

The use of experimental design and regression techniques enabled the study of main effects as well as selected two-factor and three-factor interactions between the eight variables listed above. Main effects and interactions significant at a probability level of 0.001 are discussed and interpreted in order to produce a better understanding of how the variables interrelate and interact in lime-treated materials and the extent that they influence tensile strength.

Regression techniques were used to develop a predictive equation for indirect tensile strength in terms of the variables studied. The predictive capability represents a significant advancement within the stabilized materials area and can be used to estimate tensile strengths for lime-treated materials. The complexity of the various mechanisms which occur during a lime-stabilization or lime-modification process is illustrated by the length and complexity of the regression required to predict the tensile strength within an acceptable standard error of estimate.

Thus, this study represents the first large scale investigation of lime-treated materials using the multifactored approach and the statistical techniques required to analyze the results. It is the initial step in research project 3-8-66-98, "Evaluation of Tensile Properties of Subbases for Use in New Rigid Pavement Design," to document the factors which affect the tensile strength of lime-treated materials and, thereby, create a better fundamental understanding of material behavior.

IMPLEMENTATION STATEMENT

The research work summarized was not performed for direct practical application in the field. It is one part of a comprehensive effort to develop better procedures for designing stabilized materials for use in pavement design and analysis. Nevertheless, the results are helpful to practicing engineers, in that they point out the complexities involved in the evaluation and design of lime-treated materials and provide a better understanding of tensile strength and the range of tensile strengths which can be expected from lime-treated materials.

The ultimate application of the results will be found in a comprehensive design method for stabilized materials in later reports from this project.

TABLE OF CONTENTS

CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

CHAPTER 3. EXPERIMENTAL PROGRAM

CHAPTER 4. DISCUSSION OF RESULTS

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

APPENDICES

CHAPTER 1. INTRODUCTION

One aspect of pavement performance and behavior which has received little attention concerns the tensile characteristics of materials used in the various layers of a pavement. Although increased tensile strengths have been as beneficial, little consideration has been given them in the design and analysis of pavements. This is due partly to the lack of information on the tensile characteristics of the materials used in the pavement.

In an attempt to develop information on the tensile characteristics of stabilized materials and to incorporate this information into a new design method for pavements, the Center for Highway Research at The University of Texas at Austin has adopted and modified the indirect tensile test for use in the evaluation of the tensile characteristics of stabilized pavement materials (Refs 1 and 2). Previous experiments have been conducted on asphalt-treated and cement-treated materials (Refs 3, 4, 5, and 6), but little work has been conducted on the tensile characteristics of lime-treated materials.

The purpose of this study was to determine those factors and their interactions which significantly affect the tensile strength of lime-treated materials and to obtain a preliminary indication of the nature of these affects. This experiment is a preliminary investigation which will require more detailed study.

CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

During the past 20 years a great amount of information has resulted from many field and experimental studies conducted on lime-treated materials. These data have been utilized in formulating this investigation of the tensile properties of lime-treated materials.

GENERAL EFFECTS

Previous studies (Refs 7 through 14) generally have shown that lime-treated materials exhibit the following changes with respect to the untreated soil:

(1) plasticity indices decrease,
(2) plastic limits increase,
(3) liquid limits remain relatively unchanged,*
(4) effective grain sizes increase,
(5) strengths increase,
(6) volume changes decrease,
(7) maximum dry densities decrease, and
(8) optimum moisture contents increase.

MECHANISMS OF LIME STABILIZATION

These changes generally are attributed to one or more of three mechanisms or reactions which occur when soil is treated with lime. These mechanisms, which are discussed in Herrin and Mitchell (Ref 15), Thompson (Ref 16), and Diamond and Kinter (Ref 17), are ion exchange and flocculation, cementing action, and carbonation.

In ion exchange and flocculation, calcium cations of lime replace metallic cations such as sodium and hydrogen on the surface of a clay particle, and

---

*Small increases or decreases in the liquid limit may occur depending on the type of soil.

additional calcium ions are attracted to the surface. Since the number of electrical charges on the surface of a particle are changed by both processes, and particles are attracted to each other, the soil becomes more friable, and the plasticity is lowered.

Cementing action is usually attributed to a pozzolanic reaction in which the aluminous and silicous minerals in the soil react with lime to produce a gel of calcium silicates and aluminates. This gel cements the soil particles in a manner similar to that of hydrated cement. Lime-cementing action in soil is a slow reaction which requires more time than the hydration of portland cement. Lime-soil cementation will occur only when the percentage of lime in the soil, the soil's natural properties, and climatic conditions (Ref 16) favor a pozzolanic reaction. In addition, the mixture of soil and lime must be well compacted for the desirable cementation to occur.

Carbonation occurs when carbon dioxide, which has been absorbed from the air, reacts with calcium or magnesium in the lime to form calcium or magnesium carbonate. Although some strength is gained, the cementing action is weak and is therefore, a minor source of strength (Refs 9 and 18). More important, however, is the fact that these carbonates deter pozzolanic action when the lime is mixed with a soil and thus impede strengthening (Refs 15 and 17).

These mechanisms are generally accepted as the causes of the changes associated with lime stabilization, however there is still a great deal of controversy over the subject (Refs 16 and 17).

FACTORS AFFECTING THE PROPERTIES OF LIME-TREATED MATERIALS

Several factors involving the constituents and treatment of the lime-soil-water mixture influence the type and degree of modification of lime-stabilized soil for construction utilization. The important factors as determined from research and construction practices are

(1) lime type,
(2) lime content,
(3) soil type,
(4) moisture content,
(5) time between mixing and compaction,
(6) compaction,

(7) mixing and pulverization, and
(8) curing conditions.

Although little work has been conducted on the effect of these factors on the tensile characteristics of lime-treated materials, a number of studies (Refs 8, 9, 10, 16, 19, 20, 21, 22, 23, and 24) have been made on other engineering properties, such as compressive strength, plasticity reduction, and durability characteristics. The current knowledge concerning these factors is summarized below.

Lime Type

Commercial and waste lime are available for use as a stabilizing agent. Because of impurities, however, more waste lime than commercial lime must be used to achieve the same effects. McDowell (Ref 15) found that finely ground, pure lime is more effective than waste in reducing the cohesive properties of clay soils and that strength after one year is also a function of lime purity. In addition, large quantities of waste lime are not readily available, and that which is available has quite variable physical and chemical characteristics. The variability, at this time, eliminates the study of waste lime as a stabilizing agent.

Commercial lime is either dolomitic or calcitic. Dolomitic lime is produced from either limestone or dolomite which consists of calcium carbonate plus 30 to 40 percent magnesium carbonate. Calcitic limes are produced by calcination of materials, such as chalk, shells, calcitic limestone, or calcite (Ref 26).

Dolomitic lime exists in three forms (Refs 20, 26, and 27): dolomitic quicklime, which consists of CaO and MgO ; dolomitic normal hydrated lime, which is essentially $Ca(OH)_2$ plus MgO ; and dolomitic dihydrated lime, which contains $Ca()H)_2$ plus $Mg(OH)_2$. Calcitic lime is produced in two forms, calcitic quicklime, CaO , and calcitic hydrated lime, $Ca(OH)_2$.

Davidson and others (Refs 23, 27, 28, 29, and 30) found that dolomitic lime produces higher strengths than calcitic lime. It is believed, however, that with time the differences in strength produced by the two types are very small. Research has not definitely established whether quicklime or hydrated lime gives higher strengths, although there is some evidence (Ref 29) that quick and monohydrated dolomitic lime produce greater strengths than the dihydrated forms.

It was also concluded (Ref 26) that the various manufacturing processes affect the stabilization qualities of lime. More important, however, it was found that maximum benefit is derived only from fresh lime. Lime should be sealed during storage to prevent contact with the air, since air produces carbonation, which reduces the lime's effectiveness as a stabilizer.

Lime Content

McDowell (Refs 31 and 32) has shown that increased percentages of lime generally increase the strength of soil-lime mixtures. However, he also shows that this strength increase is time dependent; it may take weeks, even years, to be fully realized. In fact, at early curing stages, the mixtures containing a high percentage of lime may show less strength than those containing a lower percentage (Ref 32). In addition, differences in strength gains due to varying lime percentages do not appear to be as marked for short curing periods as for longer curing periods. Compatible findings by Thompson (Ref 9) and Pietach and Davidson (Ref 10), show that strength increases up to a given lime content and then decreases with any additional increase in the lime content. The minimum lime content which changes the plastic properties of a soil has been termed the lime fixation point. Usually this quantity is smaller than that required for substantial strength gains (Refs 10 and 19).

The concept of optimum lime content has been used to determine the percentage of lime that a given soil must contain for the development of maximum strength when cured under fixed conditions of time, temperature, and moisture content. The problem is fixing the time and temperature. In the field, the range of these variables might be limited by existing conditions; but in the laboratory the limits may be varied greatly. Thompson (Refs 9 and 16) used 28- and 56-day curing periods in order to simulate construction conditions. For the soils studied under these conditions, the optimum lime content was approximately 3 to 7 percent.

Dawson and McDowell (Refs 20, 32, and 33) have shown that strength gains may continue for 3 to 4 or more years before leveling off to a constant value. If design loads are placed on the pavement immediately after the highway is opened to traffic, the design strength must develop in the shorter curing periods. If the present trend of increasing loads continues, long range strength gains would be desirable.

Soil Type

Soils ranging from coarse grained gravels to fine grained silts and clays have been studied. Usually it has been found (Refs 9, 15, and 16) that clays react well with lime and that relatively clean gravels and sands require the addition of material containing silica or alumina for the lime to be beneficial.

Thompson (Ref 9), who studied various Illinois soils stabilized with lime, found that several properties of the soil influenced its compressive strength.* The significant factors were

(1) Organic carbon - Excessive quantities of organic carbon in a soil greatly retard the lime-soil reaction.

(2) pH - Soil pH , an index of weathering, is a good indication of lime-reactivity which, in general, is displayed by moderately weathered and unweathered soils with high pH .

(3) Natural drainage - Soil drainage influences lime-reactivity by affecting weathering processes, i.e., the distribution and oxidation state of iron in the soil profile. Poorly drained soils exhibit a higher degree of lime-reactivity than well drained soils.

(4) Carbonates - All calcareous soils react satisfactorily with limes.

(5) Horizons - The influence of horizons on lime-reactivity is quite pronounced. A-horizons do not react with lime to any significant degree. B-horizons display varying degrees of lime-reactivity; depending on the properties of the soil, a B-horizon may be highly reactive or nonreactive. C-horizons are generally quite reactive, especially if the soil is calcareous.

(6) Clay mineralogy - Montmorillonitic and mixed-layer clays display better lime reactivity than illitic and chloritic clays.

(7) Clay content - There is no significant relationship between clay content ($<2\mu$) and lime-reactivity, but a certain minimum amount of clay (approximately 15 percent) is required to insure an adequate source of silica and/or alumina for the lime-soil pozzolanic reaction.

Of special interest is the observation that the engineering properties of a soil, including plasticity index, liquid limit, clay content ($<2\mu$), and group

---

*Compressive strength was used as a measure of lime-reactivity.

index value for the AASHO classification, do not indicate its lime-reactivity (Ref 9 and 33). Thompson considered this fact logical, since engineering properties do not adequately reflect differences in the mineralogical and chemical properties of a soil.

Mitchell and Hooper (Ref 22) worked with an expansive California clay which contained 8 percent organic matter. Although the organic matter possibly retarded property changes, 4 percent lime treatment considerably reduced swell and appreciably increased strength.

Eades and Grim (Ref 34) proposed the use of pH values to determine the amount of lime needed to stabilize a particular soil by increasing its workability and reducing its plasticity until a friable material was produced. Compressive strength gain was not included. Strength gain is related to the mineralogical components of the soil, and a strength test is necessary to show the magnitude of strength increase to be expected. In the test, the lowest percentage of lime which maintains a pH of 12.40 in a lime-soil slurry is determined.

In a study of the effect of freeze-thaw on lime-silt and lime-clay mixtures, Walker and Karabulut (Ref 21) found that strength decreases after five freeze-thaw cycles were much greater in lime-clay mixtures. Since no further loss in strength was produced beyond five cycles, it was theorized that the bond between particles was broken in the first few cycles.

In general, most soil types can be improved by the addition of lime, which decreases plasticity and increases strength. Mineralogical and chemical properties of the soil have the greatest influence on the degree of modification obtained with lime.

Time Between Mixing and Compaction

Once lime has started cementation, additional reworking will destroy earlier strength gains and the remolded soil will be weaker. In construction, long periods of oxidation prior to rolling, such as those which may occur in thinly spread windrows, are undesirable (Ref 31). Estimates of the maximum allowable time between the mixing of lime and water with soil and compaction range up to 2 days. More time may be taken with highly plastic clays treated with high percentages of lime than with other lime-treated materials (Ref 32).

Mitchell and Hooper (Ref 22) studied the influence of the time between mixing and compaction on the properties of a lime-treated expansive clay.

Their results showed that delays of 24 hours were detrimental in terms of density, swell, and strength for samples prepared using constant compactive effort. In practice, improvements in mix uniformity and handling characteristics that may result from allowing a delay between initial mixing and reworking prior to compaction may actually offset any losses in density or strength that may result from the delay, or such advantages may justify the expenditure of more compactive effort to obtain high density.

Mixing and Pulverization

To successfully stabilize a soil, the lime must be mixed thoroughly with the soil, which is difficult with heavy plastic clays. The clay may be made more workable and the number of lumps reduced by applying lime in a slurry and allowing it to migrate into the lumps and break them down. This process may be followed with a second application, in which the lime is mixed thoroughly with the broken-up soil for the purpose of increasing strength (Ref 35). One study (Ref 28) suggests that for soils difficult to pulverize, stabilization might be more effectively and economically realized if the soil is not required to pass a certain sieve size before mixing with lime. Instead, a maximum lump size can be specified; this size relates to time allowable for complete stabilization.

Compaction

Lime-soil mixtures have a lower maximum density and a higher optimum moisture content than the same untreated soil (Refs 7 and 8). The moisture content at maximum density is not always the same as that for maximum strength (Ref 8). Sandy soils may achieve maximum strengths at a moisture content less than optimum for maximum density (Ref 36), while clay soils tend to produce maximum strengths at moisture contents greater than optimum for maximum density (Refs 8 and 36). Jan and Walker (Ref 12) have shown contradictory results, i.e., maximum strength of clay may be at or slightly less than optimum moisture content for maximum density.

Montmorillonite, illite, and kaolinite clays showed significant strength increases when compactive efforts were increased from standard to modified AASHO density (Ref 23). McDowell (Ref 37) found that definite increases were produced by greater compactive effort. It was concluded that densification is of critical importance. This same trend was found in the strength and durability of lime-flyash-soil mixtures (Refs 24 and 36). Correlation of field density tests with laboratory procedures (Ref 37) has demonstrated that a compactive effort equivalent to 13.26 foot-pounds per cubic inch of material will compact specimens of flexible base material to the density usually found in finished construction.

Curing Conditions

The time of curing as well as the conditions during curing, i.e., temperature and relative humidity, have an influence on the strength development of lime-treated mixtures.

The strength of lime-treated soils increases with curing time, the rate of increase being more rapid during the initial curing period than at later times. Strength increases have been noticed in the laboratory beyond four years, and cores taken from the field after two or three years confirm this finding (Ref 33). Under normal field curing conditions, the increase in strength of lime-stabilized soil is slow and gradual, and several months are usually required for a major portion of the strength to develop. In the laboratory, the rate of curing can be considerably increased by altering the temperature and/or humidity (Ref 14).

When the soil is cured at low temperatures, the gain in strength is low; the rate of gain in strength increases at higher temperatures. Normal curing temperatures are $75 \pm 5^{\circ}$ F. While it is believed that the humidity of the air during the curing of lime-soil mixtures affects strength gain, no definite conclusions can be drawn regarding its effect. Most authors seem to believe that greater strengths are produced at higher humidities, but the opposite effect has also been observed.

Considerable work has been done by Anday (Refs 38 and 39) concerning the influence of curing time and temperature on lime-soil strength gains. Using 5 percent lime in Virginia soils, it was found that a specimen cured for 18 hours at 140° F or 2 days at 120° F could be used to predict unconfined compressive strength of specimens which had been cured 45 days at summer temperatures. It was also felt that the curing temperature of 120° F was more desirable for the following reasons:

(1) There was less condensation between the specimen and the protective coating.

(2) The temperature was lower and, therefore, more realistic.

(3) The curing time was convenient.

Anday's (Ref 39) study of Virginia soils also indicates that little lime-soil reaction can be expected at temperatures below 50° F.

Results from a study by Eades et al (Ref 18) in Virginia indicated that temperature had a definite effect on the time required to attain a specific strength gain in a lime-stabilized soil. A section constructed in June attained the same strength in 90 days that another section built in September attained in 6 months. It has been noted (Ref 40) that heat accelerates strength gain and improves durability for montmorillonitic soil treated with lime.

SUMMARY OF CURRENT STATUS OF KNOWLEDGE

Actual knowledge of the chemical and/or mechanical mechanisms which cause a strength increase in a soil treated with lime is limited. Many believe that a cementing action involving soil particles and lime causes these strength increases. Strength has usually been evaluated by means of compression and bearing tests, and consequently, a considerable amount of knowledge has been accumulated on the factors influencing compression and bearing strengths.

In summary, the following factors tend to increase strength:

(1) an increase in lime content,
(2) use of a soil containing at least 15 percent clay,
(3) better mixing and pulverization,
(4) compaction immediately following mixing,
(5) an increase in density,
(6) an increase in molding moisture content in the range below optimum,
(7) an increase in curing time, and
(8) an increase in curing temperature.

Although it can be reasoned that the same factors significantly affect tensile strength, there has been little work in determining tensile strengths of lime-treated materials. In addition, many of the previous investigations have studied only a few factors, with all others held constant. Such an approach does not allow the investigation of interaction effects involving the variable and the fixed factors. It was, therefore, felt that a preliminary investigation of the tensile strength of lime-treated materials was needed in order to determine those factors and interactions which have a significant effect on tensile strength and to determine the nature of that effect so that more detailed studies can be designed and conducted efficiently.

CHAPTER 3. EXPERIMENTAL PROGRAM

The indirect tensile test and its application to stabilized materials have been previously considered and discussed in detail by Hudson and Kennedy (Refs 1 and 2). Because this evaluation earlier indicated its applicability, the indirect tensile test was used for a preliminary evaluation of the tensile strength of asphalt-treated materials (Refs 3 and 6) and cement-treated materials (Refs 5 and 38). It was also used to evaluate the tensile strength of lime-treated materials in this study.

The test consists of applying compressive loads along the opposite generators of cylindrical specimens, an application which results in a relatively uniform tensile stress perpendicular to and along the diametral plane containing the applied load. Failure usually occurs by splitting along this loaded plane, when the tensile stress exceeds the tensile strength of the material.

TEST PROCEDURES AND EQUIPMENT

The testing procedure used in this experiment was the same as that previously used in the study of asphalt-treated and cement-treated materials (Refs 3, 4, 5, and 6). Specimens were 4 inches in diameter with a nominal height of 2 inches. Testing was conducted at 75° F 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 1 inch with the middle half-inch composed of a curved section with a radius of 2 inches. Tangent sections approximately 1/4 inch long were machined from the curved portion at each end of the strip to prevent the strip from punching into the specimen during testing.

Because curved strips were used, the loading area was known and the following equations could be used for the stresses at the center of a cylindrical specimen of a linear elastic material.

$$\sigma_{rx} = \frac{2P}{\pi a t}\left(\sin\frac{2a}{D} - \frac{a}{D}\right) \qquad (3.1)$$

$$\sigma_{ry} = \frac{-2P}{\pi a t}\left(\sin\frac{2a}{D} + \frac{a}{D}\right) \tag{3.2}$$

where

σ_{ry} = stress in the horizontal direction, in psi;

σ_{rx} = stress in the vertical direction, in psi;

P = maximum total load applied to the specimen, in pounds;

a = strip width, in inches;

t = average height, in inches;

D = diameter of the specimen, in inches.

The basic testing equipment consisted of an adjustable loading frame, a closed loop electrohydraulic loading system, and a loading head (Fig 1) with upper and lower platens constrained to remain parallel during testing.

A device for measuring the transverse strain in a specimen, was used to obtain a measure of the specimen deformation in the direction of the tensile stresses causing failure. This measuring device consisted of two cantilevered arms with attached strain gages.

Vertical deformations were measured by a DC linear-variable-differential transducer, which was used also to control the rate of load application. All measurements were recorded in the form of load-deformation plots on two x-y plotters.

SELECTION OF FACTORS

Eight factors were chosen for investigation on the basis of the literature review and were included in the experiment at two or more levels. The factors and their levels are summarized in Table 1 and are discussed below.

Type of Soil

Three different soils were evaluated. Two of these consisted of gravel aggregate mixed with two different percentages of clay, 15 and 50 percent; the third was 100 percent clay. The reactions of granular soils which might possibly be used as a subbase material were of primary interest. Granular material generally requires some clay material to react well to lime treatment. Therefore, gravel plus 15 percent clay was included as the lower level. The

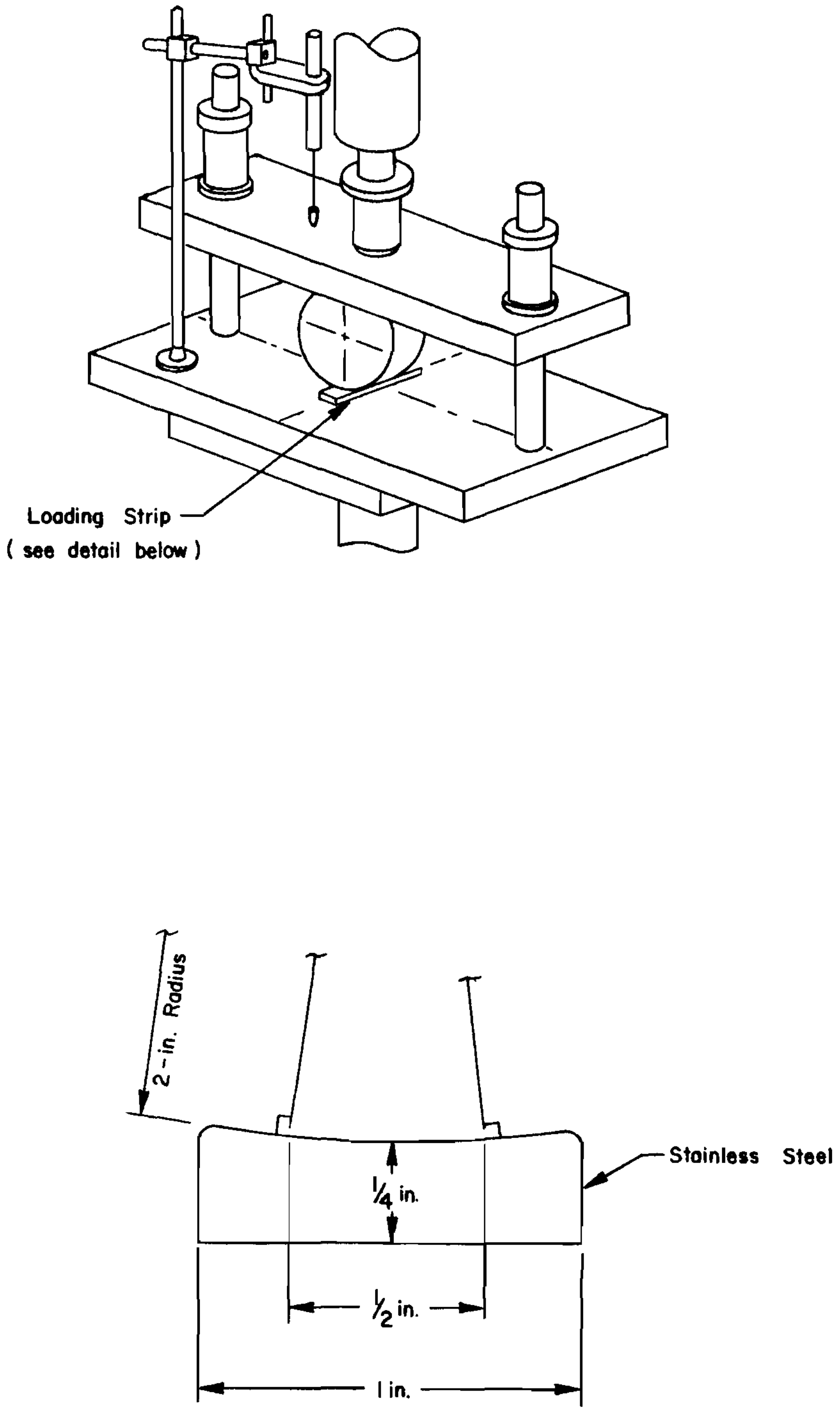


Fig 1. Configuration of loading head and loading strip.

