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

by

Humberto J. Pendola
Thomas W. Kennedy
W. Ronald Hudson

Research Report Number 98-3

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

Research Project 3-8-66-98

conducted for

The Texas Highway Department

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

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

September 1969

PREFACE

This is the third in a series of reports dealing with the findings of a research project concerned with the evaluation of properties of stabilized subbase materials. This report presents some of the factors which are important in determining the strength of cement-treated materials and reports the findings of an evaluation by indirect tensile test of nine factors thought to affect the tensile properties of cement-treated materials. The effects of these nine factors and their interactions on tensile properties are summarized here, as are the statistical design and analysis used in the evaluation.

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

Future reports will be concerned with a preliminary investigation of the tensile characteristics and behavior of lime-treated materials and with a 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 these three materials when subjected to static loads and dynamic repeated loads, (2) correlation of indirect tensile test parameters with parameters from standard Texas Highway Department tests, (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.

Humberto J. Pendola
Thomas W. Kennedy
W. Ronald Hudson

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LIST OF REPORTS

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

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

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

ABSTRACT

This study was performed to evaluate the factors and interactions affecting the tensile properties of cement-treated materials. Nine factors were investigated: cement content, molding water content, aggregate gradation, curing time, curing temperature, type of aggregate, type of curing, type of compaction, and compactive effort. The first five were investigated at three levels and the last four at two levels. A statistically designed fractional factorial experiment was run for the evaluation.

The parameter considered as a primary indicator of the tensile properties of cement-treated materials was indirect tensile strength. Analysis of variance was used to determine the significance for all the main factors, two-factor interactions, and three-factor interactions. The highly significant effects, ($\alpha = 0.01$) are discussed in this report, and tables of factors and interactions significant at alpha levels of 1 and 5 percent are shown. As a result of the regression analysis, an equation which predicts values of the indirect tensile strength within the inference space defined by the experiment was developed.

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CHAPTER 1. INTRODUCTION

The use of cement-treated materials in the construction of pavements has grown significantly in the last fifty years, due to several factors. One of the most important of the factors responsible for the widespread and increasing use of stabilized materials is the scarcity of suitable granular materials at a time when tremendous quantities are needed for building new highways. Another factor is the need for a stable working base which will minimize construction delays due to adverse weather conditions. Finally, there is the need for improved pavement performance and reduced maintenance cost (Refs 4 and 5).

One aspect of pavement performance and behavior which has received little attention concerns the tensile properties of the materials used in the various layers of a pavement. Both theoretical considerations and field observations demonstrate the importance of these tensile characteristics, yet little consideration is given to them in the design and evaluation of pavements (Refs 10 and 11). In addition, little information is available on the tensile characteristics of cement-treated materials, possibly because of the lack of simple, effective tensile testing techniques.

In an attempt to develop information on the tensile properties 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 evaluated the indirect tensile test and applied it to the evaluation of the tensile behavior of stabilized pavement materials (Refs 6, 7, and 8).

The purpose of this study was to describe the application of this test to cement-treated materials and to determine the factors and interactions between factors which significantly affect the tensile properties of cement-treated materials under static load.

CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

In general, cement-treated materials are mixtures of pulverized soils, portland cement, and water which are compacted to high unit weight and protected against moisture loss during a specified curing period. Although many terms, such as soil-cement, cement-modified soils, and plastic soil-cement, are used to designate a particular type of mixture (Refs 12, 13, 14, and 15), it is felt that all of these materials can be defined as cement-treated, and that term is used throughout this report.

GENERAL EFFECTS

The addition of portland cement to a soil usually results in a material with engineering characteristics which are significantly improved as compared to the properties of the unaltered soil. In general, cement-treated soils exhibit the following changes (Ref 12):

(1) reduced plasticity indices,

(2) increased plastic limits,

(3) reduced liquid limits (for soils with liquid limits greater than 40) or increased liquid limits (for soils with liquid limits less than 40),

(4) increased strengths,

(5) reduced permeabilities, and

(6) reduced volume changes.

MECHANISM OF PORTLAND CEMENT STABILIZATION

The improvement of the engineering properties of cement-treated materials is often attributed solely to the hydration of the portland cement. This concept assumes that the soil is inert, but in reality it is not, since certain physical-chemical reactions occur between the cement, water, and soil. The four mechanisms of cement stabilization are hydration, cation exchange, carbonation, and pozzolonic reactions (Refs 12, 16, 17, 18, and 19). The latter two are of minor importance.

Hydration of Cement

The hydration of cement is by far the most important contributor to the improvement of engineering properties. As the cement hydrates, strong linkages develop between the soil particles and form a more or less continuous skeleton of hard, strong material enclosing a matrix of unaltered soil. This skeleton not only strengthens the treated material but also fills some of the voids and thus reduces permeability and swelling tendencies and increases resistance to the deleterious effects of changes in the ambient moisture conditions (Refs 12 and 18).

Cation Exchange

The first noticeable property change that occurs when cement is mixed with a moist cohesive soil is a marked reduction in the plasticity of the treated material. This is attributed to either a cation exchange or the crowding of additional cations onto the surface of the soil particles. In both cases the electrical charge on the soil particles is altered, and flocculation or aggregation of the soil particles results. This flocculation generally occurs within a few days after mixing and probably is the second most important mechanism of cement stabilization (Refs 12 and 18).

Carbonation

Cementitious materials may be formed by the chemical reaction of carbon dioxide from air with lime generated during hydration of the cement. The reaction results in calcium carbonate, which provides an additional cementing agent (Ref 18).

Pozzolonic Reaction

Additional cementitious material results from the reaction between free lime liberated during hydration and silica or alumina from clay. The lime and the silica or alumina react in the presence of moisture to produce a cementitious material which strengthens the bonds within the treated material, but this reaction is of a long term nature and probably contributes very little to the strength of the mixture (Refs 18 and 19).

FACTORS AFFECTING THE PROPERTIES OF CEMENT-TREATED MIXTURES

Although most soils can be successfully stabilized with cement, the engineering properties of the cement-treated materials may vary widely. These variations result from many factors, the more important of which are

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

Although all these factors affect the properties of the cement-treated mixtures, a review of the literature indicated that the first ten were the most important, providing that reasonable levels were used for the last three. Thus, it was felt that the effect of these ten factors on the tensile properties of cement-treated materials should be investigated.

Although little if any work has been conducted on the effect of these factors on the tensile characteristics of cement-treated materials, numerous studies (Refs 20 through 40) have been made in terms of other engineering properties, e.g., compressive strength and durability characteristics. Summarized below is the current status of knowledge concerning the most significant factors which affect the properties of cement-treated materials.

Effect of Density and Molding Water Content

Density and water content at the time of mixing are directly related to the compressive strength. Previous experiments on fine-grained soils have shown that most soils stabilized with portland cement exhibit a parabolic moisture density curve (Refs 21, 22, and 41). Felt (Ref 21) showed that for either sandy or clayey soils an increase in density of 1 pcf resulted in an increase in compressive strength of approximately 20 psi. However, experiments by Kayyal (Ref 38) showed that strength increased with density up to a certain limit and then a further increase in density produced a decrease in strength.

The molding water content of a cement-treated mixture is important in obtaining the desired compacted density, since maximum densities are obtained at optimum water content (Ref 42). For the coarser aggregates an increase of water content slightly below the optimum produced maximum compressive strength, but the finer soils showed maximum compressive strength when the water content was increased a little above optimum. Generally, gradation influences the optimum moisture content. According to Martin (Ref 23), coarser gradations produced denser mixes and reduced the optimum moisture content.

The fact that strength reaches a maximum and decreases in a manner somewhat like that of the moisture-density curve suggests a strong relationship between density and strength. It was found (Ref 12) that for coarse soils compacted according to the modified AASHO method, strength was not significantly affected by reductions of water below optimum, but for the finer soils, the strength decreased when the water was decreased below the optimum content. However, according to Watson (Ref 43), the basic characteristics of the soil, i.e., gradation, plasticity, etc., had more effect on the compressive strength of a cement-treated mixture than on any other factor. He also stated that increasing the amount of cement in a given soil from 5 to 11 percent produced a greater increase in compressive strength than did the factors of varying density and water content.

Effect of Cement Content

Several experimenters (Refs 21, 24, 25, 43, 44, and 45) have analyzed the effect of cement content on the properties of cement-treated mixtures. The proportion of cement alters the plasticity, the volume change, the susceptibility to frost-heave, the elastic properties, the durability, and other properties in different degrees for different soils.

Felt (Ref 21) varied the cement content from 6 to 30 percent for sands, silts, and clays. As expected, all the soils increased in strength with an increase in cement content; however, the rate of increase varied with the type of soil, with the sand-cement mixture exhibiting the greatest increase. Circeo, Davidson, and Davis (Ref 30) investigated the effect of cement content on the slope of the strength-age relationship. In their experiment it was found that the slope was small at low cement contents and that the slope of the strength-age relationship increased as the cement content increased. Laboratory and field tests performed by Abrams (Ref 24) on two granular base materials treated with various quantities of cement showed that an increase in cement content resulted in an increase in the durability and strength of the materials.

Nussbaum and Larsen (Ref 25) in their experiment on load-deflection characteristics of cement-treated pavements showed that load capacity increased with increased cement content but that the effect was more significant at lower cement contents.

Effect of Type of Soil and Gradation

As previously noted, physical-chemical reactions involving the soil, cement, and water occur; thus, the type of soil should affect the quality and strength of cement-treated materials, not only because of its physical characteristics but also because of its physical-chemical characteristics.

Felt (Ref 21) showed that sandy soils exhibited higher compressive strengths than silty and clayey soils having the same percentages of cement at all ages of curing. Sandy and gravelly soils, however, may react differently with cement depending upon their chemical makeup and surface chemical properties. Some poor reactions are due to a deficiency of fines and the presence of deleterious organic matter (Refs 26 and 27). These deleterious organic compounds, such as nucleic acid and dextrose, generally have a low molecular weight and act as retarders, causing low strengths (Ref 28).

The shape of the soil particles is important since better interparticle friction and a better packing of the mixture are attained when angular aggregates are used instead of aggregates having rounded or smooth surfaces.

McLaren (Ref 46) studied the properties of a wide range of granular materials mixed with small quantities of cement. The results showed that the compressive strength was dependent on the type of materials used. White limestone and slag gave substantially higher strengths than other granular materials.

Catton (Ref 29) found in his experiment that densities and strengths were higher for well-graded coarse type aggregate, than for the fine-type soils, when they were stabilized with portland cement. As liquid limit, plasticity index, and surface area increased, the requirements on the cement to produce a structural material increased (Ref 24).

In a review and evaluation of cement-treated pavements, Mitchell and Freitag (Ref 44) said that the soils that can be hardened satisfactorily with reasonable amounts of cement are those which have approximately the following characteristics:

(1) percent finer than No. 200 sieve - less than 35,
(2) percent passing No. 4 sieve - greater than 55,
(3) maximum size of aggregate - 3 inches,
(4) liquid limit - less than 50 percent, and
(5) plasticity index - less than 25 percent.

Effect of Type of Curing

The type of curing is another important factor which affects the properties of cement-treated mixtures. The type of curing determines the amount of moisture which will be retained in the cement-treated soil mixture during the curing period. Generally, if more moisture is retained during the curing period the strength will be higher (Refs 47 and 48). It has been reported (Ref 12), however, that the influence of moisture is related more to its ability to improve workability and facilitate compaction than it is to the water requirements for hydration, since adequate water for compaction insures adequate water for hydration, provided it is not lost during the curing period. The significant moisture content is, thus, that which prevails at the time of compaction and throughout the curing.

Effect of Length of Curing

Leadabrand (Ref 49) studied the time-compressive strength relationship for two soils at different laboratory curing times of up to five years. He also took cores from field construction projects ranging in age from one to twenty years. It was found that cement-treated mixtures continued to increase in strength with increasing age in a manner similar to concrete.

Circeo, Davidson, and Davis (Ref 30) statistically analyzed the effect of curing time on compressive strength. It was found that the closest correlation for granular cement-treated mixtures was a semi-logarithmic relationship, and for silty and clayey cement-treated mixtures, the closest correlation was a logarithmic relationship between the compressive strength and the curing time. These relationships could be used to predict the compressive strength of soil-cement at a future time of curing. The slope of the strength-age relationship was found to be affected by the physical and chemical properties of the soil, the cement content, and certain chemical additives. Thus, the slope of the strength-age relationship is a good indicator of the quality of cement-treated mixtures.

Effect of Curing Temperature

Clare and Pollard (Ref 31) studied the effect of curing temperature at ages of up to three months for five different soils mixed with 10 percent cement. Their conclusions were: (1) for cement-treated road base constructed in the spring, the strength during the first three months will be 50 percent to 100 percent greater than if the base were constructed in the fall; (2) to get the same strength, less cement is necessary for a soil under tropical rather than temperate conditions; (3) cement-treated materials will harden in cold weather provided that the temperature is not below 0^{o} C; (4) the seven-day strength varies directly with temperature, changing from 2 percent to 2.5 percent with each degree centigrade change in the curing temperature, when the latter is near 25^{o} C; (5) the nature of the strength-age relationship for cohesive soils suggests that hardening is accelerated by increasing temperature (Ref 31).

These findings were corroborated by Dumbleton and Ross (Ref 32), who determined the effect of curing temperature between 0^{o} C and 45^{o} C on the strength and strength-age relationships of a heavy-clay, a silty-clay, and a sand treated with hydrated lime and portland cement. The increase of strength per unit increase of curing temperature was greater at higher rather than at lower temperature ranges for cohesive soils. With noncohesive treated sand, the increase of strength with increase of curing temperature was almost independent of temperature range.

Effect of Method of Compaction and Compactive Effort

Considerable effort has been devoted to the development of laboratory compaction procedures which will satisfactorily duplicate the effects of field compaction. As a result, several compaction procedures are now in use (Refs 38 and 39). These methods differ primarily in terms of the relative magnitudes of shear strain imparted to the specimens.

One common compaction method involves dropping a weight onto the surface of the soil. This process is referred to as impact compaction (Ref 50). Another method involves subjecting the soil to a static load which is built up slowly to some predetermined value and then released. This process is referred to as static compaction and has limited use.

In order to simulate the effect of sheepfoot rollers, a kneading compactor is used. It is effected by building up pressure on a small area of soil to a preselected value, maintaining it briefly, and then gradually releasing the pressure.

Since vibration is an effective means of compacting deposits of granular soils, another process of compaction was developed at The University of Texas at Austin to simulate the effects of vibratory rollers. It is a modification of kneading compaction in which the pressure is maintained and is applied to the soil by oscillating at a high frequency. This process is referred to as vibratory-kneading compaction (Ref 38).

Another method, the gyratory shear compaction, involves the application of a shearing action to a speciman by gyrating a mold while maintaining a static pressure on the sample. This method is currently used by the Texas Highway Department (Ref 51).

Seed and Chan (Ref 52) studied the effect of the method of compaction on the strength of clay samples and El-Rawi (Refs 33 and 34) studied the strength characteristics of a clay, a silt, and a coarse sand stabilized with portland cement using two different methods of compaction, i.e., kneading and impact. Through his study, El-Rawi found that specimens compacted wet of optimum by kneading compaction gave lower unconfined strength and lower cohesion values than those compacted wet of optimum by impact compaction.

Effect of Length of Mixing

Cement-treated pavement bases are frequently constructed using mixed-in-place procedures. The first step consists of pulverizing the soil in place and then adding the desired amount of cement to complete the dry mixing. A portion of the water is then added and the material mixed again. This process may be repeated until the optimum moisture content is achieved. Thus, several passes of the mixing equipment may be necessary, and the process may continue for two hours or more (Refs 14 and 15).

With the thought of simulating field conditions, Felt (Ref 21) dump mixed cement-treated mixtures for different periods of time in the laboratory and then molded and compacted them into test specimens. During the mixing period, water was added to the dry mix in equal increments of time, and after each addition of water the mixture was stirred for about two minutes. The water added in each increment was proportioned so that at the end of the specified time the mixture was at optimum moisture content. Water lost by evaporation was replaced just prior to molding the specimens. It was found that increasing the time of mixing decreased the compressive strength, especially when granular soils were used instead of fine soils, and also that, for durability, intermittent mixing was not as detrimental as long periods of continuous mixing.

Effect of Degree of Pulverization

Certain specifications (Refs 14 and 15) for soil-cement base construction require the soil (exclusive of gravel, stone, etc.) to be pulverized so that 80 percent passes the No. 4 sieve. Felt (Ref 21) ran some experiments directed toward analyzing the effect of clay lumps in the quality of soil-cement mixtures. He found that in some cases air-dried clay lumps added to a moist soil passing No. 4 sieve produced complete failure by disruption of the specimens, as the dry clay lumps absorbed water and swelled during the curing and testing period. When the clay lumps were moist and, thus, in a swelled condition at the time of inclusion in the test specimens, the unpulverized soil had little harmful effect. To eliminate the effect of clay lumps in fine-grained soils, it was recommended that the soil be wetted prior to compaction.

Generally, pulverization of soils improves the mixing uniformity. Baker (Ref 35) ran tests on strength of cement-treated mixtures as a function of mixing uniformity. He found that increasing the uniformity of the mix increased the strength.

Effect of Cement Type

Controlled experiments involving the use of normal and air entraining normal cement with three different soils showed that moisture-density relationships, compressive strengths, and brushing losses in wet-dry and freeze-thaw tests for the two types of cement were similar enough to allow the two types of cement to be used interchangeably in cement stabilization (Ref 21).

Davidson and Bruns (Ref 36) performed some experiments on comparison of normal and high early strength portland cements for soil stabilization. High early strength cements gave higher strengths than normal portland cements at different percentages and at different ages. This strength difference for the two types of cement was more pronounced during the first seven days than after 28 days of curing.

Effect of Repeated Loads

The factors which control the properties of cement-treated materials under repeated loading are by no means clear and well defined. The experimental data available are based on limited conditions and therefore present a rather narrow perspective by which to generalize and correlate the complex pattern of property variations which occur. Previous studies of untreated soils and base course materials under the action of repeated compressive stresses have shown that such factors as stress history, frequency and intensity of repeated stress, and the number of load repetitions may influence the properties significantly.

Nussbaum and Larsen (Ref 37) of the Portland Cement Association, Mitchell and Shen (Ref 53) of the University of California, and several other researchers have been working on different types of cement-treated soils subjected to repeated loads and on the influences of repetitive loading in the properties of cement-treated materials. Repetitive tensile stress tests on cement-treated materials have not yet been run but they will soon be performed on cement and other stabilized materials at The University of Texas Center for Highway Research, as a part of the project "Evaluation of Tensile Properties of Subbases for a New Rigid Pavement Type."

