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16. Abstract

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The effects on tensile strength produced by eight factors previously shown to be important are analyzed in detail and the effects are evaluated in terms of their significance and relationship to shrinkage cracking of cement-treated materials.

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IMPROVED TENSILE STRENGTH FOR CEMENT-TREATED BASES AND SUBBASES

by

Robert F. Cauley
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Research Report 98-11

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

Research Project 3-8-66-98

conducted for

The Texas Highway Department

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

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

December 1972

PREFACE

This is the eleventh report in a series dealing with research findings concerned with the evaluation of the properties of stabilized subbase materials. The purpose of this report is to summarize the findings of previous studies concerning tensile and shrinkage characteristics of cement-treated material, to interpret the tensile strength findings in terms of shrinkage cracking, and to make recommendations for mixture design and construction of cement-treated bases and subbases to improve tensile strength and minimize cracking.

The assistance of several individuals was required for the preparation of this report and the authors would like to acknowledge the contributors. Special thanks are extended to Mr. James N. Anagnos for his aid in interpreting the findings and information from previous studies and Dr. Clyde E. Lee for his comments and suggestions concerning the report. The assistance of the staff of the Center for Highway Research is gratefully appreciated. Special appreciation is due Mr. Chester A. McDowell and Dr. Joseph A. Kozuh.

Thanks are also due to Messrs. James L. Brown and Larry J. Buttler of the Texas Highway Department, who provided technical liaison for the project, and Messrs. Weldon R. Gibson and Clarence R. Doyle, District Laboratory Engineers for Districts 19 and 12, who provided necessary field information for the formulation of the recommendations.

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December 1972

LIST OF REPORTS

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

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

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

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

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

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

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

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

Report No. 98-9, "Evaluation and Prediction of the Tensile Properties of Asphalt-Treated Materials," by William O. Hadley, W. Ronald Hudson, and Thomas W. Kennedy, presents a detailed investigation by indirect tensile test of seven factors thought to affect the tensile properties of asphalt-treated materials and reports findings which indicate the important factors affecting each of the tensile properties and regression equations for estimation of the tensile properties.

Report No. 98-10, "Practical Method of Conducting the Indirect Tensile Test," by James N. Anagnos and Thomas W. Kennedy, describes equipment and test procedures involved in conducting the indirect tensile test along with a method of analyzing the test results.

Report No. 98-11, "Improved Tensile Strength for Cement-Treated Bases and Subbases," by Robert F. Cauley and Thomas W. Kennedy, summarizes the findings of an evaluation and interpretation of the results from previous studies concerning the tensile and shrinkage characteristics of cement-treated materials.

ABSTRACT

This report summarizes the findings of an evaluation and interpretation of the results from previous studies concerning the tensile and shrinkage characteristics of cement-treated materials.

Findings of studies performed at the Center for Highway Research to determine the tensile characteristics of cement-treated materials are summarized and a detailed discussion of the findings of a number of studies to determine the shrinkage properties of cement-treated materials is presented.

The effects on tensile strength produced by eight factors previously shown to be important are analyzed in detail and the effects are evaluated in terms of their significance and relationship to shrinkage cracking of cement-treated materials.

Based on these evaluations, a modification is proposed for the Texas Highway Department mix design procedure, which should improve tensile strength and minimize shrinkage cracking. In addition, recommendations regarding the construction of cement-treated bases and subbases for improved tensile strength and reduced shrinkage cracking are made.

KEY WORDS: tensile strength, shrinkage cracking, cement-treated, curing, cement content, water content, mix design.

SUMMARY

This report summarizes the findings of an evaluation and interpretation of the results from previous studies concerning the tensile and shrinkage characteristics of cement-treated materials.

Findings of studies performed at the Center for Highway Research to determine the tensile characteristics of cement-treated materials are summarized and a detailed discussion of the findings of a number of studies to determine the shrinkage properties of cement-treated materials is presented.

The effects on tensile strength produced by eight factors previously shown to be important are analyzed in detail and effects are evaluated in terms of their significance and relationship to shrinkage cracking of cement-treated materials. These factors included type of soil, cement content, molding water content, density and compactive effort, and curing conditions.

It was concluded that there was an optimum water content which produced maximum tensile strength and minimum shrinkage cracking for a given soil type and cement content. It was also found that the tensile strength increased and cracking decreased with a decrease in the amount of cohesive material in the mixture, an increase in cement content, sealed curing, and extended curing periods.

Based on these evaluations, a modification of the Texas Highway Department mix design procedure was proposed. This modification involved the determination of the compaction water content which would produce maximum tensile strength for a given cement content. In addition, recommendations regarding the construction of cement-treated bases and subbases for improved tensile strength and reduced shrinkage cracking are made.

IMPLEMENTATION STATEMENT

The recommendations and mix design procedure developed and summarized in this report are for direct application and trial use in the field. Utilization of the modified mix design procedure and recommended construction and curing procedures should improve the tensile strength and reduce shrinkage cracking in cement-treated bases and subbases.

These recommendations and procedures, however, are based on an evaluation of previous studies of shrinkage cracking and upon laboratory studies concerning the indirect tensile strengths of cement-treated materials. Therefore, field experience is needed in order to determine whether the recommended design procedure and construction procedures are satisfactory or whether modifications will be required. It is, therefore, recommended that these procedures be tried and evaluated in the field.

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CHAPTER 1. INTRODUCTION

The Center for Highway Research at The University of Texas at Austin has been conducting a study of the tensile properties of stabilized subbase materials for some time. Initially, Hudson and Kennedy (Refs 26 and 29), after reviewing the available literature and conducting laboratory tests, determined the indirect tensile test to be the best for the study undertaken by the Center. Experiments (Refs 2, 3, 22, 23, 24, 38, and 41) were conducted to determine the tensile characteristics of asphalt-treated, cement-treated, and lime-treated materials and to establish those factors which significantly affect the tensile properties of these materials.

This report summarizes the findings of an evaluation and interpretation of the results from previous studies concerning the tensile and shrinkage characteristics of cement-treated materials, with a view toward practical application of the indirect tensile test to projects in the field.

Chapter 2 reviews the results of studies performed at the Center for Highway Research to determine the tensile characteristics of cement-treated materials (Refs 3 and 41) and presents a detailed summary of the findings of others to determine the shrinkage properties of such materials (Refs 18, 19, and 39). Particular emphasis is given to shrinkage cracking of cement-treated pavement layers. Also included is a summary of mix design methods currently used by the Portland Cement Association and the Texas Highway Department. The effects on tensile strength produced by eight factors which have been previously found to be most important are discussed in detail in Chapter 3. These effects are then evaluated in terms of their significance and relationship to shrinkage cracking of cement-treated materials. In Chapter 4, a proposed modification of the Texas Highway Department mix design procedure, which should improve tensile strength and minimize shrinkage cracking of cement-treated materials, is described. Chapter 5 contains recommendations regarding the mix design and construction of cement-treated bases and subbases for improved tensile strength and reduced shrinkage cracking.

CHAPTER 2. SUMMARY OF PREVIOUS WORK

This chapter briefly summarizes the findings of studies performed at the Center for Highway Research and by other investigators in two major areas pertaining to cement-treated materials: factors affecting the tensile strength of cement-treated soil and shrinkage characteristics of cement-treated base materials. In addition, two mix design procedures are reviewed. The findings concerning tensile strengths are evaluated in more detail and interpreted in Chapter 3.

FACTORS AFFECTING THE TENSILE PROPERTIES OF CEMENT-TREATED MATERIALS

From a review of literature concerned with factors which affect the strength of a cement-treated soil, Pendola et al (Ref 41) found that within the limits investigated, the unconfined compressive strength was increased by

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

On the basis of this literature review, a preliminary screening experiment was conducted to determine whether the following factors also affected the tensile strength and, if so, to determine the nature of the effects:

(1) water content during compaction,
(2) cement content,
(3) type of aggregate,
(4) aggregate gradation,
(5) type of curing,
(6) length of curing period,
(7) temperature of curing,
(8) method of compaction, and
(9) compactive effort.

The results of the experiment indicated that seven of these nine factors influenced tensile strength and that the average strength was significantly increased by

(1) increasing the molding water content from 3 to 7 percent,
(2) using sealed rather than air-dried curing,
(3) increasing the cement content from 4 to 8 percent,
(4) using crushed limestone rather than rounded gravel aggregate,
(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.

Also of significance was the finding that the actual changes in strength produced by changes in any one of these factors were dependent on the levels of the other factors and that these interaction effects were very complex.

Because of this complexity and the fact that each of the factors was studied at only two levels, a more detailed and comprehensive experimental study was conducted to more closely define the nature of the effects on tensile strength produced by the following six factors, which were studied at five levels:

(1) molding water content,
(2) aggregate gradation,
(3) curing temperature,
(4) compactive effort,
(5) cement content, and
(6) aggregate type.

Curing time, type of compaction, and type of curing were held constant.

In addition, an investigation was conducted to determine whether the indirect tensile strength correlated with the results of the unconfined compression and the cohesiometer tests, both of which are used by the Texas Highway Department.

Four of the factors; cement content, aggregate type, molding water content, and curing temperature; significantly influenced the tensile strength. Indirect tensile strength was

(1) increased with increased cement content;

(2) increased with increased curing temperature;

(3) higher for limestone materials than for rounded gravel; and

(4) increased as the molding water content was increased, up to some optimum value, above which an increase in water content decreased the strength.

As in the preliminary study, it was found that the magnitude of the strength change depended on the level of other factors.

The correlation analysis indicated that there was a correlation between indirect tensile strength and both cohesiometer value and unconfined compressive strength. The equations showing the correlation between tensile and unconfined compressive strengths and between tensile strength and cohesiometer value are

$$\hat{S}_T = -11.38 + .1662q_u \quad (1)$$

$$\hat{S}_T = 1.68 + .0341C \quad (2)$$

where

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

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

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

The standard errors of estimate for the correlations of indirect tensile strength with unconfined compressive strength and tensile strength with cohesiometer value were ±56.6 psi and ±41.6 psi, respectively. Thus, although these correlations existed, there was a great deal of scatter and large errors can be expected if these equations are used to estimate indirect tensile strength.