TABLE 1. FACTORS AND LEVELS SELECTED FOR STUDY

	Level					
Factor	Low		Medium*		High	Variable Type
A - Compactive effort	Low		--		High	Qualitative
B - Compaction type	Impact		--		Gyratory shear	Qualitative
C - Curing procedure	Air-dried		--		Sealed	Qualitative
D - Molding water content, % by weight	8	10	12	16	20	Quantitative
E - Lime content, % by weight	2		4		6	Quantitative
F - Curing temperature, ° F	40		75		110	Quantitative
G - Curing time, weeks	2		4		6	Quantitative
H - Clay content, % by weight	15		50		100	Quantitative

* Midpoint levels were used only in the regression analysis.

100-percent clay level was included because lime is widely used to stabilize clay. An intermediate mixture containing gravel plus 50 percent clay was included so that the effects of clay content, which might possibly be nonlinear, could be ascertained.

Only one gradation was used for each level of clay content. The 100-percent clay specimens consisted of over-dried clay pulverized to a minus No. 20 sieve size. Clay for clay-gravel specimens consisted entirely of material finer than the No. 200 sieve. The gradations for the 15-percent and 20-percent clay specimens along with a summary of the properties of the clay and the gravel are contained in Appendix 1.

Molding Water Content

The moisture content during molding varied, depending on the percentage of clay in the soil mixture. Five different moisture contents were used in the overall experiment; however, as discussed under Design of the Experiment, no more than two moisture contents were used in any given phase of the testing program. The moisture contents chosen for study were 8, 10, 12, 16, and 20 percent by weight of dry aggregate and clay, with the higher moisture contents being associated with the soil mixtures containing high clay contents. The actual choice of moisture contents was based on preliminary work with the two compaction types. This work defined the range of moisture contents for which the soil could be compacted. It should be noted that these water contents are based on the weight of the dry mixture and not on the weight of the clay fraction only.

Lime Content

Three different levels of lime content, 2, 4, and 6 percent, by weight of dry aggregate and clay, were included in the experiment. Previous experience indicated lime contents less than 2 percent did little to increase the strength of lime-soil mixtures, while percentages greater than 6 percent required curing periods longer than six weeks to achieve strength increases greater than those for smaller lime contents. The type of lime was not a factor since calcitic lime, rather than dolomitic lime, is used almost exclusively in Texas for stabilization purposes and since almost all stabilization is done with commercial limes, because sufficient waste lime is not available. The chemical composition of the lime is summarized in Appendix 1.

Compaction Type

Two types of compaction, impact compaction and gyratory shear compaction, were used in specimen preparation. Previous findings and experience have indicated that the method of compaction definitely affects the strength properties of soil. These two methods were chosen because they represent definite differences with regard to soil densification and the shear strains imposed on the specimen during compaction. In addition, these two methods were previously used in the evaluation of cement-treated materials (Refs 4 and 5). The compactive procedure used for each compaction type is summarized in Appendix 2.

Compactive Effort

Two different levels of compactive effort were included in this investigation. They were established on the basis of the resulting relative densities and the ability to produce a testable specimen for the range of clay and moisture contents included in the study. Since there was no method of establishing a quantitative measure of compactive effort for the gyratory shear compactor, this factor was considered to be a qualitative variable with the levels described only as low or high. The compactive efforts for the low and high levels for impact compaction were 21 and 45 foot-pounds per cubic inch, respectively. The compaction procedures associated with the low and high levels for the impact and gyratory-shear compactors are summarized in Appendix 2.

Type of Curing

Two types of curing, air-dried and sealed, were selected. In the first, the specimens were exposed to the air and allowed to dry from their original moisture condition to that of an air-dried state. In the second, the specimens were wrapped with a PVC film to maintain the original moisture content throughout the curing period. These two methods of curing were intended to simulate extreme conditions in the field. Air-dried curing was considered to be the low level and sealed curing the high level.

At the end of the specified curing period the specimens were allowed to air dry at 75° F for four days, thereby reducing the effect of moisture content at the time of the test by achieving essentially a constant moisture content. Future studies will evaluate the effect of this air drying procedure.

Curing Temperature

Three curing temperatures, 40°, 75°, and 110° F, were chosen. These temperatures were considered to be representative of the range of temperatures which, in Texas, actually occur throughout the year. In addition, previous studies have indicated that essentially no lime-soil reaction occurs at temperatures below 40° F. These temperatures also had been used for previous evaluations of cement-treated and asphalt-treated materials.

Curing Time

Curing times of two and six weeks were chosen in an attempt to encompass a range of time considered reasonable for actual construction practice and to allow for long-range strength gains at the higher lime content percentages. Much longer periods would allow for larger strength gains, especially with high lime contents. Thus, even though extended curing periods may not be acceptable in construction, long-term strength increases, which may occur under traffic, are certainly desirable and of interest.

Treatment Type

In the analysis, the effect of moisture content was compacted with that of clay content. This compound factor is referred to as treatment type. The moisture content of the different soils was varied in the following manner: 15 percent clay and 8 percent water, 50 percent clay and 16 percent water, and 100 percent clay and 20 percent water. Including this compound factor made it possible to obtain additional information concerning the effect of moisture and soil type on the indirect tensile characteristics of lime-treated materials. This factor was evaluated only in certain portions of the experiment, as explained in the section on design of the experiment.

DESIGN OF THE EXPERIMENT

This experiment was designed as a preliminary investigation to evaluate the effects of all eight main factors, all two-factor interactions, and selected higher order interactions. As such it was felt that a fractional factorial design was appropriate so that the large number of factors could be investigated with a relatively small number of specimens. The use of a fractional factorial design, however, involves certain inherent limitations on the interpretation of the results. It should be remembered that all effects are confounded with other effects. It is often assumed that when two or more effects are confounded that the lower order effect, i.e., the effect containing the fewest number of factors, is the important one. This assumption has been made in the evaluation of this experiment; nevertheless, the reader should understand that in some cases the higher order interaction may in reality be the most important. In addition, this confounding may result in very complicated results which are difficult to interpret.

Appendix 3 contains a list of the effects which were evaluated and indicates the interaction effects with which each effect is confounded. Other factors that may also affect tensile strengths were not considered in this study since their effect was judged to be small in comparison with the effect produced by the factors studied. Furthermore, their inclusion would have required a larger and more complicated experiment.

Of the eight factors chosen for evaluation, three qualitative factors were studied at two levels, four quantitative factors at three levels, and one other quantitative factor at five levels. The inclusion of three levels or more for the quantitative factors was to allow the estimation of second degree as well as linear effects. Moisture content at the time of compaction was included in the overall design at five levels. The reason, as previously noted, was to use moisture contents compatible with the soil and its compaction characteristics.

There were two reasons for dividing the experiment into three blocks. The first was to reduce the number of specimens required in any one day, since day-to-day environmental effects could invalidate the results if days were not taken into account in the analysis. The second was the desire to study the effect of a wide range of clay contents. Since the range of moisture contents at the time of compaction is limited for any given clay content, it was not possible to study all three clay contents and still use the full range of moisture contents compatible with each clay content.

The overall experimental design and the design of each block were developed by Dr. Virgil Anderson, statistical consultant to the project.

Block 1 included the soil consisting of 100 percent clay which was compacted at 20 percent moisture, and therefore, did not evaluate soil type and water content at time of compaction. Even though pure clay soils are not usually used as subbase, this block was included because lime is effective in the stabilization of clay soils. Block 2 included clay-gravel mixtures consisting of two clay contents, 15 percent and 50 percent, compacted at 8 percent moisture and at 16 percent moisture, respectively. Thus, the effects of clay content in this block are confounded with moisture content at the time of compaction. Therefore, the two variables together are referred to as treatment type. Essentially this block contained two one-half replicates of the same fractional factorial contained in Block 1 except that the type of soil and molding water content were changed. In Block 3, both soil type and molding moisture content, the two variables that have previously been confounded, were evaluated individually. All three soil types were also included in this block for purposes of evaluating second degree effects. Tables 2 through 4 list the factors which were evaluated in each block of the total experiment and their levels.

Block 1, which included a 100 percent clay soil compacted at 20 percent water content, allowed all main effects and two-factor interactions to be investigated for the factors shown in Table 2. The actual effects which could be evaluated by an analysis of variance are summarized in Appendix 3. The design of this experimental block was a one-half replicate of a complete 2^6 factorial described by the identity

$$I = ABCEFG$$

Midpoint levels were introduced for three of the six factors, and duplicate specimens were used to obtain an estimate of the experimental error. Fifty-two specimens were divided in the following manner:

$$\begin{array}{rl} 1/2\ (2)^6 = & 32 \text{ experimental units at two levels} \\ & 14 \text{ experimental midpoint units} \\ & \underline{6} \text{ duplicate experimental units} \\ & 52 \text{ total experimental units} \end{array}$$

Block 2, which involved mixtures of clay and gravel, included treatment type as an additional variable and allowed all main effects, all two-factor interactions, and selected three-factor interactions to be evaluated for the factors shown in Table 3. The main effects and interactions which could be evaluated are shown in Appendix 3. The design was a one-half replicate of a complete 2^7 factorial described by the identity

TABLE 2. FACTORS AND LEVELS FOR 2^6 EXPERIMENT BLOCK 1

Factor	Level			Variable Type
	Low	Medium*	High	
A - Compactive effort	Low	--	High	Qualitative
B - Compaction type	Impact	--	Gyratory shear	Qualitative
C - Curing procedure	Air-dried	--	Sealed	Qualitative
E - Lime content, % by weight	2	4	6	Quantitative
F - Curing temperature, °F	40	75	110	Quantitative
G - Curing time, weeks	2	4	6	Quantitative

* Midpoint levels were used only in the regression analysis.

TABLE 3. FACTORS AND LEVELS FOR 2^7 EXPERIMENT BLOCK 2

	Level			
Factor	Low	Medium*	High	Variable Type
A - Compactive effort	Low	--	High	Qualitative
B - Compaction type	Impact	--	Gyratory shear	Qualitative
C - Curing procedure	Air-dried	--	Sealed	Qualitative
E - Lime content, % by weight	2	4	6	Quantitative
F - Curing temperature, ° F	40	75	110	Quantitative
G - Curing time, weeks	2	4	6	Quantitative
J - Treatment type**	8% W.C. 15% C.C.	--	16% W.C. 50% C.C.	Quantitative

* Midpoint levels were used only in the regression analysis.

** Treatment type is a combination of factors d and h from factors for 2^8 block, W.C. = water content and C.C. = clay content.

I = ABDEFG

Midpoint levels for three of the seven factors and duplicates of certain treatment combinations were introduced as shown below:

$1/2\ (2)^7$ = 64 experimental units at two levels
28 experimental midpoint units
12 duplicate experimental units
104 total number of specimens

Block 3 evaluated both soil type and moisture content at the time of compaction and allowed all main effects, all two-factor interactions, and selected three-factor interaction effects to be evaluated as shown in Appendix 3. The effects evaluated are summarized in Table 4. The design was a one-fourth replicate of a complete 2^8 factorial described by the identity

I = ABCEG = ABDFH = CDEFGH

Midpoint specimens were included for four of the eight factors along with duplicate specimens as shown below:

$1/2\ (2)^8$ = 64 experimental units at two levels
18 experimental midpoint units
12 duplicate experimental units
94 total number of specimens

Treatment combinations for all three blocks of the experiment are tabulated in Appendix 4.

PARAMETERS EVALUATED

This study evaluated one parameter, indirect tensile strength, which is the maximum stress required for the specimen to fail in indirect tension* and which is calculated from the following expression:

---

*For theory and explanation of this test see Ref 1.

TABLE 4. FACTORS AND LEVELS FOR 2^8 EXPERIMENT BLOCK 3

Factor	Level Low	 Medium*	 High	Variable Type
A - Compactive effort	Low	--	High	Qualitative
B - Compaction type	Impact	--	Gyratory shear	Qualitative
C - Curing procedure	Air-dried	--	Sealed	Qualitative
D - Molding water content, % by weight	10.5	--	15.5	Quantitative
E - Lime content, % by weight	2	4	6	Quantitative
F - Curing temperature, ° F	40	75	110	Quantitative
G - Curing time, weeks	2	4	6	Quantitative
H - Clay content, % by weight	15	50	100	Quantitative

* Midpoint levels were used only in the regression analysis.

$$S_T = \frac{2P}{\pi at}\left(\sin\frac{2a}{D} - \frac{a}{D}\right)$$

where

S_T = indirect tensile strength, psi;

P = maximum total load required to fail the specimen, in pounds;

a = strip width, in inches;

t = average height of specimens, in inches;

D = diameter of the specimen, in inches.

Originally, consideration was given to the evaluation of four additional parameters, which are defined below:

(1) Horizontal failure deformation is the horizontal deformation of the specimen at the maximum load applied, in inches, as recorded on the load-horizontal deformation plot.

(2) Vertical failure deformation is the vertical deformation of a specimen at the maximum load, in inches. This deformation is recorded on the load-vertical deformation plot and is assumed to be equal to the movement of the upper platen from the point of initial load application to the point of maximum load as measured by the LVDT.

(3) Tangent modulus of vertical failure deformation is the slope per unit of thickness of the load-vertical deformation relationship prior to failure as defined by a regression analysis.

(4) Deflection ratio is the ratio between the slope per unit thickness of load-horizontal deformation plot and the slope per unit thickness of the load-vertical deformation plot.

These four parameters were not evaluated because of problems concerned with the measurement of vertical deformations and because the horizontal deformations at failure were not well defined on the x-y plots of load versus horizontal deformations. However, they will be evaluated in later work.

EXPERIMENTAL RESULTS

The indirect tensile strength was based upon an equation which assumes no effect from Poisson's ratio. This assumption is not strictly correct since a multi-axial state of stress actually exists in the specimen. At the present time, however, there is no method available for utilizing data from the test to estimate Poisson's ratio without the extensive use of strain gages. The cost and difficulty of attaching strain gages to lime-treated specimens make this approach undesirable; therefore, the effect of Poisson's ratio has been neglected (Refs 3, 4, and 5).

For each block of specimens, the experimental results of indirect tensile strength are given in Table 5. Values marked with a triple asterisk are from replacement specimens. These values were substituted for original observations which were invalidated because of damaged specimens or because the recorder went off scale before maximum load was reached. It is recognized that such a replacement procedure could affect the results of the analysis by introducing a day-to-day effect. Past experience, however, has indicated that such an effect is probably small. Nevertheless, a test, which is described in Appendix 5, was conducted to investigate possible differences. The results of this test indicate that it is unlikely that a serious error was introduced by the required substitutions.

TABLE 5. EXPERIMENTAL RESULTS

(a). 100 Percent Clay, Block 1

Specimen Number*	Indirect Tensile Strength, psi	Specimen Number*	Indirect Tensile Strength, psi	Specimen Number*	Indirect Tensile Strength, psi
1***	318	21	73	40**	66
2**	115	22	259	41***	150
3**	75	23	120	42	124
4	160	24	45	43	64
6***	68	25	68	44	56
7	36	26	83	45	32
9	36	28	46	46	25
10	73	29	50	47	33
11	59	30	42	49	65
12	63	31	74	50	98
13	58	32	56	51	97
14***	92	33	178	52	75
15	29	35**	70	53	89
17	101	36**	43	54	24
18	43	37	92	55	33
19	28	38	109	56	50
20**	26	39	19	57	46

* Treatment combinations for each specimen are given in Appendix 4.

** Duplicate specimens.

*** These values are from replacement specimens (see Appendix 5).

(Continued)

TABLE 5. (Continued)

(b). Clay-Gravel Mixtures, Block 2

Specimen Number*	Indirect Tensile Strength, psi	Specimen Number*	Indirect Tensile Strength, psi	Specimen Number*	Indirect Tensile Strength, psi
59**	90	100	60	141**	44
60	37	101	31	142	58
61	23	103	30	143	30
63	44	104	74	144	36
64	37	105	64	145	61
66	16	107	41	146	22
67**	21	108	28	147	20
69***	91	109	31	148	15
70**	33	110	37	149**	19
71	24	111	21	150	39
72	53	112	29	151	23
73	17	113	18	152	36
74	37	114**	19	153	39
76	11	115	20	154	19
77	32	116	33	155	94
78	41	118	36	156	38
79	21	119	68	157	66
81	33	120	32	158	36
83	38	121	48	159	60
84	45	123	36	160	74
85	44	124	13	161	35
86	26	125	43	162**	13
87	87	126	26	163	72
88***	49	127	32	164	55
89	54	128	36	165	48
90	13	129**	25	166	22
91	66	130	42	167	51
92	53	132	42	168	54
93	20	133	26	169	15
94	31	135	48	170	55
95	22	136**	24	171**	71
96***	76	137**	39	172**	37
97	29	138	27	173	23
98	22	139	90	174	43
99	57	140***	30		

---

* Treatment combinations for each specimen are contained in Appendix 4.

** Duplicate specimens.

*** These values are from replacement specimens (see Appendix 5).

(Continued)

TABLE 5. (Continued)

(c). Clay and Clay-Gravel Mixtures, Block 3

Specimen No.*	Indirect Tensile Strength, psi	Specimen No.*	Indirect Tensile Strength, psi	Specimen No.*	Indirect Tensile Strength, psi	Specimen No.*	Indirect Tensile Strength, psi
175***	19	200	29	224**	58	249	10
176	32	201	12	225	24	250	47
177**	24	202	20	226	35	251	26
178	35	203	48	227	32	252**	10
179	22	204**	48	228	45	253	22
180**	43	205	25	229	13	254**	38
181	14	206**	27	230	34	255**	43
182	19	207	36	231	46	256	31
184	8	208	24	232	13	257	14
185	20	209	30	233**	22	258	35
186	32	210	10	234	62	259	8
187	4	211	27	235	6	260	17
188	22	213	31	236	42	261	16
189	22	214	17	237	13	262	10
190	39	215	74	238**	6	263	9
191	22	216	16	239	28	262	19
192	5	217	9	240	12	266	22
193	45	218	12	241	10	267	22
194	13	219	18	242	54	268**	29
196	7	220	23	244	10	269	26
197	19	221	38	245	49	270	8
198	53	222	15	246	29	271	36
199	4	223	40	247	24	272	21
						273**	44
						274	8

---

* Treatment combinations for each specimen are contained in Appendix 4.

** Duplicate specimens.

*** These values are from replacement specimens (see Appendix 5).

CHAPTER 4. DISCUSSION OF RESULTS

The principal objectives of this investigation were to determine the factors which significantly affect the tensile strength of lime-treated materials and to develop a preliminary predictive equation for strength. The indirect tensile strengths were analyzed using analysis of variance and regression techniques.

The results of the analyses of variance for indirect tensile strength are summarized in Tables 6 and 7 and in Appendix 6. The residuals shown are the pooled mean squares for all the remaining factors and interactions which were not found to be significant at a probability level of 0.05. The error mean square terms were calculated from the duplicate specimens and represent an estimate of the true error.

Initially, a separate analysis of variance was conducted for each of the three blocks using only the high and low levels for each of the factors in these blocks. The results of this analysis are contained in Appendix 6. Since the error terms are essentially equal for each of the three blocks and since the identities describing Blocks 1 and 2 are the same, Blocks 1 and 2 were combined and analyzed as a single experiment which tested three different clay and water content combinations. Thus, the clay and water contents are confounded in this combined analysis and are described as treatment type (Factor J).

The relationships of the highly significant main effects and interactions for tensile strength are shown in Figs 2 through 38 for the combined analysis of Blocks 1 and 2 and for Block 3. The data points in these figures are the average values of strength for all specimens containing a given level or combination of levels for the main effect or interaction. Midpoint means are not included in the figures nor in the analysis of variance because the levels of the other factors are not the same as those for the high and low levels and because the number of observations on the midpoint means is smaller, which might result in a larger variance at the midpoints. Hence, the midpoint means cannot be easily compared to the endpoint means. Nonlinear effects as

TABLE 6. ANALYSIS OF VARIANCE FOR TENSILE STRENGTH, BLOCKS 1 AND 2 COMBINED

Source of Variation*	Degree of Freedom	Mean Squares	F Value	Significance Level, %
B	1	39516	919	.1
J	2	20664	481	.1
F	1	15048	350	.1
BJ	2	14504	337	.1
CF	1	7058	164	.1
ABJ	2	5482	127	.1
A	1	5258	122	.1
AJ	2	4322	101	.1
AB	1	3376	78.5	.1
AEG - BCF	1	2558	59.5	.1
ACF - BEG	1	2332	54.3	.1
AEGJ-BCFJ	2	2210	51.4	.1
CFJ	2	2148	50.0	.1
AC	1	2014	46.8	.1
EGJ	2	1976	46.0	.1
ACFJ-BEGJ	2	1474	34.3	.1
E	1	1436	33.4	.1
AE	1	1194	27.8	.1
C	1	1146	26.6	.1
EG	1	1084	25.2	.1
BF	1	1072	24.9	.1
BC	1	1054	24.5	.1
BCJ	2	982	22.8	.1
ACJ	2	860	20.0	.1

---

* Factors are listed on page 34.

(Continued)

TABLE 6. (Continued)

Source of Variation*	Degree of Freedom	Mean Squares	F Value	Significance Level, %
ACG - BEF	1	840	19.5	.1
AEJ	2	834	19.4	.1
BE	1	742	17.2	.1
ABF - CEG	1	718	16.7	.1
ABEJ-CFGJ	2	714	16.6	.1
ABC - EFG	1	658	15.3	.5
AG	1	652	15.2	.5
CJ	2	594	13.8	.1
AFG - BCE	1	502	11.7	.5
G	1	494	11.5	.5
EF	1	454	10.6	.5
EFJ	2	428	9.95	.5
ABE - CFG	1	400	9.30	1.0
AEF - BCG	1	344	8.00	5.0
CGJ	2	326	7.58	1.0
EJ	2	306	7.11	1.0
BG	1	274	6.37	5.0
AEFJ-BCGJ	2	256	5.95	5.0
ABCJ-EFGJ	2	204	4.74	5.0
ABFJ-CEGJ	2	202	4.69	5.0
Residual	20	53		
Within Treatments Treated Alike	18	43		

TABLE 7. ANALYSIS OF VARIANCE FOR TENSILE STRENGTH, BLOCK 3

Source of Variation*	Degree of Freedom	Mean Squares	F Value	Significance Level, %
B	1	2008	72.4	.05
F	1	1976	71.3	.05
DH	1	1455	52.5	.05
H	1	1269	45.8	.05
A	1	721	26.0	.05
EH	1	672	24.2	.05
CF	1	658	23.7	.05
BH	1	615	22.2	.05
AH	1	580	20.9	.1
AB	1	481	17.4	.5
AF	1	373	13.5	.5
FH	1	346	12.5	.5
DF	1	257	9.3	1
CFH - DEG	1	222	8.0	5
AD	1	210	7.6	5
BD	1	184	6.6	5
BF	1	178	6.4	5
Residual	46	22		
Within Treatments Treated Alike	12	28		

* Legend of Factors

A - Compactive effort
B - Compaction type
C - Curing procedure
D - Moisture content
E - Lime content
F - Curing temperature
G - Curing time
H - Clay content
J - Treatment type

measured by the midpoint levels, will be discussed in conjunction with the regression analysis.