Effect of Shrinkage

Barksdale and Vergnalle (Ref 60) state that the most important factors which influence shrinking in portland cement-stabilized bases are the physical-chemical soil characteristics, amount of cement, compaction moisture content, degree of compaction, and method and time of curing. George (Ref 61) reports that in general, longer curing increases the total shrinkage of sandy soils, but the reverse is true for clayey soils. Shrinkage of soil-cement first decreases with proportion of cement, attains a minimum, and thereafter increases slightly with cement content. He states that it is possible to find an optimum proportion for least amount of shrinkage. Furthermore, it appears that molding moisture content has the most influence on shrinkage and that shrinkage can be reduced by improving compaction of the beam specimens.

SUMMARY OF CURRENT STATUS OF KNOWLEDGE

From the literature review it appears that soil, cement, and water enter into complex physical-chemical reactions which produce a material with engineering properties differing significantly from those of the untreated soil.

In general the literature shows that strength increases with the following:

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

Unfortunately, most of the above findings are for unconfined compressive strengths. Few if any studies have been conducted in terms of tensile strengths. In addition, the above studies have not evaluated a large number of factors simultaneously. Thus, no estimate is available on interactions which may significantly affect the properties of cement-treated materials.

CHAPTER 3. EXPERIMENTAL PROGRAM

The indirect tensile test and its application to stabilized materials were considered and discussed in detail by Hudson and Kennedy (Refs 6 and 7). From this evaluation it was concluded that of the currently available tensile tests, the indirect tensile test has the greatest potential for the evaluation of the tensile properties of highway materials.

Essentially the test consists of applying compressive loads along opposite generators of the cylindrical specimen. This results in a relatively uniform tensile stress perpendicular to and along the diametral plane containing the applied load. Failure usually occurs as splitting along this loaded plane when the tensile stress exceeds the tensile strength of the material.

STANDARD TEST PROCEDURES AND EQUIPMENT

The procedure followed for the testing of the cement-treated specimens is the same as that recommended by Hudson and Kennedy (Refs 6 and 7) with slight modifications (Ref 8).

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 to each end of the strip to prevent any punching to the specimen during testing.

Using the curved strips results in a known loading area and allows the use of the theoretical equations required for evaluating linear elastic materials (Ref 8). The stresses along the principal planes corresponding to the horizontal and vertical axes for a loading strip of 1 inch are plotted in Fig 1. The equations for the stresses at the center of a nominal 4-inch-diameter specimen for this loading configuration reduce to

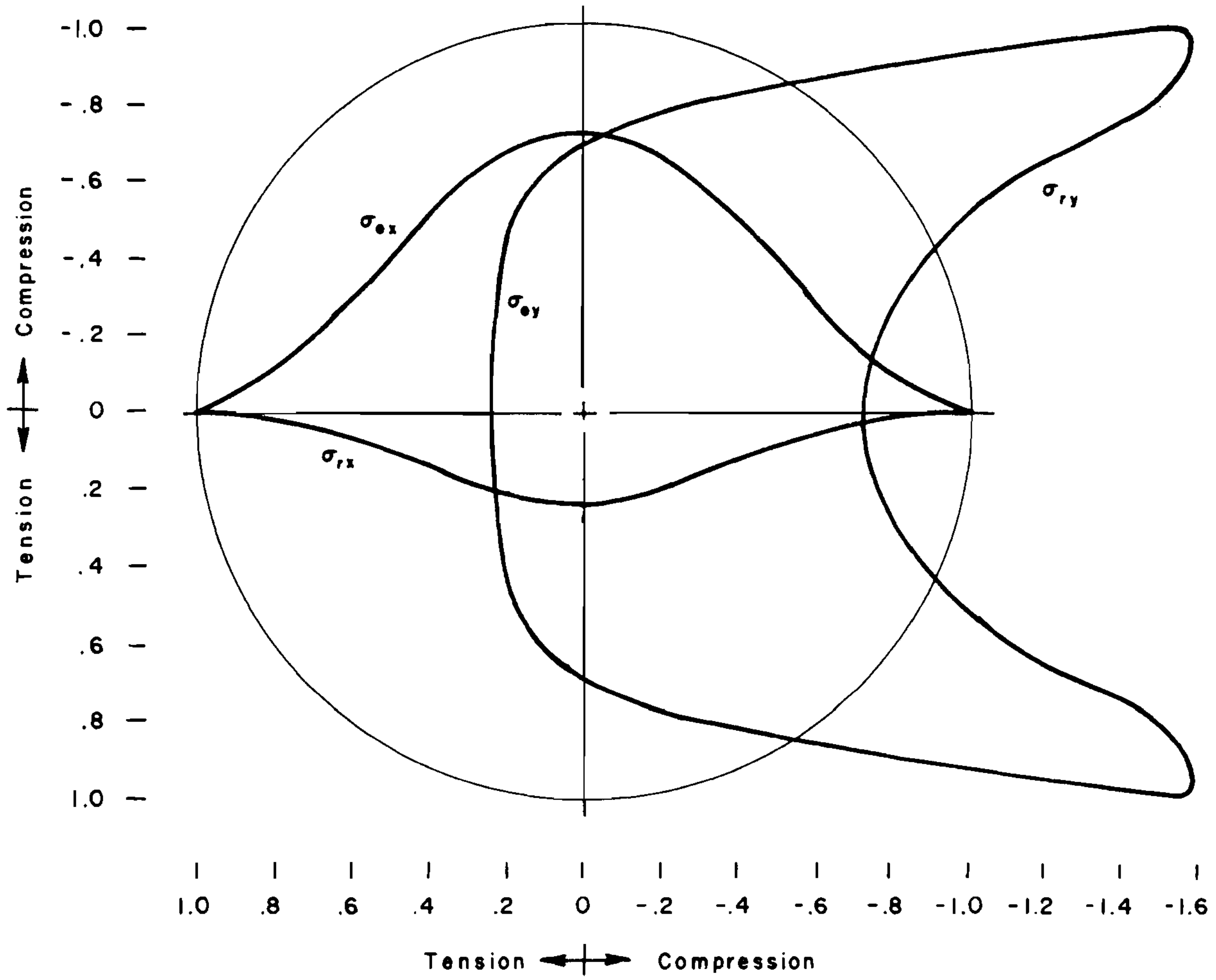

Fig 1. Stress distribution along the principal axes for a loading strip width equal to 1 inch (Ref 8).

$$(1)\quad \sigma_{rx} = \sigma_{rx} = 1.85152\,\frac{P}{\pi tD} = 0.58936\,\frac{P}{tD} \quad \text{and}$$

$$(2)\quad \sigma_{ry} = \sigma_{ry} = -5.89440\,\frac{P}{\pi tD} = -1.87624\,\frac{P}{tD}\;.$$

where

P = maximum total land, in pounds;

D = average diameter of the specimen, in inches;

t = average height of the specimen, in inches;

σ_{rx} = stresses along the horizontal plane;

σ_{ry} = stresses along the vertical plane.

The basic testing equipment was the same as previously used in other studies at The University of Texas (Refs 6, 7, and 8) and consists of an adjustable loading frame, a closed loop electrohydraulic loading system, and a loading head which is a modified, commercially available shoe-die with upper and lower platens constrained to remain parallel during tests.

Another piece of equipment, a device for measuring the transverse strain in a specimen, was used to obtain a measure of 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 also used to control the rate of load application by providing an electrical signal related to the relative movements of the upper and lower platens. All measurements were recorded on two x-y plotters.

DESIGN OF THE EXPERIMENT

This experiment was designed to evaluate the significance of all main effects, all two-factor interactions*, and selected three-factor interactions

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*Interaction is the differential response to one factor in combination with varying levels of one or more other factors applied simultaneously; that is, an interaction is an additional effect due to the combined influence of two or more factors (Ref 54).

for the nine major factors considered to affect the tensile properties of cement-treated materials. Other factors may also have significant effects on the tensile properties of cement-treated materials; nevertheless, they are not considered in this study since their effects have been judged to be small compared with the other factors and since their inclusion would have required a number of specimens so large that it would have been impractical.

Of the nine factors chosen for evaluation, it was felt that five should be studied at three levels in order to estimate the nonlinear effects of the main factors and the interactions included in the experiment. For the remaining four factors only two levels were included since the levels could not be assigned meaningful quantitative values. The factors and levels selected for this investigation are summarized in Table 1.

The need for information on a large number of factors and their interactions required a statistically designed experiment. To investigate all main effects and all interactions would have required a complete factorial experiment, which was highly desirable, but would have required so many experimental units that it could not have been handled economically (Ref 54). A complete factorial would have included five factors at three levels and four factors at two levels making the total number of required specimens equal to $3^5 \times 2^4$ or 3888. Since this is an impractical number to test in a controlled experiment, a 1/4 replicate of a complete factorial was used, with all of the factors at two levels. In addition, midpoint specimens were introduced for five of the factors in order to estimate nonlinear effects, and duplicate specimens were used to obtain an estimate of the experimental error. The experimental units were divided in the following manner:

$$
\begin{array}{rcrl}
1/4\,(2)^9 & = & 128 & \text{experimental units at two levels} \\
 & & 44 & \text{experimental midpoint units} \\
 & & \underline{\;\;8} & \text{duplicate specimens} \\
 & & 180 & \text{Total number of specimens}
\end{array}
$$

The fractional factorial is described by the statistical identity

$$I = ABCDE = DEFGH = ABCFGH$$

This design allows the analysis of all main effects, all two-factor interactions, and selected three and four-factor interactions. The treatment

TABLE 1. FACTORS AND LEVELS SELECTED FOR THE EXPERIMENT

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

combinations are tabulated in Appendix 2. The actual statistical design was developed by Dr. Virgil Anderson, statistical consultant to the project.

The preparation of the specimen was divided into three basic stages: (1) mixing, (2) compaction, and (3) curing. The procedures used for each stage can be seen in Appendix 3. The order for mixing, compacting, and testing the specimens was completely randomized except that all specimens cured for a specified period were tested on the same day.

Since the total number of specimens was too large for mixing and compacting in one day, the experiment was divided into two series of 90 specimens each. The first 90 specimens were mixed and compacted in one day and the second 90, nine days later, in order to avoid interference with the testing of the first series of specimens.

In the mixing phase four factors out of nine were introduced in the experiment. The error mean squares introduced during the mixing process were then related to these four factors. For the compaction phase two more factors were added, possibly adding errors and interactions with the four factors associated with the mixing phase. In the curing phase three more factors were added and consequently the errors collected along the experiment are related to all nine factors of the experimental process. All the main factors and the two and three-factor interactions considered in the design of the experiment are summarized in Table 2.

The analysis of variance of each of the dependent variables determines the significance and order of significance of all the main factors and interactions. Following the analysis of variance, a regression analysis was conducted in order to obtain a predictive equation for indirect tensile strength for any combination of the factors included in this experiment.

SELECTION OF FACTORS

The factors and levels selected for this investigation and summarized in Table 1 are discussed below.

Molding Water Content

The water content during mixing and compaction was selected on the basis of the type of material, gradation, cement content, and the workability of the specimens. Preliminary tests indicated that molding water contents of 3 and 7 percent were the limits for good compaction for the combination of

TABLE 2. MAIN FACTORS AND INTERACTIONS CONSIDERED IN THE EXPERIMENTAL DESIGN

Main Factors

A
B
C
D
E
F
G
H
J

Two-Factor Interactions

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

Three-Factor Interactions

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

Main Effects Legend

A - Molding water content
B - Curing time
C - Aggregate gradation
D - Type of curing
E - Aggregate type
F - Curing temperature
G - Compactive effort
H - Type of compaction
J - Cement content

all the factors included in the experiment. Six percent was the optimum water content for a mixture of crushed limestone having the medium level of gradation and cement content. For a mixture of rounded gravel having a medium level of gradation and cement content, the optimum water content was slightly higher. The final choices were then 3, 5, and 7 percent, to designate the low, medium, and high levels of water content. This equal spacing of the levels also facilitated the statistical design of the experiment.

Curing Time

In selecting curing times an effort was made to encompass a period of time which could be considered to be reasonable in actual construction practice and at the same time to space the curing times far enough apart so that the effect on the properties of the cement-treated materials could be detected. The final choice of curing times was seven, fourteen, and twenty-one days, with the extreme values equally spaced on either side of the medium value.

Aggregate Type

The two types of aggregates chosen were crushed limestone and a rounded gravel from Seguin, Texas, both of which are used in Texas for the construction of subbases and have been used in a prior study (Refs 8 and 9) of asphalt-treated materials. The particle shape and surface texture of these two materials are quite different. The gravel has a smooth, subrounded, and nonporous surface expected to develop less bond with the cement matrix than the rough, angular, crushed limestone particles. In addition, the inherent strengths of the two aggregates are different, with the gravel being stronger. Figure 2 shows that in this study the bond between the gravel and the cement matrix tended to fail before the aggregate particle, while in the case of the limestone the aggregate failed before the bond.

Aggregate Gradation

Three different aggregate gradations were used. The gradations are similar to Texas Highway Department Specifications (Ref 57): Type A for coarse graded base course, Type B for fine graded base, and Type D for surface course materials. In addition, they fall within Winterkorn's classification of soils for bituminous stabilization (Ref 58) and are the same as

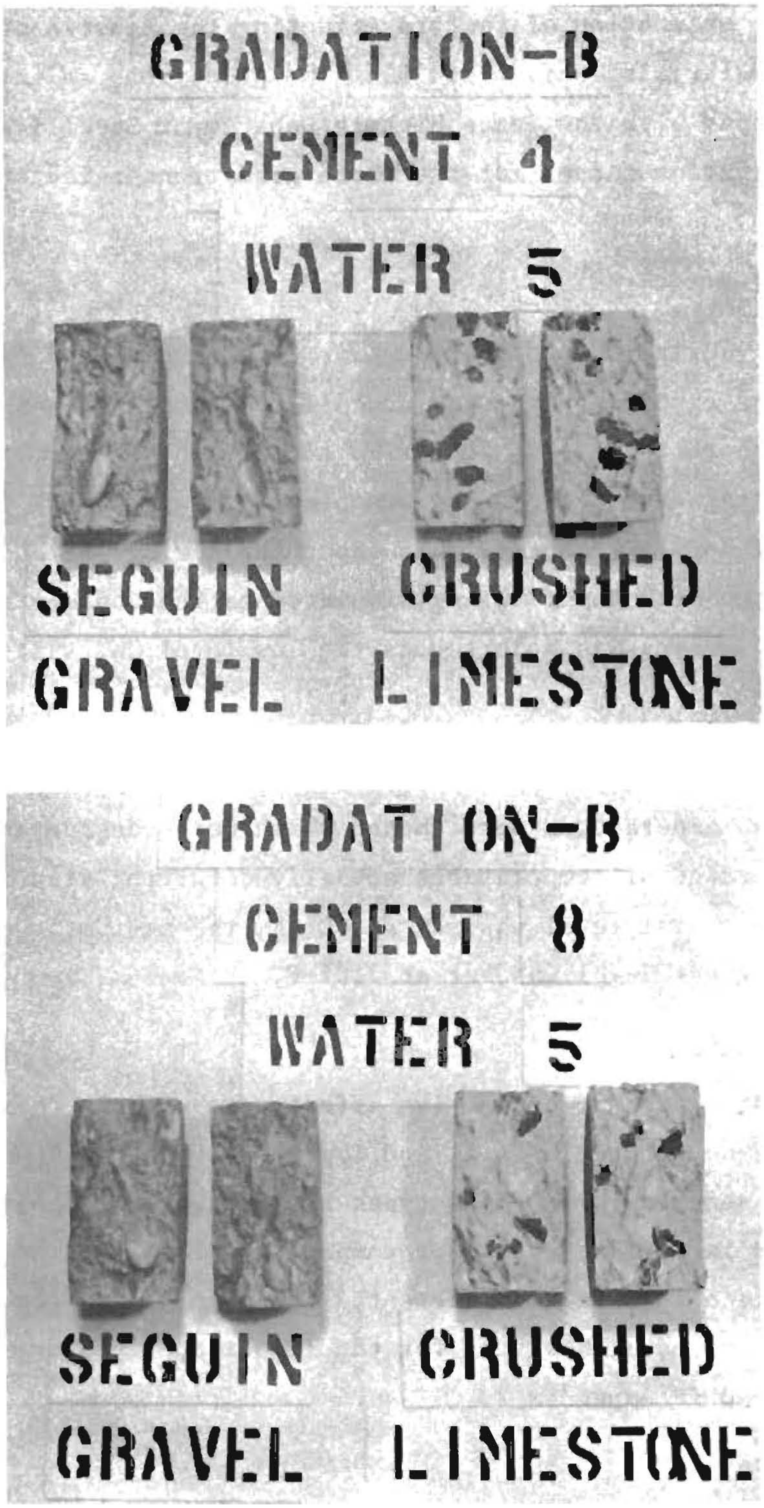

Fig 2. Typical failures of crushed limestone and rounded gravel specimens.

those used in the evaluation of factors affecting the tensile properties of asphalt-treated materials (Refs 8 and 9). The gradations selected are shown in Appendix 1, along with the Texas Highway Department Specifications. The grain size distribution curves for the three gradations selected are shown in Fig 3.

Type of Curing

Two types of curing were selected: air dried and sealed. 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. The other method of curing consisted of sealing the specimens by wrapping them with a PVC film to maintain the original moisture content throughout the curing period. It was felt that these two methods of curing simulated extreme conditions in the field. Air-dried curing was selected as the low level and sealed-curing as the high level.

Curing Temperatures

Three curing temperatures were chosen which were considered to be representative of the range of temperatures actually occurring at different times in the year. The lowest level was set at 40° F, the medium level was set at 75° F, and the highest level was set at 110° F.

Compactive Effort

Two different levels of compactive effort were used in this investigation. These levels were designated as high and low and were established on the basis of the resulting density for the two types of soils used in this study. This approach resulted in extreme levels of compactive efforts although the resulting densities were not radially different. The compaction procedures associated with the low and high levels for the impact and gyratory-shear compactors are summarized in Appendix 2.