Subsequent to the completion of these two experiments, techniques were developed which allow the modulus of elasticity, Poisson's ratio, and tensile strains to be estimated using supplemental data obtained from the indirect tensile test (Ref 23). The test method and equipment needed for conducting the indirect tensile test and for estimating strength, modulus of elasticity, and Poisson's ratio are described in Ref 2.

A more detailed discussion of indirect tensile strength and the factors affecting it is contained in Chapter 3.

SHRINKAGE CRACKING IN CEMENT-TREATED BASES

As a cement-treated pavement layer loses moisture, it attempts to shrink. The restraint provided by subgrade friction prevents contraction and creates tensile stresses in the layer. When the tensile strength of the cement-treated material is exceeded, shrinkage cracks develop which may allow water to migrate through the layer, causing softening of the subgrade and loss of support (Ref 39).

Several reports (Refs 16, 17, 18, 19, and 20) have been published which provide a detailed analysis of the mechanism of shrinkage and of the factors which affect the shrinkage characteristics of cement-treated materials.

In analyzing shrinkage cracking of cement-treated soils, George (Refs 16 and 18) used three criteria for quantifying pavement damage due to cracking in a cement-treated subbase: crack spacing, crack width, and crack intensity. Crack spacing was found to be primarily a function of the tensile strength of the mixture. The coefficient of sliding friction between the base and the subgrade and the specific weight of the mixture were also found to affect crack spacing. Crack width, a function of total shrinkage, was dependent upon crack spacing, tensile strength, specific weight, and the modulus of elasticity of the cement-treated material in tension. Crack intensity is defined as the area of cracking per unit area of slab in units of in^2/in^2 (Refs 16 and 18) and is an overall measure of the extent of cracking. Crack intensity is used as the unit of measure in the following discussion, since this parameter includes both crack spacing and crack width and since George (Ref 18) considered that this was the best parameter for quantifying shrinkage cracking.

Although the amount of shrinkage is important, it would appear that the rate of shrinkage is also a primary factor. High shrinkage rates produce high tensile stresses, which in turn produce cracking; however, the relative importance of shrinkage rate and total shrinkage is not absolutely clear.

Factors Affecting Shrinkage

In his evaluations of shrinkage cracking, George (Refs 18 and 20) concluded that the important factors were type of soil, cement content, molding moisture content, density, and rate of evaporation of moisture from the cement-treated material.

Type of Soil. The type of soil to be treated is probably the most important factor affecting the shrinkage characteristics of cement-treated materials. In fine-grained soils, shrinkage occurs primarily in the soil portion of the cement-treated mixture, while in coarse grained soils, shrinkage occurs in the hydrated cement paste (Ref 19). In addition to the difference in the mechanism of shrinkage, the behavioral characteristics of the two types of soils are different.

The total shrinkage of clay soils is directly related to the quantity of minus-2 micron material (Ref 18) and is dependent on the type of clay mineral. George (Ref 18) and Nakayama and Handy (Ref 39) found that total shrinkage was larger for montmorillonitic soil cement mixtures, but that the rate of shrinkage was larger for a cement-treated kaolinitic soil. A possible explanation is that the expanding-lattice structure and the resulting high adsorption characteristics of montmorillonite, which inherently provide larger volume changes, inhibit the loss of water so that the rate of evaporation is smaller for montmorillonite than for kaolinite. Thus, though the amount of shrinkage may be larger for montmorillonite, the rate of shrinkage is less. Based on his findings, George (Refs 18 and 19) recommended that if the clay mineral is kaolinite, the clay content should not exceed 15 percent and if the clay mineral is montmorillonite, the clay content should be limited to 8 percent.

In coarse-grained soils, the shrinkage occurs primarily in the cement paste so that the type of coarse material is not as important. Nevertheless, the quantity and relative size of coarse aggregate is important. Coarse aggregates tend to minimize shrinkage by acting as rigid inclusions and possibly in some cases by reducing the amount of void space and consequently the amount of hydrated cement paste. At the same time, however, stress concentrations develop at the aggregate-cement paste interface, which cause shrinkage cracks to appear and to extend outward radially from the aggregate (Ref 18). When the aggregates are closely spaced, these cracks become interconnected and the crack intensity is increased. This problem is intensified for materials exhibiting a large amount of shrinkage.

George (Ref 18) recommended that large aggregates (greater than 1 inch nominal size) be avoided if possible. Likewise, it was recommended that a well-graded material be used since well-graded coarse materials exhibit less shrinkage (Ref 19), probably due to the fact that well-graded materials tend to have less cement paste because of the smaller quantity of voids.

Cement Content. The relationship between cement content and shrinkage of a cement-stabilized base has been the subject of several studies. Nakayama and Handy (Ref 39) found no relation between total shrinkage and cement contents of 8 to 14 percent. George (Refs 18 and 20), however, varied cement from 0 to 20 percent and found that there was an optimum cement content for a minimum amount of shrinkage. For granular soils, shrinkage was a minimum at a cement content somewhat below that needed to satisfy freeze-thaw durability criteria (ASTM D560-57) and thereafter increased slightly with increased cement content. The time rate of shrinkage and crack intensity, however, decreased as the cement content increased. This apparent conflict, i.e., increasing shrinkage with decreasing crack intensity, is explained in terms of the tensile strength of the mixture. At low cement contents, the tensile strength is a minimum and cracks are closely spaced. As the cement content is increased, the tensile strength of the base is increased and cracks are spaced farther apart; i.e., crack intensity is reduced. Thus, the adverse effect of increased shrinkage due to increased cement content is offset by the higher tensile strength (Ref 18).

In clay soils, it was found that crack intensity is nearly constant with increased cement content (Ref 18), due to the fact that shrinkage in a cohesive soil is caused primarily by shrinkage of the clay rather than of the hydrated cement paste.

George (Ref 18) recommended that the cement content be equal to or greater than that specified by freeze-thaw test criteria (ASTM D560-57) and that Type II cement be used rather than Type I. It was also suggested that 1 to 2 percent of the cement be replaced by an equal amount of lime in order to minimize shrinkage cracking.

Molding Water Content. Appreciably higher shrinkage has been observed (Refs 18, 19, and 39) for both cohesive and noncohesive soils at molding water contents wet of the optimum for standard Proctor density (AASHO T-99).

George (Ref 20) found that shrinkage increased exponentially with increased water content and explains this in terms of effective stresses and pore water pressures in the cement-treated specimens. At high water contents, the effective stress is low and the specimen is more susceptible to volume change upon drying. As molding water content is decreased, the pore water pressure becomes more negative, producing higher effective stresses, which resist shrinkage. In order to avoid this problem, it was recommended that cement-stabilized materials be compacted on the dry side of the optimum water content for maximum density (Ref 20).

In support of this recommendation, Lambe (Ref 30) and Seed and Chan (Ref 18) found that shrinkage of clay soils is higher for a dispersed structure and lower for a flocculated structure. A flocculated structure is obtained when the specimen is compacted to a high density at a water content dry of optimum, indicating that cement-treated clay soils should be compacted on the dry side of optimum.

Density. Although apparently not as important as molding water content, density has an effect on the shrinkage of cement-treated materials. George (Ref 45) recommended that soil-cement base material be compacted to the highest density possible and specified that a minimum of 95 percent of modified AASHO density (AASHO T-180) be achieved.

In view of the above and the effect of molding water content, it was recommended that a soil-cement base be compacted at a water content slightly on the dry side of optimum, to the highest density possible but to at least 95 percent of that determined by modified AASHO compaction (AASHO T-180).

Evaporation of Water. Shrinkage of cement-treated materials is primarily caused by loss of moisture and there is an apparent correlation between shrinkage and evaporation. For the two clay soils, George (Ref 19) found that the shrinkage per gram of water lost for montmorillonite soil-cement was greater than that for kaolinite, resulting in higher total shrinkage for the montmorillonite mixture. As mentioned previously, the rate of evaporation was the major cause of shrinkage cracking of cement-stabilized mixtures containing kaolinite. When shrinkage takes place slowly, the strain capacity of the mixture is greater than when shrinkage takes place rapidly and the tensile stresses developed are less (Ref 17). Thus, it was recommended that a cement-stabilized base be cured with a means provided for moisture retention and for a period of time which would result in improved tensile strength and minimal shrinkage.

Summary of Shrinkage Cracking

(1) Crack intensity increased with the type and amount of clay-sized particles in the soil. With regard to soil type, clay content exerted the most influence on cracking. It was recommended that every effort be made to use soils with as small a quantity of clay as possible

(2) Large aggregates (greater than 1 inch nominal size), by virtue of their ability to intensify the stress in the shrinking matrix, enhance crack intensity. Well-graded soil, including aggregate up to 5/8-inch nominal size, is preferred since aggregates of this size serve to minimize cracks by acting as rigid inclusions in the matrix.

(3) Shrinkage increases slightly with increasing cement content. The increased tensile strength associated with the higher cement contents offsets the adverse effect of the shrinkage, resulting in a decrease in cracking. In order to minimize cracking, it was found that cement contents slightly in excess of those required to meet durability criteria for freeze-thaw tests (ASTM D560-57) for granular soils were desirable. For fine-grained soils, a cement content which meets the ASTM freeze-thaw criteria gave a satisfactory mix.

(4) Compaction at moisture contents wet of optimum results in appreciably higher total shrinkage. Compaction of both granular and cohesive soils should take place at a water content at or below the optimum water content for maximum density.

(5) Cement-treated subbases should be compacted to the maximum density possible, preferably to at least 95 percent of modified AASHO density (AASHO T-180).

(6) Crack spacing and crack width are dependent upon tensile strength, specific weight of the mixture, tensile modulus of elasticity of the cement-treated material, and coefficient of friction between the base and the subgrade. It was recommended (Ref 18) that the base be placed over rough subgrade and that mixed-in-place construction be utilized in order to develop the highest coefficient of friction.

(7) The rate of evaporation of water from the surface of the fresh soil-cement base is one of the most important factors influencing shrinkage and shrinkage cracking. A high rate of evaporation produces a high rate of shrinkage, large shrinkage stresses, and substantial cracking.

In a later section of this report, the shrinkage cracking problem is evaluated in conjunction with a detailed analysis of factors which affect the tensile strength of cement-treated materials.