STATISTICAL INFERENCE

Conclusions drawn from this experiment are valid and applicable only within the inference space of the population defined by the experiment, i.e., the levels of the factors studied and the procedures used. Any attempt to apply the results outside of this particular inference space should be made with care. As previously mentioned, the analysis of variance involved only two levels for each factor, except treatment type, which was included at three levels. In addition, it must be remembered that since this experiment involved fractional factorial designs, confounding of effects occurred causing difficulty in interpreting results. Consequently, the results of this preliminary experiment should be considered exploratory.

ANALYSIS OF VARIANCE

As previously noted, Blocks 1 and 2 were combined and analyzed together, and Block 3 was analyzed separately (Tables 6 and 7, respectively). The results of the combined analysis will be discussed, with the results from Block 3 used to explain the effects further. As shown in Table 6, 39 factors and their interactions were found to significantly affect the tensile strength of lime-treated materials at a probability level of 0.01; 30 were significant at a probability level of 0.001.

Although all of these effects were measurable and were significant under the controlled conditions of this test, some were not large and probably would make little difference in actual application of results. Only those effects judged to be of practical significance are discussed herein.

Main effects can be referred to only in terms of the average effect, since the actual effect for any set of conditions is dependent on the interactions associated with these conditions. Consequently, significant higher order interactions are discussed first and main effects last.

Four-Factor Interactions

Three four-factor interactions were found to have a significant effect on the tensile strength of lime-treated materials at a probability level of 0.001. These occurred in the combined analysis of Blocks 1 and 2 when they were confounded with other four-factor interactions.

The primary importance of these confounded four-factor interactions is that they emphasize possible complex interrelationships between the factors studied. Since they are confounded it is impossible to determine which interaction produced the effect. It should be noted, however, that all of these four-factor interactions contained Factor J, a treatment type, which involved both clay content and water content.

Three-Factor Interactions

Ten three-factor interactions were found to have a significant effect on the tensile strength of lime-treated materials at a probability level of 0.001; four were confounded with other three-factor interactions.

As previously noted, it is impossible to determine which interaction produced the effect when the interaction is confounded with another interaction containing the same number of factors; however, Daniel (Ref 41) states that when interactions are confounded, the interaction containing the greatest number of significant main effects probably is the most important.

This criterion for analyzing the confounded three-factor interactions indicates that the following are probably the more important:

Compaction Type × Curing Procedure × Curing Temperature (Interaction B×C×F)

Compactive Effort × Curing Procedure × Curing Temperature (Interaction A×C×F)

Compaction Type × Lime Content × Curing Temperature (Interaction B×E×F)

Compactive Effort × Compaction Type × Curing Temperature (Interaction A×B×F)

The six significant three-factor interactions which were not confounded are graphically shown in Figs 2 through 7 and are discussed below.

Compactive Effort × Compaction Type × Treatment Type (Interaction A×B×J - Fig 2). The average strength increased from a minimum for specimens containing 15 percent clay compacted by gyratory shear at a moisture content of 8 percent, to a maximum for specimens containing 100 percent clay compacted by impact compaction at a moisture content of 20 percent. These trends were true for both low and high compactive efforts, although specimens compacted at high compactive efforts were slightly stronger. An exception to this latter observation was detected for specimens containing 50 percent clay and compacted by

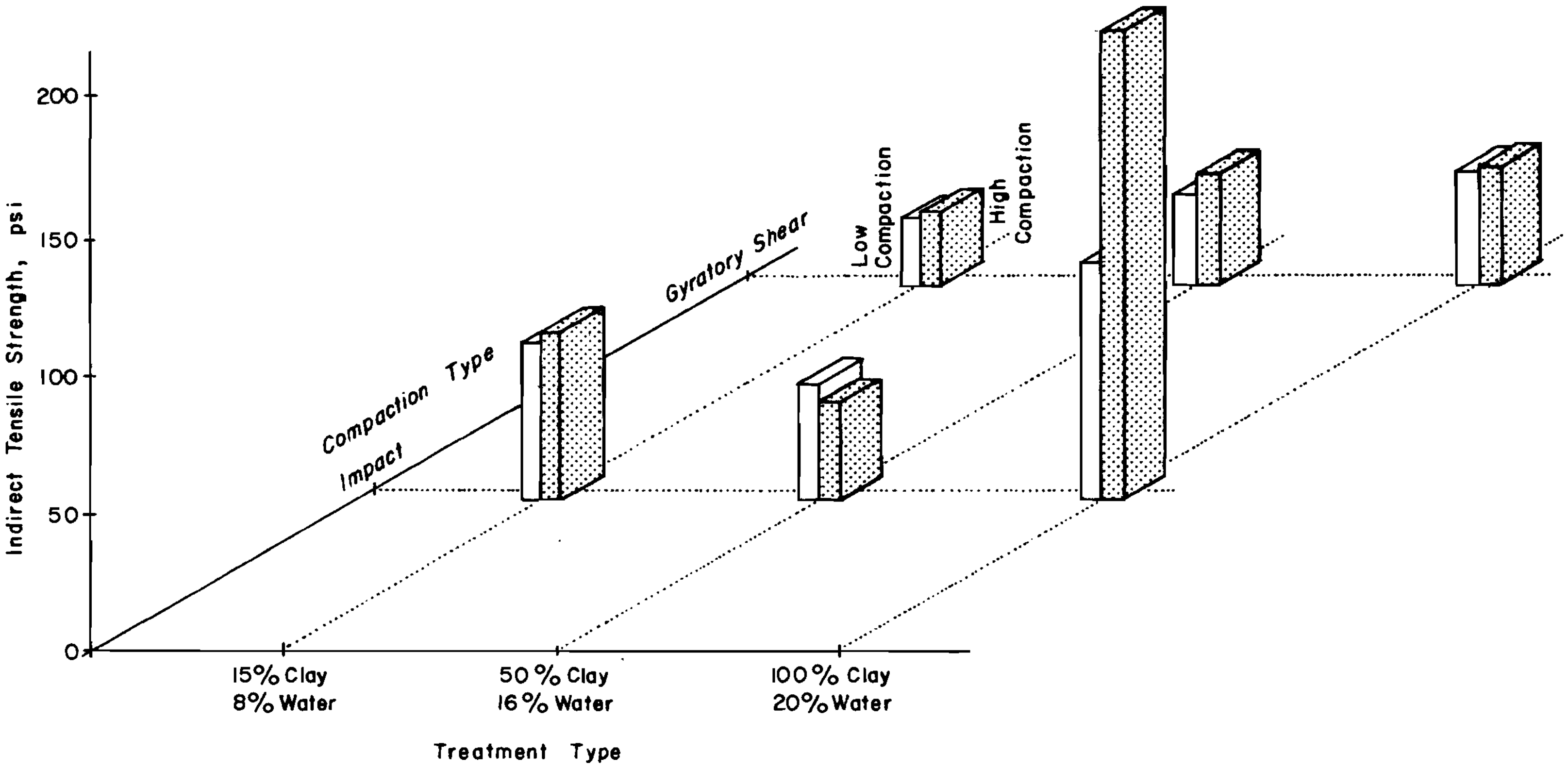


Fig 2. Effect of interaction between compactive effort, type of compaction, and treatment type (interaction A×B×J).

impact compaction at a moisture content of 16 percent. For these conditions, the low compactive efforts resulted in slightly stronger specimens. More important, however, is the relative strengths for the 100 percent clay specimens compacted by impact compaction at 20 percent moisture. For these conditions the strength of specimens compacted at high compactive efforts was essentially twice that of specimens compacted at low compactive efforts, whereas for other conditions the difference was very small.

Curing Procedure x Curing Temperature x Treatment Type (Interaction CxFxJ - Fig 3). The average strength tended to increase with increasing clay content and increasing curing temperature, although specimens containing 50 percent clay exhibited slightly lower strengths than those containing 15 percent clay. The most significant characteristics of this interaction are the substantial strength increases associated with 100 percent clay specimens and the fact that the air-dried specimens were stronger at a curing temperature of 40° F while sealed specimens were stronger at 110° F. This latter phenomenon probably can be attributed to the fact that the lime-soil reaction was retarded at the lower temperature and, therefore, did not benefit from the higher moisture content associated with sealed curing. This higher moisture content, however, did result in lower strengths. In the case of the specimens cured at 110° F the benefit derived from sealed curing more than offset the strength increase associated with drying.

Lime Content x Curing Time x Treatment Type (Interaction ExGxJ - Fig 4). The average strength tended to decrease slightly as the clay content increased from 15 to 50 percent and then increased substantially as the clay content was increased to 100 percent. Generally, the average strength was higher for specimens containing 6 percent lime and for specimens cured 6 weeks. The one exception was for specimens containing 100 percent clay and cured for 6 weeks. In this case the average strength was less than that for specimens cured 2 weeks and less than that for specimens containing 2 percent lime.

Compaction Type x Curing Procedure x Treatment Type (Interaction BxCxJ - Fig 5). As previously noted, the average strength was a minimum for specimens containing 50 percent clay and a maximum for specimens containing 100 percent clay, with the 15 percent clay specimens displaying intermediate strength values. It can also be noted that, at the intermediate level of clay content, the method of curing and type of compaction had essentially no effect, but at

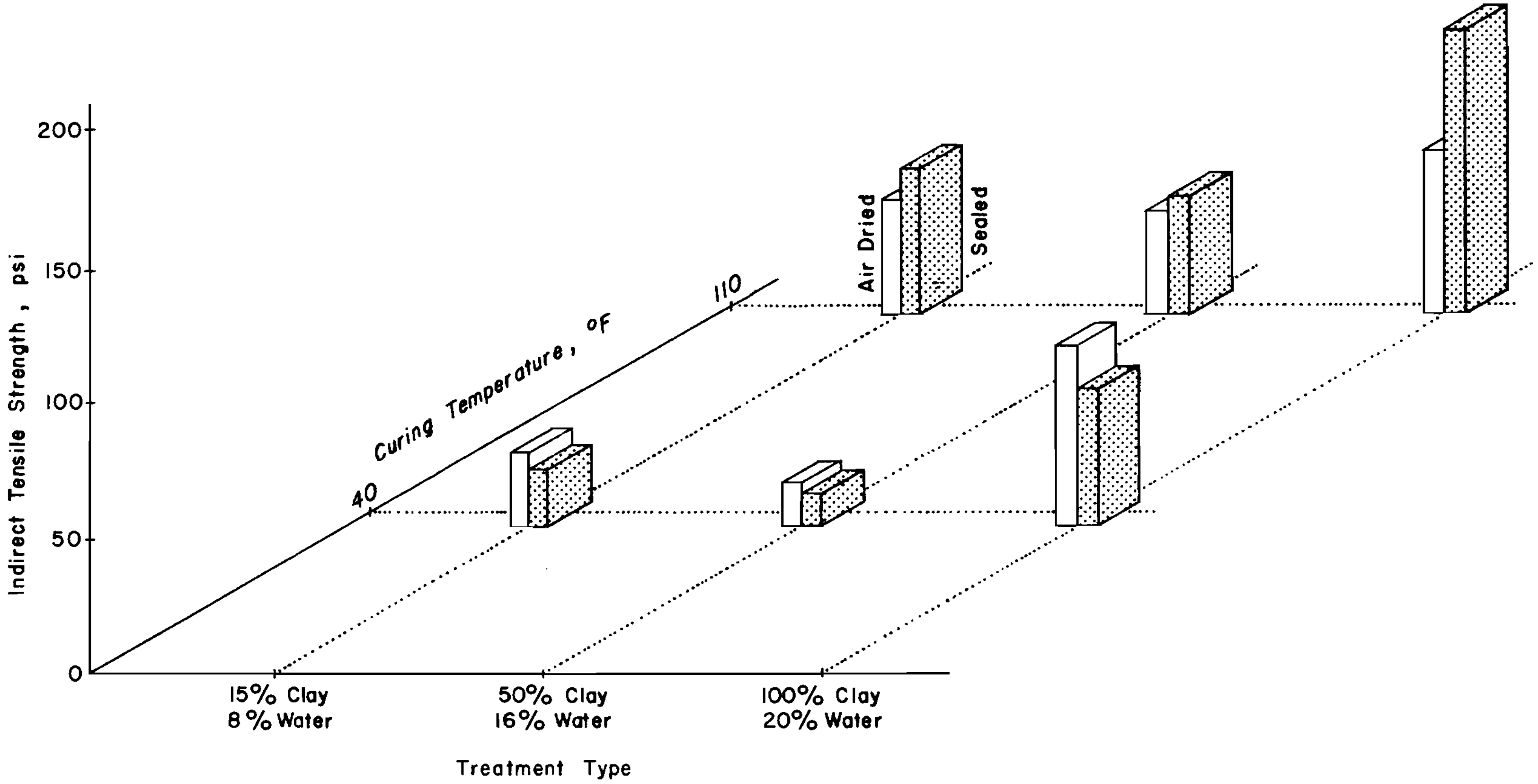


Fig 3. Effect of interaction between curing procedure, curing temperature, and treatment type (interaction C×F×J).

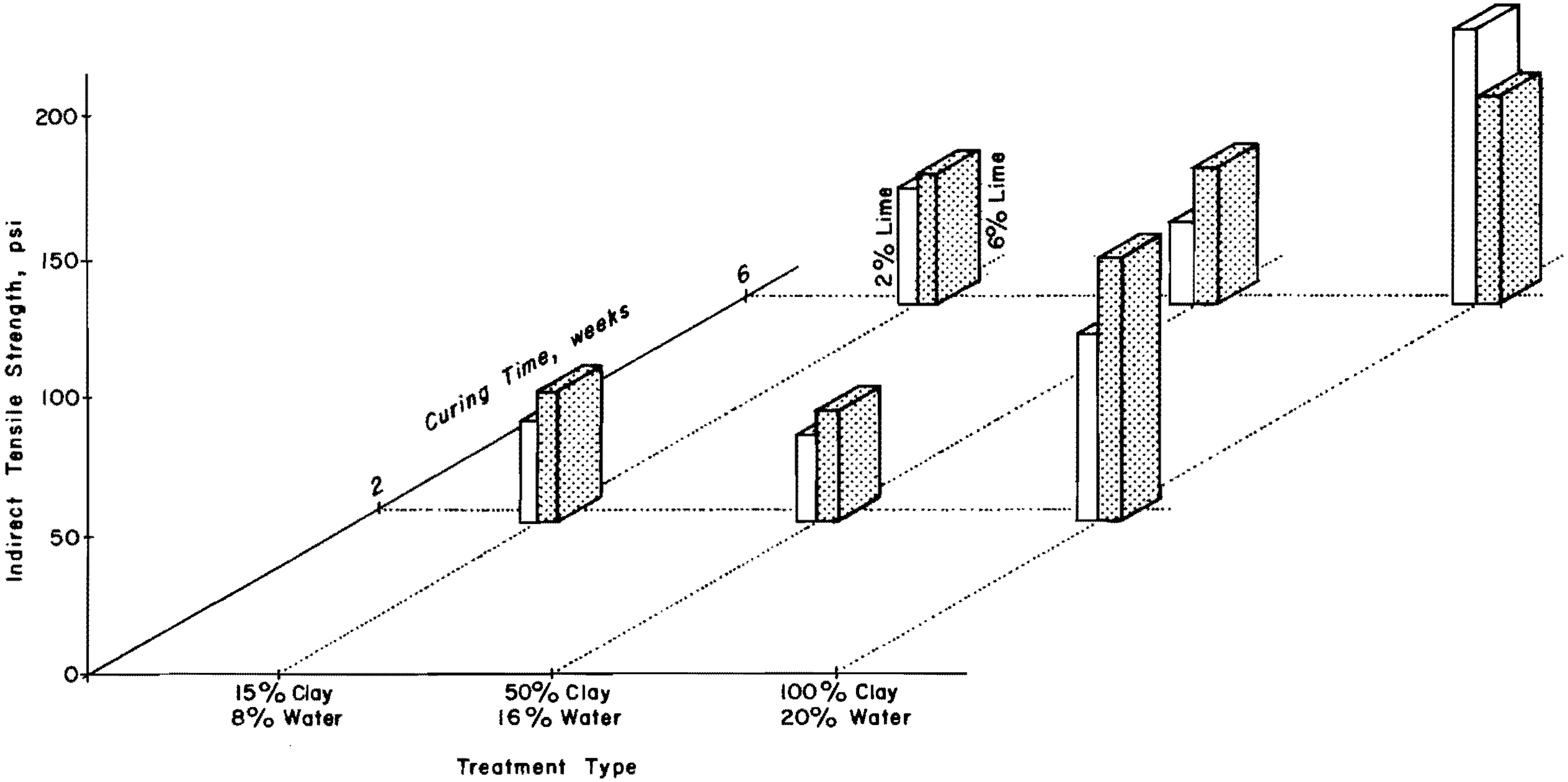


Fig 4. Effect of interaction between lime content, curing time, and treatment type (interaction E×G×J).

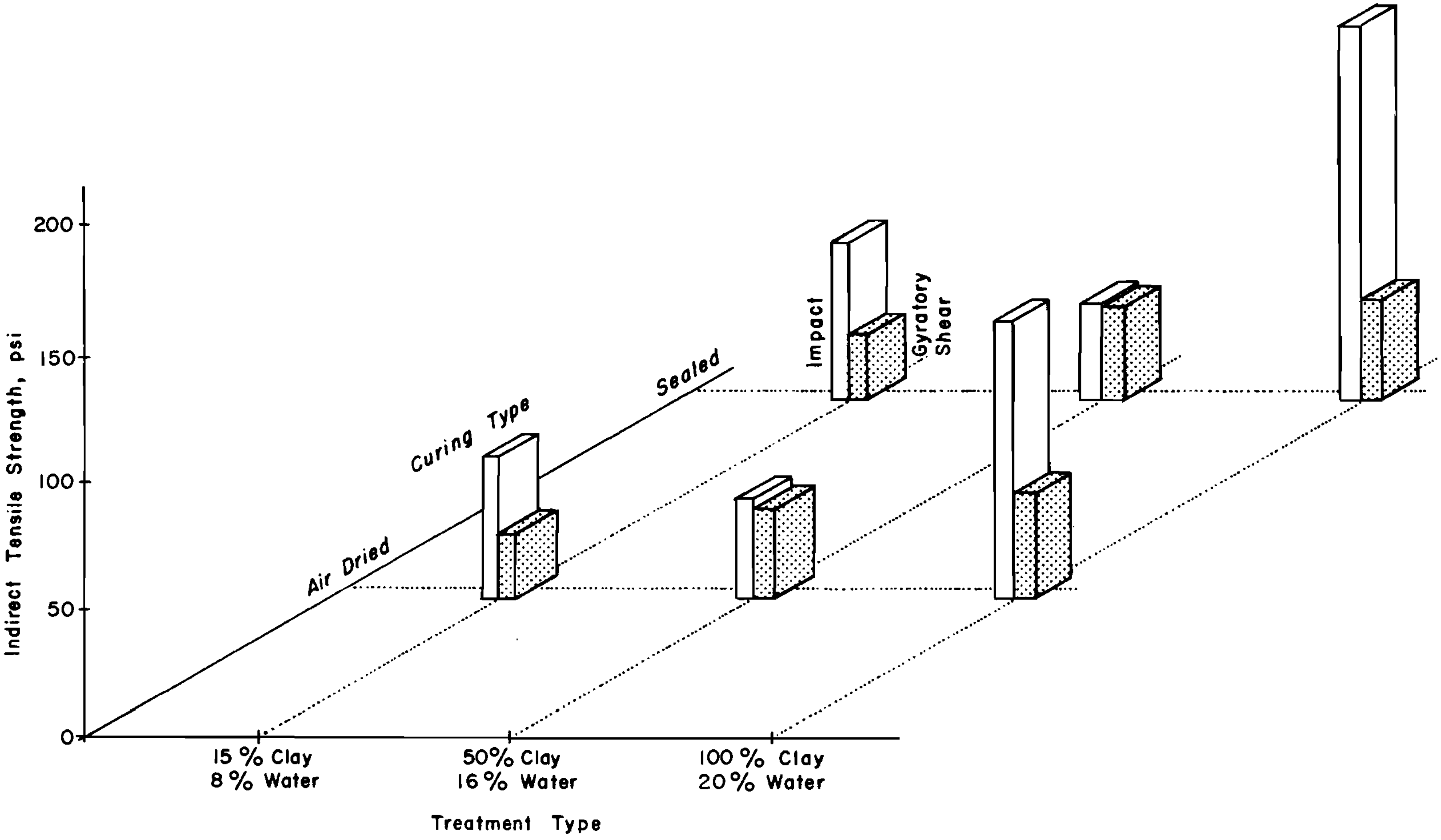


Fig 5. Effect of interaction between compaction type, curing procedure, and treatment type (interaction B×C×J).

the low and high levels of clay content, sealed curing and impact compaction produced stronger specimens.

Compactive Effort x Curing Procedure x Treatment Type (Interaction AxCxJ - Fig 6). As previously discussed, the average strength tended to decrease slightly and then increase substantially as the clay content increased from 15 to 50 to 100 percent. It can also be seen, in Fig 6, that curing procedure and compactive effort had very little effect at the lower levels of clay content, but sealed curing and high compactive effort produced specimens with higher average strengths for the 100 percent clay specimens.

Compactive Effort x Lime Content x Treatment Type (Interaction AxExJ - Fig 7). As has been the case in the previously discussed interactions, strength tended to decrease slightly when the clay content was increased from 15 to 50 percent; the change, however, was very small. In addition, the increased compactive effort produced little effect on the clay-gravel specimen. However, strength increased when lime content increased from 2 to 6 percent. The most significant change occurred when the clay content increased from 50 to 100 percent. It also can be seen that, for the 100-percent clay specimens, increased compactive effort produced an increased strength, but that, at a low compactive effort increased lime content resulted in a decreased strength, while the reverse was true at the high compactive effort.

In all six of these three-factor interactions, the dominate factor affecting strength was treatment type (Factor J). The general trend was for the average strength to be a minimum for specimens containing 50 percent clay and compacted at 16 percent moisture and to be a maximum for specimens containing 100 percent clay and compacted at 20 percent moisture. The change in strength between specimens containing 50 and 100 percent clay was very large, while the specimens containing 15 percent clay were only slightly stronger than those containing 50 percent clay.

Two Factor Interactions

Fourteen two-factor interactions were found to be significant at a probability level of 0.01; 11 of these were highly significant at a probability level of 0.001. These effects, which are considered to have practical significance, are discussed below and illustrated in Figs 8 through 18.