Type of Compaction

Two different types of compaction, impact compaction and gyratory shear compaction, were used in this experiment. These two types were chosen because past experience showed that they give differences in the strength properties of cement-treated materials and represent extremes with regard to

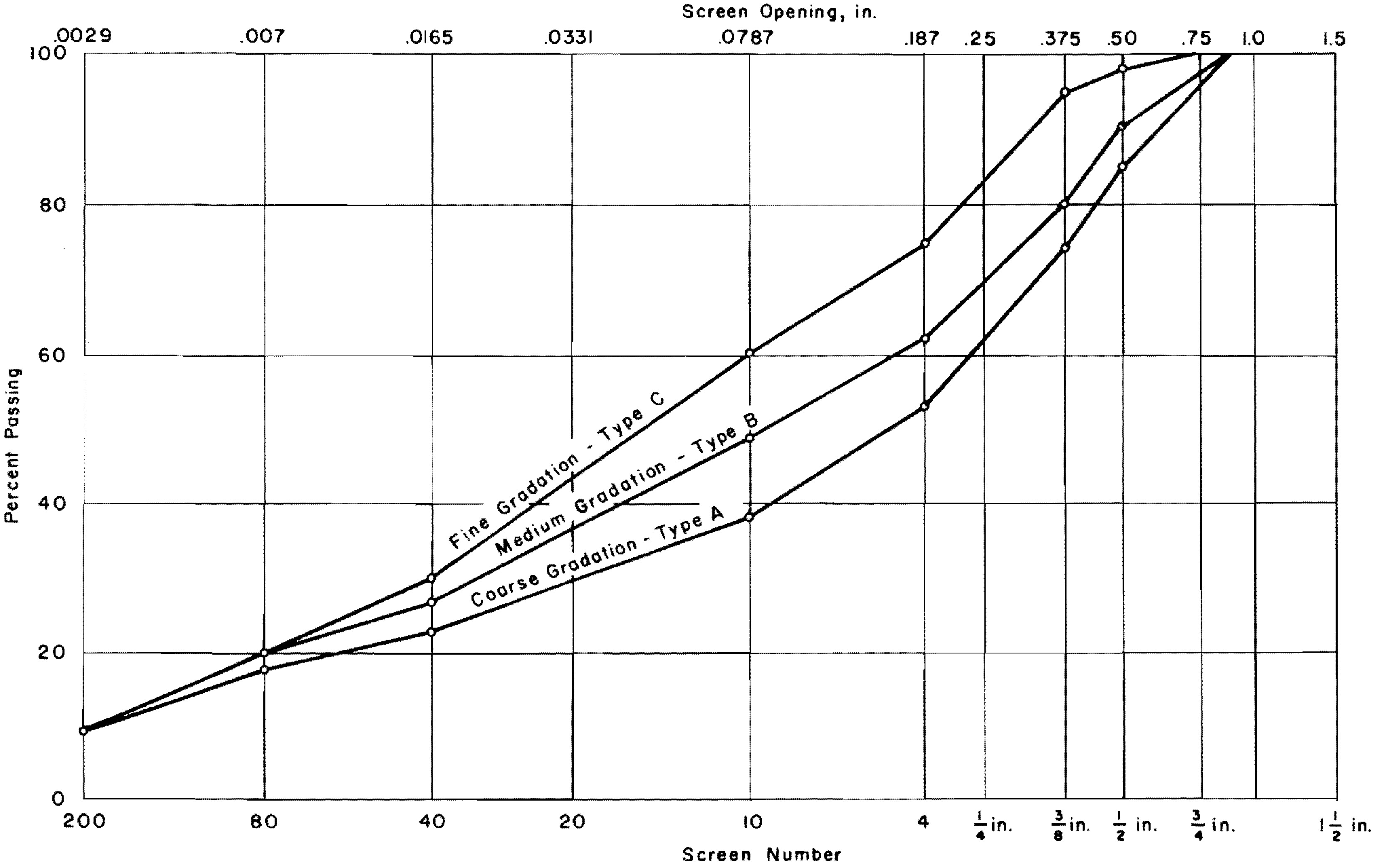

Fig 3. Grain size distribution curves.

the effect produced on the soils and the shear strains imposed on the specimen during compaction.

Originally, kneading compaction which produces a compactive action similar to a sheepfoot roller was also considered; however, it was not included in the design because the time consumed for the compaction of each specimen was too long compared with the time required by either the gyratory shear or the impact compactor. The compaction procedures are described in Appendix 2.

Cement Content

The greatest use for cement-treated mixtures is in the construction of base and subbase courses. For this reason the cement content used with the various soils was in the range that would normally be used in pavement base construction. The three different percentages of cement content selected for the low, medium, and high level were 4, 6, and 8 percent, respectively.

The three levels are equally spaced and should give a relatively wide variation in the tensile properties. According to established criteria for cement-treated soils, the cement content for soils similar to those used in this experiment varies from a minimum of 3 percent to a maximum of 9 percent by weight of aggregate. This range encloses the three different levels of cement selected for the experiment.

PARAMETERS EVALUATED

Indirect tensile strength was evaluated in this experiment.

(1) Indirect tensile strength is the tensile stress required to fail the specimens when a diametrical load is applied to the specimen. The relationship used to calculate its value is

$$S_T = 0.58936 \frac{P_{max}}{tD}$$

where

P_{max} = maximum load required to break the specimen in pounds;

D = average diameter of the specimen, in inches;

t = average height of the specimen, in inches.

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

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

(3) Vertical failure deformation - the vertical deformation of a specimen at the maximum load, recorded on the load-vertical-deformation plot and 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.

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

(5) Deflection ratio - 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.

The two deformation measurements, although recorded, were not evaluated; validity of the load-deformation data was questioned because of the method used to secure the loading strips to the platens and because of the small magnitude of the horizontal deformations. Therefore, tangent modulus and deflection ratio were not evaluated for this report either.

EXPERIMENTAL RESULTS

The indirect tensile strength is based upon a simple equation which assumes no effect due to Poisson's ratio on the treated material. This assumption is not strictly correct since a multiaxial 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 involved in attaching strain gages to cement-treated specimens make this approach undesirable (Ref 8); therefore, the effect of Poisson's ratio was neglected although it is anticipated that future work will allow this effect to be evaluated.

The maximum load needed for the tensile strength calculation was obtained from the load versus vertical deformation plot. The test results obtained for the tensile strength are summarized in Table 3.

TABLE 3. EXPERIMENTAL RESULTS

Specimen No.	Indirect Tensile Strength, psi
1	34.7
2	126.4
3	20.3
4	174.6
5	14.3
6	248.9
7	123.3
8	140.5
9	212.0
10	257.2
11	174.6
12	90.5
13*	139.0
14	39.3
15	54.1
16	50.0
17	268.9
18*	252.0
19	57.8
20	66.6
21	103.8
22	237.9
23	290.7
24	197.5
25	366.5
26	260.2
27	157.5
28	115.6
29	431.8
30*	129.3
31	118.0
32	80.8
33	89.8
34	44.0
35	169.6
36	74.2
37	41.6
38	68.0
39	364.1
40	57.7
41	86.4
42	27.0
43	316.0
44	41.1
45	53.7
46	74.3
47	113.7
48	39.4
49	72.2
50	225.4
51	272.5
52	243.3
53	25.3
54	238.0
55	91.6
56	242.6
57	103.1
58	111.3
59	187.7
60	101.9
61	84.9
62*	206.5
63	105.7
64	183.5
65	40.4
66*	190.5
67	137.6
68	60.4
69	99.6
70	32.3
71*	202.6
72	134.0
73	283.2
74	70.9
75*	127.7
76	114.8
77	70.5
78	212.9
79	37.0
80*	145.4
81	102.1
82	139.8
83	221.7
84	57.0
85	162.4
86	131.1
87	45.2
88	169.4
89	251.8
90	100.1

*Duplicate specimens.

(Continued)

TABLE 3. (Continued)

Specimen No.	Indirect Tensile Strength, psi	Specimen No.	Indirect Tensile Strength, psi
91	375.2	136	102.8
92	196.8	137	122.6
93	117.1	138	113.4
94	47.1	139	106.9
95	41.4	140	147.2
96	44.8	141	48.0
97	175.8	142	77.0
98	96.0	143	132.9
99	385.3	144	159.1
100	63.7	145*	82.3
101	26.0	146	147.5
102	497.1	147	55.0
103	54.3	148	207.4
104*	70.9	149	113.9
105	259.2	150*	74.5
106	71.8	151	122.0
107	41.1	152	170.3
108	374.3	153	128.2
109	254.1	154	365.1
110	106.3	155*	93.5
111	245.6	156	197.8
112	54.7	157	104.5
113*	105.6	158	26.4
114	63.8	159	59.5
115*	98.1	160	74.7
116	108.5	161	192.3
117	98.0	162	37.0
118	283.3	163	123.0
119	62.0	164	13.1
120	40.6	165	303.8
121	93.1	166	247.5
122*	136.8	167	291.2
123	115.5	168	108.3
124	63.7	169	73.1
125	30.9	170	40.4
126	127.1	171	42.0
127	227.6	172	146.4
128	142.4	173	233.5
129	157.8	174	43.6
130	495.5	175	162.9
131	39.6	176*	92.4
132	88.0	177	280.2
133	50.3	178	252.8
134	125.9	179	68.0
135	180.3	180	22.4

*Duplicate specimens.

An analysis of variance was conducted with a computer program capable of handling nine independent variables. According to the statistical design, the analysis of variance was conducted for 128 specimens, which constitute one-fourth of the complete factorial and represent all the factors containing the low and high levels, that is, nine factors, each at two levels. Midpoint levels were not used in the analysis of variance.

The estimate of true error mean square was calculated using the data from the duplicate specimens and was used to evaluate the significance level of each of the main effects and interactions. This error term was calculated using seven sets of duplicates instead of eight, because one of the duplicated specimens (No. 66), was discarded due to an apparent error in weighing the materials for the specimen. The sets of duplicates and the error term between treatments treated alike are included in Appendix 4.

CHAPTER 4. DISCUSSION OF RESULTS

The principal objective of this study was to determine which factors significantly affect the tensile strength of cement-treated materials. Those factors or interactions found to significantly affect the tensile strength at alpha levels of 0.01 and 0.05 are presented in Table 4. All other factors and interactions were considered to have no significant effect. The residual shown in the table is the pooled mean squares for those factors and interactions which were not significant. The error mean square term was calculated from the duplicate specimens and represents an estimate of the true error.

The relationships of the highly significant main factors and their interactions for tensile strength are shown in Figs 4 through 13. 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, causing the variance to be larger. Hence, the midpoint means cannot be compared to the endpoint means. Nonlinear effects as measured by the midpoint levels will be discussed in conjunction with the regression analysis.

STATISTICAL INFERENCE

In this experiment, as in any other, the conclusions drawn are applicable only within the inference space of the population defined by the experiment design, i.e., within the range of combinations of values of the variables tested. No attempt should be made to apply the results outside of this particular inference space. As previously mentioned, however, an attempt has been made to evaluate nonlinear effects for five of the factors. This will be discussed in terms of the regression analysis.

Since there were interactions which were found to significantly affect the tensile strength, they must be considered in order to analyze the

TABLE 4. ANALYSIS OF VARIANCE FOR TENSILE STRENGTH

Source of Variation	Degree of Freedom	Mean Squares	F Value	Significance Level %
A	1	524,050	1480.0	1
D	1	142,607	404.0	1
J	1	127,391	361.0	1
E	1	108,056	306.0	1
AJ	1	57,196	162.0	1
AD	1	53,895	153.0	1
DE	1	34,340	97.3	1
G	1	29,248	82.9	1
EJ	1	23,795	67.4	1
AE	1	23,416	66.3	1
DJ	1	18,769	53.2	1
B	1	12,769	36.2	1
AC	1	11,012	31.2	1
H	1	8,430	23.9	1
ADJ	1	7,357	20.8	1
AH	1	6,992	19.8	1
EF	1	6,139	17.4	1
AB	1	5,798	16.4	1
DEJ	1	5,342	15.1	1
AFHJ-BCGJ	1	4,399	12.5	1
BG	1	4,337	12.3	1
EG	1	4,223	12.0	5
AEJ	1	4,212	11.9	5
BC	1	3,238	9.17	5
C	1	3,168	8.98	5
AEF	1	2,587	7.33	5
CDFJ	1	2,571	7.28	5
AEG	1	2,422	6.86	5
BDH	1	2,388	6.77	5
CEH	1	2,165	6.13	5
BEJ	1	2,128	6.03	5
BDFJ	1	2,077	5.88	5
BF	1	2,036	5.77	5
CH	1	2,013	5.70	5
BCJ	1	1,989	5.63	5
Residual	92	464		
Within treatments treated alike	7	353		

Legend

A - Molding water content
B - Curing time
C - Aggregate gradation
D - Type of curing
E - Aggregate type
F - Curing temperature
G - Compactive effort
H - Type of compaction
J - Cement content

behavior associated with specific combinations of factors. It is not adequate to consider the main effects alone, without evaluation of the interaction effects; in this report interactions will be discussed first.

ANALYSIS OF VARIANCE

As shown in Table 4, 35 factors and their interactions were found to significantly affect the tensile strength of cement-treated materials at a probability level of 0.05 or greater with 21 of these at a probability level 0.01. Not all of these effects have practical significance, however; i.e., the effect may have been measurable and under the controlled conditions of this test may have been significant, but the effect was not large and probably would make little difference in application of the results by engineers. Therefore, only those factors shown to be practically significant are discussed.

In this study, the significant effects were produced by two, three, and four-factor interactions; and it is mandatory that the higher order interaction effects be considered first, since any observed effect is the result of interrelationships between the various main factors. Thus, main effects can be referred to only in terms of the average effect since the effect is dependent on the interactions existing for any combination of factors. On this basis, significant higher order interactions will be discussed first and main effects last.

Four-Factor Interactions

In the experiment design, no four-factor interactions were included for evaluation. Nevertheless, three such interactions were found to significantly affect the indirect tensile strength at a probability level of 0.05 with one of these interaction effects being significant at 0.01. Unfortunately this highly significant interaction was confounded with another four-factor interaction.

The highly significant four-factor interaction involved the interaction between molding water content, curing temperature, type of compaction, and cement content and the interaction between curing time, aggregate gradation, compactive effort, and cement content. Since these two interactions are confounded, as shown in Table 4, there is some doubt as to which one produced the significant effect. According to Daniel (Ref 55), when two interactions are confounded, the interaction containing the greater number of significant main effects probably is the more important. However, in this case both four-factor interactions contain three highly significant main factors, and, thus, it is impossible to attribute the significance solely to one of the two interactions. Nevertheless, its existence along with the other two interactions which were signifciant at a probability level of 0.05 points out the complexity and interrelationship of the factors affecting the properties of cement-treated materials.

Three-Factor Interactions

A total of nine three-factor interactions was found to be significant at a probability level of 0.05; however, only two of these interactions were significant at a probability level of 0.01. These two highly significant three-way interactions are graphically shown in Figs 4 and 5 and are discussed in the following paragraphs.

Molding Water Content x Type of Curing x Cement Content (Interaction AxDxJ - Fig 4). The tensile strength increased from the point of low cement content and low molding water content to the point of high cement content and high molding moisture content, and the strength increase was much greater for the increased moisture content than for the increased cement content. Although the same basic trends were noted regardless of the type of curing, it can be seen that the strength increases were much greater for specimens cured by sealing rather than air drying.

Type of Curing x Aggregate Type x Cement Content (Interaction DxExJ, Fig 5). The interaction of these three factors indicates that the strengths of both the limestone and the gravel specimens increased from the point of low cement content with air-dried curing to the point of high cement content and sealed curing. In addition, it appears that the effect produced by increasing the cement content from 4 to 8 percent was essentially the same as the effect produced by sealed curing rather than air-dried curing. Although the trends for the strengths of both the limestone and gravel specimens were similar, the strength increases were much greater for the limestone specimens.

Two-Factor Interactions

From a total of 36 analyzable two-factor interactions, 15 were significant at a level of 0.05 or greater, with 11 of these significant at a level

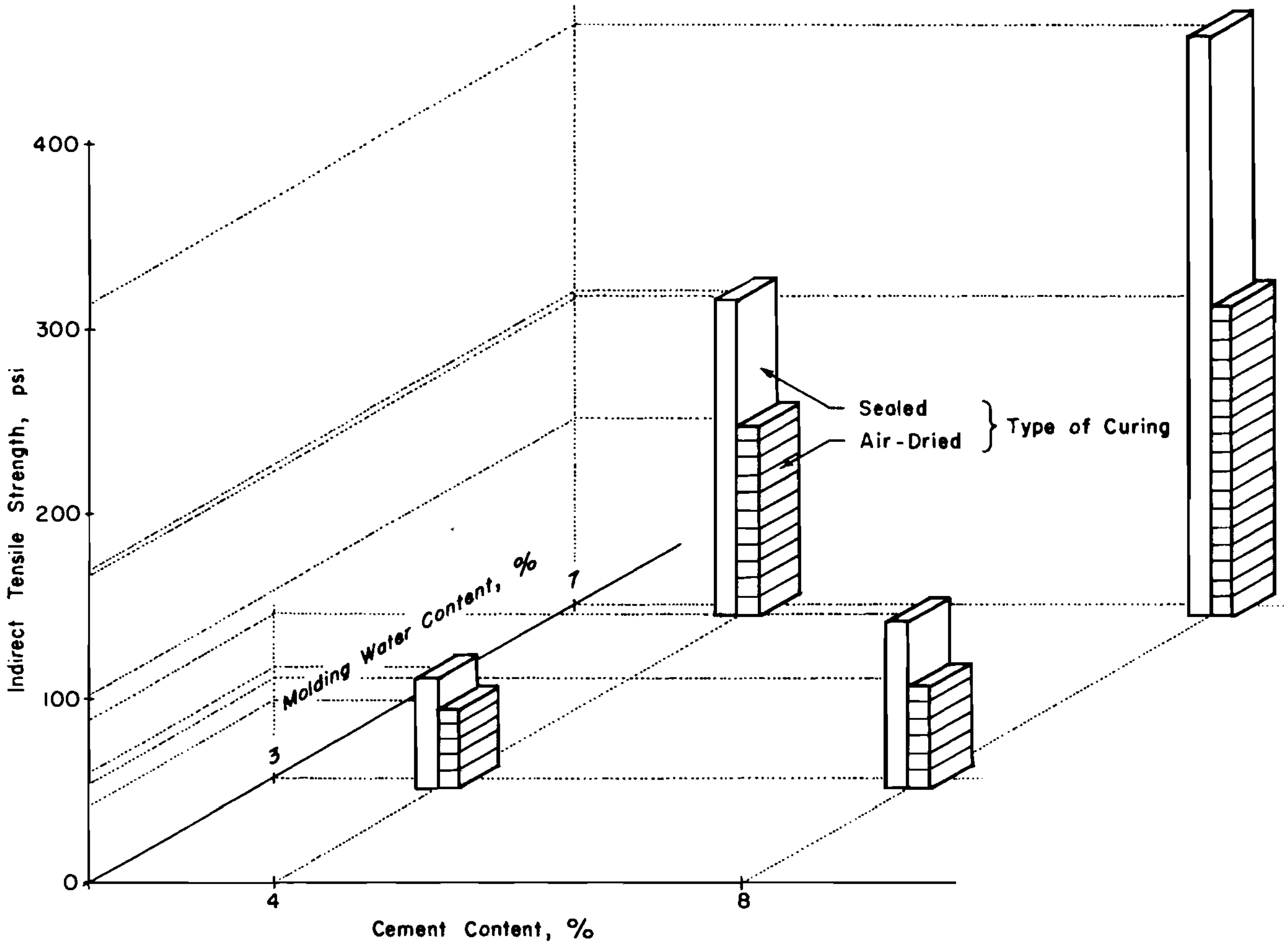

Fig 4. Effect of interaction between molding water content, type of curing, and cement content (interaction AxDxJ).