MIX DESIGN PROCEDURES

The procedures used by two agencies, the Portland Cement Association (PCA) and the Texas Highway Department (THD) are summarized below. The PCA method is suggested for use with any type of soil in any part of the country; whereas, the method used by the Texas Highway Department is an example of a simplified mix design developed through experience with the use of locally available materials in the design and construction of cement-treated bases and subbases within the State of Texas.

Portland Cement Association Method

The mix design procedure currently used by the Portland Cement Association is contained in the "Soil-Cement Laboratory Handbook" (Ref 48) and is summarized below:

Choose an Initial Cement Content. This preliminary estimated cement content is based upon the classification of the material to be stabilized according to the American Association of State Highway Officials Soils Classification System (AASHO Designation M 145-49). Table A1.1, in Appendix A, gives the estimated cement requirements of various AASHO soil groups.

Perform Moisture-Density Tests. Using the cement content chosen above, the optimum moisture content for maximum density is determined in accordance with AASHO Test Method T134-70.

Verify the Preliminary Estimated Cement Content. Tables A1.2 and A1.3, in Appendix A, take into consideration the maximum density and other properties of the soil, which permits a more accurate estimate of the required cement content. Table A1.2 is for sandy soils and Table A1.3 is for silty and clayey soils. These two tables are for B and C-horizon soils, respectively.

For A-horizon soils, Table A1.1 is used, with consideration given to the color of the soil.

Mold and Test Wet-Dry and Freeze-Thaw Specimens. Specimens should be molded and tested at cement contents two percentage points above and below that which has been estimated, in accordance with AASHO Test Methods T135-70 and T136-70, respectively. The Portland Cement Association has established the following criteria for the attainment of a hard, durable soil-cement suitable for base-course construction:

(1) Soil-cement losses during 12 cycles of either the wet-dry test or the freeze-thaw test shall conform to the following limits:

Soil Groups A-1, A-2-4, A-2-5, and A-3, not over 14 percent;

Soil Groups A-2-6, A-2-7, A-4, and A-5, not over 10 percent;

Soil Groups A-6 and A-7, not over 7 percent.

(2) Compressive strengths should increase both with age and with increases in cement content in the ranges of cement content producing results that meet the wet-dry and freeze-thaw requirements of (1) above.

Texas Highway Department Method

The basic mix design for cement-stabilized bases currently used by the Texas Highway Department utilizes only two tests: the moisture-density test and the unconfined compressive strength test (Ref 49), with the standard specifications (Ref 50) calling for a mix producing a minimum average unconfined compressive strength of 650 psi at the age of seven days. The contractor is required to submit representative samples of the base course materials to the engineer, who prepares, cures, and tests specimens at cement contents of 4, 6, and 8 percent in accordance with procedures outlined in test method Tex-120-E (Ref 49). The cement content required to produce the specified minimum strength is periodically checked by testing specimens sampled prior to compaction and molded from the mixture as used on the roadway.

The specification also allows the contractor to proceed with construction of the cement-treated base while the results of the tests on the representative samples are pending, using the cement contents shown in Table 1 for the indicated aggregate.

TABLE 1. CEMENT CONTENTS FOR SPECIFIC AGGREGATES (PERCENT BY DRY WEIGHT) (Ref 50)

Aggregate Material	Percent Cement
Sand-shell	7.0
Processed gravel	6.7
Bank-run gravel	5.9
Iron ore	5.9
Crushed stone	4.7

CHAPTER 3. FACTORS INFLUENCING TENSILE STRENGTH AND SHRINKAGE CRACKING OF CEMENT-TREATED MATERIALS

George (Refs 18 and 19) has related shrinkage cracking to tensile strength and has suggested that factors which improve tensile strength will minimize cracking. Unfortunately, there is little, if any, information available to substantiate this hypothesis. The purpose of this chapter is to evaluate the relationships between tensile strength and various factors which affect tensile strength and to relate the tensile characteristics of cement-treated materials to findings concerning shrinkage cracking. In addition, a rationale is developed for including tensile strength considerations in the design of cement-treated mixtures not only to improve tensile strength but to minimize shrinkage cracking.

Figures 1 through 7 illustrate the relationship between tensile strength and various mixture and construction factors for cement-treated materials. These relationships were developed using a regression equation obtained from a previous analysis (Ref 3). A detailed description and the range of variables used to develop the equation are presented in Appendix B.

The behavior trends illustrated in these relationships are interpreted and discussed in terms of the various factors which were previously found to have an important effect on tensile strength. The trends are then analyzed and related to previously reported observations concerning unconfined compressive strength and shrinkage cracking of cement-treated soils.

AGGREGATE TYPE AND GRADATION

The tensile properties of cement-treated materials were studied for two types of soil: a basically smooth, nonporous gravel and an angular, rough-textured, comparatively porous crushed limestone. Figures 1 and 2 show the relationship between tensile strength and type of soil and tensile strength and gradation.

Figure 1 shows that the mixtures containing limestone aggregate were stronger than mixtures containing gravel for tensile strengths greater than

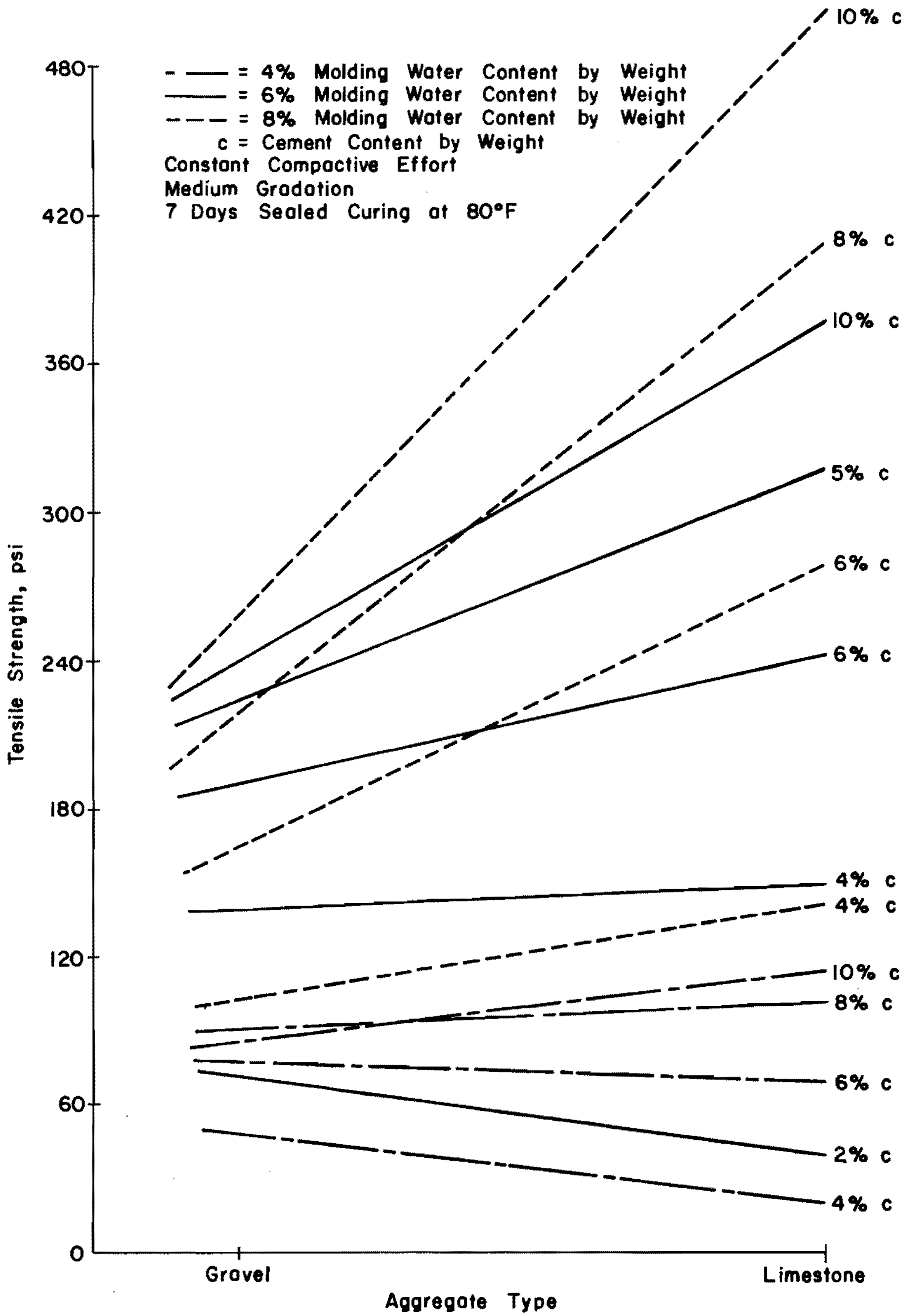

Fig 1. Relationship between tensile strength and type of aggregate.