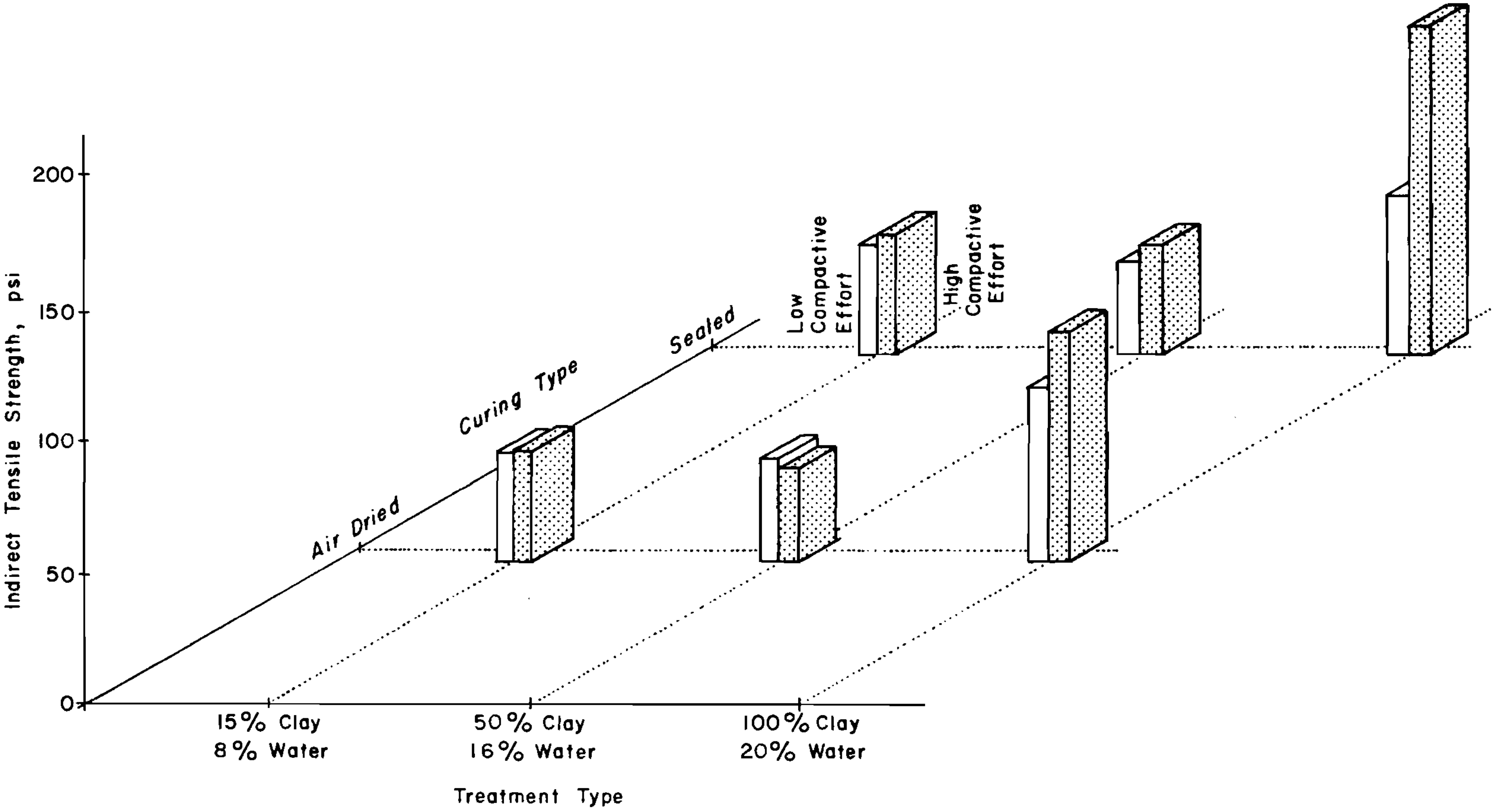


Fig 6. Effect of interaction between compactive effort, curing procedure, and treatment type (interaction A×C×J).

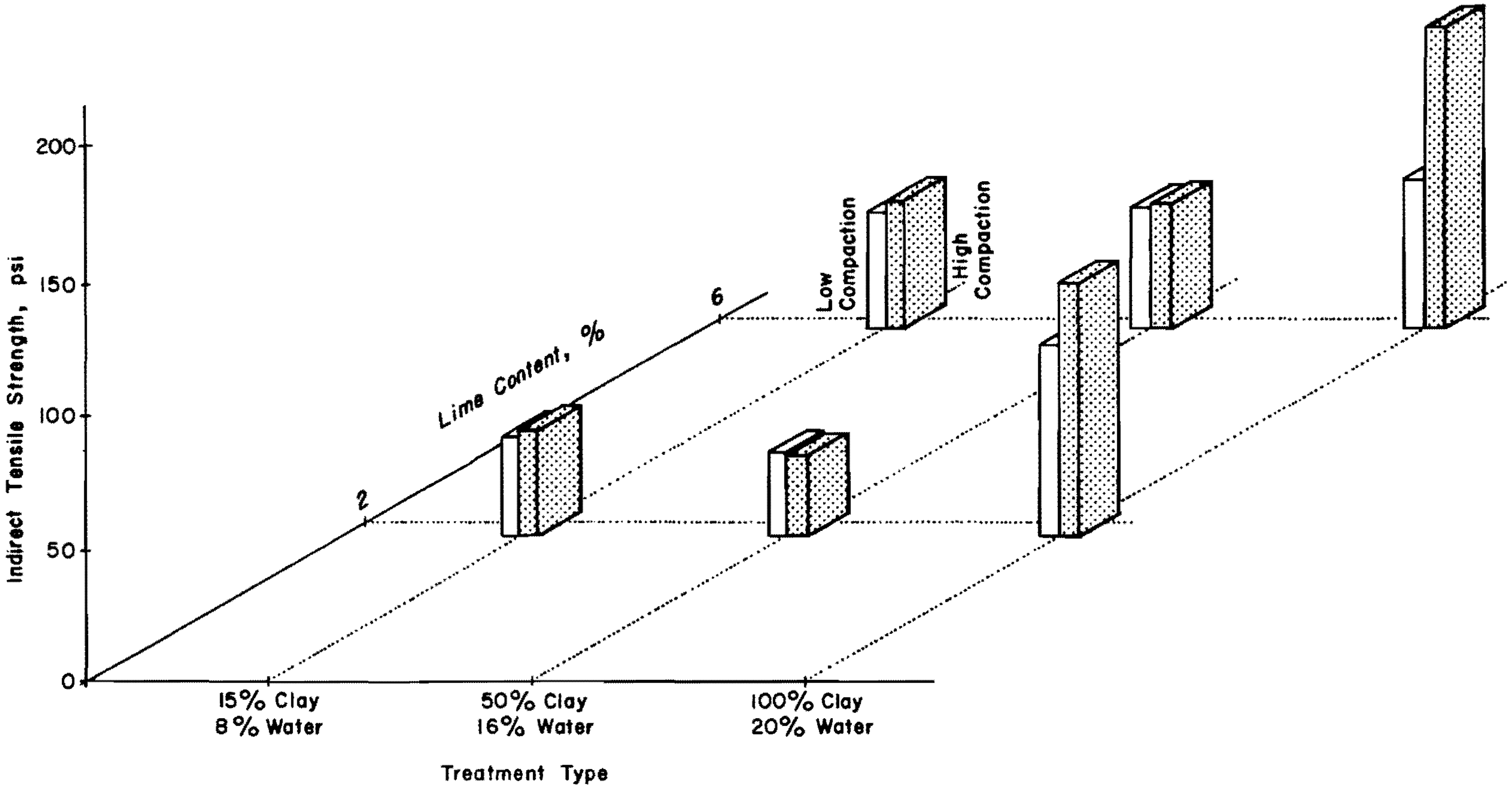


Fig 7. Effect of interaction between compactive effort, lime content, and treatment type (interaction E×J).

Compaction Type x Treatment Type (Interaction BxJ - Fig 8). The average strength of specimens compacted by gyratory shear compaction increased slightly with the increased clay and moisture contents. For specimens compacted by impact compaction, however, the average strength was nonlinear, decreasing toward 50 percent clay and then increasing, with the maximum strength occurring for specimens consisting of 100 percent clay compacted at a water content of 20 percent. As previously noted, the effect of type of compaction was negligible for 50 percent clay mixtures but substantial for 100 percent clay.

Curing Procedure x Curing Temperature (Interaction CxF - Fig 9). This interaction was found to be highly significant in all three blocks when each block was analyzed separately. It may be noted that for a curing temperature of 40° F the average strength of sealed specimens was lower than the average strength of the air-dried specimens, but the reverse was true for specimens cured at 110° F. It may also be noted that while the average strength increased with an increase in curing temperature from 40 to 110° F, the amount of this increase was much greater for the sealed specimens.

This behavior is probably a function of the moisture content at the time of testing and the probability that the reaction of lime with soil was negligible at 40° F. Thus, at 40° F the air-dried specimens were stronger because they were drier at the time of testing. However, at 110° F, a significant lime-soil reaction probably occurred. This reaction requires moisture, which is associated with sealed curing. In addition, air-drying at these temperatures caused some cracking of the specimens, which may have reduced the average strength of the air-dried specimens cured at 110°F.

Compactive Effort x Treatment Type (Interaction AxJ - Fig 10). The average strengths for specimens containing 15 and 50 percent clay compacted with high and low compactive efforts were essentially equal; however, the average strength increased when the clay content was increased to 100 percent, and the amount of this increase was much greater for a higher compactive effort. Apparently increased compactive effort produced a significant effect only in those soils composed of 100 percent clay with little if any benefit occurring for soils containing gravel.

Compactive Effort x Compaction Type (Interaction AxB - Fig 11). The low and high compactive efforts used to compact specimens with the gyratory shear

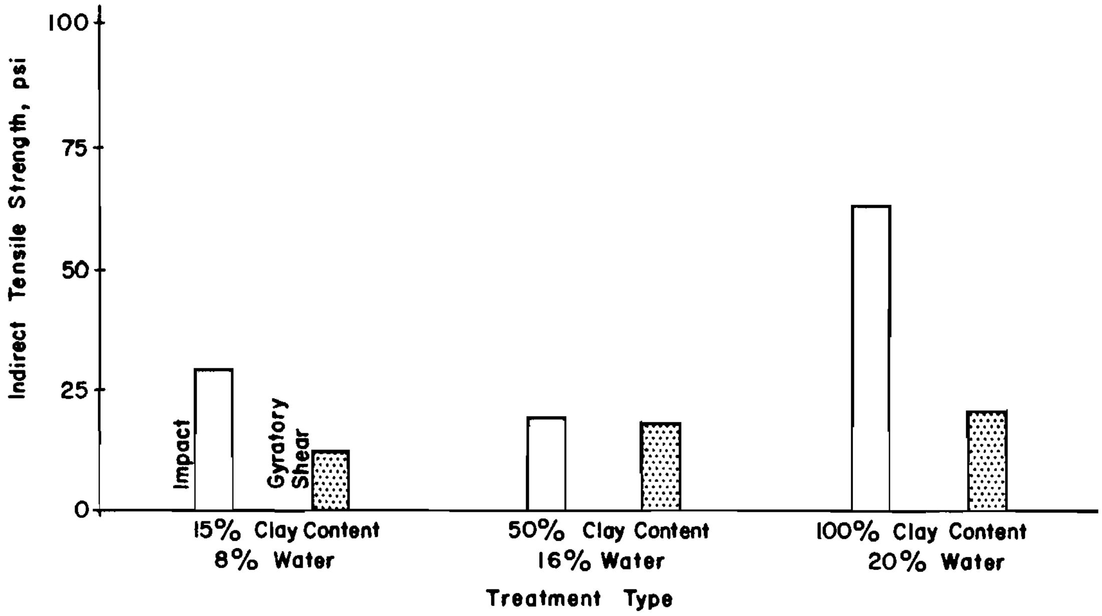


Fig 8. Effect of interaction between compaction type and treatment type (interaction B×J).

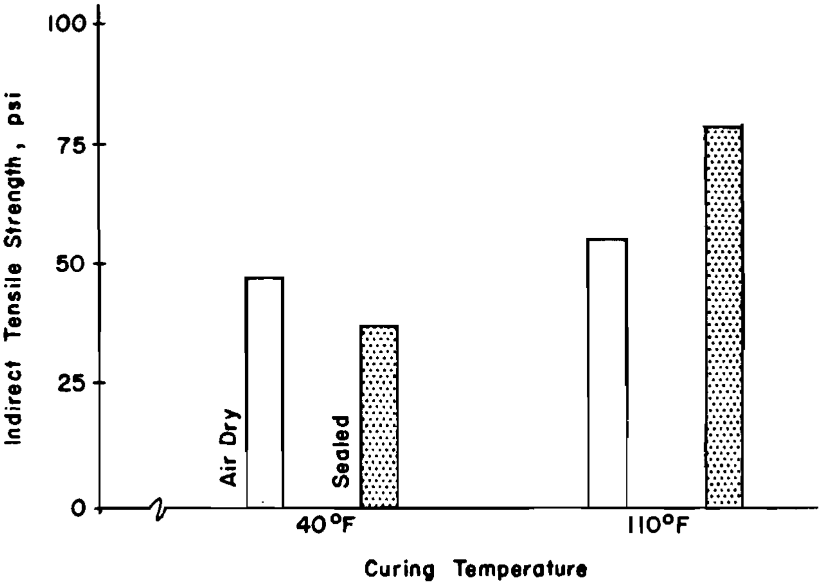


Fig 9. Effect of interaction between curing procedure and curing temperature (interaction C×F).

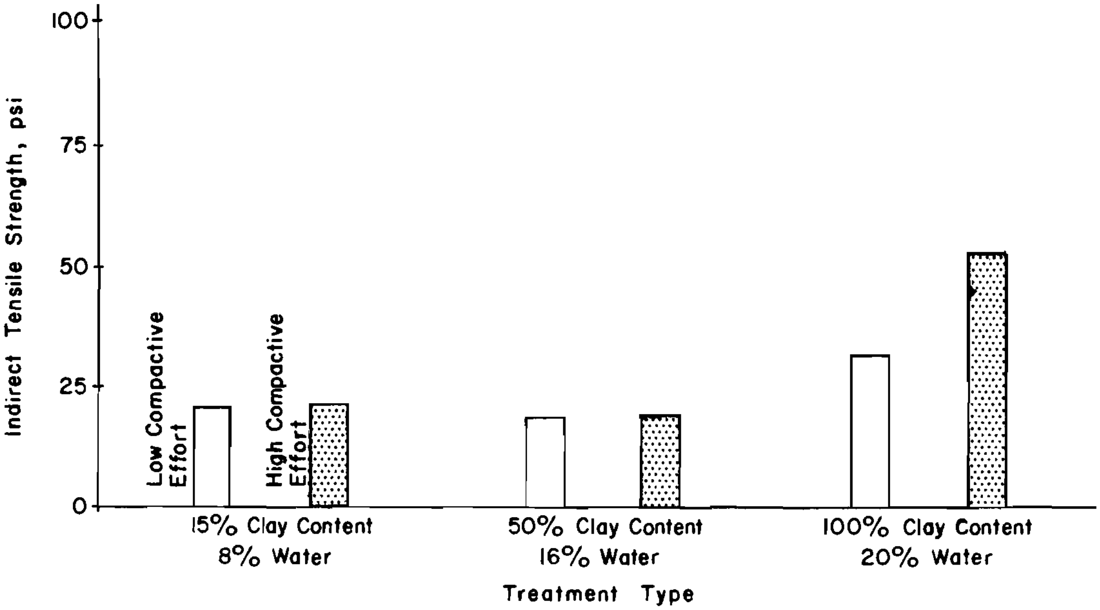


Fig 10. Effect of interaction between compactive effort and treatment type (interaction A×J).

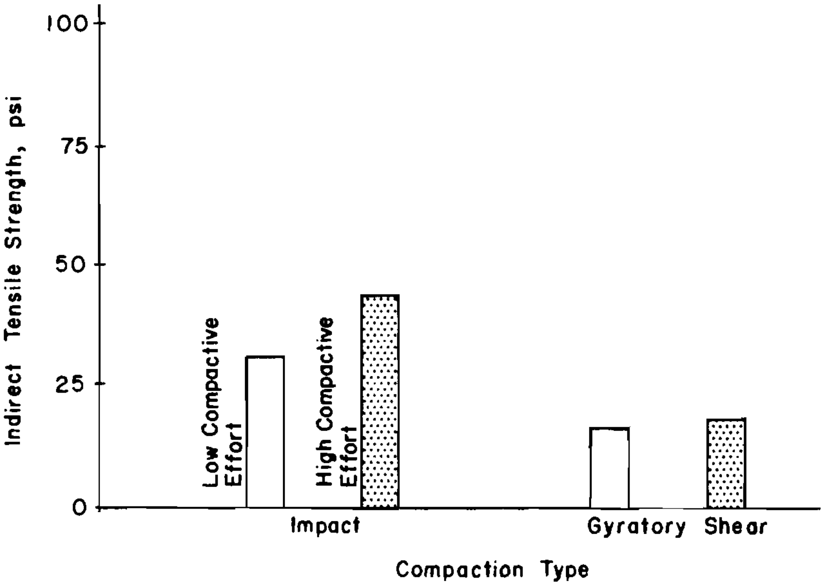


Fig 11. Effect of interaction between compactive effort and compaction type (interaction A×B).

compactor produced specimens of essentially equal average strengths. Impact compaction produced specimens which had substantially larger average strength values, with the largest increase being associated with the high compactive effort. A comparison of the densities for the four conditions illustrated in Fig 11 shows no obvious differences in density which could account for the observed behavior. Similar behavior was also observed in Block 3 (Fig 29).

Compactive Effort x Curing Procedure (Interaction AxC - Fig 12). The high compactive effort produced stronger specimens for both air-dried and sealed curing conditions, but the increase in strength was much greater for the sealed specimens. The increased strength of the sealed specimens might have resulted because the higher densities and increased particle contact, which were caused by the greater compactive effort, were beneficial to the lime-soil reaction. In addition, this reaction would also benefit from adequate moisture during curing. It also can be noted that although sealed curing resulted in much higher strengths for specimens compacted at a high compactive effort, the strength of specimens compacted at a low compactive effort decreased slightly.

Compactive Effort x Lime Content (Interaction AxE - Fig 13). The higher compactive effort produced a much greater increase in strength for specimens containing 6 percent lime than for specimens containing 2 percent lime. In addition, it would appear that specimens compacted at low compactive effort benefited little from increased lime content, whereas the increased lime content resulted in an increased strength in specimens compacted at the high compactive effort. This finding emphasizes the need for adequate compaction if strength is to develop as the result of the lime-soil reaction. Without adequate compaction the beneficial effects of the increased lime content were not realized.

Lime Content x Curing Time (Interaction ExG - Fig 14). Specimens with a low lime content increased in strength with the increased curing time, whereas specimens at the higher lime content decreased in strength. In fact, the increased curing time resulted in a slightly lower average strength for the specimens containing 6 percent lime. Similar behavior has been observed in other studies. It would be anticipated that if the high lime content specimens were cured for a long period, their strength would eventually increase substantially.

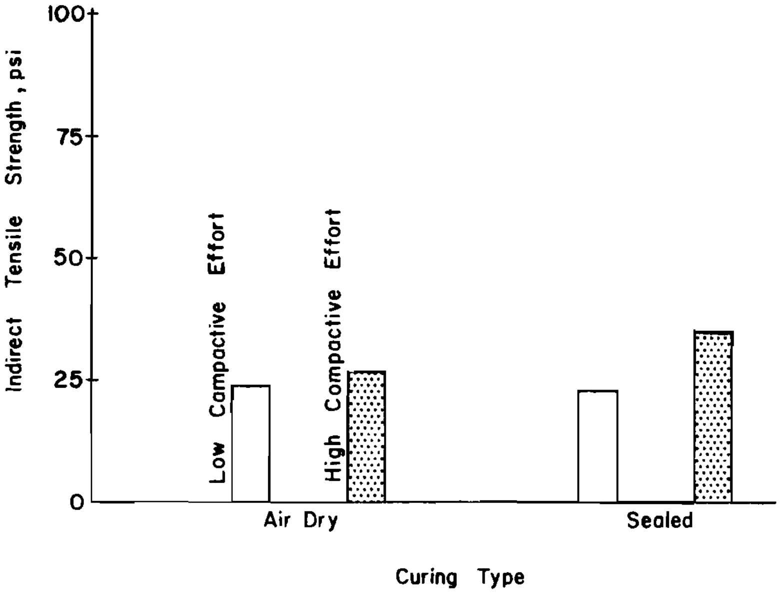


Fig 12. Effect of interaction between compactive effort and curing procedure (interaction A×C).

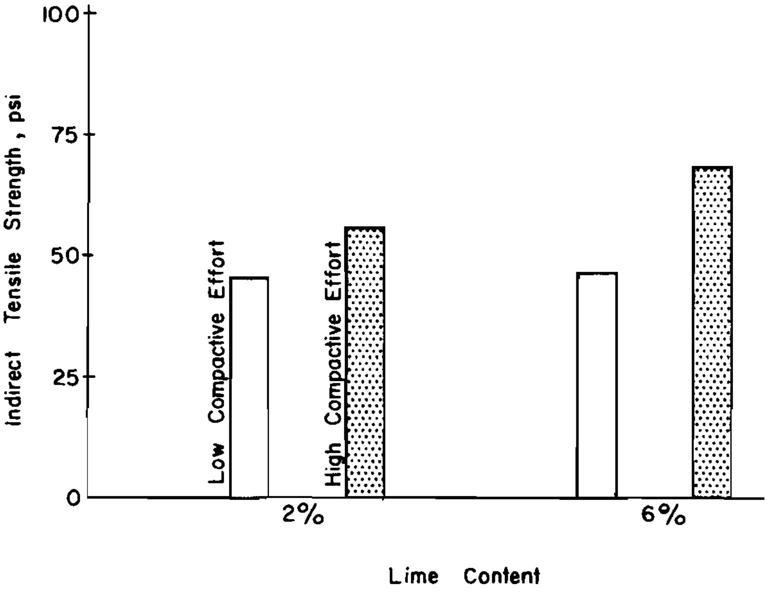


Fig 13. Effect of interaction between compactive effort and lime content (interaction A×E).

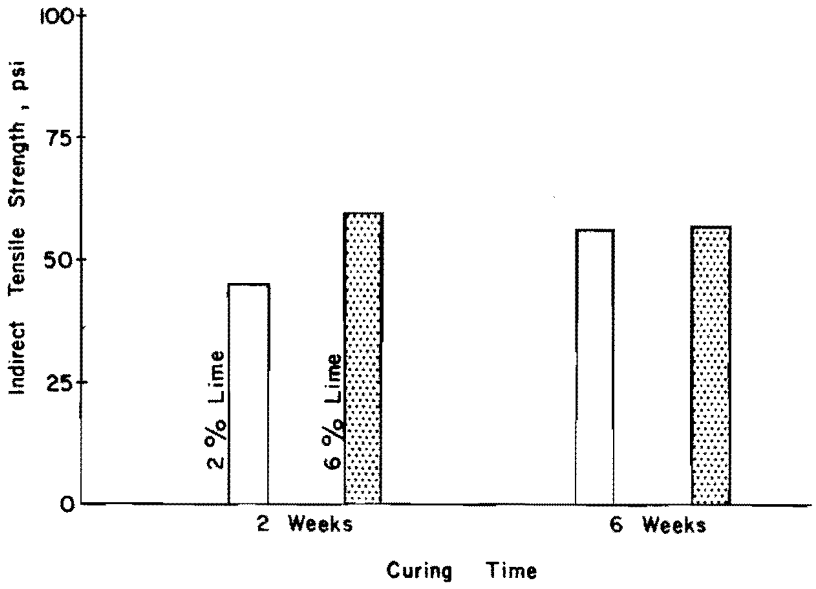


Fig 14. Effect of interaction between lime content and curing time (interaction E×G).

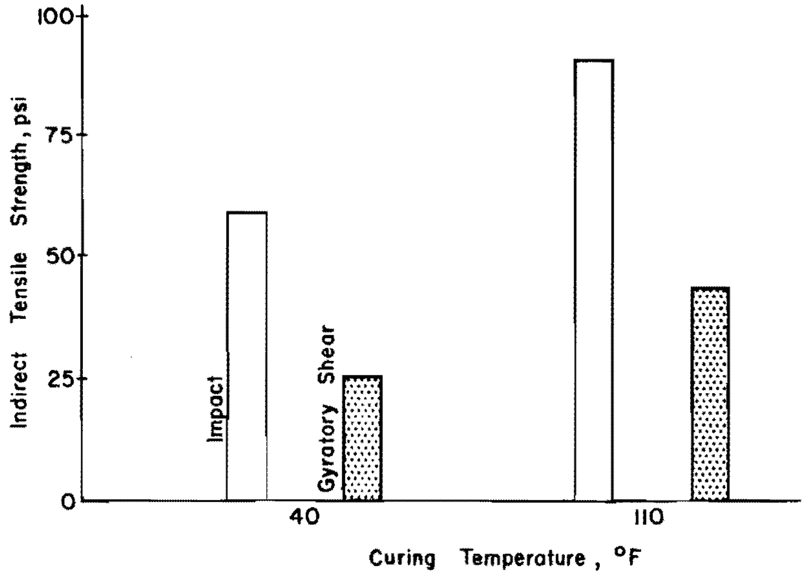


Fig 15. Effect of interaction between compaction type and curing temperature (interaction B×F).