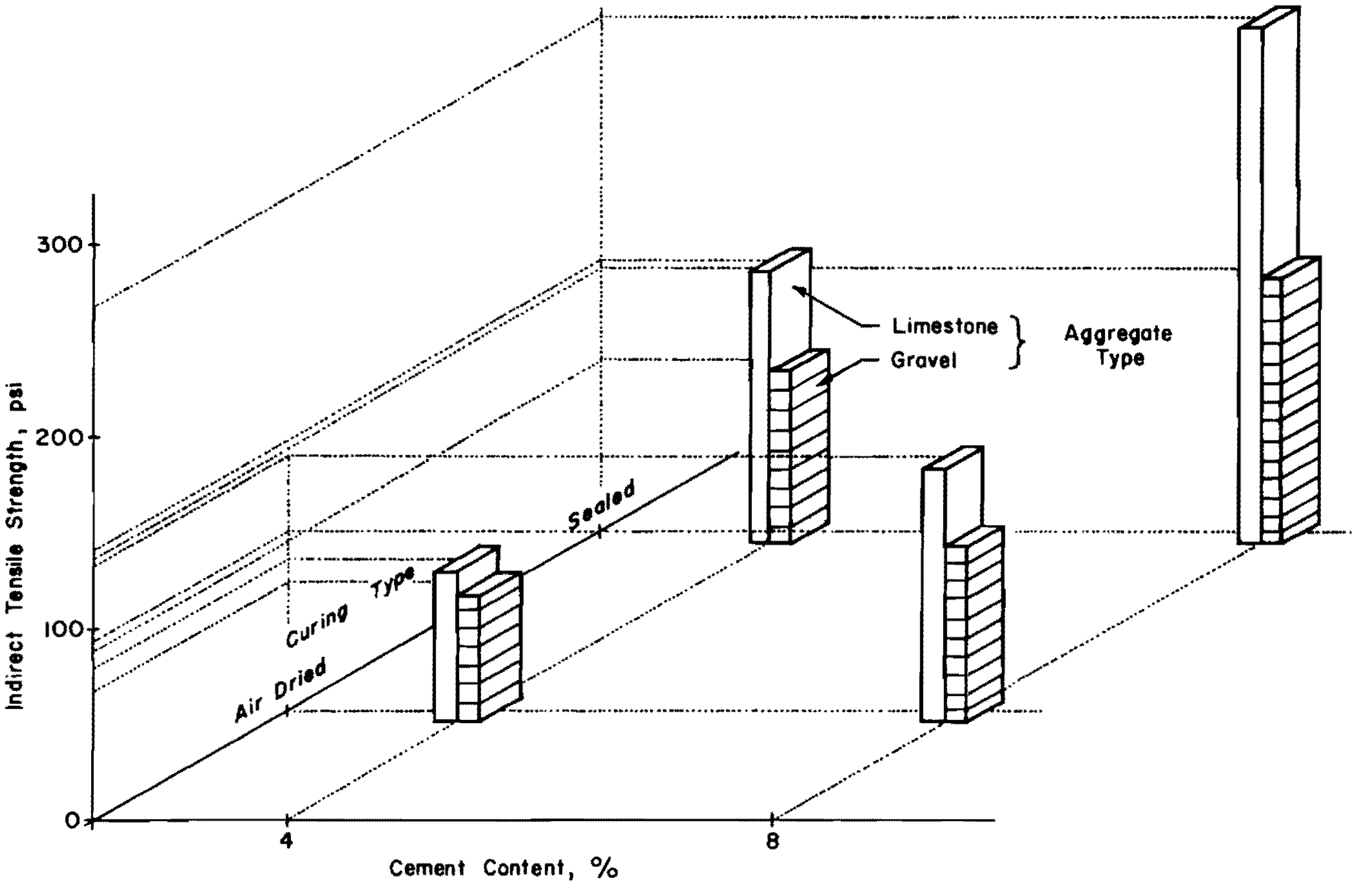

Fig 5. Effect of interaction between type of curing, aggregate type, and cement content (interaction DXEXJ).

of 0.01. These 11 highly significant two-factor interactions are discussed below and are illustrated in Figs 6 through 16.

Molding Water Content x Cement Content (Interaction AxJ - Fig 6). Tensile strength increased with the increased molding water content; however, the increase was much greater for specimens containing the higher cement content. Likewise, strength increased with increased cement content but the increase was much greater for specimens compacted at the higher water content. Thus, it appears that the beneficial effect of additional cement is limited unless there is an adequate supply of water for hydration of the cement.

Molding Water Content x Type of Curing (Interaction AxD - Fig 7). The increase in the molding water content resulted in a greater increase in strength for the specimens which were sealed during the curing period than for the specimens cured by air drying. Such a phenomenon is logical since increased water would be expected to increase the efficiency of the hydration process. In the case of the sealed specimens this increased water was retained for hydration of the cement, while in the air-dried specimen it was lost; and, thus, its benefit was not fully realized.

Type of Curing x Aggregate Type (Interaction DxE - Fig 8). It was found that the strength increase, associated with changing the aggregate from gravel to limestone, was much greater for the sealed specimens than for the air-dried specimens, although the strengths were greater for the limestone specimens in all cases. As previously noted, when the specimens were cured by sealing, more water was available for hydration, resulting in an improved cement matrix. Apparently the benefits of the improved matrix were more fully realized by the limestone aggregate, which could develop a better cement-aggregate bond due to its angularity and rough surface texture.

Aggregate Type x Cement Content (Interaction ExJ - Fig 9). The strength increase associated with the increased cement content was greater for specimens containing limestone than for those containing gravel. It is felt that this interaction effect illustrates once again that the limestone is able to benefit more from a stronger matrix than the rounded gravel.

Molding Water Content x Aggregate Type (Interaction AxE - Fig 10). The strength increase associated with the increase in water content was greater for the limestone than for the gravel. As in the case of the interaction,

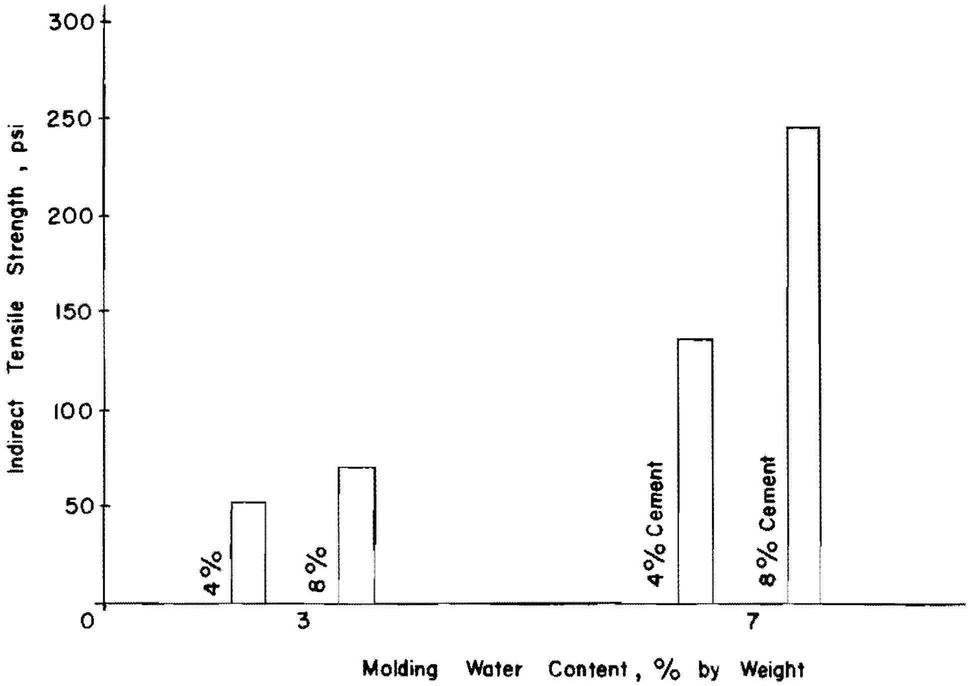

Fig 6. Effect of interaction between molding water content and cement content (interaction AxJ).

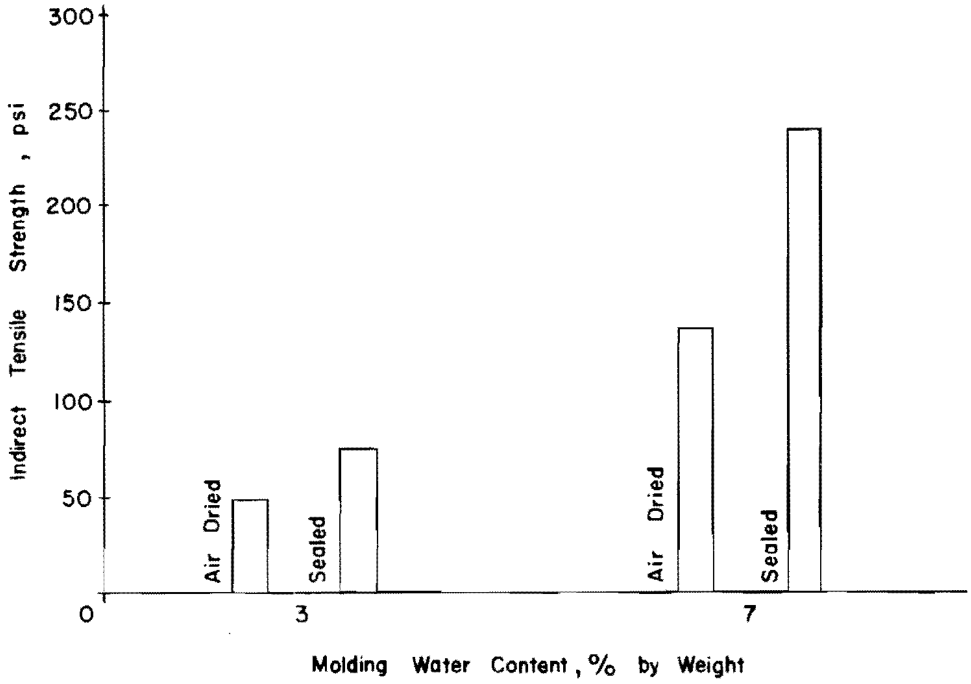

Fig 7. Effect of interaction between molding water content and type of curing (interaction AxD).

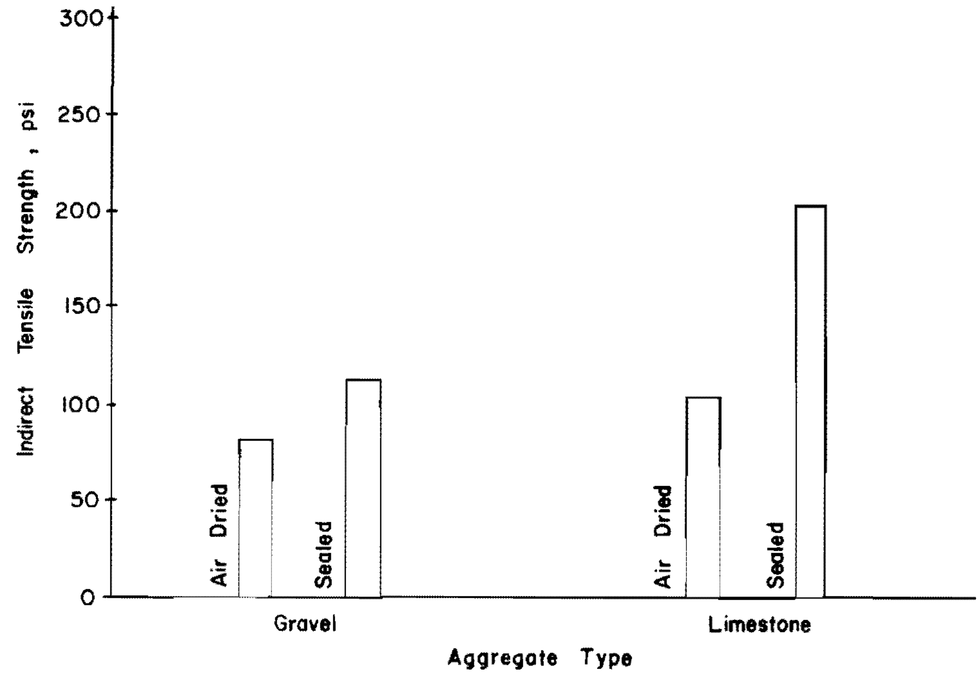

Fig 8. Effect of interaction between type of curing and aggregate type (interaction DXE).

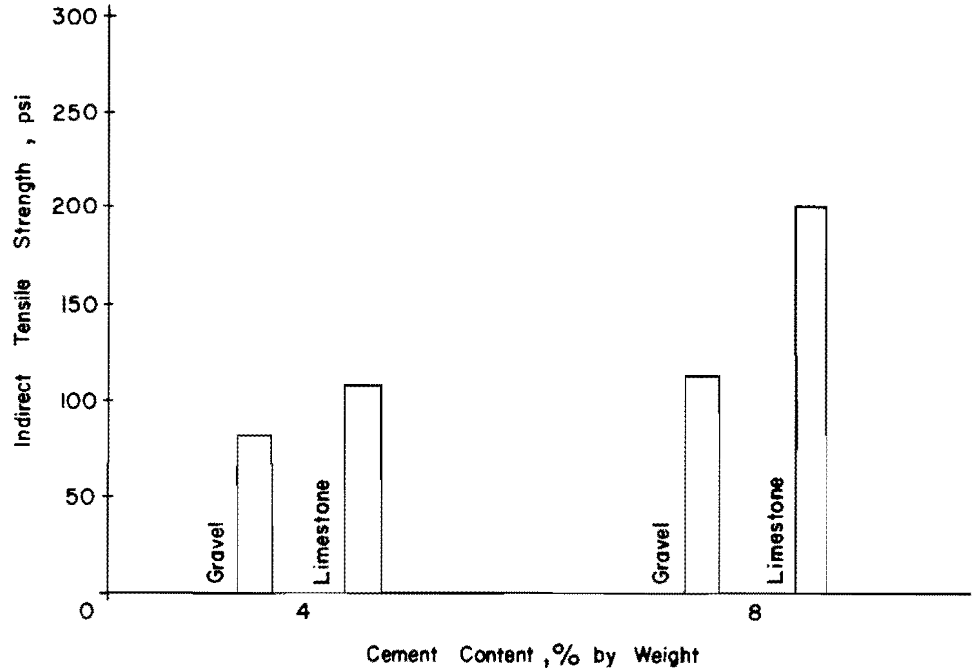

Fig 9. Effect of interaction between aggregate type and cement content (interaction ExJ).

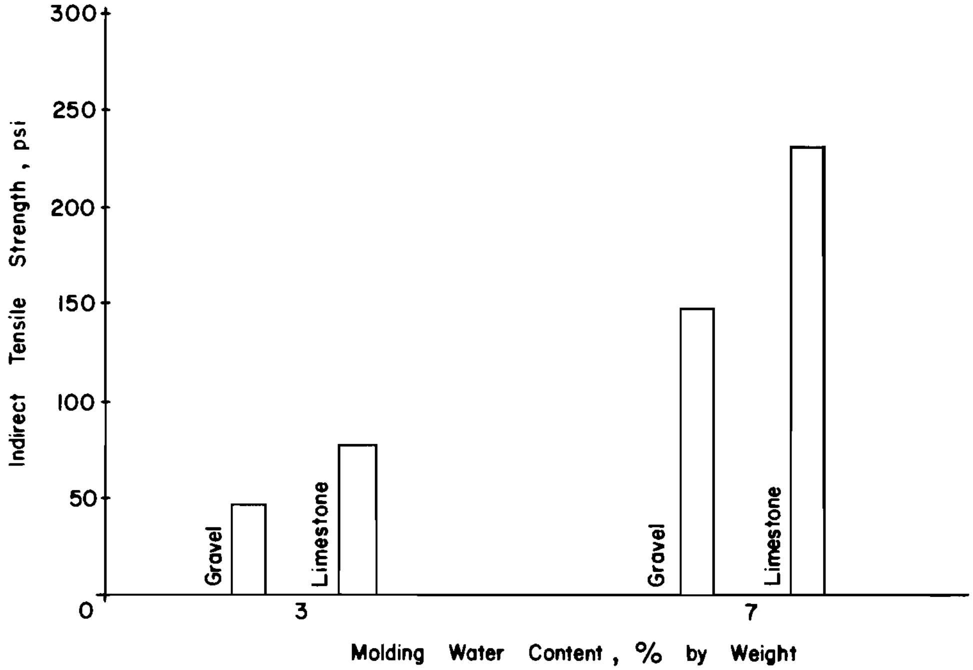

Fig 10. Effect of interaction between molding water content and aggregate type (interaction AxE).

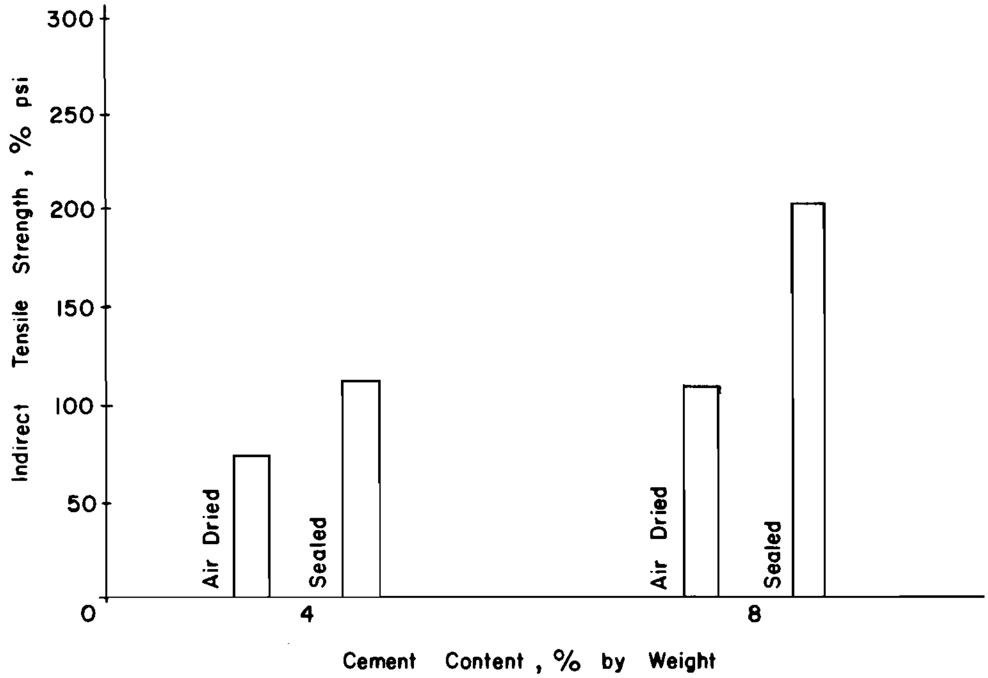

Fig 11. Effect of interaction between type of curing and cement content (interaction DXJ).