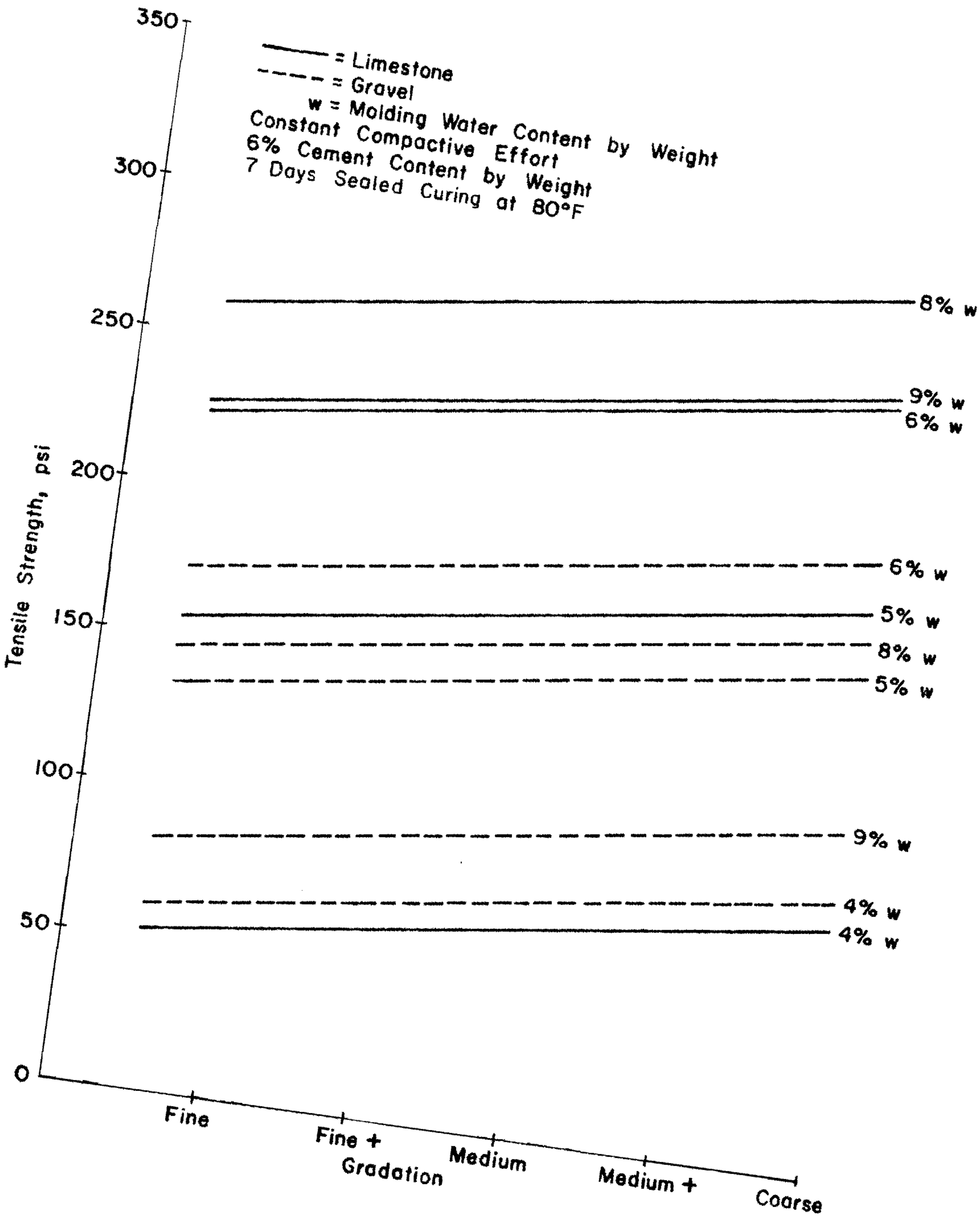

Fig 2. Relationship between tensile strength and gradations of crushed limestone and rounded gravel.

approximately 125 psi, and that the strength differential increased as molding water content and cement content increased. It was also found (Ref 41) that in specimens prepared with limestone, the aggregate failed before the cement matrix did, while with gravel, the initial failure was at the aggregate-cement interface. This would indicate that the surface texture and angularity of the aggregate may be more important than its inherent strength, since the limestone mixture, even though containing the weaker aggregate, had higher tensile strength. Aggregates with a rough surface texture and angularity provide a stronger bond with the cement matrix and better packing of the cement-treated mixture.

At tensile strengths below 125 psi, cementation is apparently more effective with the gravel than with the limestone aggregate. This can be attributed to the absorptive qualities of the limestone, which cause a decrease in the water available for hydration and in turn reduce the amount of cement which can be hydrated.

As indicated in Fig 2, for both aggregates, tensile strength increased as gradation became coarser. The increase in strength was probably due to the decreased surface area of the coarse-graded material, as compared with the fine-graded material. Catton (Ref 7) found that as the surface area of the soil decreased, the amount of cement required to produce an acceptable structural material decreased. It has also been found (Refs 44 and 53) that a well-graded soil is preferable to one which has a uniform or open gradation, since higher densities are attainable, the void content is minimized, and these soil types required the least amount of cement for adequate stabilization. Appendix C contains the actual gradations shown in Fig 2 as fine, fine +, etc.

With regard to the cement stabilization of soils containing cohesive material, current Texas specifications (Ref 50) require that the soil be pulverized so that a minimum of 80 percent passes a No. 4 sieve, and it has been shown (Ref 15) that this requirement is satisfactory from the standpoint of the durability characteristics of a soil-cement mixture. A more appropriate criterion for the establishment of a maximum acceptable percentage of cohesive material in a cement-stabilized mixture, however, may be the shrinkage characteristics of the mixture.

George (Ref 18) found that the shrinkage crack intensity increases with the type and amount of clay-sized particles in the soil. Cement-treated mixtures containing kaolinite were found to shrink faster, while total shrinkage was higher for those containing montmorillonite. It was recommended that the clay content be limited to 8 percent if the clay mineral is montmorillonite, 15 percent if it is kaolinite, and appropriately interpolated amounts of each if the soil contains both clay types. Also, the soil should not contain large aggregates (greater than 1 inch nominal size), since these aggregates intensify the stress in the shrinking matrix and enhance crack intensity.

Thus, it would appear that a well-graded soil with a minimum of cohesive material may be specified for a cement-treated mixture and that possibly an angular coarse aggregate with a rough surface texture should be used rather than a rounded, smooth gravel.

CEMENT CONTENT

Cement content is the most significant factor affecting unconfined compressive strength, shrinkage cracking, and tensile strength of cement-treated soils (Ref 15, 21, 39, and 41). It has been previously shown that compressive and tensile strengths increase with an increase in cement content, provided there is adequate moisture for hydration of the cement. In addition, shrinkage crack intensity decreases, even though overall shrinkage is higher, since the greater tensile strengths offset the increase in shrinkage (Ref 18). However, a detailed evaluation of the relationship between tensile strength and cement content has not been made.

The relationship between tensile strength and cement content for various molding water contents and two aggregate types was developed from data obtained from two previous experimental investigations (Ref 3 and 41) and is shown in Fig 3. From this figure, it would appear that there was an optimum cement content which produces maximum tensile strength for each aggregate type and molding water content. This optimum was obvious for the rounded gravel, but the curves for crushed limestone suggest that there would have also been an optimum cement content if specimens containing more than 12 percent cement had been included. The optimum cement content probably represents the maximum amount of cement which can be hydrated at the given water content in a given curing time. Davidson et al (Ref 12) suggest that the same type of relationship exists between cement content and the unconfined compressive strength of cement-treated soils.

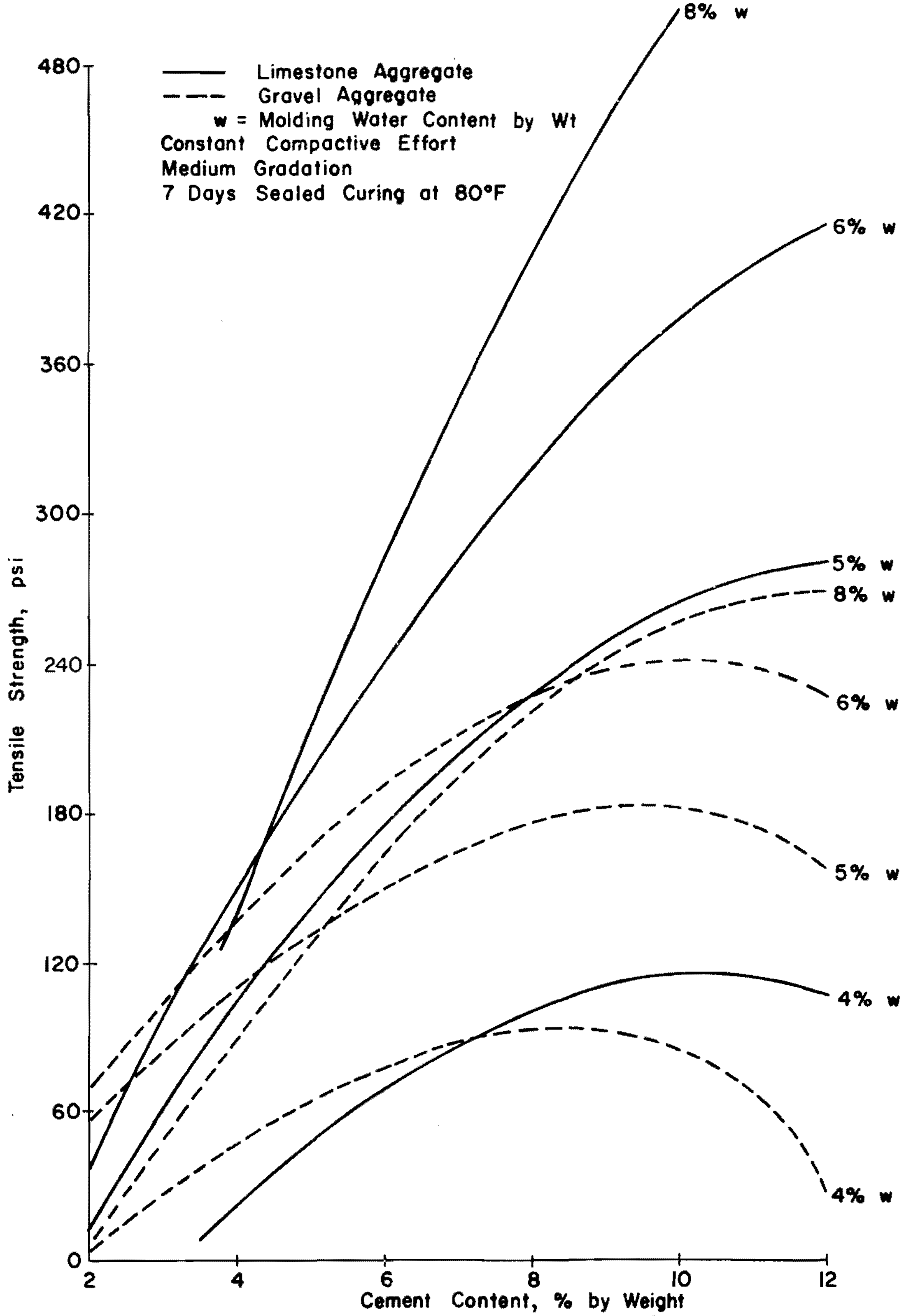

Fig 3. Relationship between tensile strength and cement content.

The optimum cement content for specimens composed of gravel aggregate and compacted at water contents at or below optimum for tensile strength increased with molding water content; however, mixtures containing higher cement and water contents would have to be tested in order to determine whether this trend exists for limestone as well.

The interrelationship between strength, cement content, and molding water content is also evidenced by the fact that on the low side of the optimum cement, the increase in strength per unit increase in cement is larger at higher molding water contents. This could be due to both better compaction and more complete hydration of the cement.