Compaction Type X Curing Temperature (Interaction BXF - Fig 15). Both impact compaction and curing at 110° F produced specimens with higher strengths than those compacted by gyratory shear and cured at 40° F. The increase in strength resulting from curing at 110° F, however, was greater for specimens compacted by impact compaction. The cause of the improved strength associated with impact compaction is not apparent.

Compaction Type X Curing Procedure (Interaction BXC -Fig 16). These results indicate that sealed curing resulted in a substantial increase in the strength of specimens compacted by impact compaction, but had essentially no effect on specimens compacted by gyratory shear compaction. This behavior is similar to that observed in the interaction effect produced by compaction type X curing temperature (Fig 15).

Compaction Type X Lime Content (Interaction BXE - Fig 17). Increasing the lime content from 2 to 6 percent increased the average strength for all specimens regardless of the method of compaction; however, the strength increase was larger for impact compacted specimens but practically negligible for specimens compacted by gyratory shear.

Curing Procedure X Treatment Type (Interaction CXJ -Fig 18). For the specimens composed of a mixture of clay and gravel, the method of curing appeared to have little effect, although the sealed specimens did exhibit slightly higher strengths. In addition, it can be noted that increasing the clay content from 15 to 50 percent had little effect, although the average strength of the specimens containing 50 percent clay was slightly less than the average for the specimens containing 15 percent clay. The 100 percent clay specimens, however, did exhibit a substantial increase in strength; the magnitude of the increase was much greater for those specimens cured by sealing.

Main Effects

Six of the main effects were found to be significant at a probability level of 0.001. Figures 19 through 24 illustrate the effects produced by these factors. It can be seen that the average indirect tensile strength was significantly increased by

(1) using impact rather than gyratory shear compaction (Factor B), Fig 19;

(2) using 100 percent clay rather than a mixture of clay and gravel (Factor J), Fig 20;

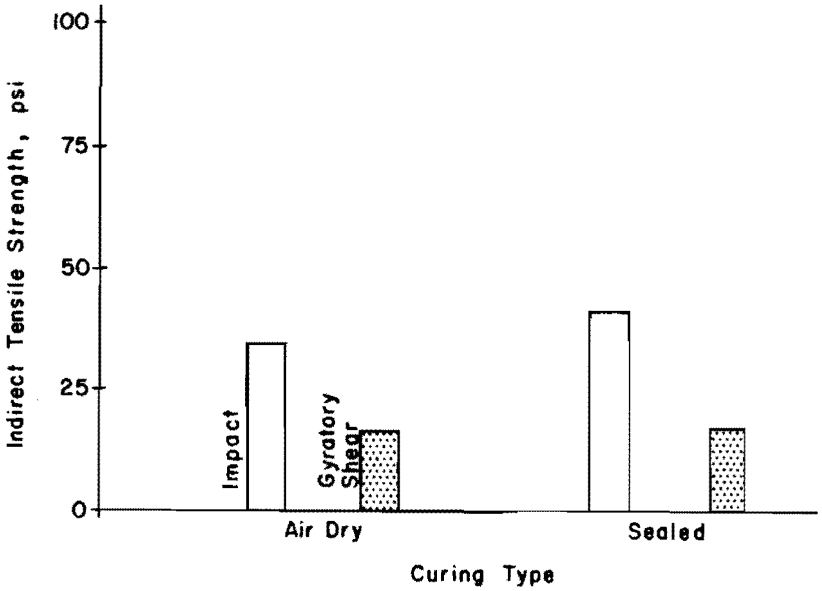


Fig 16. Effect of interaction between compaction type and curing procedure (interaction B×C).

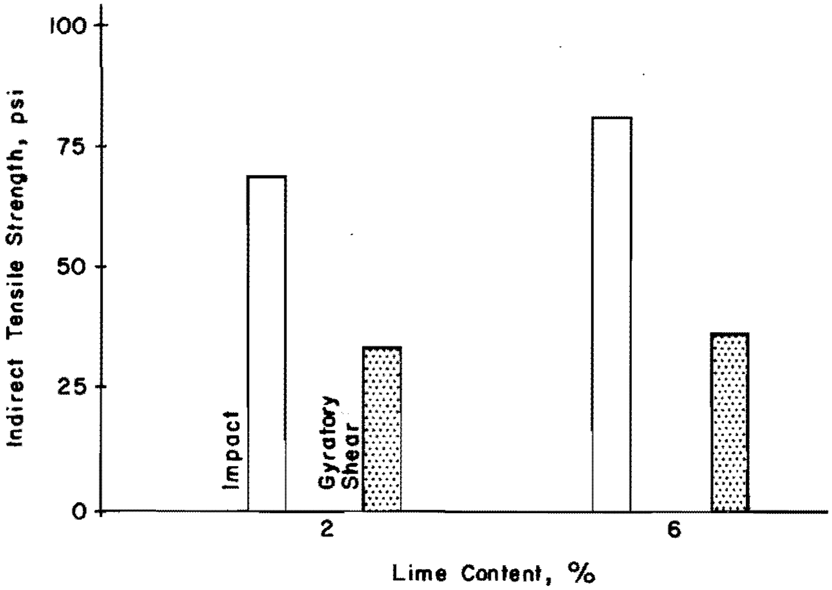


Fig 17. Effect of interaction between compaction type and lime content (interaction B×E).

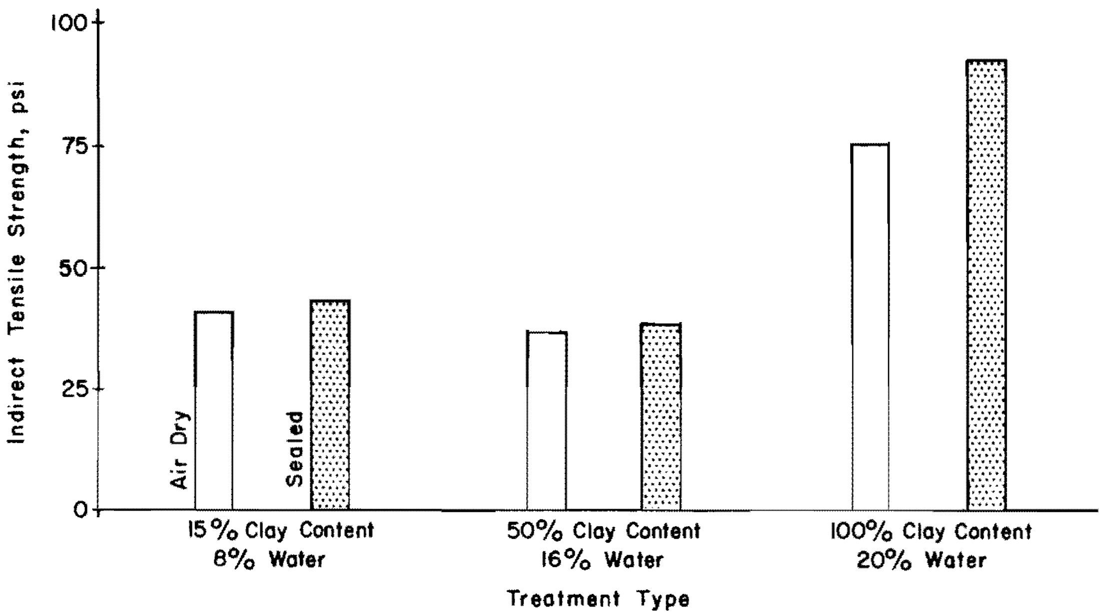


Fig 18. Effect of interaction between curing procedure and treatment type (interaction C×J).

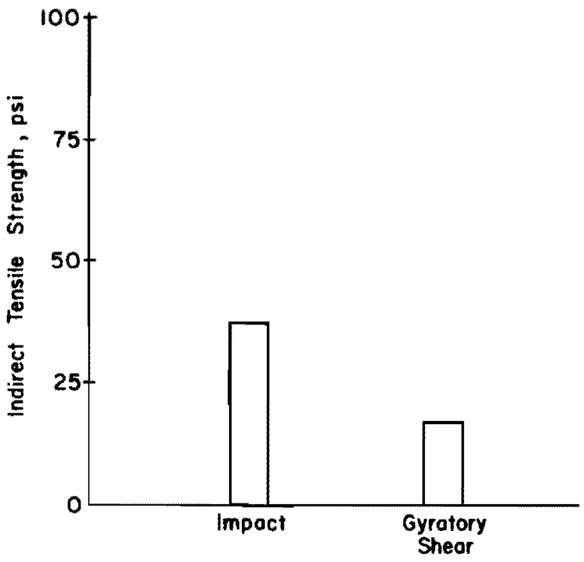


Fig 19. Effect of compaction type (Factor B).

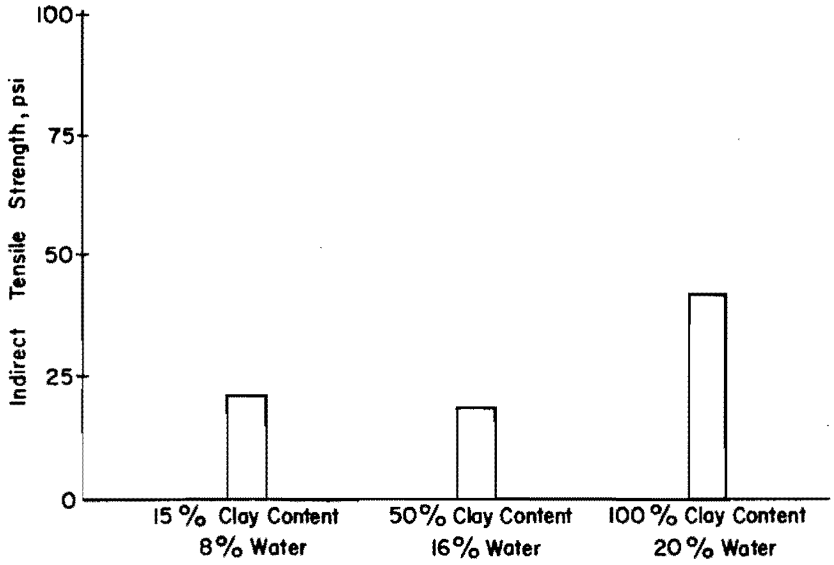


Fig 20. Effect of treatment type (Factor J).

(3) curing at a temperature of 110° F rather than 40° F (Factor F), Fig 21;

(4) using a high compactive effort (Factor A), Fig 22;

(5) increasing the lime content from 2 percent to 6 percent (Factor E), Fig 23; and

(6) using sealed rather than air-dried curing (Factor C), Fig 24.

The main effect of compaction type (Factor B) was significant in the analysis of Block 3 as well as in the separate analyses of Blocks 1 and 2, which are contained in Appendix 6. Similarly, curing temperature (Factor F) was significant in all three blocks while compactive effort was significant in Block 1 and Block 3. Block 2 was not significantly affected because compactive effort had a greater effect on clay specimens than on mixtures of clay and gravel, as evidenced by the Interaction A×J in Blocks 1 and 2 and by A×H from Block 3. The latter two main effects, lime content and type of curing, are of little practical significance although they are highly significant statistically. In the case of lime content, it is felt that the curing time was not sufficiently long to allow the beneficial effects of the increased lime content to be realized. As shown, sealed curing resulted in only a slight increase in strength, and it is doubtful that such a small difference could be considered of practical significance unless increased curing time magnified the difference. In this regard, it can be noted that only curing time failed to produce an effect judged to be highly significant and of practical significance.

Block 3

The primary purpose of Block 3 was to allow the effect of clay content and water content to be evaluated separately, since their effects were confounded in Blocks 1 and 2. In terms of the levels used for these two parameters, it would appear that clay content (Factor H) has a greater effect than water content (Factor D) since it appeared in five two-factor interactions and as a main effect, all of which were significant at a probability level of 0.01. Water content, however, occurred in only two two-factor interactions significant at a 0.01 level. Nevertheless, the main effect associated with treatment type, the very high strengths associated with 100-percent clay specimens compacted at 20 percent water content, appears to have been the result of water content rather than clay content.

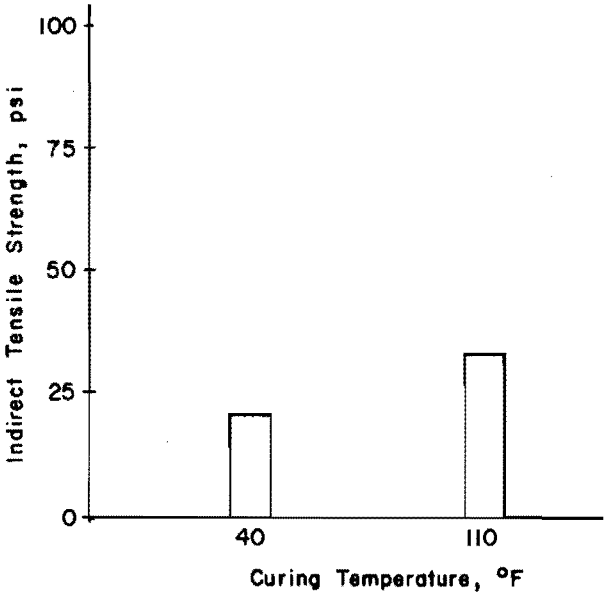


Fig 21. Effect of curing temperature (Factor F).

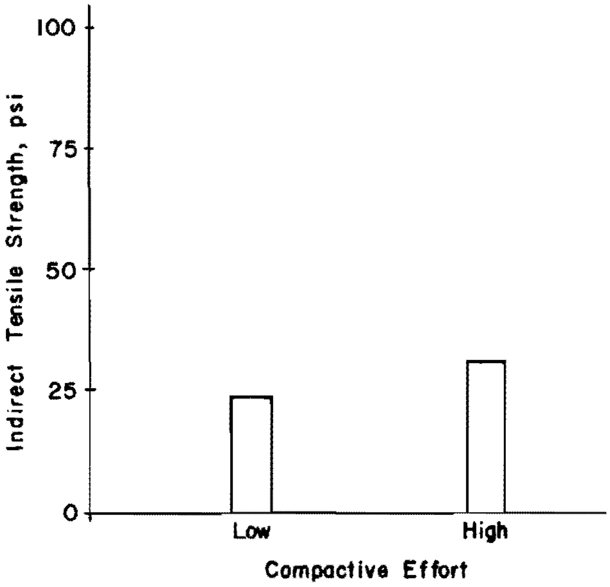


Fig 22. Effect of compactive effort (Factor A).

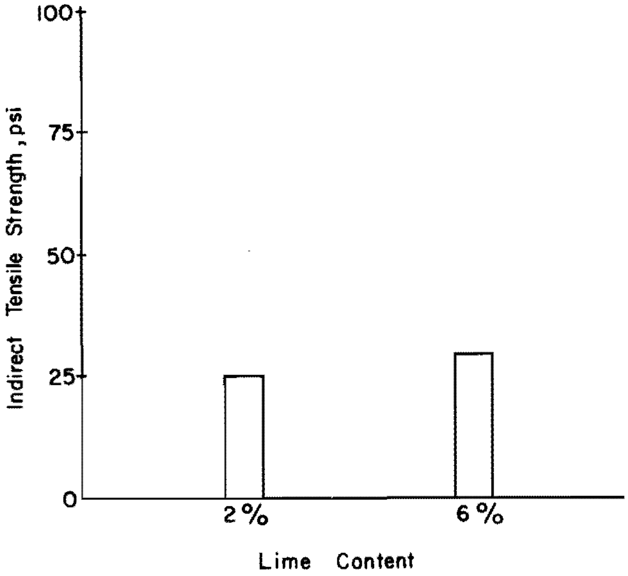


Fig 23. Effect of lime content (Factor E).

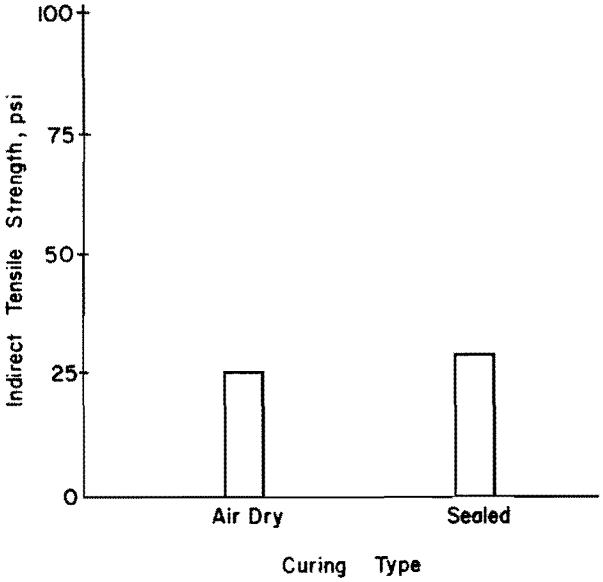


Fig 24. Effect of curing type (Factor C).

Effects significant at a probability level of 0.01 are graphically illustrated in Figs 25 through 38 and are discussed below.

Water Content × Clay Content (Interaction D×H - Fig 25). An increase in clay content from 15 to 100 percent had little effect on the strength of specimens compacted at a water content of 12 percent; however, the same increase in clay content caused a decrease in strength for specimens compacted at 10 percent moisture. Similarly, it can be observed that the increased water content produced a decreased strength for soils containing 15 percent clay and an increased strength for the specimens composed entirely of clay. If this effect is compared with that of treatment type (Factor J) in the combined analysis of Blocks 1 and 2, it can be seen that while clay specimens compacted at 20 percent were stronger than the mixtures of gravel in Blocks 1 and 2, the clay specimens in Block 3 were weaker. Since there is a definite interaction and since it appears that the strength of the clay specimens increased with increased water content, the average strengths for the various combinations of clay and water content have been combined in Fig 26. From this figure, it would appear that the high strengths associated with the 100 percent clay specimens compacted at 20 percent water content were caused by the water content at the time of compaction.

Lime Content × Clay Content (Interaction E×H - Fig 27). An increase in lime content from 2 percent to 6 percent resulted in an increased average strength for specimens containing 15 percent clay and a decreased strength for specimens composed entirely of clay. Likewise, an increase in clay content from 15 to 100 percent resulted in a decrease in strength regardless of whether the specimen contained 2 or 6 percent lime; however, the decrease in strength was much greater for specimens containing 6 percent lime.

Compaction Type × Clay Content (Interaction B×H - Fig 28). Specimens compacted by impact compaction were significantly stronger than specimens compacted by gyratory shear. The differences in strengths, however, were much greater for specimens containing 100 percent clay. Thus, it would appear that the reaction causing differences in strength between specimens compacted by the impact method and those compacted by the gyratory shear method was more effective on clay soils. A similar observation was made in Blocks 1 and 2 for

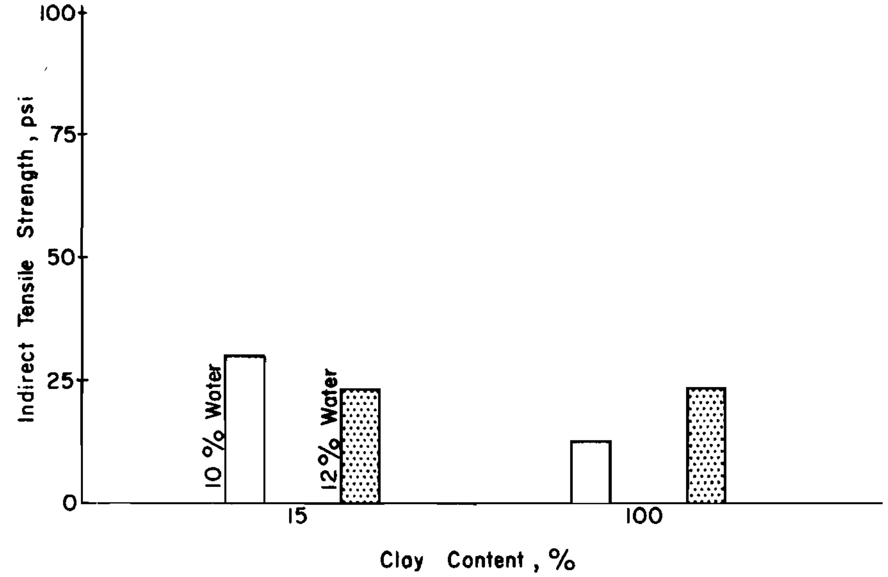


Fig 25. Effect of interaction between water content and clay content (Interaction D×H).

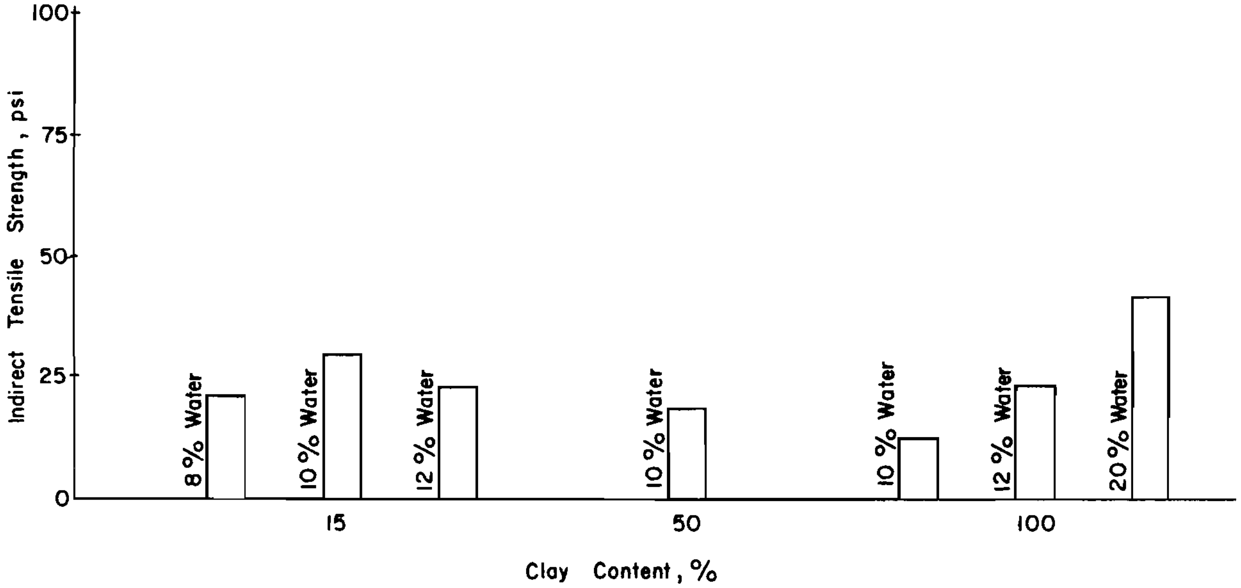


Fig 26. Effects of clay content.