"Type of Curing X Aggregate Type," (Fig 8), the limestone benefited more than the gravel from the improved matrix resulting from better hydration.

Type of Curing X Cement Content (Interaction DXJ - Fig 11). The average strength increased with the increase in cement content in both specimens cured by sealing and by air drying. However, the strength increase was much greater for the sealed specimens than for the air-dried specimens. Thus, the benefit of the increased cement content was more fully realized when the specimens were cured under the more ideal curing conditions, as would be expected.

Molding Water Content X Aggregate Gradation (Interaction AXC - Fig 12). It was found that a molding water content of 7 percent produced stronger specimens than a 3 percent water content but that the increase in strength was much greater for specimens containing a finely graded aggregate. In addition, a change from finely graded aggregate to a coarse graded aggregate produced a strength increase for specimens compacted at 3 percent water while the reverse was true for specimens compacted at 7 percent water.

Molding Water Content X Type of Compaction (Interaction AXH - Fig 13). As in the previous interaction the increased molding water content resulted in higher strengths; however, the amount of this increase was dependent on the type of compaction, with impact compacted specimens producing a greater increase in strength than the gyratory shear specimens.

Curing Temperature X Aggregate Type (Interaction EXF - Fig 14). It appears that the increased curing temperature from 40° F to 110° F produced higher tensile strengths for specimens containing gravel; however, there was little effect on the strength of the limestone specimens.

Molding Water Content X Curing Time (Interaction AXB - Fig 15). Increased water content at the time of molding resulted in stronger specimens. Although specimens cured for 21 days seemed to have a larger strength gain than specimens cured 7 days, examination of Fig 15 indicates that the difference in the rate of increase associated with the two different curing times is very small and of little practical significance.

Curing Time X Compactive Effort (Interaction BXG - Fig 16). Increased curing time apparently had little effect on the strength of specimens compacted at a low compactive effort, while the average strength of specimens

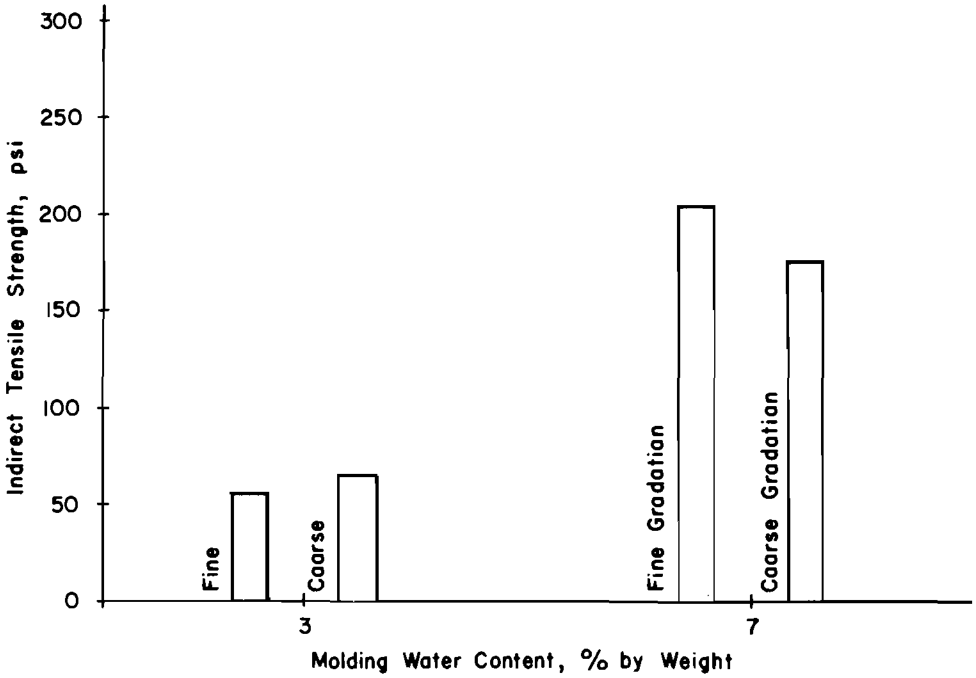

Fig 12. Effect of interaction between molding water content and aggregate gradation (interaction AXC).

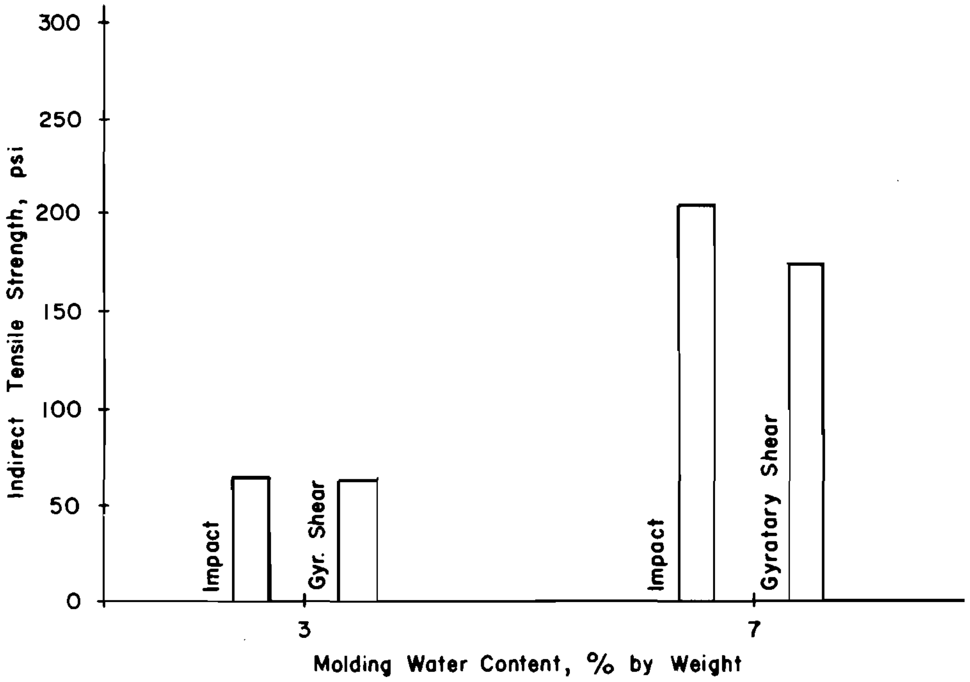

Fig 13. Effect of interaction between molding water content and type of compaction (interaction AxH).

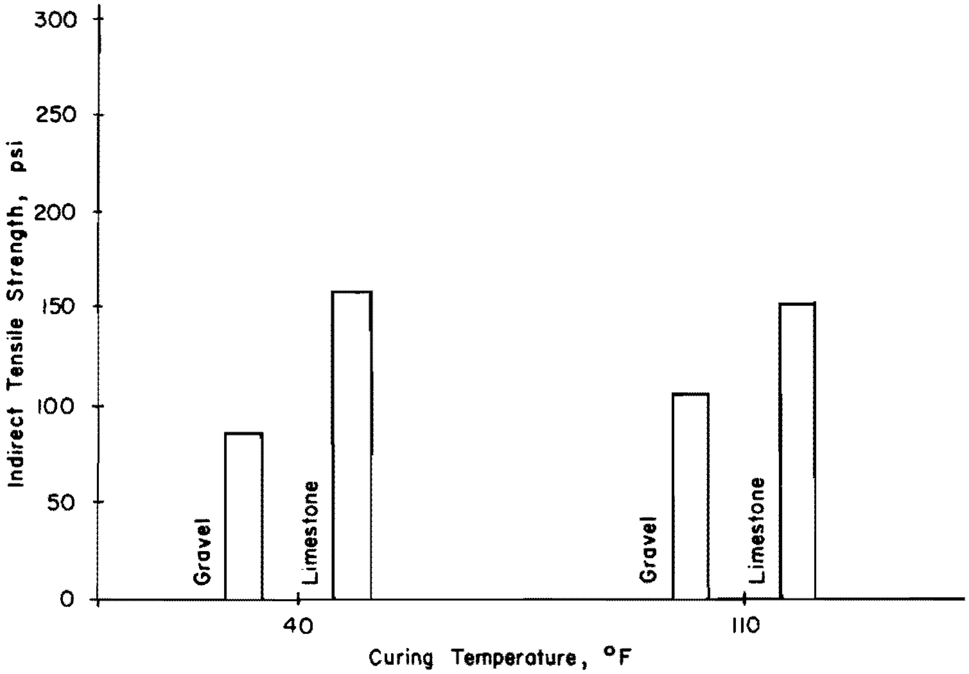

Fig 14. Effect of interaction between aggregate type and curing temperature (interaction ExF).

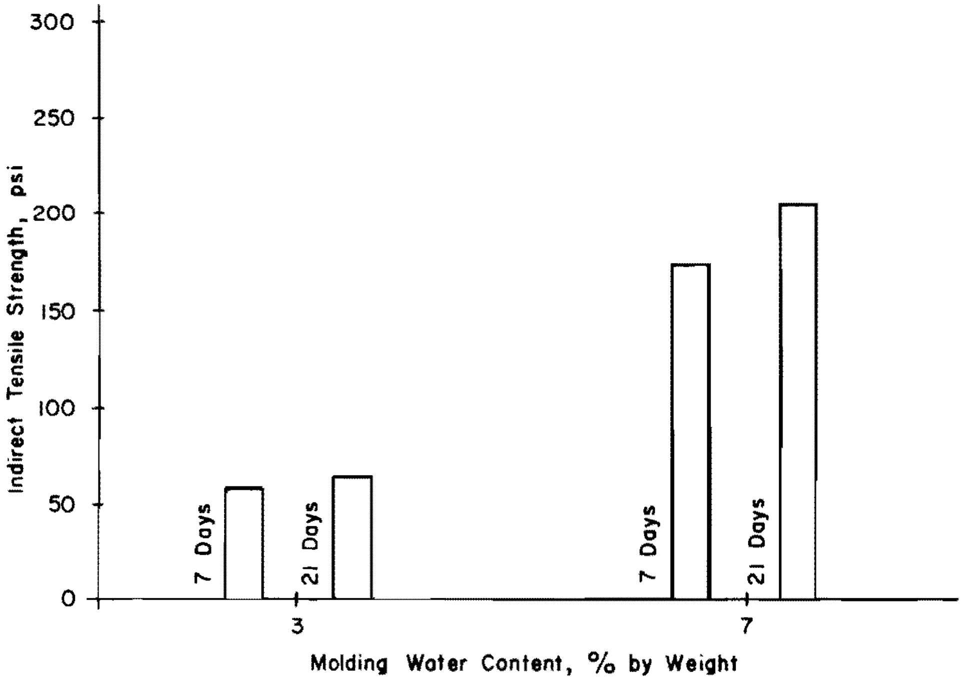

Fig 15. Effect of interaction between molding water content and curing time (interaction AxB).

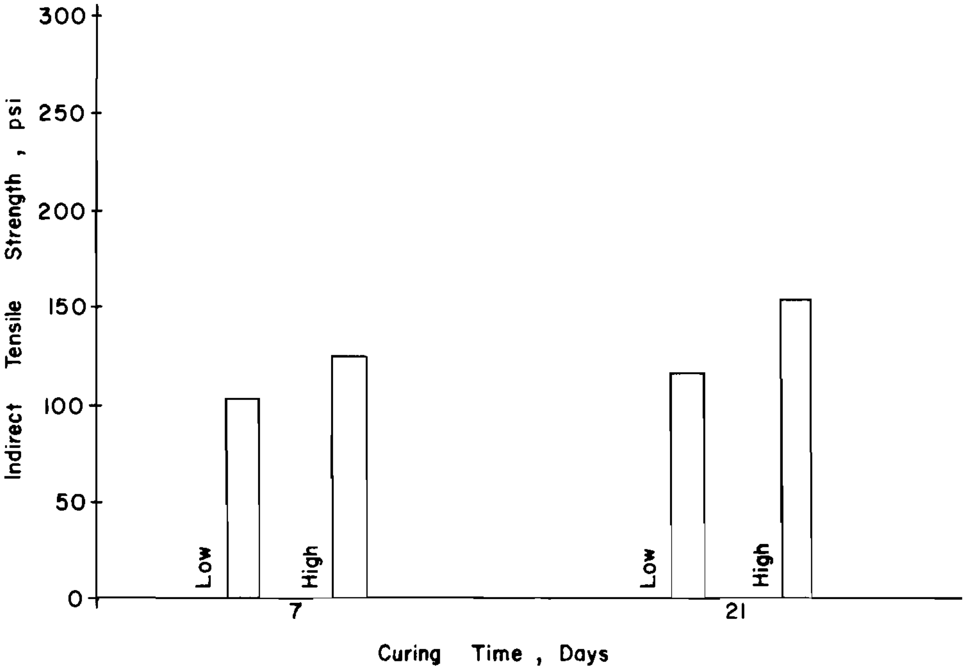

Fig 16. Effect of interaction between curing time and compactive effort (interaction BxG).

compacted at a high compactive effort was increased by increasing the curing time from 7 to 21 days.

Main Effects

Seven of the nine main effects were found to be significant at a probability level of 0.01. Figures 7 through 28 illustrate the effects produced by these factors and show that the average indirect tensile strength was significantly increased by

(1) increasing the molding water content from 3 to 7 percent (Factor A - Fig 17),

(2) sealed rather than air-dried curing (Factor D - Fig 18),

(3) increasing the cement content from 4 to 8 percent (Factor J - Fig 19),

(4) using crushed limestone rather than rounded gravel aggregates (Factor E - Fig 20),

(5) using a high compactive effort (Factor G - Fig 21),

(6) curing for 21 days rather than 7 days (Factor B - Fig 22), and

(7) using impact compaction rather than gyratory shear compaction (Factor H - Fig 23).

EVALUATION AND DISCUSSION

This experiment was designed to investigate, but not necessarily to explain, the causes of the effects produced by all nine factors and their interactions. Nevertheless, it is desirable and possible to postulate the causes of the observed behavior and, in most cases, to advance logical explanations for future consideration.

In Table 4 (p 30), by comparing the relative values of the mean squares, it can be seen that the water content during mixing and compaction was by far the most important factor affecting strength. In addition to its highly significant main effect, it was also involved in six highly significant two-factor interaction effects, one three-factor interaction effect, and one four-factor interaction effect. It would appear that these effects were primarily concerned with the hydration process rather than compaction or mixing, since, in four of the six highly significant two-factor interactions molding water content was associated with a factor concerned with hydration, i.e., cement content, type of curing, aggregate type, and curing time. In these interactions it can be reasoned that the interaction is the result of

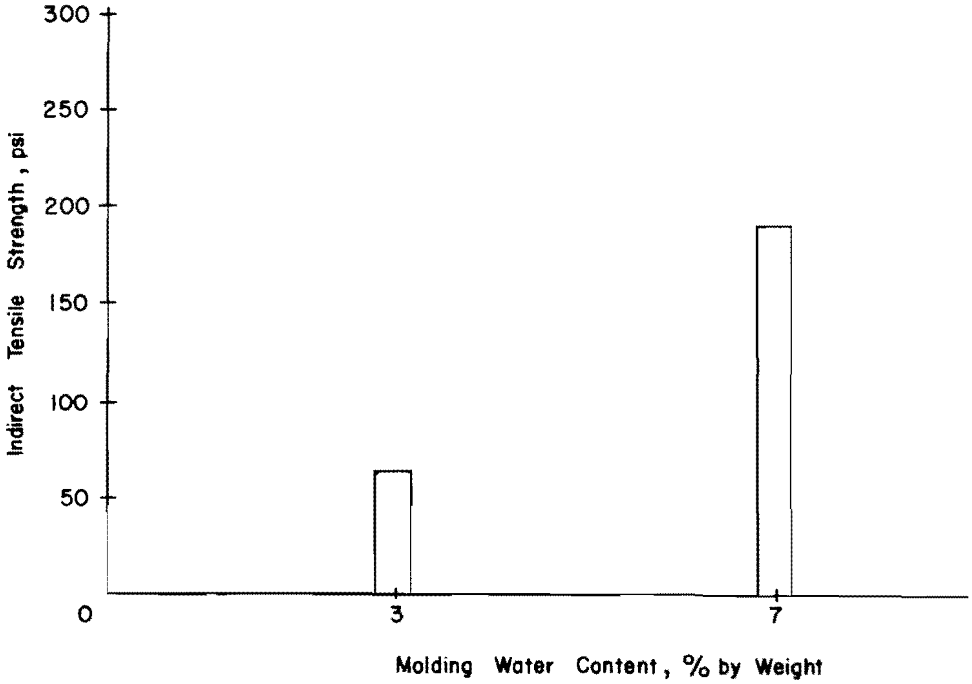

Fig 17. Effect of molding water content (Factor A).

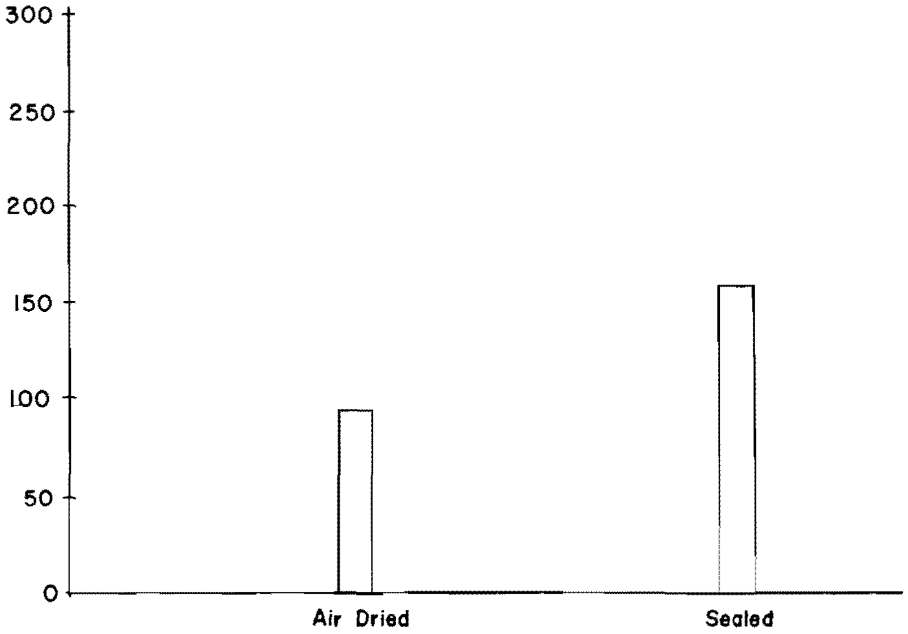

Fig 18. Effect of type of curing (Factor D).