For the granular materials studied, shrinkage would be expected to vary directly with the amount of hydrated paste. Therefore, increased cement contents would produce a greater amount of shrinkage; however, shrinkage cracking has been found to decrease with increased cement content, presumably because of the increased tensile strength and the ability to resist cracking.

Thus, it would appear that a cement content should be specified which will result in maximum tensile strength for the specified water content and type of material, with the maximum being limited by economic considerations and the minimum being established by the strength and durability requirements. As previously discussed, George recommended cement contents which were equal to or greater than that required by ASTM D560-57 freeze-thaw durability criteria. In Texas, the minimum should probably not be less than those shown in Table 1 until cement-treated materials have been studied in greater detail both in the laboratory and in the field.

MOLDING WATER CONTENT

As discussed in the previous section, molding water content is closely related to the tensile strength of cement-treated materials. Water serves two purposes in a cement-treated mixture:

(1) it facilitates compaction, and

(2) it hydrates the cement.

Thus, relationships between molding water content and indirect tensile strength were developed and are illustrated in Figs 4 and 5. The relationships shown in these figures definitely indicate that there is an optimum molding water content which provides maximum tensile strength. However, the actual optimum

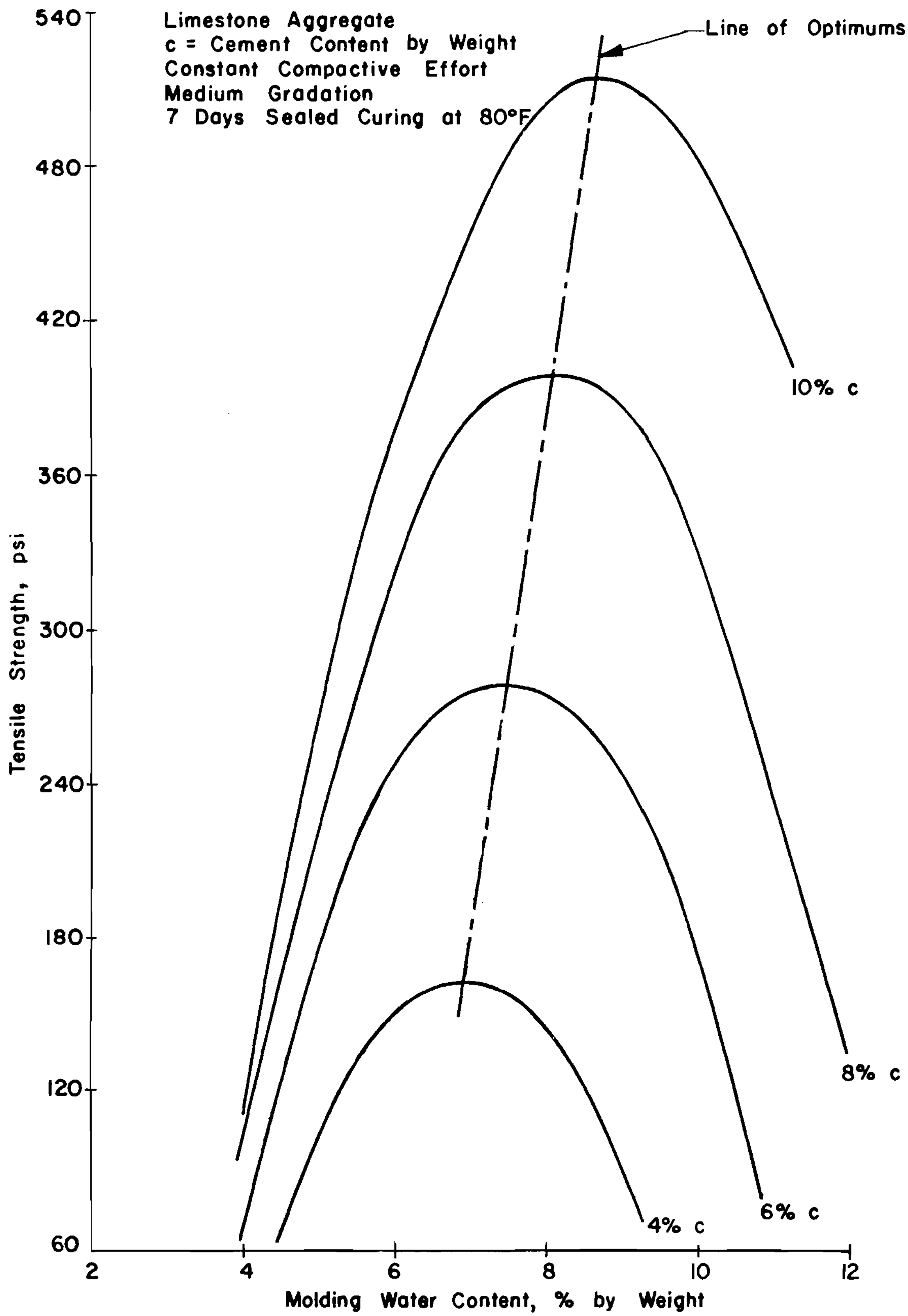

Fig 4. Relationship between tensile strength and molding water content for crushed limestone.

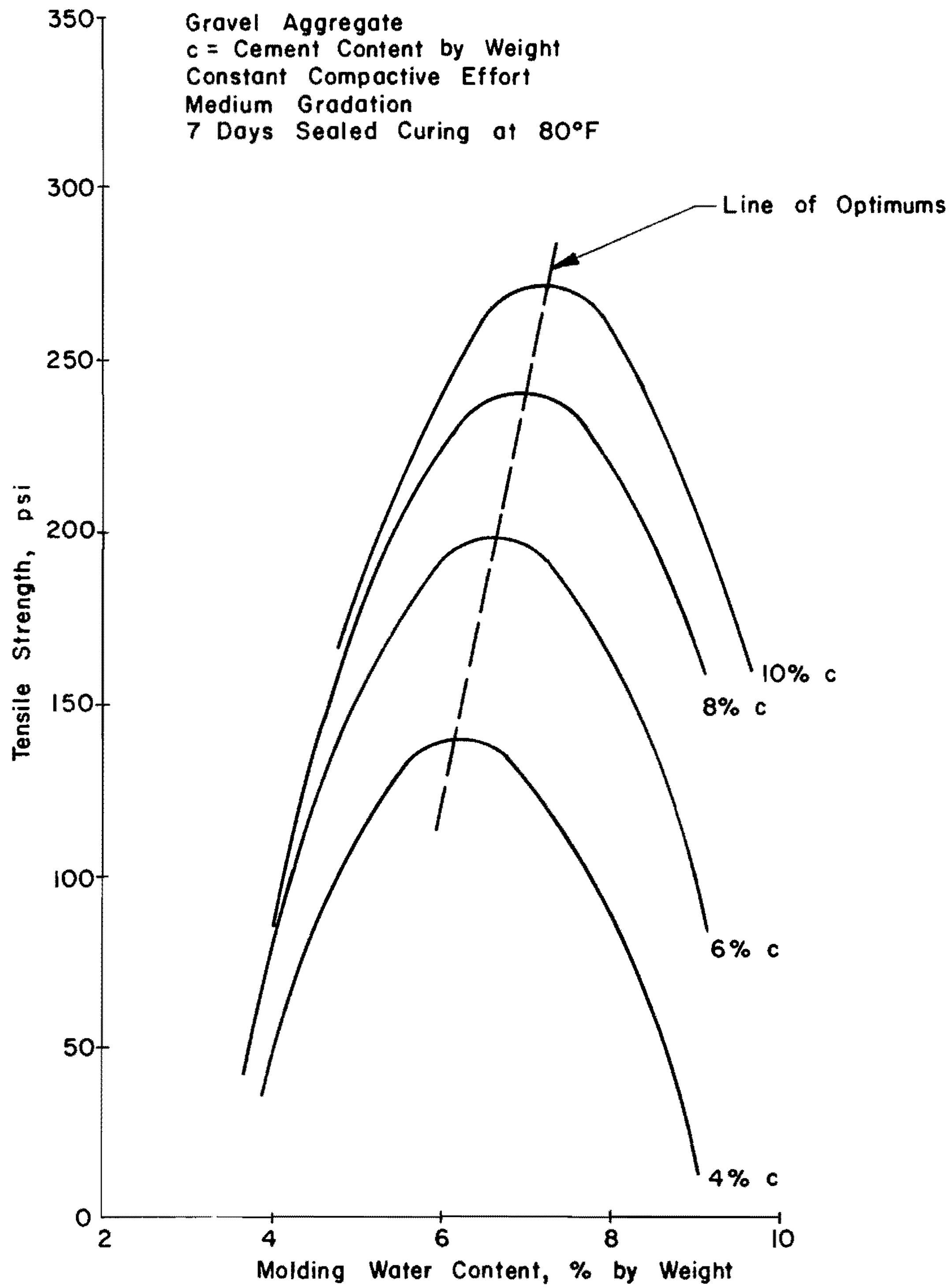

Fig 5. Relationship between tensile strength and molding water content for rounded gravel.

is dependent on aggregate type, cement content, and probably curing time. Nevertheless, for a given type of material, type and amount of compaction, and curing condition, there appears to be a line-of-optimums.

The molding moisture content for a cement-treated soil has traditionally been determined from the results of moisture-density tests (ASTM 558-57 and AASHO T134-70), and it has been found (Refs 11 and 15) that the optimum moisture content for maximum density does not vary significantly with increased cement contents. In addition, for cement-treated mixtures, the optimum moisture for maximum density does not necessarily coincide with optimum moisture content for maximum strength (Ref 12 and 15).

Strength and density tests for various types of cement-treated soils have shown that the moisture contents for maximum strength are on the dry side of standard AASHO optimum moisture for sandy soils and on the wet side for clay soils. For mixtures containing both sand and clay, it has been found that the difference between optimum moisture for maximum density and optimum moisture for maximum strength is practically negligible for sand-clay mixtures containing about 25 percent or more clay (Ref 12). With delays prior to compaction of up to six hours, Lightsey et al (Ref 35) found that maximum compressive strength and durability did not occur at optimum moisture for density. In granular soils, excess moisture improved the strength and durability characteristics of the mixture. However, with no delay, maximum compressive strengths were obtained at water contents on the dry side of the optimum for density. In cement-treated clay soils, which normally are stronger when compacted on the wet side of optimum, increasing the molding water content two to three percentage points above optimum had no appreciable effect on the compressive strength and durability of the mixture with delays in compaction of from four to six hours (Ref 35).