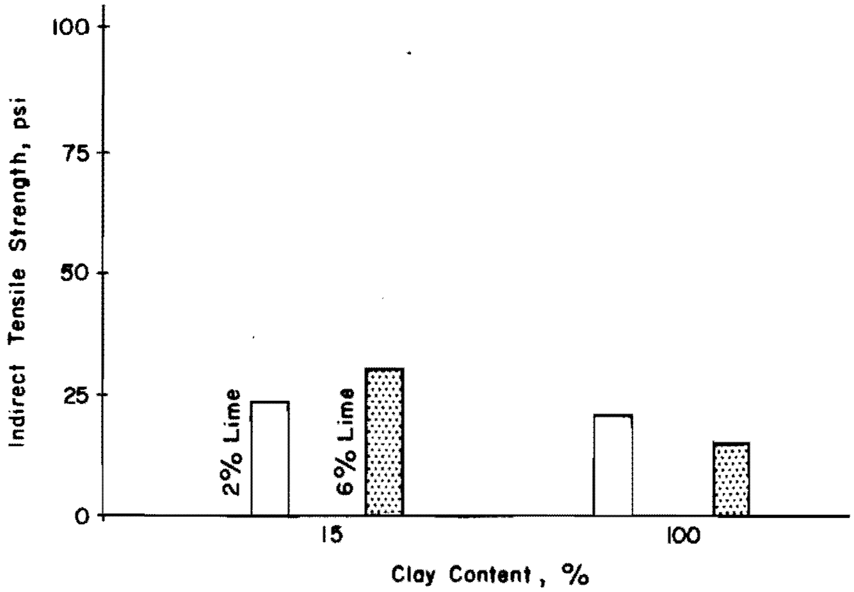


Fig 27. Effect of interaction between lime content and clay content (Interaction E×H).

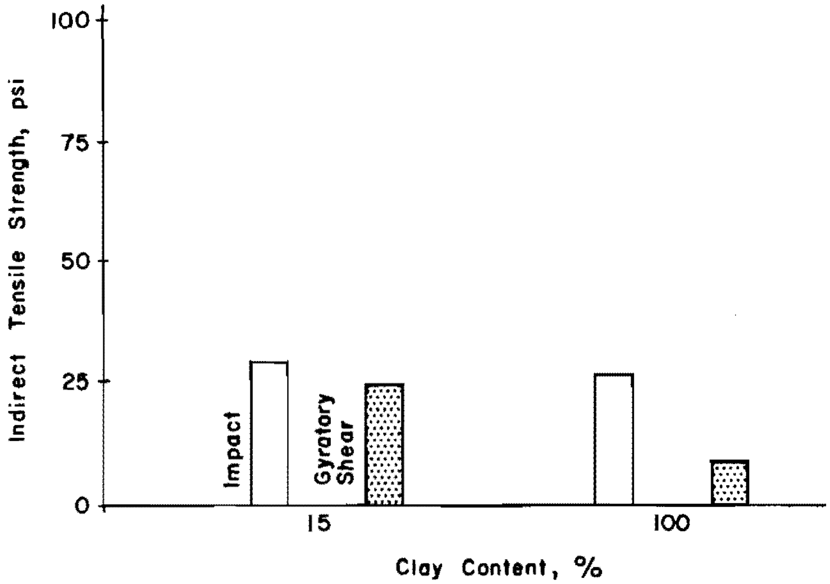


Fig 28. Effect of interaction between compaction type and clay content (Interaction B×H).

compaction type × treatment type (Interaction B×J), (Fig 8), except that the magnitude of strength was less for clay specimens due to the effect of water content.

Compactive Effort × Clay Content (Interaction A×H - Fig 29). Increased compactive effort had little effect on the strength of specimens containing 15 percent clay but resulted in a substantial increase in the strength of specimens containing 100 percent clay. By comparing this interaction effect with the interaction of compactive effort × treatment type (A×J), shown in Fig 10, it can be seen that the two exhibited similar effects. Because of the effect of water content in the interaction that included treatment type, however, the strengths of the specimens containing 100 percent clay were greater than those of the specimens containing 15 percent clay, while the reverse was true for the interaction that included clay content.

Curing Temperature × Clay Content (Interaction F×H - Fig 30). The average strengths were greater for specimens cured at 110° F than for specimens cured at 40° F. The increase associated with the increased curing temperature was much greater for specimens containing 15 percent clay than for those containing 100 percent clay. In addition, it may be noted that the increase in clay content resulted in a decrease in strength; this decrease was much greater for specimens cured at 110° F than for specimens cured at 40° F. This decreased strength might possibly have been caused by cracking, which would occur at 110° F.

Water Content × Curing Temperature (Interaction D×F - Fig 31). Increasing the curing temperature from 40° F to 110° F resulted in increased strengths. The magnitude of the increase was much greater for specimens compacted at 12 percent water than for those compacted at 10 percent water. In addition, increased water content during compaction resulted in decreased strengths for specimens cured at 40° F and in increased strengths for specimens cured at 110° F. This comparison would suggest that little, if any, soil-lime reaction occurred at 40° F; therefore, the reduced strength of the specimens cured at 40° was due to their higher water content at the time of test. On the other hand, because a soil-lime reaction reaction had occurred, the increased water content was very beneficial under the curing conditions of 110° F.

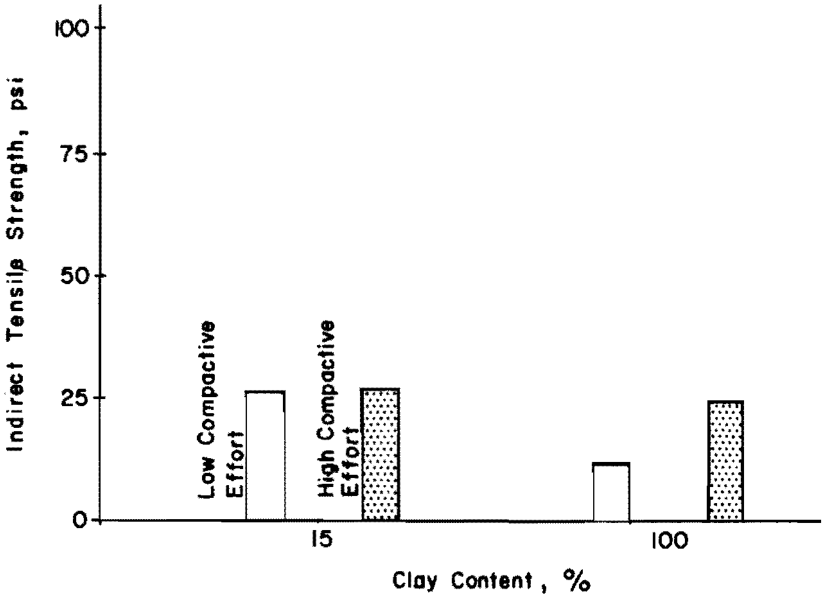


Fig 29. Effect of interaction between compactive effort and clay content (Interaction A×H).

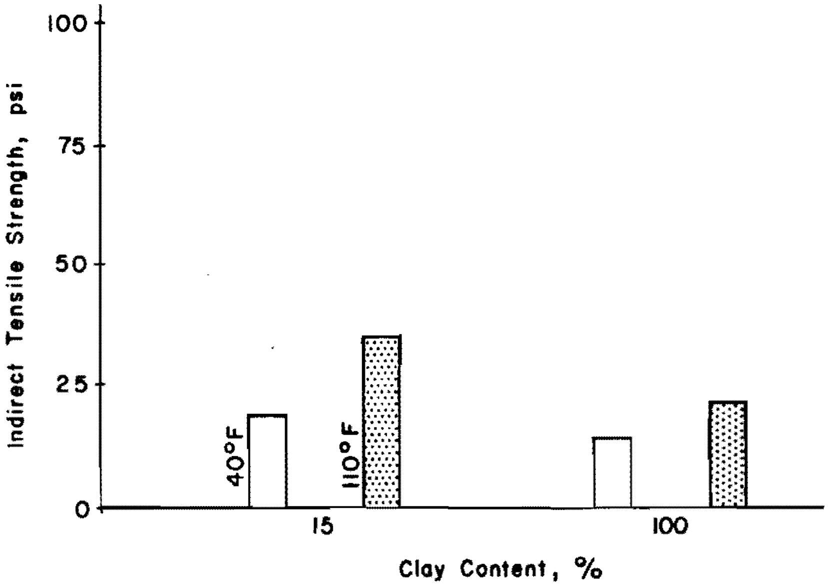


Fig 30. Effect of interaction between curing temperature and clay content (Interaction F×H).

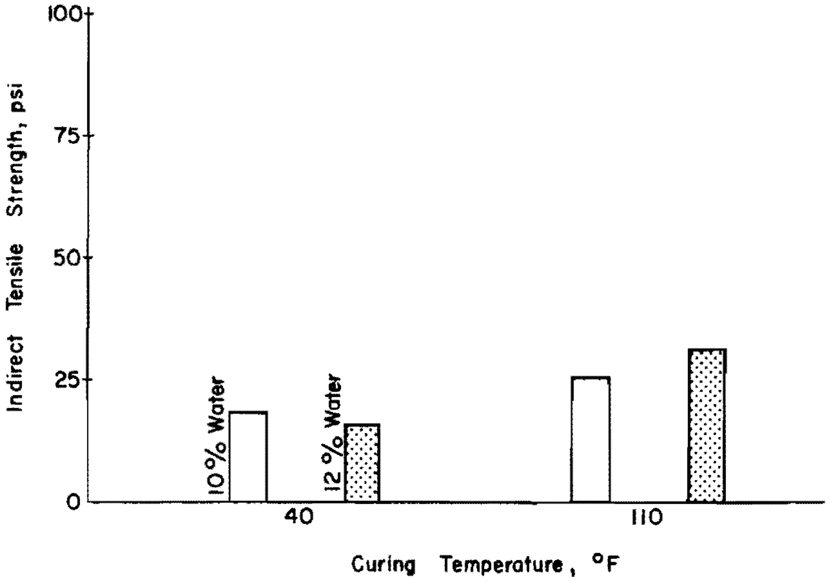


Fig 31. Effect of interaction between water content and curing temperature (Interaction D×F).

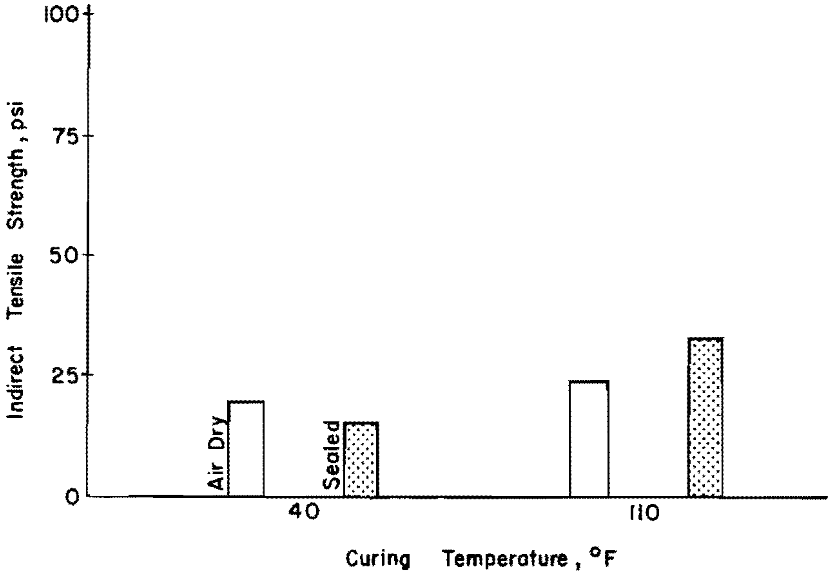


Fig 32. Effect of interaction between curing procedure and curing temperature (Interaction C×F).

Curing Procedure x Curing Temperature (Interaction CXF - Fig 32). This interaction was found to be highly significant in all three blocks. It may be noted that, for a curing temperature of 40° F, the average strengths of specimens cured by sealing were lower than the average strengths of the air-dried specimens, but the reverse was true for those specimens cured at 110° F. In fact, in all three blocks the strength of the sealed specimens increased with an increased curing temperature, while the strength of the air-dried specimens decreased.

This behavior may be associated with the moisture content at the time of testing. It is also possible that the reaction of lime with soil was negligible at a curing temperature of 40° F. Thus, at 40° F the air-dried specimens may have had greater strength because they were drier at the time of testing. At 110° F, however, air drying may have brought about cracking and a resulting decrease in strength. On the other hand, a significant lime reaction which would cause a substantial increase in strength, may have occurred in the sealed specimen.

Compactive Effort x Compaction Type (Interaction AxB - Fig 33). An increase in compactive effort did not result in a change in the strength of specimens compacted in the gyratory shear compactor, while it did result in a substantial increase in the strength of specimens compacted by impact compaction.

It would be expected that the strength would increase with increased compaction, but examination of wet densities did not indicate such an effect. Because there is no way to describe compactive effort quantitatively, it is possible that the difference in compactive effort for the low and high levels of gyratory shear compaction may have been small.

Compactive Effort X Curing Temperature (Interaction AXF - Fig 34). Compactive effort had little effect on specimens cured at 40° F. However, specimens cured at 110° F and compacted at a high compactive effort were substantially stronger than those compacted at a low compactive effort. Thus, the beneficial effects of increased density were enhanced by the 110° F temperature, while at 40° F very little reaction between the soil and lime occurred.

Main Effects. Only four main effects were significant at a probability level of 0.01. These four effects are shown in Figs 35 through 38 in which it can be seen that strength was significantly increased by

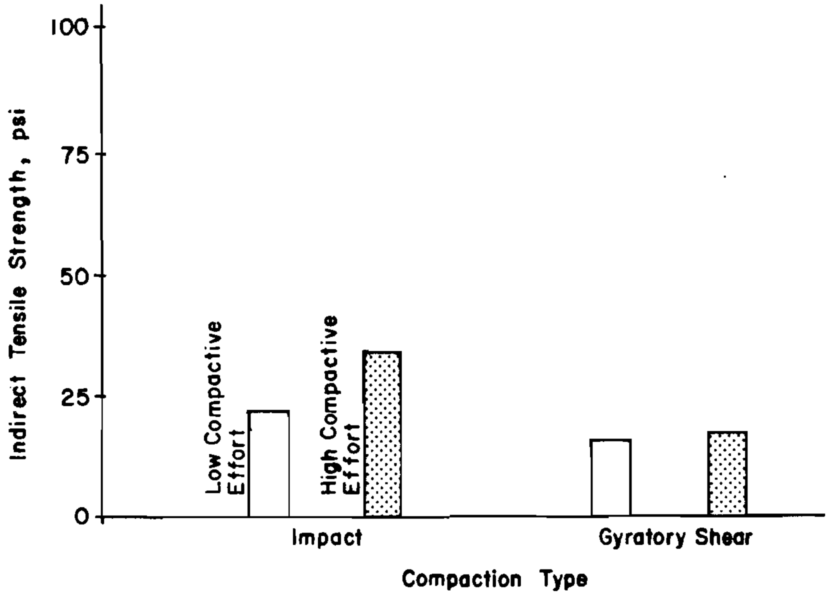


Fig 33. Effect of interaction between compactive effort and compaction type (Interaction A×B).

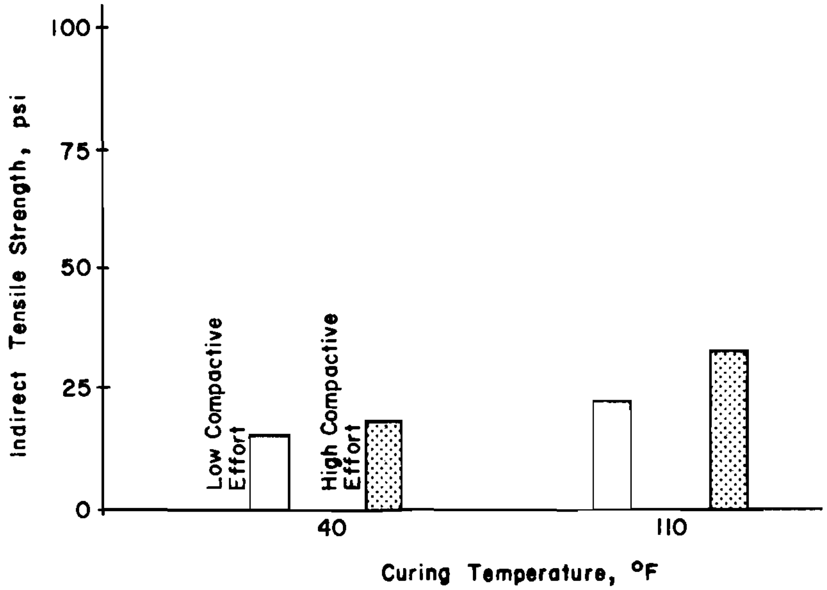


Fig 34. Effect of interaction between compactive effort and curing temperature (Interaction A×F).

(1) using impact compaction rather than gyratory shear compaction (Factor B), Fig 35;

(2) curing at 110° F rather than 40° F (Factor F), Fig 36;

(3) using a mixture of gravel with 15 percent clay rather than 100 percent clay and no gravel (Factor H), Fig 37; and

(4) using a high compactive effort (Factor A), Fig 38.

The third main effect is in contrast to the findings from the combined analysis of Blocks 1 and 2, which showed that the specimens composed of 100 percent clay and compacted at 20 percent water content were significantly stronger. As previously indicated, however, the higher strength associated with specimens composed of 100 percent clay and compacted at 20 percent water content was caused by the water content rather than the clay content.

REGRESSION ANALYSIS

A stepwise regression analysis was conducted to obtain a preliminary predictive equation for indirect tensile strength and to evaluate the quadratic characteristics of the response surfaces.

The initial regression analysis was conducted for each of the three blocks using all main effects, two-way interactions, and measurable three- and four-way interactions. Stepwise regression analysis was conducted using the results from these analyses and inputting all main effects and all two-way interactions from all three blocks. From this analysis, an equation was developed which allows indirect tensile strengths to be estimated within a standard error for the inference space defined by this experiment.

The quadratic characteristics of the response surfaces were evaluated using an F test. A partial F value for each variable considered in the regression analysis was compared with the critical F value. If the critical F value was smaller than the F value associated with any of the effects being evaluated, i.e., linear, quadratic, or linear-quadratic, the term was considered to have a significant effect, and the relationship between the dependent variable and the variable tested was curvilinear.

Regression Equations

The following regression equation was obtained for indirect tensile strength:

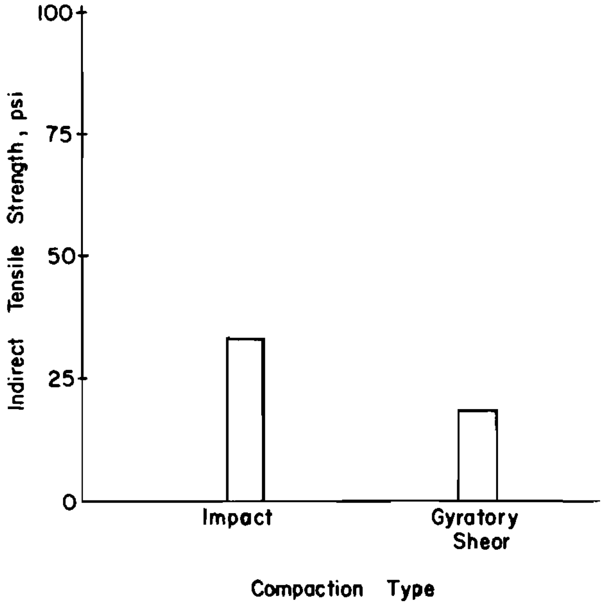


Fig 35. Effect of compaction type (Factor B).

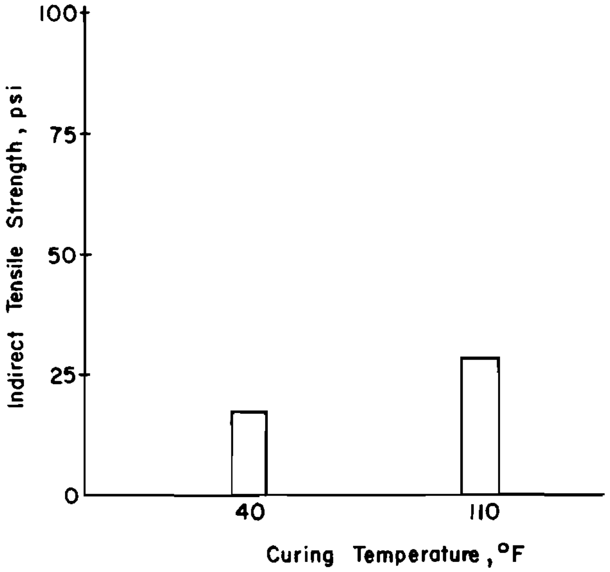


Fig 36. Effect of curing temperature (Factor F).

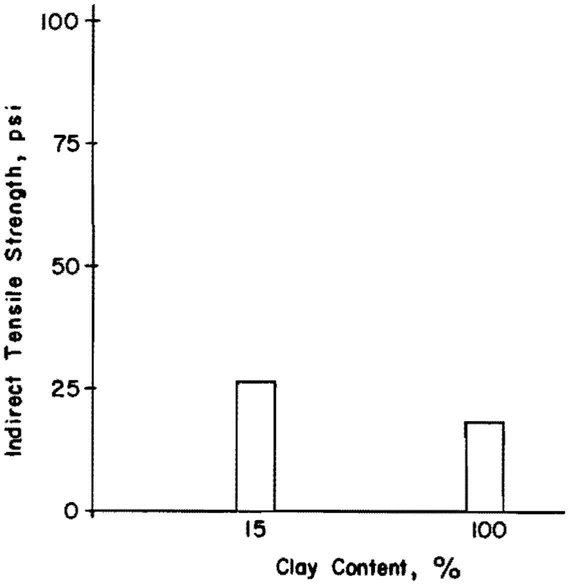


Fig 37. Effect of clay content (Factor H).

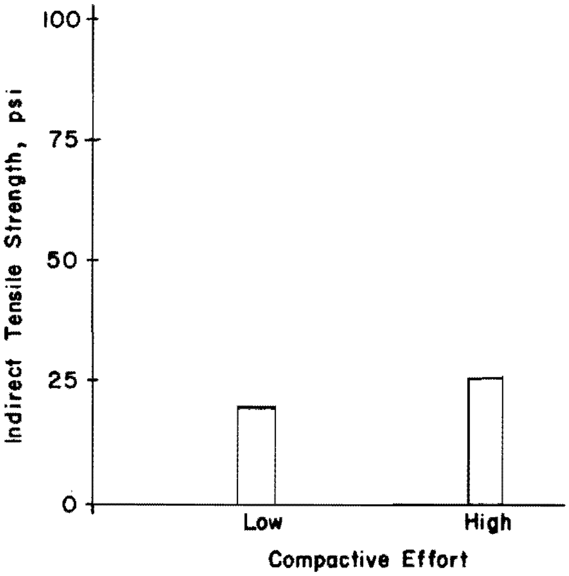


Fig 38. Effect of compactive effort (Factor A).

$$
\begin{aligned}
S_T = {} & 144.4088 - 54.3664B - 11.5896D - 1.5873H + 5.0769AB \\
& - 7.793AC - 1.3943AD + 4.1335BD - 0.1471BF + 1.2549BH \\
& + 0.2087DH + 0.0017F^2 - 0.0089H^2 - 0.1691ABH + 0.1021ACF \\
& + 0.0442ACH + 0.1178ADE - 0.0051ADF + 0.1072ADG + 0.0222ADH \\
& - 0.0569BCH + 0.0136BDF - 0.0876BDG - 0.0017BFH + 0.0009CFH \\
& - 0.0042EGH
\end{aligned}
$$

where

S_T = predicted value of indirect tensile strength, in psi,

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

i = level of the factor (see Table 8 for levels used in this analysis).

The multiple correlation coefficient for the indirect tensile strength predictive equation was $R = 0.90$, and the standard error of the estimate was ± 16.8.

The factors and interactions found significant in the analysis of variance are not the same as those found significant in the regression analysis, for several reasons. First, in the regression analysis, all the blocks were combined. Also, new levels of the quantitative factors were introduced in the regression analysis; these were not studied in the analysis of variance. Most important, however, is the fact that each analysis of variance used orthogonally coded factor levels, while the prediction equation used in the regression analysis was generated from the actual uncoded, correlated factor levels. This uncoded analysis moved the response surface away from the origin (the VIEWER) and thereby dislocated trends. Consequently, the prediction equation should not be regarded as an accurate estimate of the physical properties of individual factors shown on the response surface, but should instead be regarded as one large term that does a reliable job of estimating tensile strength.