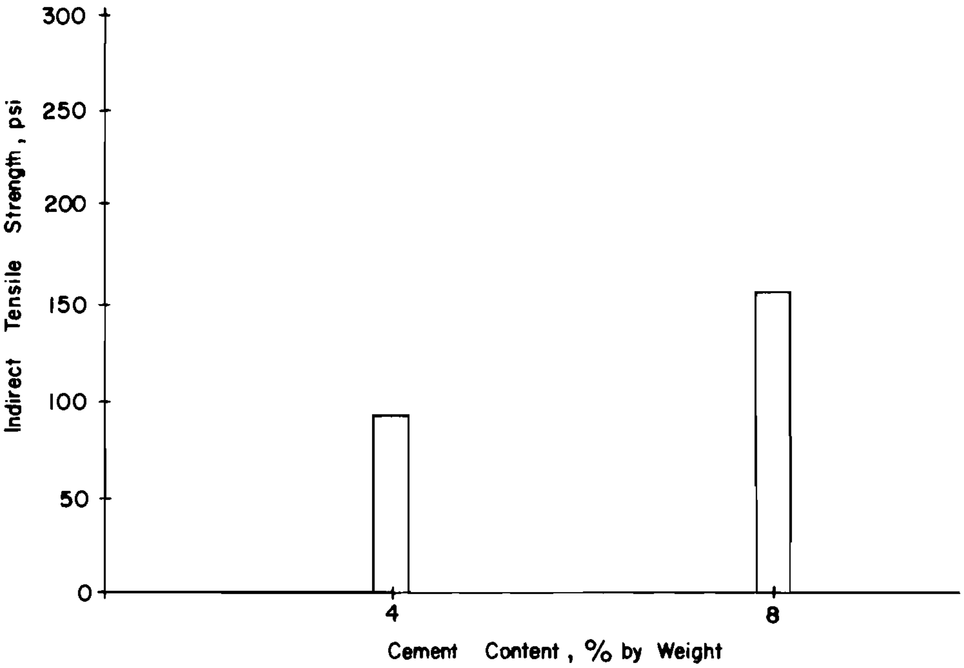

Fig 19. Effect of cement content (Factor J).

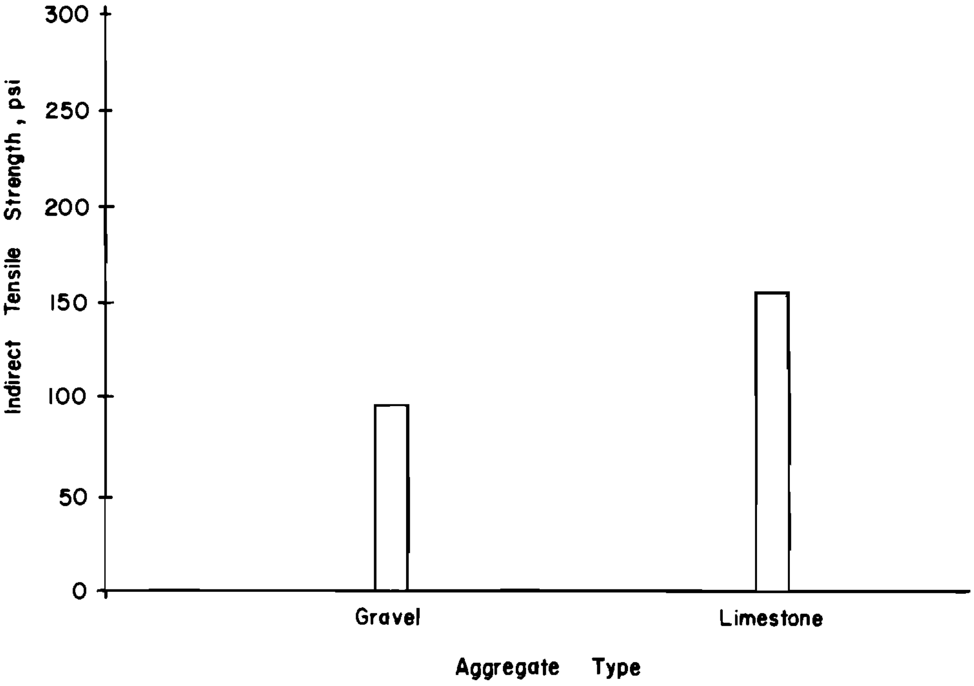

Fig 20. Effect of aggregate type (Factor E).

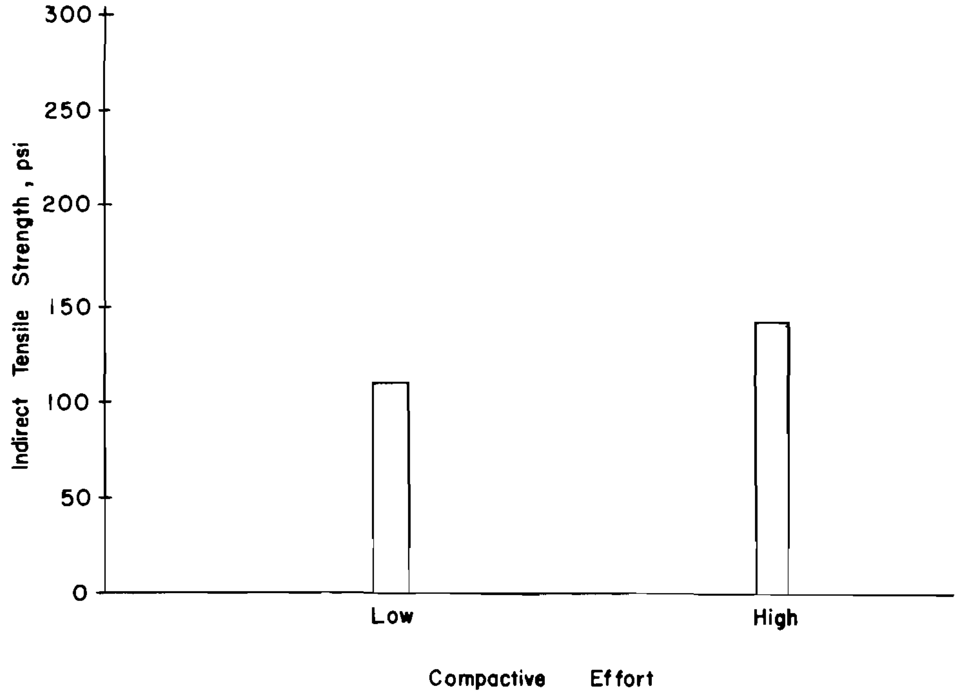

Fig 21. Effect of compactive effort (Factor G).

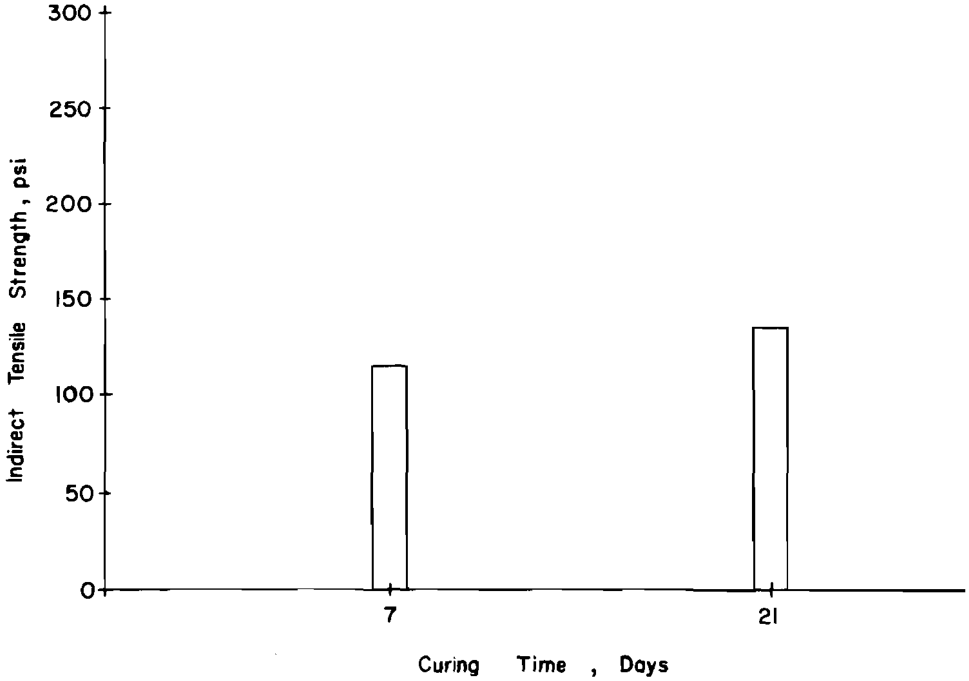

Fig 22. Effect of curing time (Factor B).

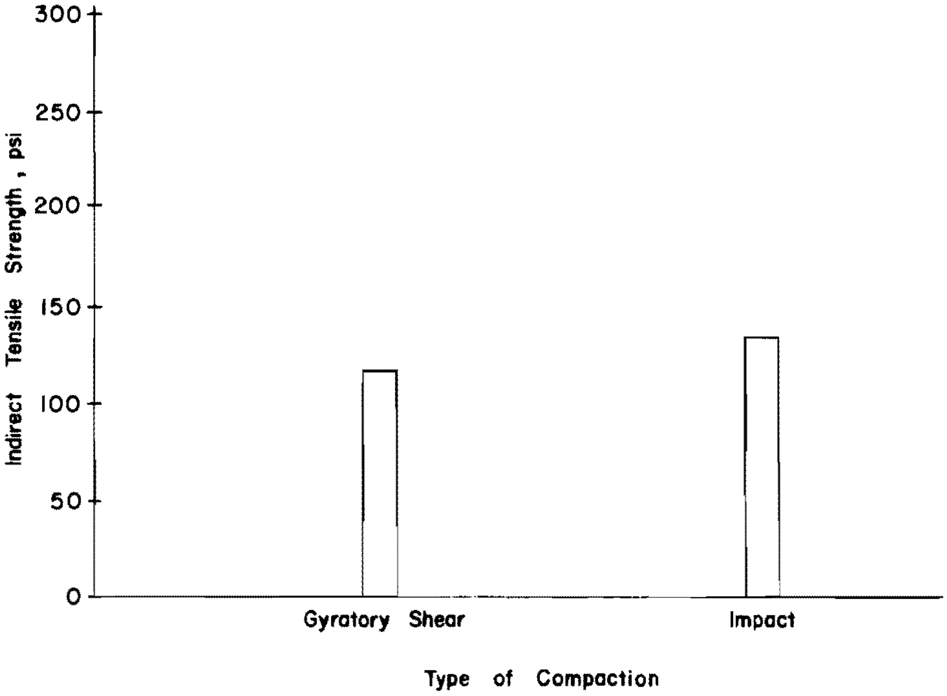

Fig 23. Effect of type of compaction (Factor H).

improved hydration or the ability of the soil to benefit from improved hydration. Thus, the strength gain for increased molding water contents was greater for higher cement contents, was greater for sealed specimens in which the water was retained for hydration, was greater for limestone than for gravel since the rough surface texture of the limestone could develop a better bond with the improved matrix, and was greater for the longer curing time which allowed better hydration to occur. The other two highly significant two-factor interactions involved aggregate gradation and type of compaction. Both had relatively low mean squares and were considered to be relatively unimportant in comparison to most of the other highly significant effects involving molding water content.

It may be noted that of the nine factors chosen for investigation, seven were found to produce highly significant effects. The remaining two factors, aggregate gradation and curing temperature, were judged to produce no effects of practical significance although aggregate gradation indicated some significance at the probability level of 0.05. It is not surprising that curing temperature did not produce a significant main effect since there was evidence that water needed for hydration was removed from the specimens at the upper level of temperature (110° F). Thus, the beneficial effect of increased curing temperature was offset by the loss of water associated with the increase in temperature.

In general, any factor which could be expected to increase the strength of the cement matrix or improve the bond between the cement matrix and soil particles resulted in increased strengths.

REGRESSION ANALYSIS

A stepwise regression analysis was conducted in order to obtain a predictive equation for indirect tensile strength and to evaluate the quadratic characteristics of the response surfaces (Ref 58). The high and low levels as well as the applicable intermediate levels of all factors were used as input. From the analysis a predictive equation was developed, allowing the indirect tensile strength to be estimated within some 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., quadratic, linear-quadratic, or quadratic-quadratic terms, the term was considered to have a significant effect, which means that the relationship between the dependent variable and the variable tested was curvilinear. This test of significance was performed for the two dependent variables.

Regression Equation

The regression equation obtained for the indirect tensile strength is

$$S_T = -110.85 - 21.35E_i + 20.68A_iJ_i + 1.25A_iE_iJ_i$$
$$+ 11.31D_iE_i - 4.70A_i^2 - 1.63A_iJ_i^2 + 0.15A_i^2D_iJ_i$$
$$+ 0.30A_i^2H_i + 1.22A_iC_i + 0.05B_i^2G_i$$

where

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

A , B , D , E , G , H , J = factors considered for prediction;

i = level of the factor (see Table 5 for levels used in this analysis).

The multiple correlation coefficient for the tensile strength predictive equation is $R = 0.95$ and the standard error of estimate is equal to ±32.02. This is not considered critical since the lack of fit error of this regression is significant at $\alpha = 0.10$. The equation was obtained utilizing a stepwise regression computer routine with the capability of handling up to ten factors. Although many main effects do not appear significant in this regression equation, it must be noted that these factors cannot be ignored in the application of the regression. The equation is only valid within the factor space studied, which is a function of all factors and levels involved. Any attempt to extrapolate beyond the factor space with the regression equation is a violation of the statistical principles and is incorrect.

TABLE 5. LEVELS OF FACTORS USED IN REGRESSION EQUATIONS

Factor	Description	Level
A. Molding water content, %	3 5 7	$A_0 = 3$ $A_1 = 5$ $A_2 = 7$
B. Curing time, days	7 14 21	$B_0 = 7$ $B_1 = 14$ $B_2 = 21$
C. Aggregate gradation	Coarse Medium Fine	$C_0 = 0$ $C_1 = 1$ $C_2 = 2$
D. Type of curing	Air dried Sealed	$D_0 = 0$ $D_2 = 2$
E. Type of aggregate	Rounded gravel Crushed limestone	$E_0 = 0$ $E_2 = 2$
F. Curing temperature, ^{o}F	40 75 110	$F_0 = 40$ $F_1 = 75$ $F_2 = 110$
G. Compactive effort	Low High	$G_0 = 0$ $G_2 = 2$
H. Type of compaction	Impact Gyratory shear	$H_0 = 2$ $H_2 = 0$
J. Cement content, %	4 6 8	$J_0 = 4$ $J_1 = 6$ $J_2 = 8$

Furthermore, it may be noted that the factors and interactions included in the predictive equation are not identical to those shown to be highly significant by the analysis of variance. This is partially due to the fact that an additional level for each factor was included in the regression analysis; thus, the data for the two analyses were not the same. A second cause is that the predictive equation is concerned only with those variables which provide the best estimate of the dependent variable. Hence, if two independent variables are highly correlated, it is possible that the regression analysis may include only one of them.

Nonlinear Effects

The above regression equation can, to a certain extent, be used to evaluate the nonlinear effects for the five factors that contain a midpoint level. A factor which appears in the equation in terms of a squared term can be judged to produce a nonlinear effect. Thus, it appears that molding water content (Factor A), curing time (Factor B), and cement content (Factor J) produce curvature of the response surface of indirect tensile strength.

CHAPTER 5. CONCLUSIONS, RECOMMENDATIONS, AND APPLICATIONS

CONCLUSIONS

This report describes a screening experiment performed to evaluate the effects of nine factors and their interactions on the tensile strengths of cement-treated materials. Conclusions are limited to the range of variables studied in the experiment. The application of a fractional factorial is questionable if complex interactions are present; therefore, further work will be needed. This study, however, gives a great deal of information about the complexity of the interactions of factors involved in cement-treated materials.

Seven of the nine factors evaluated in this study produced significant main effects on the indirect tensile strength at a probability level of 0.01. From the data it was found that the average strength was significantly increased by

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

Eleven of the 36 two-factor interactions evaluated produced significant effects on the indirect tensile strength at a probability level of 0.01. These interactions were

(1) molding water content X cement content,
(2) molding water content X type of curing,
(3) type of curing X aggregate type,
(4) type of aggregate X cement content,
(5) molding water content X aggregate type,
(6) type of curing X cement content,

(7) molding water content X aggregate gradation,
(8) molding water content X type of compaction,
(9) curing temperature X aggregate type,
(10) molding water content X curing time, and
(11) curing time X compactive effort.

Two three-factor and one four-factor interactions were found to be significant at a probability level of 0.01. The four-factor interaction was confounded with another four-factor interaction and therefore could not be evaluated. The three-factor interactions were

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

In addition to the highly significant effects summarized above, one main effect, four two-factor interaction effects, seven three-factor interaction effects and two four-factor interaction effects were found to be significant at a probability level of 0.05.

Curing temperature was the only factor which did not produce a significant main effect at a level of 0.05. This should not be interpreted to mean that curing temperature was not important since there was evidence that moisture needed for hydration was driven from the specimens cured at 110° F. Thus, the benefits of increased temperature may have been offset by the loss of moisture.

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

In general, any factor which could be expected to increase the strength of the cement matrix or improve the bond between the cement matrix and soil particles resulted in increased strengths.

The large number of interactions significant at a probability level of 0.01 indicates the complexity of the relationships between tensile strength and the factors involved.

In evaluating the effects produced by various factors, it is not adequate to infer only from main effects; rather one must consider the interactions between the factors involved in order to predict tensile strength.

Significant nonlinear effects were produced by molding water content, cement content, and curing time.

RECOMMENDATIONS

Based on 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 cement-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 those factors found to significantly influence the tensile strength of cement-treated materials. The design should allow a more complete evaluation of the interaction effects and should contain additional levels for the quantitative variables in order to more closely define the response surface and to develop adequate predictive regression equations.

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

Applications

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

The ultimate application of the results will be in a comprehensive design method for stabilized materials.

REFERENCES

1. Kawala, E. J., "Cement-Treated Subbases for Concrete Pavements," Technical Bulletin 235, American Road Builders Association, 1958.

2. Mills, W. H., Jr., "Road Base Stabilization with Portland Cement," Engineering News-Record, Vol 112, No. 22, November 1935.

3. Mills, W. H., Jr., "Stabilizing Soils with Portland Cement, Experiments by South Carolina Highway Department," Proceedings, Sixteenth Annual Meeting of the Highway Research Board, 1936.

4. Catton, Miles, "Early Soil Cement Research and Development," Development Department Bulletin, D42, Portland Cement Association, 1959 (Reprint from Journal of the Highway Division, Proceedings of the American Society for Testing Materials, 1959).

5. Johnson, A. W., "Cement-Treated Soil Mixtures," Highway Engineering Handbook, 1960.

6. 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.

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

8. Hadley, William O., W. Ronald Hudson, and Thomas W. Kennedy, "An Evaluation of Factors Affecting the Tensile Properties of Asphalt-Treated Materials," Research Report No. 98-2, Center for Highway Research, The University of Texas at Austin, August 1968.