As discussed in Chapter 2, water content is also important from the standpoint of minimizing shrinkage and shrinkage cracking. Appreciably larger shrinkage strains have been observed for mixtures compacted on the wet side of the optimum moisture content for density, and it was recommended that cement-treated materials be compacted on the dry side to minimize total shrinkage.

Therefore, cement-treated mixtures should be compacted on the dry side of optimum for density in order to maximize tensile strength and minimize total shrinkage, both of which minimize cracking. In addition, delays in compaction should be taken into consideration when the water content for compaction is being established.

DENSITY AND COMPACTIVE EFFORT

Cement-stabilized soils which have been compacted to adequate density generally have given satisfactory field performance provided minimum strength requirements were achieved. Adequate density usually has been defined in terms of moisture-density relationships for the cement-treated mixture, such as standard or modified AASHO moisture-density tests. Since compaction at optimum moisture content does not necessarily produce maximum strength, it can be safely assumed that maximum density does not necessarily produce maximum strength.

The relationship between indirect tensile strength and density is shown in Fig 6. A cursory examination of this figure indicates no relationship between tensile strength and density. It should be noted, however, that the specimens were compacted using a gyratory shear compactor and that even a low compactive effort produced a high density and the range of densities was comparatively small, 130 to 136 pcf. Therefore, it is not surprising that density did not have a significant effect upon tensile strength since it can be reasoned that once a given level of compaction has been achieved, additional compaction has little, if any, beneficial effects and other factors are much more important.

Shrinkage, however, is also affected by density, with shrinkage cracking decreasing with an increase in compactive effort. For purposes of minimizing shrinkage, it has been suggested that cement-treated materials be compacted to the highest density possible, and George (Ref 18) recommended a minimum of 95 percent of modified AASHO density.

Since high density would presumably reduce total shrinkage and have little effect on tensile strength, high density would presumably minimize cracking. The only danger in this approach is the possibility that other factors might reduce tensile strength. For example, if a high compactive effort is used without a corresponding decrease in water content, the soil would be compacted substantially on the wet side of optimum, which might cause a loss of tensile strength or, if the water content is reduced, there might be inadequate water for the hydration of the cement.

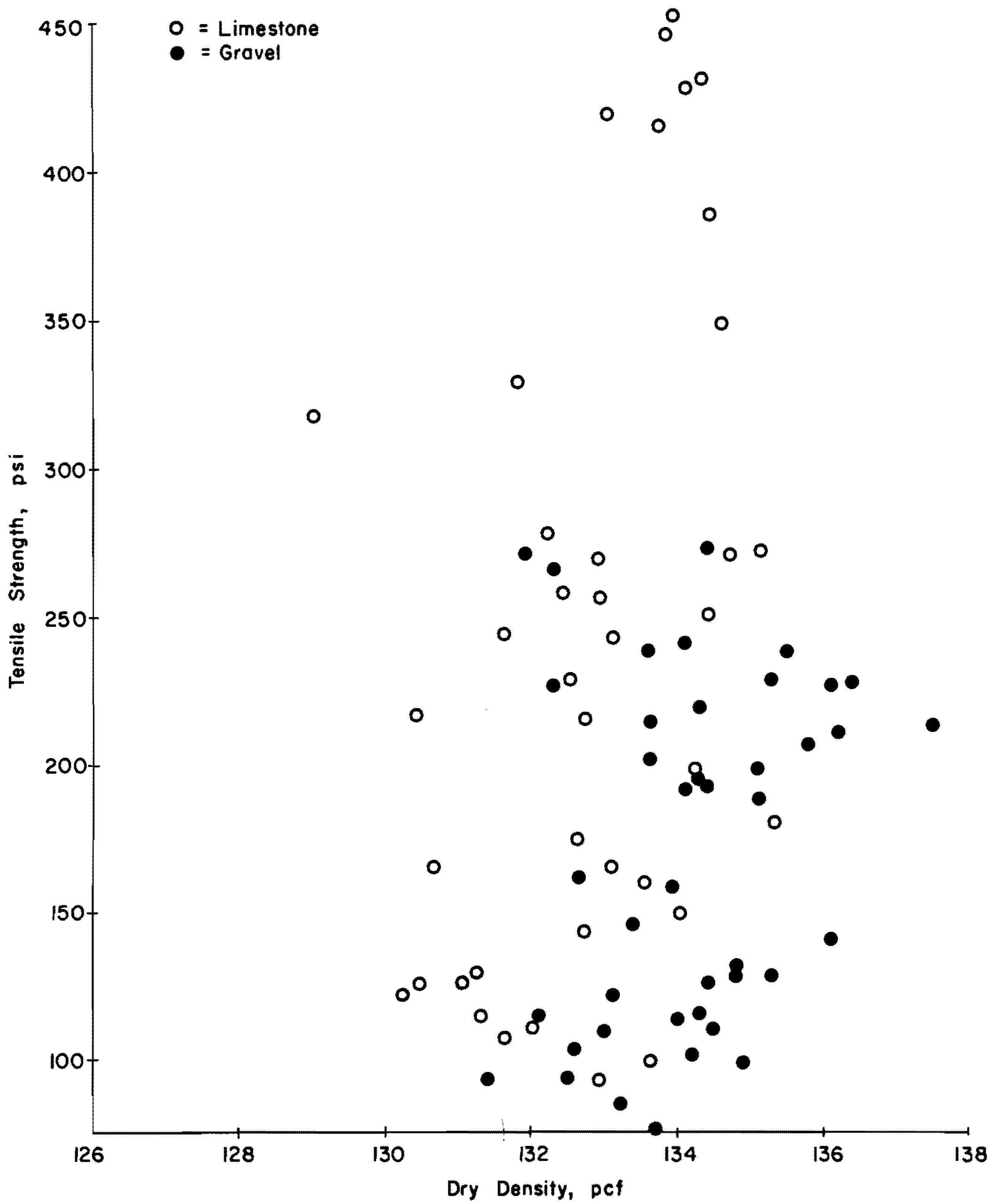

Fig 6. Scatter diagram showing relationship between tensile strength and dry density for crushed limestone and rounded gravel.

CURING

Curing Temperature

Extreme temperatures during the curing period can cause problems in the construction of cement-treated bases and subbases. At temperatures below about 40° F, hydration of the cement stops (Ref 9).

Currently it is recommended (Ref 50) that a cement-treated material should not be mixed or placed when the air temperature is below 40° F and falling but may be mixed or placed when the air temperature is above 35° F and rising. However, even if these conditions are satisfied, the hydration of the cement will be slow if the temperature is below about 60° F. In addition, a cement-treated material should be protected from freezing for a period of seven days after placement.

Extremely high temperatures also have a significant effect on cement-treated mixtures. Figure 7 shows that indirect tensile strengths increase with increased curing temperature for different cement contents and two different aggregates. These results agree with those obtained from previous studies which have found that higher curing temperatures produce higher compressive strengths for cement-treated materials (Refs 3 and 41). These higher strengths can be attributed to a faster hydration rate because of the increased temperature; therefore, greater strengths would be expected at earlier ages, although the effect on ultimate strength is probably negligible.

With regard to shrinkage and shrinkage cracking, high temperatures are detrimental since higher temperatures cause an increase in the rate of evaporation. Since shrinkage is related to loss of moisture and cracking is closely related to rate of moisture loss, high temperatures and the accompanying loss of water would tend to promote cracking.

It has been recommended that cement-treated subbases and bases should not be constructed in hot weather or under conditions of high wind and low humidity (Refs 19 and 20). However, since these conditions are prevalent in many parts of Texas for a major portion of the year, special attention should be given to sealing the surface of cement-treated bases and subbases immediately after compaction and maintaining the seal for an adequate period of curing.

Type of Curing

The results of previous studies regarding the effect of type of curing generally have always indicated the desirability of sealing the surface to