TABLE 8. LEVELS OF FACTORS USED IN REGRESSION EQUATIONS

Factor	Description	Level
A - Compactive effort	Low	$A_0 = 0$
	High	$A_2 = 2$
B - Compaction type	Rainhart	$B_0 = 0$
	Gyratory shear	$B_2 = 2$
C - Curing procedure	Air dry	$C_0 = 0$
	Sealed	$C_2 = 2$
D - Molding water content, % by weight	8	$D_8 = 8$
	10	$D_{10} = 10$
	12	$D_{12} = 12$
	16	$D_{16} = 16$
	20	$D_{20} = 20$
E - Lime content, % by weight	2	$E_2 = 2$
	4	$E_4 = 4$
	6	$E_6 = 6$
F - Curing temperature, °F	40	$F_{40} = 40$
	75	$F_{75} = 75$
	110	$F_{110} = 110$
G - Curing time, weeks	2	$G_2 = 2$
	4	$G_4 = 4$
	6	$G_6 = 6$
H - Clay content, % by weight	15	$H_{15} = 15$
	50	$H_{50} = 50$
	100	$H_{100} = 100$

Nonlinear Effects

The predictive equation can, to a certain extent, be used to evaluate the nonlinear effects for the five factors that contain more than two levels, i.e., quantitative factors (see Table 1). A factor which appears in the equation in the form of a squared term suggests a possible nonlinear effect. Thus, it appears that curing temperature (Factor F) and clay content (Factor H) may produce curvature of the response surface of indirect tensile strength; however, the coefficients on these terms are quite small and contribute very little to the equation. Evaluation of Factor J in the combined analysis of Blocks 1 and 2 indicates that clay content produces curvature of the response surface (Fig 20), but that this effect was closely associated with that of water content at the time of compaction. Thus, the effects of clay content should be considered further.

DISCUSSION

A number of effects appear to have dominated the results of the experiment. Several effects also appear to have definite practical significance to the engineer. These effects are discussed in detail in the following paragraphs.

The first effect is associated with type of compaction (Factor B). In both the combined analysis of Blocks 1 and 2 and in the individual analyses of Blocks 1, 2, and 3, it was found that impact compaction produced significantly stronger specimens than did gyratory shear compaction even though the densities of the two specimens were essentially equal. This effect was most pronounced for the specimens composed entirely of clay, as evidenced by the interaction of compaction type × treatment type (B×J) in Blocks 1 and 2 and by the interaction of compaction type × clay content (B×H) in Block 3. This observation is unexplained although two possible explanations will be suggested. One is that the structural arrangements of the clay particles were very different in specimens compacted by different methods. Previous research has indicated that impact compaction would be expected to produce a more flocculated clay structure, which has been shown to be stronger in triaxial compression. Whether this explanation can be applied to tensile testing is unknown at this time. A second hypothesis is that the specimens compacted by gyratory shear have a shell around the periphery that is denser than the core. It is possible that the overall density of the specimen is essentially equal to that of the specimen compacted by impact compaction; failure of the specimen occurs in the center of the specimen, which is less dense.

In support of the hypothesis that this effect was caused by density is the fact that compactive effort produced an effect similar to that produced by compactive type. Higher compactive efforts resulted in higher strengths; however, the effect was much more pronounced for the clay specimens than for clay-gravel specimens, as is evidenced by the interaction of compactive effort X treatment type (A×J) in Blocks 1 and 2 and by the interaction of compactive effort X clay content (A×H) in Block 3.

Furthermore, the three factors, compactive effort, compactive type, and treatment type, also interact to produce a three-factor interaction effect. As shown in Fig 2, clay specimens compacted by impact compaction produce higher average strengths regardless of compactive effort; however, the most striking difference is the effect of the high compactive effort on specimens compacted by impact compaction.

The reason a strength difference between high and low compactive effort was not noted for the clay-gravel specimens may be that the clay in these specimens tended to act as a mortar around the aggregate. In addition, the aggregate was not randomly distributed throughout the specimen; rather, the larger aggregates were placed in the mold prior to compaction with the clay fines spread around this center to insure a smooth, uniform specimen. Furthermore, since specimens fail near the center, it was thought that the influence of the aggregate should be concentrated in that region so that a valid indication of the aggregate effect could be obtained. This cluster of aggregate is not as compactable as the clay. After a minimum void ratio is obtained, the compactive energy is absorbed by the aggregates reacting against each other, and, consequently, a high compactive effort is ineffective.

A second main effect which had a large influence on the tensile strength of the specimens involved treatment type (Factor J), which was the factor related to both clay content (Factor H) and molding water content (Factor D) and which was contained in Block 2 and in the combined analysis of Blocks 1 and 2. It is interesting to note that, in the combined analysis of Blocks 1 and 2, the clay specimens which were compacted at 20 percent moisture were found to be much stronger, while in the analysis of Block 3, the clay specimens compacted at 10 and 12 percent moisture were weaker. This apparent contradiction was the result of an interaction in which water content during compaction was the primary variable. In the combined analysis of Blocks 1 and 2 the water content was 20 percent, while in Block 3 the water content was lower. As shown in Fig 26, the 20 percent water content resulted in much stronger specimens than did the water contents of 10 and 12 percent, which were used in Block 3. Evidence of such an interaction effect was detected in Block 3 since moisture content X clay content (Interaction DXH) was found to produce a significant effect.

As is shown in Fig 26, the mean tensile strength decreases for 10 percent water content as the clay content increases. In the 15 percent clay specimens, the clay acted as a mortar within an aggregate matrix. Enough water was present for the lime stabilization effect to take place. However, as the clay content was increased, the clay particles themselves began to absorb the water, since water's affinity for the hydroscopically dry Taylor Marl is much greater than that of lime, and the moisture was not utilized in the hydration process. Hence, the tensile strength decreased.

Most of the additional effects which were shown to be statistically significant are consistent with previous findings. Nevertheless, some discussion of these is warranted.

As in previous studies that used other strength tests, increased lime content resulted in greater strength. As a main effect, the increase in strength was very small and of little practical significance. Lime content, however, was a factor in a number of interactions which might have practical significance. It was noted, for example, that lime content interacted with curing time, as shown in Fig 14, where it can be seen that the increased curing time resulted in increased strength for specimens containing 2 percent lime but in slightly decreased strength for specimens containing 6 percent lime. This observation is consistent with previous findings and indicates that longer curing times are required for adequate evaluation of the effects of both time and higher lime content.

It also was found that all curing factors, except curing time, produced significant effects. As would be expected, a higher curing temperature (Factor F) produced much higher strengths. In fact, the results of the analysis of variance indicates that curing temperature was one of the dominate factors. It is felt, however, that additional temperatures should be considered, since little reaction apparently occurs between the lime and the soil at the relatively low temperature of 40° F. It also was found that sealed curing (Factor C) resulted in significantly higher strengths than air-dried curing but that the difference was not very great.

The complex interrelationships and large number of higher order interactions which developed suggest that full factorial designs be used in future experiments, rather than the fractional factorial design used in this experiment. In addition, it is felt that future experiments should test only clay-aggregate mixtures, since the pure clay treated with lime appears to react differently than did the mixtures.

On the basis of this experiment it is recommended that two of the original eight factors be eliminated in future experiments. Although type of compaction produced a large effect on strength, it is felt that gyratory shear compaction should be used, since it produced more uniform specimens and since it is commonly used by the Texas Highway Department. Type of curing should be eliminated, and an attempt should be made to provide sealed curing conditions.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The study described in this report was a preliminary experiment designed to evaluate the effects of eight factors and their interactions on indirect tensile strength, to determine which effects were significant for lime-treated materials, and to develop a preliminary regression equation which could be used to predict tensile strengths.

Conclusions are limited to the range of variables included and evaluated in the experiment. It was not the intent of this study to provide a detailed and final answer to all questions concerned with the tensile strength of lime-treated materials. Although a great deal of information was obtained from the study, caution should be exercised in the application of these results because of their extreme complexity. The information resulting from the experiment is summarized in the following paragraphs.

Seven of the eight factors evaluated in this study produced significant main effects on the indirect tensile strength, at a probability level of 0.01. The data indicated 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 temparture of 110° 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 for 6 weeks rather than 2 weeks.

It should be remembered that the actual effect of an individual factor can be expressed only in terms of the other factors involved, as evidenced by the large number of significant interactions.

The only factor which did not cause a significant main effect was the molding water content; however, it was involved in a number of highly significant interaction effects. Thus, it was found that all of the 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 still relatively short.

Eleven two-factor interactions produced, on the indirect tensile strength, effects significant 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, ten three-factor and three 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 six three-factor interactions which were not confounded and which could be evaluated were

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

The significant effects appear 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 combined the 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 too short since 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 more temperatures should be included, since temperature was one of the dominant factors. In this experiment, the lower temperature did not produce a significant lime-soil reaction.

It should also be noted that 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 more closely simulate the worst condition.

RECOMMENDATIONS

On the basis of this study, as well as other portions of the investigation directed toward ultimately developing an adequate design procedure for stabilized subbases, it is recommended that

(1) a method be developed to relate the elastic properties of lime-treated materials to the applied loads and the resulting deformations of the specimen being tested by indirect tension; information on the elastic properties is necessary to the development of a design procedure and should be evaluated in terms of the effects produced by the various factors which may influence the tensile characteristics of the material;

(2) a detailed investigation be conducted for certain factors found to significantly influence the tensile strength of lime-treated materials; the design should allow a more complete evaluation of the interaction effects and should include additional levels of the quantitative variables so that the response surface can be more closely defined and adequate predictive regression equations developed;

(3) an evaluation be made to determine the factors which significantly affect the tensile characteristics of lime-treated materials subjected to repeated indirect tensile stresses and at the same time to determine the nature of these effects.

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, 1968, pp 36-48.

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

4. 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, January 1969.

5. Moore, Raymond K., Thomas W. Kennedy, and W. Ronald Hudson, "Factors Affecting the Tensile Strength of Cement-Treated Materials," a paper presented at the 49th Annual Meeting of the Highway Research Board, January 1970.

6. Hadley, William O., W. Ronald Hudson, Thomas W. Kennedy, and Virgil L. Anderson, "A Statistical Experiment to Evaluate Tensile Properties of Asphalt-Treated Materials," a paper presented at the Annual Meeting of the Association of Asphalt Paving Technologists, February 1969.

7. Thomas, C. E., W. G. Jones, and W. C. Davis, "Lime and Phosphoric Acid Stabilization in Missouri," Highway Research Record No. 92, Highway Research Board, 1965, pp 43-68.

8. Ladd, C. C., Z. C. Moh, and T. W. Lambe, "Recent Soil-Lime Research at the Massachusetts Institute of Technology," Bulletin 262, Highway Research Board, 1960, pp 64-85.

9. Thompson, M. R., "Lime-Reactivity of Illinois Soils as It Relates to Compressive Strength," Illinois Cooperative Highway Research Program Series No. NP-4, 1964.

10. Pietach, P. E., and D. T. Davidson, "Effects of Lime on Plasticity and Compressive Strength of Representative Iowa Soils," Bulletin 335, Highway Research Board, 1963, pp 11-30.

11. Gallaway, B. M., and S. J. Buchanan, "Lime Stabilization of Clay Soil," Texas Engineering and Experiment Station Bulletin No. 124, 1951.

12. Jan, M. A., and R. D. Walker, "Effect of Lime, Moisture and Compaction on a Clay Soil," Highway Research Record No. 29, Highway Research Board, 1963, pp 1-12.

13. Jones, C. W., "Stabilization of Expansive Clay With Hydrated Lime and With Portland Cement," Bulletin 193, Highway Research Board, 1958, pp 40-47.

14. Brand, W., and W. Schoenberg, "Impact of Stabilization of Loess with Quicklime on Highway Construction," Bulletin 231, Highway Research Board, 1959, pp 18-23.

15. Herrin, M., and H. Mitchell, "Lime-Soil Mixtures," Bulletin 304, Highway Research Board, 1961, pp 99-138.

16. Thompson, M. R., "Factors Influencing the Plasticity and Strength of Lime-Soil Mixtures," Bulletin 492, Engineering Experiment Station, University of Illinois, 1967.

17. Diamond, S., and E. B. Kinter, "Mechanisms of Soil-Lime Stabilization: An Interpretive Review," Highway Research Record No. 92, Highway Research Board, 1965, pp 83-95.

18. Eades, J. L., F. P. Nichols, Jr., and R. 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.

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

20. Dawson, R. F., and C. McDowell, "A Study of an Old Lime-Stabilized Gravel Base," Bulletin 304, Highway Research Board, 1961, pp 93-98.

21. Walker, R. D., and C. Karabulut, "Effect of Freezing and Thawing on Unconfined Compressive Strength of Lime-Stabilized Soils," Highway Research Record No. 92, Highway Research Board, 1965.

22. Mitchell, J. K., and D. R. Hooper, "Influence of Time Between Mixing and Compaction on Properties of a Lime-Stabilized Expansive Clay," Bulletin 304, Highway Research Board, 1961, pp 14-31.

23. Melvyn, D. R., and D. T. Davidson, "Relation of Strength to Composition and Density of Lime-Treated Clayey Soils," Bulletin 304, Highway Research Board, 1961, pp 65-75.

24. Hoover, J. M., R. L. Handy, and D. T. Davidson, "Durability of Soil-Lime-Fly-Ash-Mixtures Compacted Above Standard Procter Density," Bulletin 193, Highway Research Board, 1958, pp 1-11.

25. McDowell, C., "Properties of Lime for Soil Stabilization," Foundations for Pavements and Lightweight Structures, Part II, Reducing Volume Change and Strengthening of Clay Soil Foundations, Texas Highway Department, October 1966.

26. Wang, J. W. H., D. T. Davidson, E. A. Rosauer, and M. Mateos, "Comparison of Various Commercial Limes for Soil Stabilization," Bulletin 335, Highway Research Board, 1963, pp 65-79.

27. Lu, L. W., D. T. Davidson, R. L. Handy, and J. G. Laguros, "The Calcium-Magnesium Ratio in Soil-Lime Stabilization," Proceedings, Vol 36, Highway Research Board, 1957.

28. Davidson, L. K., T. Demirel, and R. L. Handy, "Soil Pulverization and Lime Migration in Soil-Lime Stabilization," Highway Research Record No. 92, Highway Research Board, 1965, pp 103-117.

29. Laguros, J. G., D. T. Davidson, et. al., "Evaluation of Lime for Stabilization of Loess," Proceedings, American Society of Testing and Materials 56: 1301, 1956.

30. Wang, J. W. H., M. Mateos, and D. T. Davidson, "Compactive Effects of Hydraulic, Calcitic and Dolomitic Limes and Cement in Soil Stabilization," Highway Research Record No. 29, Highway Research Board, 1963, pp 42-54.

31. McDowell, C., "Development of Lime Stabilization for Improvement of Load Carrying Capacities of Pavements," Foundations for Pavements and Lightweight Structures, Part II, Reducing Volume Change and Strengthening of Clay Soil Foundations, Texas Highway Department, October 1966.

32. Highway Research Board Lime and Lime-Fly Ash Soil Stabilization Committee, "Stabilization of Soils with Lime, Lime-Fly Ash and Other Lime Reactive Material," Foundations for Pavements and Lightweight Structures, Part II, Reducing Volume Change and Strengthening of Clay Soil Foundations, Texas Highway Department, October 1966.

33. McDowell, C., "Evaluation of Soil-Lime Stabilization Mixtures," Foundations for Pavements and Lightweight Structures, Part II, Reducing Volume Change and Strengthening of Clay Soil Foundations, Texas Highway Department, October 1966.

34. Eades, James L., and Ralph E. Grim, "A Quick Test to Determine Lime Requirements for Lime Stabilization," Highway Research Record No. 139, Highway Research Board, 1966, pp 61-72.

35. Highway Research Board Lime and Lime-Fly Ash Soil Stabilization Committee, "Recommended Lime Stabilization Practices," Foundations for Pavements and Lightweight Structures, Part II, Reducing Volume Change and Strengthening of Clay Soil Foundations, Texas Highway Department, October 1966.

36. Mateos, M., and D. T. Davidson, "Compaction Characteristics of Soil-Lime-Fly-Ash-Mixtures," Highway Research Record No. 29, Highway Research Board, 1963, pp 27-41.

37. McDowell, C., and W. H. Moore, "Improvement of Highway Subgrades and Flexible Bases by the Use of Hydrated Lime," Foundations for Pavements and Lightweight Structures, Part II, Reducing Volume Change and Strengthening of Clay Soil Foundations, Texas Highway Department, October 1966.

38. Anday, M. C., "Accelerated Curing for Lime-Stabilized Soils," Bulletin 304, Highway Research Board, 1961, pp 1-13.

39. Anday, M. C., "Curing Lime-Stabilized Soils," Highway Research Record No. 29, Highway Research Board, 1963, pp 13-23.

40. Davidson, D. T., M. Mateos, and H. F. Barnes, "Improvement of Lime Stabilization of Montmorillonitic Clay Soils with Chemical Additives," Bulletin 262, Highway Research Board, 1960, pp 33-50.

41. Daniel, Cuthbert, "Sequences of Fractional Replicates," American Statistical Association Journal, Vol 57, June 1962, p 408.

42. Texas Highway Department, Manual of Testing Procedures, Vol 1, Materials and Test Division, Test Method Tex-206-F, Revised Edition, 1966.

APPENDICES

APPENDIX 1

PROPERTIES AND GRADATIONS OF MATERIALS USED IN EXPERIMENT

APPENDIX 1. PROPERTIES AND GRADATIONS OF MATERIALS USED IN EXPERIMENT

LIME

The lime used in the experiment was a hydrated calcitic lime manufactured by the Austin White Lime Company, Austin, Texas. The following properties were reported by Texas Highway Department laboratories.

Composition	Percentage by Weight
$Ca(OH)_2$	92.80
CaO	0.0
Free water content, H_2O	1.31
$CaCO_3$	4.66
Inert matter, SiO_2 etc.	1.22
Retained on No. 30 sieve	0.0

CLAY

The clay used is known locally as Taylor Marl and is described as follows:

Liquid limit	59
Plastic limit	18
AASHO classification	A-7
Unified classification	CH
Specific gravity	2.67

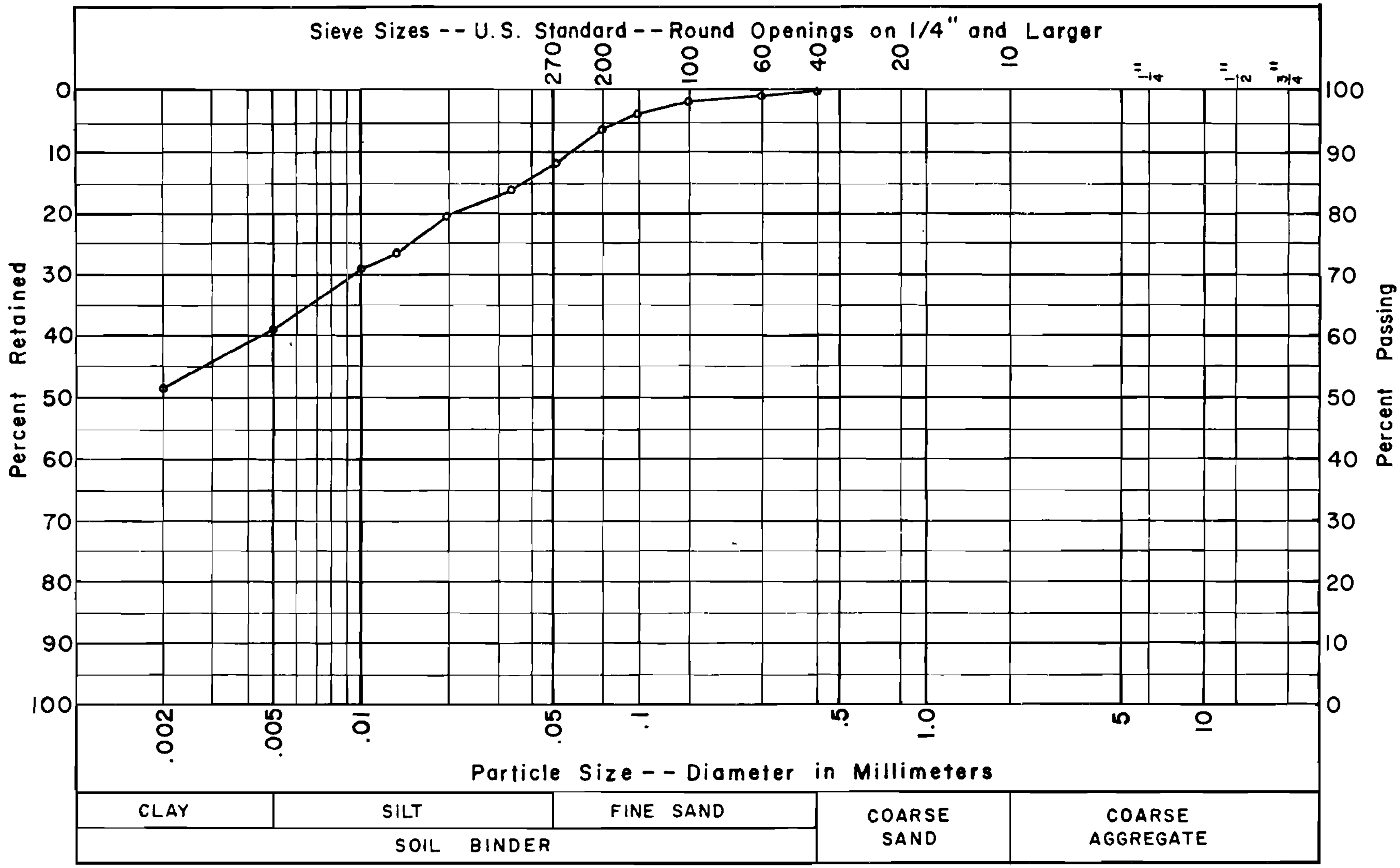
For grain size distribution see page 84.

GRAVEL

The aggregate used in the experiment was a rounded, pit run gravel known locally as Seguin gravel. It is quarried near Seguin, Texas, and is currently used as base material. Its properties are as follows:

GRAIN SIZE DISTRIBUTION CURVE

TAYLOR MARL CLAY



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 lbs/ft^3
Wet Ball Mill	37.2
Los Angeles abrasion	(100 rev.) 7.2 (50 rev.) 27.3
50 low optimum moisture	7.3%
Liquid limit*	21.3%
Plastic index*	7.4%
Linear shrinkage*	5.6%

AGGREGATE GRADATIONS

The aggregations used in this experiment are shown in the following tabulations:

15% Clay Gradation

Sieve Size	Percent Passing by Weight
7/8 inch	100
1/2 inch	85
3/8 inch	74
4 inches	58
10 inches	43
40 inches	28
80 inches	23
200 inches**	15

50% Clay Gradation

Sieve Size	Percent Passing by Weight
7/8 inch	100

---

*Atterberg limits tests were conducted on material passing the No. 40 sieve.

**Material passing the No. 200 sieve was considered to be the clay binder, a mixture of silt and clay minerals.

50% Clay Gradation (Continued)

Sieve Size	Percent Passing by Weight
1/2 inch	91
3/8 inch	85
4 inches	76
10 inches	67
40 inches	58
80 inches	55
200 inches*	50

---

*Material passing the No. 200 sieve was considered to be the clay binder, a mixture of silt and clay minerals.

APPENDIX 2

PREPARATION OF THE SPECIMENS

APPENDIX 2. PREPARATION OF THE SPECIMENS

BATCHING AND MIXING PROCEDURE

(1) Oven dry the clay at 140° C; pulverize the dried clay and screen with No. 200 sieve, rejecting all sizes which are retained on the sieve. Oven dry the aggregate at 140° C and screen into appropriate fractions as required by experiment gradation specifications.