9. Hadley, William O., et al, "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, January 1969.

10. Burmister, D. M., "Evaluation of Pavements Systems of the WASHO Road Test by Layered System Methods," Bulletin 177, Highway Research Board, 1958.

11. Burmister, D. M., "Stress and Displacement Characteristic of a Two-Layered Rigid Base Soil System: Influence Diagrams and Practical Applications," Proceedings, Thirty-sixth Annual Meeting of the Highway Research Board, 1956.

12. Davidson, D. T., "Soil Stabilization with Portland Cement," Bulletin 292, Highway Research Board, 1961.

13. "Procedures for Testing Soils," American Society for Testing Materials, April 1958.

14. Soil Cement Laboratory Handbook, Portland Cement Association, 1966.

15. Soil Cement Construction Handbook, Portland Cement Association, 1966.

16. Winterkorn, Hans, and W. Aichhorn, "Fundamentals of Soil Stabilization on Street and Road Construction," Road Research Center of the Austrian Society of Engineers, Vienna, 1960.

17. Za-Chieh Moh, "Reaction of Soil Mineral with Cement and Chemicals," Highway Research Record No. 86, Highway Research Board, 1965.

18. Herzog, A., and J. K. Mitchell, "Reactions Accompanying Stabilization of Clays with Portland Cement," Highway Research Record No. 36, Highway Research Board, 1963.

19. Handy, R. L., "Cementation of Soil Minerals with Portland Cement or Alkalis," Bulletin 198, Highway Research Board, 1958.

20. Mills, W. H., "Report of Subcommittee on use of Portland Cement in Soil Stabilization, Condition Survey of Soil-Cement Roads," Proceedings, Twentieth Annual Meeting of the Highway Research Board, 1940.

21. Felt, E. J., "Factors Influencing Physical Properties of Soil-Cement Mixtures," Bulletin 108, Highway Research Board, 1955, Development Department Bulletin, D16, Portland Cement Association, Research and Development Laboratories.

22. Davidson, D. T., et al, "Moisture-Density, Moisture-Strength, and Compaction Characteristics of Cement-Treated Soil Mixtures," Bulletin 353, Highway Research Board, 1962.

23. Martin, Iury, "Effect of Water Content on the Compressive Strength and Density of Various Aggregate-Cement Mixtures for Highway Cement-Treated Bases," Bulletin 251, Washington State University, Pullman, 1960.

24. Abrams, "Laboratory and Field Test of Granular Soil-Cement Mixture for Base Course," Development Department Bulletin, D37, Portland Cement Association, Research and Development Laboratories, 1959, (Reprint from American Society for Testing Materials, Special Technical Publication, No. 254).

25. Nussbaum, P. J., and T. J. Larsen, "Load-Deflection Characteristics of Soil-Cement Pavements," Highway Research Record No. 86, Highway Research Board, 1965.

26. Clare, K. E., and P. T. Sherwood, "The Effect of Organic Matter on the Setting of Soil-Cement Mixtures," Journal of Applied Chemistry, Vol 4, London, November 1954.

27. Norling, L. T., and R. G. Packard, "Expanded Shortcut Test Method for Determining Cement Factors for Sandy Soils," Bulletin 198, Highway Research Board, 1958.

28. Winterkorn, Hans, "Surface Chemical Factors Influencing the Stabilization of Soils with Cement," Proceedings, Twenty-second Annual Meeting of the Highway Research Board, 1942.

29. Catton, M. D., "Research on the Physical Relations of Soil and Soil-Cement," Proceedings, Twentieth Annual Meeting of the Highway Research Board, 1940.

30. Circeo, L. J., D. T. Davidson, and H. T. Davis, "Strength Maturity Relations of Soil-Cement Mixtures," Bulletin 353, Highway Research Board, 1962.

31. Clare, K. E., and A. E. Pollard, "Effect of Temperature on Soil-Cement," Geotechnique, Vol 4, 1959.

32. Dumbleton, M. J., and N. F. Ross, "Effect of Temperature in the Gain of Strength of Soils Stabilized with Hydrated Lime and Portland Cement," Research Note RN/3655, B.S. 438, Road Research Lab, Great Britain, January 1960.

33. El-Rawi, N. M., "Strength Characteristics of Soil-Cement Mixtures," unpublished Ph.D. Dissertation, Oklahoma State University, 1967.

34. El-Rawi, N. M., T. Allan Haliburton, and Robert L. Janes, "Effect of Compaction Method on Strength Parameters of Soil-Cement Mixtures," Highway Research Record No. 255, Highway Research Board, 1967.

35. Baker, C. N., "Strength of Soil-Cement as a Function of Mixing," Bulletin 98, Highway Research Board, 1954.

36. Davidson, D. T., and B. W. Bruns, "Comparison of Type I and Type III Portland Cements for Soil Stabilization," Bulletin 267, Highway Research Board, 1960.

37. Nussbaum, P. J., and T. J. Larsen, "Fatigue of Soil-Cement," Journal, Vol 9, No. 2, Portland Cement Association, Research and Development Laboratories, May 1967.

38. Kayyal, Kassim M., "Strength Characteristics of Soils Compacted by Four Methods," unpublished Ph.D. Dissertation, The University of Texas, January 1965.

39. Johnson, A. W., and J. R. Sallberg, "Factors Influencing Compacting Test Results," Bulletin 319, Highway Research Board, 1962.

40. Davidson, D. T., and R. L. Handy, "Cement Requirements of Selected Soil Series in Iowa," Bulletin 267, Highway Research Board, 1960.

41. Catton, M., and E. J. Felt, "Weight in Water Methods of Determining the Moisture Content of Soil-Cement Mixtures in the Field," Proceedings, Twenty-third Annual Meeting of the Highway Research Board, 1943.

42. Road Research Laboratory, "Soil Mechanics for Road Engineers," Department of Scientific and Industrial Research, H. M. Stationary Office, London, 1952.

43. Watson, John D., "The Unconfined Compressive Strength of Soil-Cement Mixtures," Proceedings, Twenty-first Annual Meeting of the Highway Research Board, 1941.

44. Mitchell, J. K., and D. R. Freitag, "A Review and Evaluation of Soil-Cement Pavements," Journal of the Soil-Mechanics and Foundation Division, Vol 85, Part I, Proceedings of the American Society of Civil Engineers, December 1959.

45. Le Clerc, R. V., and Sandahl, H. E., "A Rapid Field Method for Determining Cement Content of Plastic Cement-Treated Base," Bulletin 267, Highway Research Board, 1960.

46. McLaren, D., B. Broad, and G. Wert, "Cement Stabilization of Granular Road Base Materials," Research Note RN/3665, Road Research Lab, Great Britain, January 1960.

47. "Prevention of Moisture Loss in Soil Cement with Bituminous Materials," Research Report 8F, Highway Research Board, September 1949, p 34.

48. Maner, A. W., "Curing Soil-Cement Bases," Proceedings, Thirty-first Annual Meeting of the Highway Research Board, 1952.

49. Leadabrand, J. A., "Some Engineering Aspects of Soil-Cement Mixtures," Mid-South Section Meeting, American Society of Civil Engineers, April 1956.

50. Texas Highway Department, Manual of Testing Procedures, Vol I, Materials and Test Division, Test Method Tex-113-E, Revised Edition, 1966.

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

52. Seed, H. B., and C. K. Chan, "Structure and Strength Characteristics of Compacted Clay," Journal of the Soil Mechanics and Foundation Division, Vol 85, No. SM5, Proceedings of the American Society of Civil Engineers, 1959.

53. Mitchell, J. K., and Chen-Kong Shen, "Behavior of Soil-Cement in Repeated Compression and Flexure," Institute of Transportation and Traffic Engineering, University of California, Berkeley, 1966.

54. Ostle, Bernard, Statistics in Research, The Iowa State University Press, Ames, Iowa.

55. Anderson, Virgil L., "Design and Optimum Techniques for Consulting Statisticians and Experimenters," unpublished notes, Purdue University, p 148.

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

57. "Standard Specifications for Road and Bridge Construction," Texas Highway Department, 1962.

58. Winterkorn, H. F., "Granulometric and Volumetric Factors in Bituminous Soil Stabilization," Proceedings, Thirty-sixth Annual Meeting of the Highway Research Board, 1957.

59. Draper, N. R., and H. Smith, Applied Regression Analysis, John Wiley and Sons, Inc., New York, 1966.

APPENDICES

APPENDIX 1

TYPES OF GRADATIONS USED IN THIS EXPERIMENT

APPENDIX 1. TYPES OF GRADATIONS USED IN THE EXPERIMENT

COARSE GRADATION - Type A

Sieve Size	Texas Highway Department Specifications,* Percent by Weight	Gradation Used, Percent by Weight
Passing 2 inch	100	100
Passing 1-3/4 inch	95-100	100
Passing 1-3/4 inch Retained 7/8 inch	15-40	0
Passing 7/8 inch Retained 3/8 inch	15-40	26
Passing 3/8 inch Retained No. 4	10-25	21
Passing No. 4 Retained No. 10	5-20	15
Total Retained on No. 10	65-80	62
Passing No. 10 Retained No. 40	0-20	15
Passing No. 40 Retained No. 80	3-15	5
Passing No. 80 Retained No. 200	2-15	8
Passing No. 200	0-8	10

*Reference 57.

(continued)

APPENDIX 1. (Continued)

MEDIUM GRADATION - Type B

Sieve Size	Texas Highway Department Specifications,* Percent by Weight	Gradation Used, Percent by Weight
Passing 1 inch	100	100
Passing 7/8 inch	95-100	100
Passing 7/8 inch Retained 3/8 inch	20-50	20
Passing 3/8 inch Retained No. 4	10-40	18
Passing No. 4 Retained No. 10	5-25	13
Total Retained No. 10	60-75	51
Passing No. 10 Retained No. 40	0-30	22
Passing No. 40 Retained No. 80	4-20	7
Passing No. 80 Retained No. 200	3-20	10
Passing No. 200	0-8	10

*Reference 57.

(continued)

APPENDIX 1. (Continued)

FINE GRADATION - Type C

Sieve Size	Texas Highway Department Specifications,* Percent by Weight	Gradation Used, Percent by Weight
Passing 1/2 inch	100	98
Passing 3/8 inch	95-100	95
Passing 3/8 inch Retained No. 4	20-50	20
Passing No. 4 Retained No. 10	10-30	15
Total Retained No. 10	60-75	40
Passing No. 10 Retained No. 40	0-30	30
Passing No. 40 Retained No. 80	4-25	10
Passing No. 80 Retained No. 200	3-25	10
Passing No. 200	0-8	10

*Reference 57.

APPENDIX 2

TREATMENT COMBINATIONS

APPENDIX 2. TREATMENT COMBINATIONS

Specimen Number	Test Order	Level of Factor[1]								
		A	B	C	D	E	F	G	H	J
1	91	-1	+1	-1	+1	-1	-1	-1	+1	+1
2	36	0	0	-1	-1	-1	0	-1	-1	0
3	1	-1	-1	-1	-1	-1	-1	-1	-1	-1
4	92	+1	+1	-1	-1	-1	-1	-1	-1	+1
5	93	-1	+1	-1	-1	+1	-1	-1	+1	-1
6	94	0	+1	0	+1	+1	0	+1	+1	0
7	2	-1	-1	-1	+1	+1	+1	-1	+1	+1
8	37	0	0	0	-1	-1	0	-1	-1	+1
9	3	+1	-1	-1	-1	+1	+1	+1	+1	+1
10	95	+1	+1	-1	+1	+1	-1	+1	+1	-1
11	96	+1	+1	+1	-1	+1	-1	-1	+1	+1
12	97	+1	+1	+1	+1	-1	-1	-1	+1	-1
13	38	0	0	0	-1	-1	0	-1	-1	0
14	98	-1	+1	-1	+1	-1	+1	-1	-1	+1
15	99	-1	+1	+1	+1	+1	-1	-1	-1	-1
16	4	+1	-1	+1	-1	-1	-1	+1	+1	-1
17	39	0	0	+1	+1	+1	0	+1	+1	0
18	40	0	0	0	+1	+1	0	+1	+1	0
19	5	-1	-1	-1	+1	+1	-1	-1	-1	-1
20	100	-1	+1	-1	-1	+1	+1	+1	+1	+1
21	6	+1	-1	-1	-1	+1	-1	-1	+1	-1
22	101	+1	+1	+1	+1	-1	-1	+1	-1	+1
23	102	+1	+1	-1	+1	+1	+1	+1	-1	-1
24	103	-1	+1	+1	+1	+1	-1	+1	+1	+1
25	104	+1	+1	-1	+1	+1	+1	-1	+1	+1
26	7	0	-1	0	+1	+1	0	+1	+1	0

(continued)

APPENDIX 2. (Continued)

Specimen Number	Test Order	Level of Factor[1]								
		A	B	C	D	E	F	G	H	J
27	105	-1	+1	+1	+1	+1	+1	+1	-1	+1
28	8	+1	-1	+1	-1	-1	+1	-1	+1	+1
29	106	+1	+1	-1	+1	+1	-1	-1	-1	+1
30*	41	0	0	0	-1	-1	0	-1	-1	0
31	9	+1	-1	+1	-1	-1	-1	-1	-1	+1
32	107	-1	+1	+1	+1	+1	+1	-1	+1	-1
33	108	0	+1	0	-1	-1	0	-1	-1	0
34	109	-1	+1	-1	+1	-1	+1	+1	+1	-1
35	10	+1	-1	+1	+1	+1	-1	-1	-1	-1
36	11	-1	-1	-1	+1	+1	-1	+1	+1	-1
37	12	-1	-1	+1	-1	+1	+1	+1	+1	-1
38	13	-1	-1	+1	-1	+1	-1	-1	+1	+1
39	14	+1	-1	+1	+1	+1	-1	+1	+1	+1
40	15	-1	-1	+1	-1	+1	+1	-1	-1	+1
41	110	-1	+1	-1	-1	+1	-1	+1	-1	+1
42	16	-1	-1	+1	+1	-1	-1	-1	+1	-1
43	42	+1	0	0	+1	+1	0	+1	+1	0
44	43	-1	0	0	-1	-1	0	-1	-1	0
45	17	-1	-1	+1	+1	-1	+1	-1	-1	-1
46	18	0	-1	0	-1	-1	0	-1	-1	0
47	44	0	0	0	-1	-1	+1	-1	-1	0
48	19	-1	-1	+1	+1	-1	-1	+1	-1	+1
49	20	+1	-1	+1	-1	-1	+1	+1	-1	-1
50	45	0	0	0	+1	+1	0	+1	+1	+1
51	46	0	0	0	+1	+1	+1	+1	+1	0
52	47	0	0	-1	+1	+1	0	+1	+1	0
53	111	-1	+1	-1	-1	+1	+1	-1	-1	-1
54	112	+1	+1	+1	+1	-1	+1	+1	+1	+1
55	113	+1	+1	+1	-1	+1	+1	+1	+1	-1
56	21	+1	-1	+1	+1	+1	+1	+1	-1	-1

(continued)

APPENDIX 2. (Continued)

Specimen Number	Test Order	Level of Factor[1]								
		A	B	C	D	E	F	G	H	J
57	114	+1	+1	-1	-1	-1	+1	-1	+1	-1
58	48	0	0	0	-1	-1	0	-1	-1	-1
59	49	0	0	0	+1	+1	0	+1	+1	-1
60	22	+1	-1	-1	-1	+1	+1	-1	-1	-1
61	23	-1	-1	+1	+1	-1	+1	+1	+1	+1
62*	50	0	0	0	+1	+1	0	+1	+1	0
63	51	0	0	0	-1	-1	-1	-1	-1	0
64	115	+1	+1	+1	+1	-1	+1	-1	-1	-1
65	24	-1	-1	-1	-1	-1	+1	-1	+1	-1
66	116	+1	+1	+1	-1	+1	+1	-1	-1	+1
67	52	0	0	+1	-1	-1	0	-1	-1	0
68	25	-1	-1	+1	-1	+1	-1	+1	-1	-1
69	26	-1	-1	-1	+1	+1	+1	+1	-1	-1
70	117	-1	+1	+1	-1	-1	+1	-1	+1	+1
71*	118	+1	+1	+1	-1	+1	+1	-1	-1	+1
72	119	+1	+1	-1	-1	-1	-1	+1	+1	+1
73	27	+1	-1	-1	+1	-1	+1	-1	-1	+1
74	120	-1	+1	+1	-1	-1	+1	+1	-1	+1
75	28	+1	-1	-1	+1	-1	+1	+1	+1	-1
76	29	+1	-1	+1	+1	+1	+1	-1	+1	-1
77	30	-1	-1	-1	-1	-1	+1	+1	-1	+1
78	53	0	0	0	+1	+1	-1	+1	+1	0
79	121	-1	+1	+1	-1	-1	-1	-1	-1	+1
80*	31	+1	-1	-1	+1	-1	+1	+1	+1	-1
81	54	-1	0	0	+1	+1	0	+1	+1	0
82	32	+1	-1	-1	+1	-1	-1	-1	+1	+1
83	33	+1	-1	-1	-1	+1	-1	+1	-1	+1
84	122	-1	+1	-1	+1	-1	-1	+1	-1	-1
85	123	+1	+1	+1	-1	+1	-1	+1	-1	-1
86	34	+1	-1	-1	+1	-1	-1	+1	-1	-1

(continued)

APPENDIX 2. (Continued)

Specimen Number	Test Order	Level of Factor[1]								
		A	B	C	D	E	F	G	H	J
87	35	-1	-1	-1	-1	-1	-1	+1	+1	+1
88	55	+1	0	0	-1	-1	0	-1	-1	0
89	124	+1	+1	-1	-1	-1	+1	+1	-1	+1
90	125	-1	+1	+1	-1	-1	-1	+1	+1	-1
91	126	+1	0	0	+1	+1	0	+1	+1	0
92	56	+1	-1	+1	+1	+1	-1	+1	+1	-1
93	145	+1	+1	+1	+1	-1	-1	+1	-1	-1
94	57	-1	-1	+1	-1	+1	+1	-1	-1	-1
95	58	-1	-1	+1	-1	+1	-1	+1	-1	+1
96	146	-1	+1	-1	-1	+1	+1	+1	+1	-1
97	147	+1	+1	-1	+1	+1	+1	-1	+1	-1
98	148	+1	+1	+1	-1	+1	+1	-1	-1	-1
99	59	+1	-1	+1	+1	+1	+1	+1	-1	+1
100	60	+1	-1	+1	-1	-1	+1	-1	+1	-1
101	61	-1	-1	+1	+1	-1	-1	+1	-1	-1
102	149	+1	+1	-1	+1	+1	-1	+1	+1	+1
103	150	-1	+1	+1	-1	-1	+1	+1	-1	-1
104	151	-1	+1	+1	+1	+1	-1	+1	+1	-1
105	127	0	0	0	+1	+1	+1	+1	+1	0
106	62	-1	-1	+1	+1	-1	+1	+1	+1	-1
107	152	-1	+1	+1	-1	-1	-1	-1	-1	-1
108	63	+1	-1	+1	+1	+1	-1	-1	-1	+1
109	64	0	-1	0	+1	+1	0	+1	+1	0
110	153	-1	+1	+1	+1	+1	-1	-1	-1	+1
111	128	0	0	0	+1	+1	-1	+1	+1	0
112	154	-1	+1	+1	-1	-1	-1	+1	+1	+1
113	65	-1	-1	-1	+1	+1	-1	+1	+1	+1
114	66	+1	-1	+1	-1	-1	-1	-1	-1	-1
115	129	0	0	0	-1	-1	0	-1	-1	-1