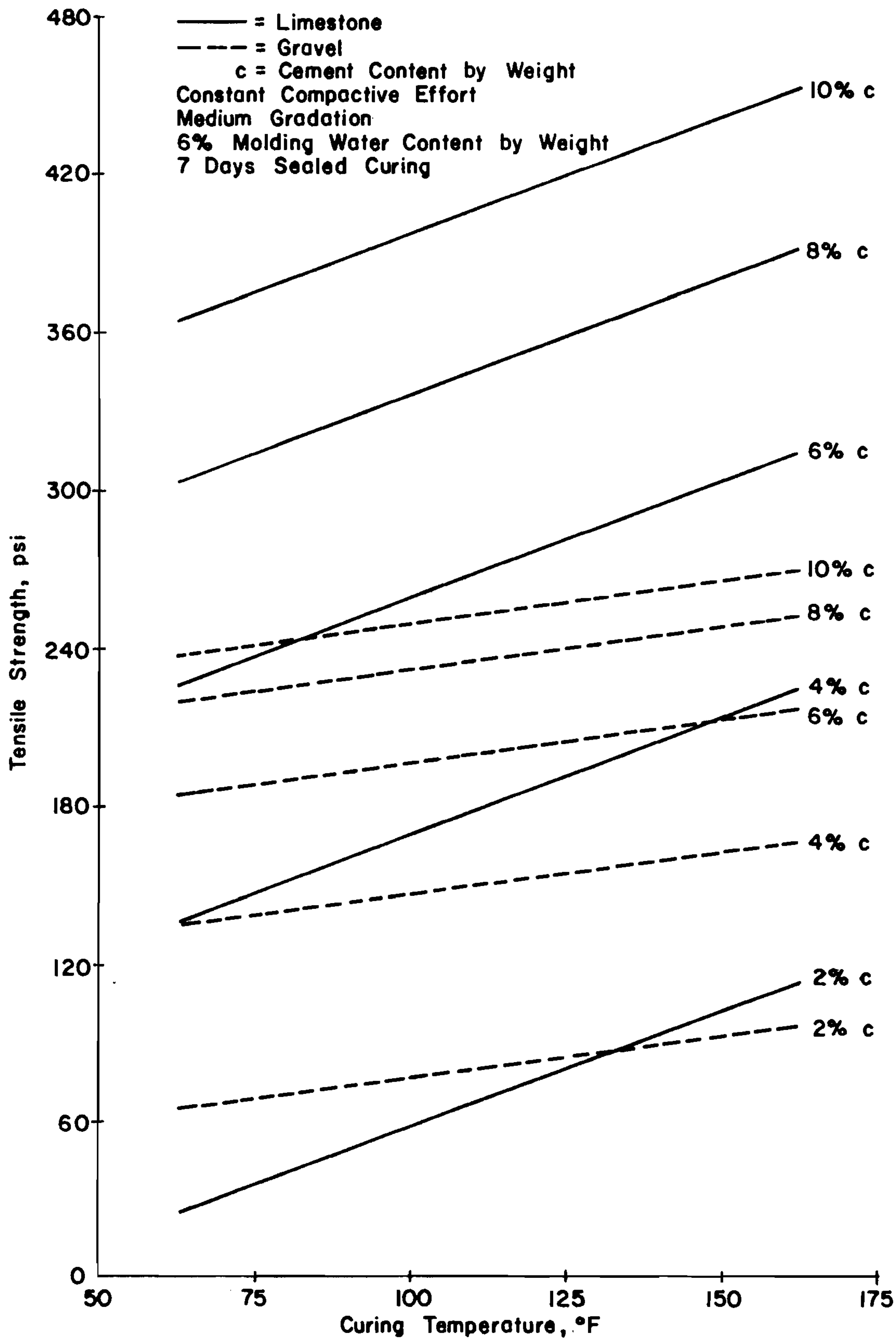

Fig 7. Relationship between tensile strength and curing temperature.

prevent loss of moisture. Sealing maintains an adequate amount of moisture for the hydration of the cement and thus increases the tensile strength. Pendola (Ref 41) found that the average indirect tensile strength for 4-inch-diameter specimens cured for 7 and 21 days in a sealed condition was approximately 200 and 150 percent, respectively, of the average strength for specimens which were subjected to air-dried curing. Others have shown similar results for compressive strength (Refs 36 and 43).

Thus, it has been recommended that cement-treated mixtures should be sealed immediately after compaction and cured in a sealed condition for an adequate period of time.

Length of Curing

Since cement continues to hydrate for extended periods of time, it can be safely assumed that longer periods of sealed curing produce higher strengths. Thus, the curing period should be long enough to develop adequate strength to resist expected loads and shrinkage stresses. With regard to shrinkage, George (Ref 19) found that longer curing in general increases the total shrinkage of sandy soils, but that the reverse was true for clayey soils. Nevertheless, he recommended (Ref 18) that shrinkage cracking can be minimized by an adequate period of curing, since the rate of evaporation of water from the surface of the fresh cement-treated base was found to be the most important factor influencing shrinkage and shrinkage cracking.

Currently the Texas Highway Department determines its cement-treated mixture design on the basis of seven days of sealed curing so that hopefully stresses induced by construction, traffic, or shrinkage will not exceed the strength of the base or subbase. In view of previous findings and current practice, it is recommended that sealed or moist curing be provided for a minimum of seven days.

This chapter has characterized another stage in the development of a rationale for the mix design of cement-treated materials based upon tensile strength. Previous studies (Ref 3 and 41) have established which factors are most significant in such a mix design.

The analysis and interpretation contained in this chapter and the relationships which have been presented in graphical form represent a first attempt at establishing a quantitative measure of the effect that these factors have on the tensile and shrinkage characteristics of cement-treated materials and provide a basis for implementation of a mix design utilizing tensile strengths as the basic measure of adequacy. The next chapter outlines a procedure which may eventually permit the design of cement-treated mixtures to be based solely, or at least partially, on tensile strength criteria.

CHAPTER 4. A MIX DESIGN BASED UPON INDIRECT TENSILE STRENGTH

INTRODUCTION

Tensile stresses are created in the individual layers of flexible pavement structures by moving traffic. As a vehicle moves along the highway, the layers of the pavement structure deflect under the weight of the vehicle and create tensile stresses at the interface of the layers. In addition, drying causes a cement-treated base or subbase to contract or shrink and, if interlayer friction restrains the base from contracting, tensile stresses are produced. Shrinkage cracking occurs when the tensile stresses exceed the tensile strength of the cement-treated pavement layer.

Since the tensile properties of cement-treated subbase and base courses have been shown to be of primary importance with regard to improving the performance characteristics of pavements, these tensile properties should be considered in the design of the cement-treated courses.

However, at this time, there is essentially no information available which will allow a cement-treated mixture to be designed on the basis of tensile strength criteria. Theoretical analyses can be used to predict the magnitude of the tensile stress in a pavement subjected to loads but, even if these predictions are accurate, there is no way of relating tensile properties of the materials to the ability of the pavement structure to resist environmental influences or the effects of repeated applications of load. This can be accomplished only through additional laboratory studies and field evaluation of the performance of pavements composed of materials with known tensile properties.

In view of the interpretation of the available information on tensile properties of cement-treated materials that has been presented in previous chapters of this report, it seems desirable to structure a mix design methodology which will recognize the effects of tensile strength and shrinkage on the performance of cement-treated bases and subbases. The procedure outlined in this chapter is a suggested approach to the development of a mix design procedure that should result in improved load-carrying capacity of the pavement and minimal shrinkage cracking of cement-treated materials.

MIX DESIGN

The design of cement-treated mixtures is concerned with establishing the cement content, the molding water content, and the compactive effort, which will result in a material with sufficient strength and durability to resist load and environmental stresses.

It is, therefore, suggested that additional tests be added to the mix design procedure currently used by the Texas Highway Department. The present mix design procedure requires that a cement content be chosen which will produce a minimum average compressive strength of 650* psi at the age of seven days. Normally, three test cylinders are prepared, cured, and tested in accordance with test method Tex-120E (Ref 49) for each of the following cement contents: 4 percent, 6 percent, and 8 percent. From these tests, the cement content required to produce a cement-treated base material with a seven-day compressive strength of 650 psi is determined by the engineer.

Procedure for Supplementary Tests

In addition to specimens prepared as a part of the above procedure, it is recommended that supplementary specimens be prepared to determine the cement content and molding water content which will produce maximum tensile strength. The following steps may be used to establish a cement content and compaction water content which will improve tensile strength and reduce shrinkage cracking. Since this procedure is a supplement to that used by the Texas Highway Department, its use is intended for those soil types currently specified in Texas Highway Department Specifications (Ref 50). Generally, good quality, granular materials are economically available in the State of Texas and, for a mix design involving these materials, cement contents of 4 percent, 6 percent, and 8 percent should be used in preparing the supplementary specimens (step (1) below). However, if it should become necessary to use other

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* An unconfined compressive strength of 650 psi corresponds with an indirect tensile strength of approximately 75 psi according to the correlations reported in Ref 3.

materials, the cement contents contained in Table A1.1 are suggested as reasonable guidelines for initiating the supplemental procedure. The figures referred to in the following steps are hypothetical relationships which may serve to clarify the mix design procedure.

(1) Determine the optimum water content for maximum density for the material with 6 percent cement content. Optimum water contents for 4 and 8 percent may be estimated from the following relationship (Ref 49):

$$W = W_m + 0.25(C - C_m) \tag{3}$$

where

W = estimated optimum molding water content (percent) for either the high or low level of cement content;

W_m = the optimum moisture content (percent) for the middle level of cement content, determined from the moisture-density curve;

C = the high or low level of cement content (percent).

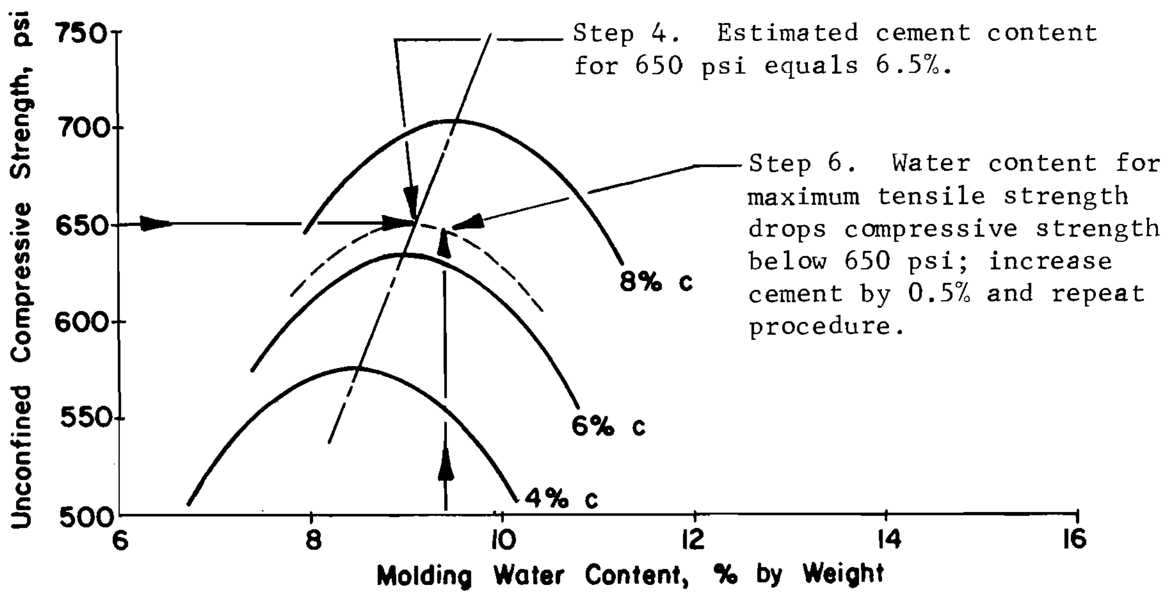
C_m = the middle level of cement content.

(2) For each cement content, mold duplicate specimens at optimum water content and at water contents which are 1 percent, 2 percent, and 3 percent below the optimum value. Compaction and curing procedures are as outlined in test method Tex-120-E (Ref 49). One of the duplicate specimens should be tested in compression (Tex-120-E) and one in indirect tension (Ref 2).