(2) Select the gradation to be used. Batch the material by weight in the following manner:

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

  (b) Weigh the portion of aggregate which passes the No. 10 sieve and store in a different container.

(3) On the day before mixing and compacting, weigh out the appropriate amount of lime (2, 4, and 6 percent by total weight of aggregate) for each specimen and store in a separate container. Seal the container to preserve the freshness of the lime.

(4) Hand mix the lime with the dry material which passed the No. 10 sieve.

(5) Add the required mixing water (percentage based on the total weight of aggregate and lime) to the coarse fraction of aggregate (retained on the No. 10 sieve) and mix until the aggregate surfaces are wet.

(6) Add the premixed fines and lime to the wet coarse aggregate. Hand mix briefly to distribute moisture uniformly throughout the fines.

(7) Machine mix for one minute and then remove the fines stuck to the bottom of the bowl; mix an additional one and one-half minutes. (The mixing procedure in the experiment used a Model AS-200 machine manufactured by the Hobart Company, Troy, Ohio.)

COMPACTION PROCEDURES

Gyratory Shear Compaction

(1) Coat the mold and base plate with a thin layer of kerosene and place a circular-shaped paper at the bottom of the mold to avoid losing fines during gyration.

(2) Place the first layer of material in the mold, keeping the coarser aggregates away from the walls of the mold. Pour the remainder of the material into the mold, punching several times with a rod. Level the top of the mold with a thin layer of fines.

(3) Put another rounded paper at the top of the leveled material and place the mold directly below the ram of the compactor.

(4) Apply pressure to the specimen until 40 psi is reached on the low pressure gage. Gyrate the specimen three times and stop. Repeat until 75 psi, in the case of the lower compactive effort, or 125 psi, in the case of the higher compactive effort, is registered during gyration.

(5) Release the pressure in the low pressure system. Now, at approximately one stroke per second, increase the pressure to 200 pounds, as measured on the high pressure gage. Then release the pressure and remove the ram from the mold.

(6) Take the 4 x 2-inch specimen from the mold using the extractor. Details and specifications for the gyratory shear compactor can be seen in Ref 42.

Automatic Rainhart Impact Compaction

(1) Proceed in the same manner as in Steps 1 and 2 for the gyratory shear compaction.

(2) Set the specified number of blows in the automatic counter. For low compactive effort set 35 blows and for high compactive effort set 75 blows.

(3) After the mixture is compacted, apply a static leveling load of 1,000 pounds, using a mechanical screw jack for leveling the specimen.

(4) Remove the specimen from the mold using the extruding apparatus.

CURING AND TESTING PROCEDURE

(1) After extruding it from the compaction mold, weigh the specimen and measure its height and diameter.

(2) Wrap the specimen with a commercially available PVC film or leave it as extruded from the mold, according to the type of curing desired for each specimen.

(3) Store the specimen in the environmental chamber at 40° F, in the air-conditioned laboratory at 75° F, or in an oven at 110° F, according to the curing temperature desired.

(4) Remove the specimen from the curing temperature after 14, 28, or 42 days according to curing time and remove PVC film. Weigh the specimen and measure its height and diameter.

(5) Allow the specimen to dry at 75° F for four days in order to stabilize moisture content for all specimens at approximately the same level and thus eliminate the influence of moisture content on testing.

(6) Test the specimen at 75° F ± 2° F by placing a preload of 25 pounds on the specimen and then loading at a rate of 2 inches per minute.

APPENDIX 3

FACTORS AND INTERACTIONS ANALYZED IN EXPERIMENT

APPENDIX 3. FACTORS AND INTERACTIONS ANALYZED IN EXPERIMENT*

100 Percent Clay, Block 1

Main Effects	Two-Factor Interactions		Confounded Three-Factor Interactions
A	A×B	B×G	A×B×C - E×F×G
B	A×C	C×E	A×B×G - C×E×F
C	A×E	C×F	A×B×E - C×F×G
E	A×F	C×G	A×B×F - C×E×G
F	A×G	E×F	A×C×G - B×E×F
G	B×C	E×G	A×C×E - B×F×G
	B×E	F×G	A×C×F - B×E×G
	B×F		A×E×G - B×C×F
			A×F×G - B×C×E
			A×E×F - B×C×G

Clay-Gravel Mixtures, Block 2

Main Effects	Two-Factor Interactions		Three-Factor Interactions	
A	A×B	C×E	A×B×J	B×F×J
B	A×C	C×F	A×C×J	B×G×J
C	A×E	C×G	A×E×J	C×E×J
E	A×F	C×J	A×F×J	C×F×J
F	A×G	E×F	A×G×J	C×G×J
G	A×J	E×G	B×C×J	E×F×J
J	B×C	E×J	B×E×J	E×G×J
	B×E	F×G		
	B×F	F×J		
	B×G	G×J		
	B×J			

---

*In a half-replicate, each effect is totally confused with another effect; in a quarter-replicate each effect is totally and mutually confused with three other effects. Effects which are confused in this way are termed <u>ALIASES</u>. Theoretically, the magnitude of an individual effect can be assigned to any or all effects in its alias set; practically, however, when common sense and engineering judgment are applied, one effect in an alias set can usually be selected as the chief contributor. Effects shown in this appendix have been assumed to be the most important effect in each alias set.

Clay-Gravel Mixture, Block 2 (Continued)

Confounded
Three-Factor Interactions

A×B×C - E×F×G
A×B×G - C×E×F
A×B×E - C×F×G
A×B×F - C×E×G
A×C×G - B×E×F
A×C×E - B×F×G
A×C×F - B×E×G
A×E×G - B×C×F
A×F×G - B×C×E
A×E×F - B×C×G

Clay and Clay-Gravel, Block 3

Main Effects

A
B
C
D
E
F
G
H

Two-Factor Interactions

A×B
A×C
A×C
A×E
A×F
A×G
A×H
B×C
B×D
B×E
B×F
B×G
B×H
C×D
C×E
C×F
C×G
C×H
D×E
D×F
D×G
D×H
E×F
E×G
E×H
F×G
F×H
G×H

Three-Factor Interactions

A×C×D
A×C×F
A×C×H
A×D×E
A×D×G
A×E×F
A×E×H
A×F×G
A×H×G
B×C×D
B×C×F
B×C×H
B×D×E
B×D×G
B×E×F
B×E×H
B×F×G
B×G×H

Confounded
Three-Factor Interactions

C×D×E - F×G×H
C×D×F - E×G×H
C×D×G - E×F×H
C×D×H - E×F×G
C×E×F - D×G×H
C×E×H - D×F×G
C×F×G - D×E×H
C×F×H - D×E×G
C×G×H - D×E×F

Legend of Factors

A - Compactive effort
B - Compaction type
C - Curing procedure
D - Molding water content
E - Lime content
F - Curing temperature
G - Curing time
H - Clay content
J - Treatment type (used in Block 2 in which molding water content and clay content were confounded)

APPENDIX 4

TREATMENT COMBINATIONS

APPENDIX 4. TREATMENT COMBINATIONS

100 Percent Clay, Block 1

Spec	Level of Factor					
No.	A	B	C	E	F	G
1	2	0	2	6	110	2
2*	2	0	2	2	40	2
4	2	0	0	6	110	6
6	0	2	0	2	110	2
7	0	2	2	2	110	6
9	2	2	0	6	40	6
10	0	0	0	6	110	2
11	0	2	2	6	110	2
12**	0	0	0	6	75	4
13**	2	2	2	4	75	6
14**	0	0	0	4	110	4
15**	2	2	2	4	75	2
17**	0	0	0	4	75	2
18**	2	2	2	4	75	4
19	0	2	0	6	40	2
20*	0	2	0	6	40	2
21**	2	2	2	4	110	4
22	2	0	2	2	110	6
23	0	0	2	2	110	2
24	2	2	2	2	110	2
25**	0	0	0	4	40	4
26	0	0	2	2	40	6
28**	2	2	2	6	75	4
29	0	2	0	2	40	6
30	0	2	0	6	110	6
31**	0	0	0	4	75	4
32**	2	2	2	2	75	4
33	2	0	0	2	40	6
36*	0	2	0	2	40	6
37**	0	0	0	2	75	4

Spec	Level of Factor					
No.	A	B	C	E	F	G
38	2	0	2	2	40	2
39	0	2	2	2	40	2
40*	2	0	0	2	110	2
41	2	0	0	6	40	2
42	2	0	2	6	40	6
43	2	2	2	6	110	6
44	0	0	2	6	40	2
45	2	2	2	2	40	6
46**	2	2	2	4	40	4
47	2	2	0	6	110	2
49	0	0	0	6	40	6
50	0	0	0	2	110	6
51	0	0	0	2	40	2
52**	0	0	0	4	75	6
53	0	0	2	6	110	6
54	0	2	2	6	40	6
55	2	2	0	2	40	2
56	2	0	0	2	110	2
57	2	2	0	2	110	6
58	2	2	2	6	40	2

Note: Factors D and H were at the following levels for this block.

D = 20
H = 100

---

* Duplicate specimens.

** Midpoint specimens.

Clay-Gravel Mixtures, Block 2

Spec.		Level of Factor					
No.	A	B	C	E	F	G	J
60	2	2	0	6	110	2	2
61**	2	2	2	4	75	2	0
63	2	2	2	2	110	2	2
64	2	0	0	2	40	6	0
66	2	0	0	2	40	6	2
67*	2	0	0	2	40	6	0
69	0	0	2	6	110	6	0
70*	2	2	0	2	110	6	0
71	0	2	0	6	40	2	2
72**	0	0	0	4	75	2	0
73	2	2	2	6	40	2	0
74	0	0	0	2	40	2	0
76	0	2	2	2	40	2	0
77**	2	2	2	4	75	6	2
78	0	0	0	2	110	6	2
79	0	0	2	2	40	6	2
81	2	2	0	2	110	6	0
83	0	2	2	2	110	6	2
84	2	2	0	2	110	6	2
85	2	0	2	6	40	6	0
86	2	2	0	2	40	2	2
87	2	0	0	6	110	6	0
88	0	2	0	2	110	2	2
89**	0	0	0	4	40	4	0
90	0	2	2	6	40	6	0
91	0	0	2	6	110	6	2
92	0	2	2	6	110	2	2
93	2	2	0	2	40	2	0
94**	2	2	2	2	75	4	2
95	0	2	2	6	40	6	2
96	2	2	2	6	110	6	2
97	0	0	2	6	40	2	2
98	0	2	2	2	40	2	2
99*	0	0	0	2	75	4	0
100	0	0	0	6	110	2	2

Spec.		Level of Factor					
No.	A	B	C	E	F	G	J
101	2	2	2	6	40	2	2
103**	2	2	2	2	75	4	0
104**	0	0	0	4	110	4	0
105**	0	0	0	6	75	4	0
107**	0	0	0	6	75	4	2
108	2	0	0	6	40	2	2
109**	0	0	0	6	75	4	2
110**	0	0	0	2	75	4	2
111	0	2	0	6	40	2	0
112	2	2	0	6	40	6	0
113	0	2	0	2	40	6	0
114*	0	2	0	2	40	6	2
115**	2	2	2	6	75	4	0
116	0	0	2	2	40	6	0
118	2	2	2	6	110	6	0
119	0	0	2	2	110	2	0
120**	2	2	2	4	75	2	2
121	2	0	0	6	30	2	0
123**	2	2	2	6	75	4	2
124	0	2	0	2	40	6	2
125**	0	0	0	4	75	2	2
126	0	0	0	2	40	2	2
127	2	0	2	6	40	6	2
128	0	0	2	2	110	2	2
130	2	2	0	6	40	6	2
132	2	0	2	2	110	6	2
133	2	0	0	2	110	2	2
135**	2	2	2	4	110	4	0
136*	2	0	2	2	40	2	2
137*	0	0	0	2	110	6	2
138**	2	2	2	4	75	6	0
139	2	0	2	2	110	6	0
140	0	2	0	2	110	2	0
142	2	0	0	6	110	6	2
143	2	0	2	2	40	2	0

(Continued)

---

* Duplicate specimens.

** Midpoint specimens.

Clay-Gravel Mixtures, Block 2 (Continued)

Spec.	Level of Factor						
No.	A	B	C	E	F	G	J
144**	0	0	0	4	75	6	2
145**	0	0	0	4	75	4	0
146	2	0	2	2	40	2	2
147**	2	2	2	4	40	4	2
148**	2	2	2	4	40	4	0
150**	0	0	0	4	110	4	2
151	2	2	0	6	110	2	0
152	0	2	2	6	110	2	0
153	2	2	2	2	110	2	0
154	2	2	2	2	40	6	2
155	2	0	2	6	110	2	0
156	0	2	2	2	110	6	0
157	0	0	0	2	110	6	0
158**	0	0	0	4	40	4	2
159	2	0	2	6	110	2	2
160**	0	0	0	4	75	6	0
161**	2	2	2	4	75	4	2
162*	2	2	2	2	40	6	2
163	0	0	0	6	110	2	0
164	0	0	0	6	40	6	2
165	0	0	2	6	40	2	0
166**	2	2	2	4	75	4	0
167	2	0	0	2	110	2	0
168	0	0	0	6	40	6	0
169	2	2	2	2	40	6	0
170**	2	2	2	4	110	4	2
171*	0	0	0	6	40	6	0
172*	0	2	2	2	110	6	0
173	0	2	0	6	110	6	0
174	0	2	0	6	110	6	2

Note: J denotes the levels of D and H as follows:

when J = 0,
D = 16 and
H = 50

when J = 2,
D = 8 and
H = 15

---

* Duplicate specimens.

** Midpoint specimens.

Clay and Clay-Gravel, Block 3

Spec. No.	Level of Factor A	B	C	D	E	F	G	H
175	0	2	0	12	6	40	2	15
176**	0	0	0	10	4	75	2	50
177*	2	2	0	10	2	40	2	15
178	2	0	0	10	2	110	6	15
179**	2	2	2	12	4	75	4	50
181	0	2	2	12	6	40	6	15
182	2	2	2	10	6	40	2	15
184	0	2	2	12	2	40	2	15
185	2	2	0	12	2	110	2	15
186**	0	0	0	10	6	75	4	50
187	0	0	2	10	6	110	2	100
188	2	0	2	10	6	40	6	100
189	0	0	2	12	2	40	6	100
190**	0	0	0	10	2	75	4	50
191	0	0	0	12	2	40	2	100
192	2	2	0	10	6	110	6	100
193**	0	0	0	10	4	75	6	50
194	2	2	2	12	2	40	6	100
196	0	2	0	12	6	110	2	100
197	2	0	0	12	2	40	6	15
198	2	0	2	12	6	110	6	100
199	0	2	0	10	2	40	6	100
200**	2	2	2	12	6	75	4	50
201	0	2	0	12	2	40	6	15
202	2	2	0	10	2	40	2	15
203**	2	2	2	12	4	110	4	50
204*	2	0	0	10	6	110	2	15
205**	2	2	2	12	4	75	6	50
207	0	2	2	10	2	110	2	15
208**	2	2	2	12	4	75	2	50
209	0	2	0	10	2	110	6	16
210	0	0	0	10	6	110	6	100
211	2	0	0	12	6	40	2	15
213	0	0	2	12	2	110	6	15
214	2	0	2	12	6	40	6	15
215	2	0	2	12	2	110	2	100
216	2	2	0	12	2	40	2	100
217	0	2	2	12	6	110	6	100
218	2	2	2	10	2	40	6	15
219**	2	2	2	12	4	75	4	100
220	0	0	2	10	6	40	2	15
221**	0	0	0	10	4	75	4	15
222	0	0	0	10	2	110	2	100
223**	0	0	0	10	4	40	4	50
224*	0	2	2	10	6	110	6	15
225	2	0	0	10	2	40	6	100
226	2	2	2	12	2	110	6	15
227	0	2	0	10	6	110	2	15
228	0	0	2	12	6	110	2	15
229	2	2	2	10	2	110	6	100
230	2	0	0	10	6	110	2	15
231**	0	0	0	10	4	75	4	50
232**	2	2	2	12	4	75	4	15
233*	2	2	0	12	2	110	2	15
234	2	0	2	10	6	110	6	15
235	0	2	2	10	2	40	2	100
236	2	0	2	10	2	110	2	15
237	2	2	0	12	6	40	6	100
238*	0	2	0	12	6	110	2	100
239	0	0	0	12	6	110	6	15
240	2	2	0	10	2	110	2	100
241	2	0	2	12	2	40	2	15
242	2	0	0	12	2	110	6	100
244	0	2	2	12	2	110	2	110
245**	0	0	0	10	4	110	4	50
246	2	2	0	12	6	110	6	15
247*	2	2	2	12	4	40	4	50
249	2	2	2	12	6	40	2	100
250	0	2	2	10	6	110	6	15
251	0	0	0	10	2	40	2	15
253	2	0	2	10	2	40	2	100
254*	2	2	2	12	6	110	2	15
256	2	2	2	12	6	110	2	15
257	0	0	0	12	6	40	6	100
258	0	0	0	10	6	40	6	15
259**	0	0	0	10	4	75	4	100
260	0	0	2	10	2	40	6	15
261	0	0	2	12	6	40	2	100
262	0	2	0	12	2	110	6	100
263	0	2	2	10	6	40	6	100
264	2	0	0	10	6	40	2	100
266	0	0	0	12	2	110	2	15
267**	2	2	2	12	2	75	4	50
268*	2	2	0	12	6	110	6	15
269	2	2	0	10	6	40	6	15
270	0	2	0	10	6	40	2	100
271	2	0	0	12	6	110	2	100
272	0	0	2	10	2	110	6	100
273*	2	0	0	12	2	110	6	100
274	2	2	2	10	6	110	2	100

---

* Duplicate specimens.

** Midpoint specimens.

APPENDIX 5

MISSING VALUE RESULTS

APPENDIX 5. MISSING VALUE RESULTS

A second series of specimens was prepared and tested. These results were used to replace observations which were lost in the original experiment. Each specimen was duplicated twice, and an average of the strengths was used as the replacement observation. In addition, five specimens with valid results in the original experiment were randomly chosen to be duplicated as a check on the error between experiments. The results of the second experiment and the test for errors are summarized in the following tabulations.

Results of Second Experiment

Original Specimen No.	Average Indirect Tensile Strength
1	318.0
6	67.6
14	91.6
41	149.5
69	91.0
88	48.6
96	75.6
140	35.8
175	19.4

Tests for Experimental Error

Original Experiment

Mean Squares from Duplicates (30 Specimens) = 36.85

Second Experiment

Mean Squares of Duplicated Specimens (9 Specimens) = 178.63

Mean Squares of Duplicates Between Experiments (5 Specimens) = 374.0

F Tests

$$F_{(5,9)} = \frac{374.0}{178.63} = 2.09$$

significant at $\alpha = 0.25$
not significant at $\alpha = 0.10$

$$F_{(9,30)} = \frac{178.63}{36.85} = 4.85$$

significant at $\alpha = 0.0005$

On the basis of the above tests and from past experiences, it is concluded that the test values from the replacement specimens can be substituted into the original experiment.

APPENDIX 6

ANALYSES OF VARIANCE

TABLE A6.1. ANALYSIS OF VARIANCE FOR TENSILE STRENGTH, BLOCK 1

Source of Variation*	Degree of Freedom	Mean Squares	F Value	Significance Level, %
B	1	59512	1933.0	0.1
AB	1	14012	455.0	0.1
A	1	13862	456.0	0.1
CF	1	10310	335.0	0.1
AEG - BCF	1	6950	226.0	0.1
F	1	6110	199.0	0.1
ACF - BEG	1	5212	169.0	0.1
EG	1	4812	156.0	0.1
AC	1	3548	115.0	0.1
BC	1	2968	96.4	0.1
AE	1	2838	92.2	0.1
C	1	2268	73.7	0.1
ABE - CFG	1	1756	57.0	0.1
EF	1	1256	40.8	0.1
CG	1	1190	38.7	0.1
ABF - CEG	1	1020	33.1	0.5
ABC - EFG	1	980	31.8	0.5
ACG - BEF	1	920	29.9	0.5
BF	1	914	29.7	0.5
AEF - BCG	1	852	27.7	0.5
AG	1	810	26.3	0.5
AFG - BCE	1	436	14.1	1.0
AF	1	382	12.4	5.0
CE	1	313	10.2	5.0
G	1	282	9.16	5.0
Residual	6	82		
Within Treatments Treated Alike	6	31		

*Legend of Factors

A - Compactive effort
B - Compaction type
C - Curing procedure
D - Moisture content
E - Lime content
F - Curing temperature
G - Curing time
H - Clay content
J - Treatment type

TABLE A6.2. ANALYSIS OF VARIANCE FOR TENSILE STRENGTH, BLOCK 2

Source of Variation*	Degree of Freedom	Mean Squares	F Value	Significance Level, %
F	1	8846	181.0	.05
B	1	5166	105.0	.05
BJ	1	4092	83.5	.05
E	1	1844	37.6	.05
CF	1	922	18.8	0.1
BE	1	784	16.0	0.5
BFJ	1	578	11.8	0.5
J	1	395	8.05	5.0
BF	1	324	6.62	5.0
Residual	54	58		
Within treatments treated alike	12	49		

*<u>Legend of Factors</u>

A - Compactive effort
B - Compaction type
C - Curing procedure
D - Moisture content
E - Lime content
F - Curing temperature
G - Curing time
H - Clay content
J - Treatment type

TABLE A6.3. ANALYSIS OF VARIANCE FOR TENSILE STRENGTH, BLOCK 3*

Source of Variation**	Degree of Freedom	Mean Squares	F Value	Significance Level, %
B	1	2008	72.4	.05
F	1	1976	71.3	.05
DH	1	1455	52.5	.05
H	1	1269	45.8	.05
A	1	721	26.0	.05
EH	1	672	24.2	.05
CF	1	658	23.7	.05
BH	1	615	22.2	.05
AH	1	580	20.9	.1
AB	1	481	17.4	.5
AF	1	373	13.5	.5
FH	1	346	12.5	.5
DF	1	257	9.3	1.0
CFH - DEG	1	222	8.0	5.0
AD	1	210	7.6	5.0
BD	1	184	6.6	5.0
BF	1	178	6.4	5.0
Residual	46	22		
Within treatments treated alike	12	28		

---

*Same as Table 7 in text.

**Legend of Factors

A - Compactive effort
B - Compaction type
C - Curing procedure
D - Moisture content
E - Lime content
F - Curing temperature
G - Curing time
H - Clay content
J - Treatment type

THE AUTHORS

S. Paul Miller was formerly a Research Engineer Assistant for the Center for Highway Research at The University of Texas at Austin and is presently in the United States Air Force.

Thomas W. Kennedy is an Associate Professor of Civil Engineering at The University of Texas at Austin. His experience includes work with the Illinois Division of Highways and research at the University of Illinois and the Center for Highway Research at The University of Texas at Austin, where he has conducted extensive investigations in the areas of (1) highway geometrics, (2) concrete durability, (3) tensile strength of stabilized subbase materials, and (4) time-dependent deformation of concrete and has contributed numerous publications in the field of transportation engineering. He is a member of several professional societies and has participated in committee work for the Highway Research Board and the American Concrete Institute.

W. Ronald Hudson is an Associate Professor of Civil Engineering and Associate Dean of the College of Engineering at The University of Texas at Austin. He has had a wide variety of experience as a research engineer with the Texas Highway Department and the Center for Highway Research at The University of Texas at Austin and was Assistant Chief of the Rigid Pavement Research Branch of the AASHO Road Test. He is the author of numerous publications and was the recipient of the 1967 ASCE J. James R. Croes Medal. He is presently concerned with research in the areas of (1) analysis and design of pavement management systems, (2) measurement of pavement roughness performance, (3) slab analysis and design, and (4) tensile strength of stabilized subbase materials.