(continued)

APPENDIX 2. (Continued)

Specimen Number	Test Order	Level of Factor[1]								
		A	B	C	D	E	F	G	H	J
116	67	+1	-1	-1	+1	-1	-1	-1	+1	-1
117	130	0	0	0	-1	-1	-1	-1	-1	0
118	68	+1	-1	-1	+1	-1	-1	+1	-1	+1
119	155	-1	+1	-1	-1	+1	-1	+1	-1	-1
120	69	-1	-1	+1	-1	+1	-1	-1	+1	-1
121	70	+1	-1	-1	-1	+1	+1	+1	+1	-1
122	156	0	+1	0	-1	-1	0	-1	-1	0
123	131	0	0	0	-1	-1	0	-1	-1	0
124	71	-1	-1	+1	-1	+1	+1	+1	+1	+1
125	157	-1	+1	-1	+1	-1	-1	-1	+1	-1
126	158	+1	+1	-1	-1	-1	+1	-1	+1	+1
127	159	+1	+1	+1	-1	+1	+1	+1	+1	+1
128	160	+1	+1	+1	+1	-1	+1	-1	-1	+1
129	132	+1	0	0	-1	-1	0	-1	-1	0
130	161	+1	+1	-1	+1	+1	+1	+1	-1	+1
131	72	-1	-1	-1	-1	-1	+1	-1	+1	+1
132	162	+1	+1	-1	-1	-1	-1	+1	+1	-1
133	73	-1	-1	-1	-1	-1	+1	+1	-1	-1
134	163	+1	+1	+1	-1	+1	-1	-1	+1	-1
135	74	+1	-1	-1	+1	-1	+1	-1	-1	-1
136	75	-1	-1	-1	+1	+1	-1	-1	-1	+1
137	76	0	-1	0	-1	-1	0	-1	-1	0
138	133	0	0	-1	-1	-1	0	-1	-1	0
139	134	0	0	0	-1	-1	+1	-1	-1	0
140	77	+1	-1	-1	-1	+1	-1	+1	-1	-1
141	78	-1	-1	+1	+1	-1	-1	-1	+1	+1
142	164	-1	+1	+1	+1	+1	+1	-1	+1	+1
143	165	-1	+1	+1	+1	+1	+1	+1	-1	-1
144	166	+1	+1	+1	+1	-1	+1	+1	+1	-1
145*	79	-1	-1	-1	+1	+1	-1	+1	+1	+1

(continued)

APPENDIX 2. (Continued)

Specimen Number	Test Order	Level of Factor[1]								
		A	B	C	D	E	F	G	H	J
146	80	+1	-1	-1	-1	+1	-1	-1	+1	+1
147	81	-1	-1	+1	+1	-1	+1	-1	-1	+1
148	167	+1	+1	+1	+1	-1	-1	-1	+1	+1
149	135	0	0	0	-1	-1	0	-1	-1	+1
150*	168	-1	+1	+1	+1	+1	-1	+1	+1	-1
151	82	+1	-1	+1	-1	-1	+1	+1	-1	+1
152	169	0	+1	0	+1	+1	0	+1	+1	0
153	83	+1	-1	-1	-1	+1	+1	-1	-1	+1
154	84	+1	-1	+1	+1	+1	+1	-1	+1	+1
155*	170	0	+1	0	-1	-1	0	-1	-1	0
156	171	+1	+1	-1	+1	+1	-1	-1	-1	-1
157	136	0	0	+1	-1	-1	0	-1	-1	0
158	172	-1	+1	+1	-1	-1	+1	-1	+1	-1
159	173	-1	+1	-1	-1	+1	+1	-1	-1	+1
160	174	-1	+1	-1	+1	-1	+1	+1	+1	+1
161	137	0	0	-1	+1	+1	0	+1	+1	0
162	175	-1	+1	-1	+1	-1	+1	-1	-1	-1
163	176	+1	+1	-1	-1	-1	-1	-1	-1	-1
164	85	-1	-1	-1	-1	-1	-1	-1	-1	+1
165	138	0	0	+1	+1	+1	0	+1	+1	0
166	86	+1	-1	-1	+1	-1	+1	+1	+1	+1
167	177	+1	+1	+1	-1	+1	-1	+1	-1	+1
168	139	-1	0	0	+1	+1	0	+1	+1	0
169	178	-1	+1	-1	-1	+1	-1	-1	+1	+1
170	87	-1	-1	-1	+1	+1	+1	-1	+1	-1
171	140	-1	0	0	-1	-1	0	-1	-1	0
172	88	-1	-1	-1	+1	+1	+1	+1	-1	+1
173	141	0	0	0	+1	+1	0	+1	+1	-1
174	179	-1	+1	-1	+1	-1	-1	+1	-1	+1
175	180	+1	+1	-1	-1	-1	+1	+1	-1	-1

(continued)

APPENDIX 2. (Continued)

Specimen Number	Test Order	Level of Factor[1] A	B	C	D	E	F	G	H	J
176*	142	0	0	0	-1	-1	0	-1	-1	-1
177	143	0	0	0	+1	+1	0	+1	+1	0
178	144	0	0	0	+1	+1	0	+1	+1	+1
179	89	+1	-1	+1	-1	-1	-1	+1	+1	+1
180	90	-1	-1	-1	-1	-1	-1	+1	+1	-1

*Duplicate specimens.

[1] Level of Factor

-1 Low Level
0 Middle Level
+1 High Level

APPENDIX 3

PREPARATION OF THE SPECIMENS

APPENDIX 3. PREPARATION OF THE SPECIMENS

BATCHING AND MIXING PROCEDURE

1. Select the aggregate and gradation to be used. Batch the material by weight in the following way:

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

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

2. Add the appropriate amount of portland cement (4, 6, and 8 percent by total weight of aggregate) to the portion of aggregate passing No. 10 sieve.

3. Mix the fine aggregate and cement by hand.

4. Add half of the required mixing water (3, 5, and 7 percent by total weight of aggregate and cement) to the coarse portion of the aggregate and hand mix until the surfaces of all the coarse aggregate are wet.

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

6. Machine mix for 1 minute and then remove the fines stuck to the bottom of the bowl; mix an additional 1-1/2 minutes. The mixing procedure used in the experiment was performed using a Model AS-200 machine manufactured by the Hobart Company (Ohio). Figure 24 shows the type of mixer used.

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.

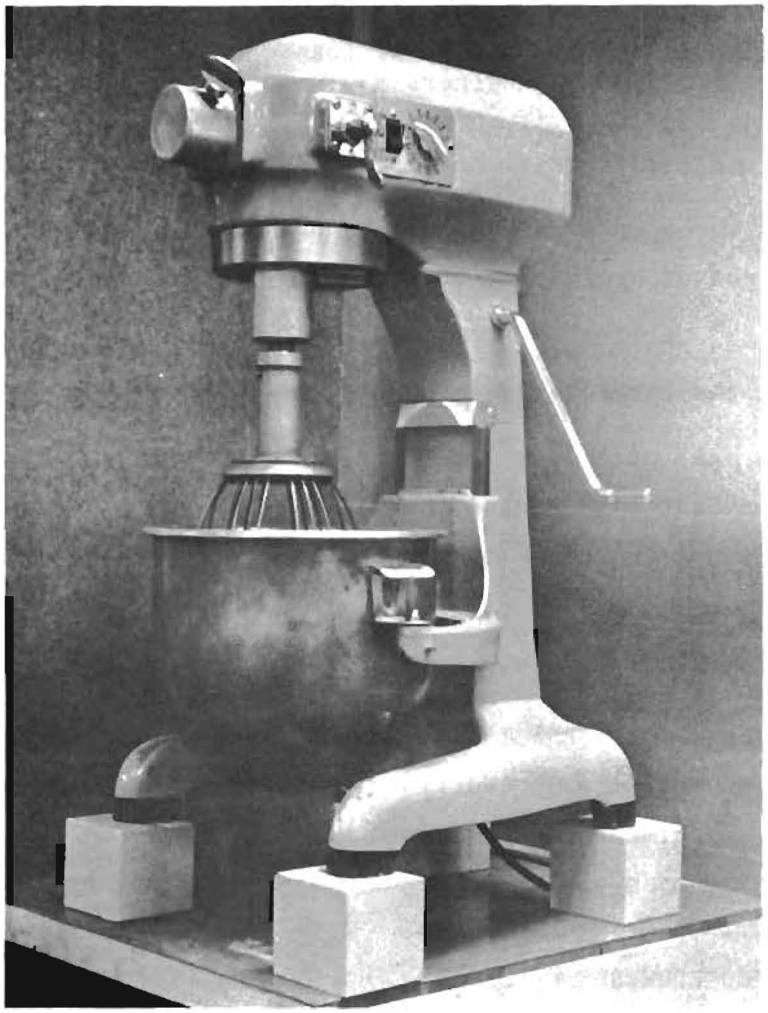

Fig 24. Automatic mixing apparatus.

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 it 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 30 psi is reached on the low pressure gage. Gyrate the specimen three times and stop. Repeat until 60 psi, in the case of the lower compactive effort, or 160 psi, in the case of the higher compactive effort, is registered during gyration (Fig 25).

5. Release the pressure in the low pressure system. Now, at approximately one stroke per second, increase the pressure to 1,000 pounds, as measured on the high pressure gage. Then, release the pressure and remove ram from the mold.

6. Take the 4 by 2 inch specimen out of the mold using the extractor shown in Fig 25. Details and specifications for the gyratory shear compaction can be seen in Ref 51.

Automatic Rainhart Impact Compaction

1. Proceed in the same way 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 30 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 shown in Fig 26. The same figure shows the Rainhart Impact Compactor (Ref 50) used for compacting the 4 by 2-inch specimens.

CURING AND TESTING PROCEDURE

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

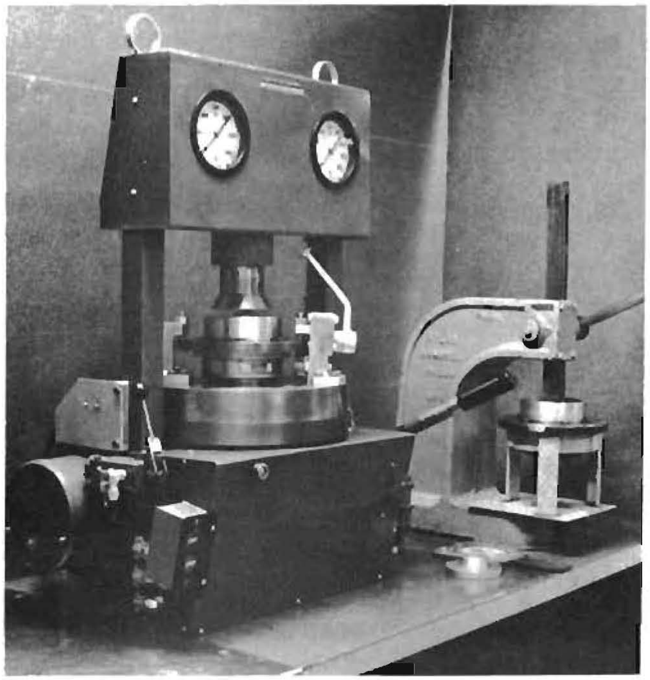

Fig 25. Mechanical extruding apparatus and gyratory shear compactor.

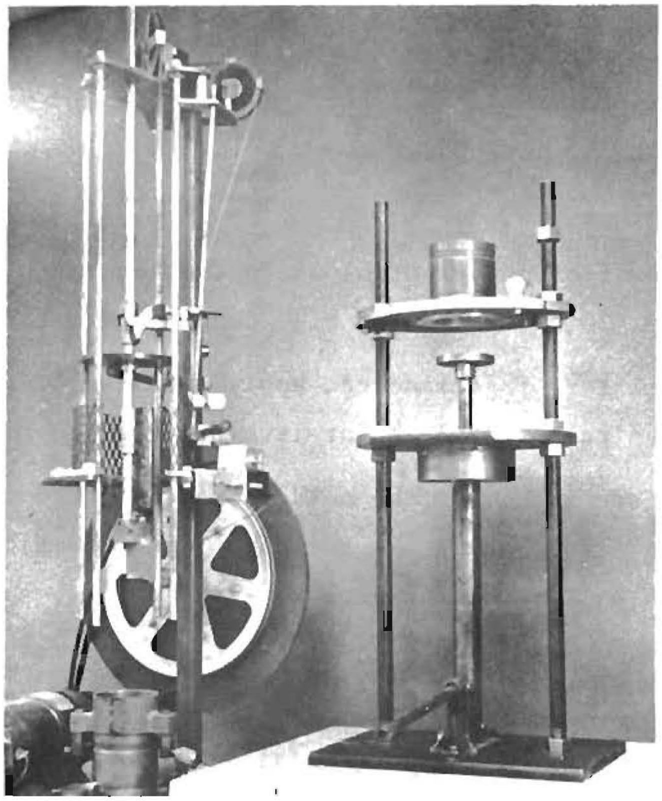

Fig 26. Rainhart automatic compactor and mechanical extruding apparatus.

2. Store the specimen in the environmental chamber at 40° F, in the air-conditioned laboratory at 75° F, or in the oven at 110° F, according to the curing temperature of the specimen.

3. Remove the specimen from the corresponding curing temperature after 6, 13, or 20 days, according to the curing time, and remove the PVC film. Determine the specific gravity.

4. Allow the specimen to dry for 24 hours with the help of an electric fan to eliminate the influence of moisture content on testing.

5. Test the specimen at 75° F $\pm$ 2° F with the indirect tensile test equipment shown in Fig 27. Place an arbitrary preload of 25 pounds on the specimen prior to applying a loading rate of 2 inches per minute.

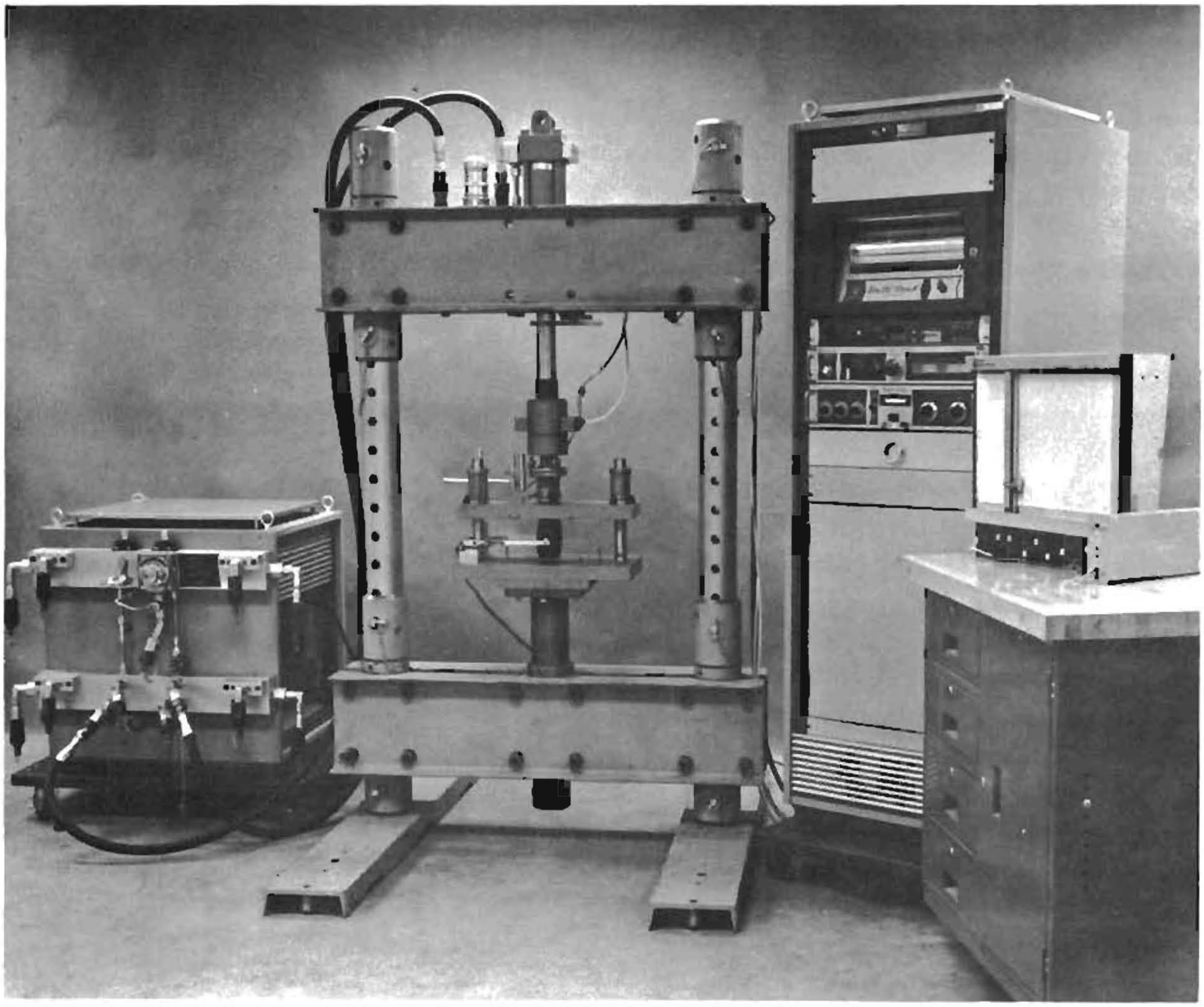

Fig 27. Basic indirect tensile testing equipment.

APPENDIX 4

DUPLICATE SPECIMENS AND ERROR TERM CALCULATIONS

APPENDIX 4. DUPLICATE SPECIMENS AND ERROR TERM CALCULATIONS

INDIRECT TENSILE STRENGTH

Specimen Number	Tensile Strength	Mean Squares
75	127.7	156.6
80	145.4	
13	139.0	47.0
30	129.3	
18	252.0	1035.1
62	206.5	
113	105.6	271.4
145	82.3	
104	70.9	6.5
150	74.5	
122	136.8	937.5
155	93.5	
115	98.1	16.3
176	92.4	

Total Sum of Squares	2,470.4
Degrees of Freedom	7
*Error Term = $\frac{2,470.4}{7}$ =	353

*Within treatments treated alike