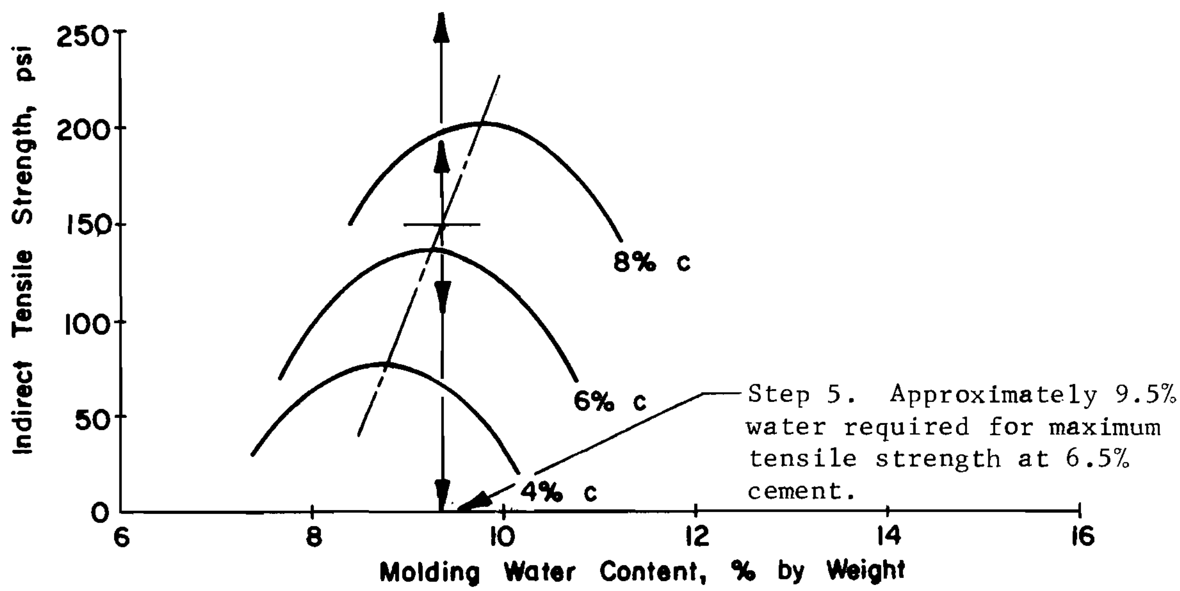
(3) For each cement content, plot the relationships between unconfined compressive strength and molding water content (Fig 8(a)) and between indirect tensile strength and molding water content (Fig 8(b)).

(4) From the relationships between compressive strength and molding water content, estimate the cement content which provides an unconfined compressive strength of 650 psi (Fig 8(a)).

(5) Using the relationships between indirect tensile strength and molding water content, determine the water content which provides maximum tensile strength for the cement content determined in step (3) (Fig 8(b)).



(a) Compressive strength versus molding water content.



(b) Tensile strength versus molding water content.

Note: Step 1. For illustrative purposes, assume that the optimum moisture content for maximum density was 10% for material with 6% cement. Equation 3 then gives estimated water contents of 9.5 and 10.5% for 4 and 8% cement, respectively. C = cement content.

Fig 8. Hypothetical relationships between compressive and tensile strength and molding water content.

(6) Insure that the water content determined in step (4) still provides for a minimum of 650 psi compressive strength at the cement content established in step (3). If the minimum compressive strength requirement has been met, then a mix design has been obtained which should give maximum tensile strength for the given cement and water content, while meeting current specifications for minimum compressive strength. If the molding water content which gives maximum tensile strength appears to cause compressive strength to drop below 650 psi, then the cement content should be increased by one-half percentage point and the steps repeated, beginning with step (3). This iteration should be carried out until a mix design is obtained which gives maximum tensile strength and a minimum of 650 psi unconfined compressive strength.

METHOD OF TEST FOR INDIRECT TENSION

Specimen Size

Since the Texas Highway Department uses 6-by-8-inch specimens for unconfined compressive testing of cement-treated materials, 6-by-8-inch specimens should be used for indirect tensile testing. Four-inch-diameter specimens can be used but it is recommended that the same size specimen be used for both unconfined compression and indirect tension.

Loading Rate

The loading rate currently used for compressive tests on cement-treated materials is 0.14-inch per minute, and it is proposed that this loading rate be used for indirect tensile testing of these materials.

Equipment Required

For testing in unconfined compression, the apparatus outlined in test methods Tex-101-E, Tex-110-E, and Tex-117-E and a compressive testing machine meeting the requirements given in ASTM Designation D1633-63 should be used (Ref 49).

The indirect tensile test requires equipment capable of applying compressive loads at a controlled deformation rate, a means of measuring the applied load, and 1/2-inch-wide curved-face loading strips, which are used to apply and distribute the load uniformly along the entire length of the specimen (Ref 2). Thus, the compression testing machine mentioned above may also be used for testing in indirect tension, provided a guided loading head with loading strips attached to the upper and lower parallel platens is used. Such a device is described in detail in Report 98-10 (Ref 2).

For testing done by the Texas Highway Department, a motorized gyratory press may be used for loading specimens and requires only minor modifications to be utilized as the loading device. These modifications are also described in detail in Report 98-10 (Ref 2).

Based on the reported findings of previously conducted studies of the strength and shrinkage characteristics of cement-treated materials and the findings concerning the indirect tensile strengths of cement-treated materials, it is felt that the above procedure should improve the tensile strengths of cement-treated bases and subbases and minimize shrinkage cracking. At the present time, however, the procedure has not been laboratory or field tested. Experimentation with the procedure as a supplement to mix design procedures currently used is encouraged so that information regarding the effects of tensile strength and shrinkage of cement-treated materials can be developed and evaluated.

CHAPTER 5. RECOMMENDATIONS

This report was prepared in order to consolidate the findings and recommendations from two experimental studies concerned with the tensile properties of cement-treated materials (Refs 3 and 41) and to interpret these findings in terms of the results of studies concerning shrinkage (Refs 16, 17, 18, 19, and 20). The purpose of this chapter is to summarize the recommendations which are the result of the above evaluation and interpretation.

SUMMARY OF RECOMMENDATIONS

Materials

(1) A well-graded soil with a minimum of cohesive material should be used for cement-treated subbases whenever possible.

(2) If it is necessary to use a soil containing cohesive material, it is recommended that the clay content be limited to 8 percent for montmorillonite, 15 percent for kaolinite, and appropriately interpolated amounts of each if the soil contains both clay types.

(3) The soil should not contain aggregate larger than 1 inch nominal size.

(4) Type II cement should be used rather than Type I for the purpose of minimizing shrinkage cracking.

(5) Depending upon the clay content of the soil, it may be desirable to replace 1 or 2 percent cement with lime to minimize shrinkage.

Mix Design

(1) It is recommended that the mix design procedure outlined in the preceeding chapter be used to establish the required water and cement content for a cement-treated base or subbase. The procedure involves compaction on the dry side of optimum moisture for maximum density and results in minimum compressive strength of 650 psi and maximum tensile strength for the given water and cement content.

Construction and Curing

(1) Expected delays in compaction of the subbase should be taken into consideration when the moisture content of a cement-treated mixture is specified. The recommendation is that 2 to 4 percent excess compaction moisture be added if the time between mixing and compaction

is greater than two hours and the soil is granular and if the delay is less than two hours and the soil is fine-grained.

(2) Cement-treated bases and subbases should be compacted to 95 to 100 percent of the density specified in test method Tex-113-E (Ref 49).

(3) The cement-treated subbase should be sealed immediately after compaction and cured under sealed conditions for at least seven days in order to reduce the possibility of damage due to construction traffic and to reduce shrinkage cracking.

(4) A cement-treated subbase should not be constructed under extremely cold weather conditions. Current guidelines, which specify that the subbase not be mixed or placed when the air temperature is below 40^{o} F and falling but may be mixed or placed when the air temperature is above 35^{o} F and rising, appear to be satisfactory. Also, the subbase should be protected to prevent its freezing for a period of seven days after placement and until it has hardened.

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APPENDIX A

TABLES FOR PORTLAND CEMENT ASSOCIATION MIX DESIGN METHOD

TABLE A1.1. CEMENT REQUIREMENTS OF AASHO SOIL GROUPS (Ref 48)

AASHO Soil Group	Physical Description	Usual Range in Cement Requirement		Estimated Cement Content and that used in Moisture-Density Test, Percent by Wt	Cement Contents for Wet-Dry and Freeze-Thaw Tests, Percent by Wt
		Percent by Vol	Percent by Wt		
A-1-a	Gravel and sand	5-7	3-5	5	3-5-7
A-1-b	Coarse sand	7-9	5-8	6	4-6-8*
A-2	Silty or clayey gravel and sand	7-10	5-9	7	5-7-9
A-3	Uniform sand, nonplastic	8-12	7-11	9	7-9-11
A-4	Sandy loam	8-12	7-12	10	8-10-12
A-5	Silt and clay loam	8-12	8-13	10	8-10-12
A-6	Lean clay	10-14	9-15	12	10-12-14
A-7	Fat clay	10-14	10-16	13	11-13-15

*These cement contents conform with those recommended by the Texas Highway Department (Ref 50).

TABLE A1.2. AVERAGE CEMENT REQUIREMENTS OF B AND C-HORIZON SANDY SOILS (Ref 48)

Material retained on No. 4 sieve, per cent	Material smaller than 0.05 mm., per cent	Cement content, per cent by wt. — Maximum density, lb. per cu. ft.					
		105-109	110-114	115-119	120-124	125-129	130 or more
0-14	0-19	10	9	8	7	6	5
	20-39	9	8	7	7	5	5
	40-50	11	10	9	8	6	5
15-29	0-19	10	9	8	6	5	5
	20-39	9	8	7	6	6	5
	40-50	12	10	9	8	7	6
30-45	0-19	10	8	7	6	5	5
	20-39	11	9	8	7	6	5
	40-50	12	11	10	9	8	6

TABLE A1.3. AVERAGE CEMENT REQUIREMENTS OF B AND C-HORIZON SILTY AND CLAYEY SOILS (Ref 48)

AASHO group index	Material between 0.05 mm. and 0.005 mm., per cent	Cement content, per cent by wt. Maximum density, lb. per cu. ft. 90-94	95-99	100-104	105-109	110-114	115-119	120 or more
0- 3	0-19	12	11	10	8	8	7	7
	20-39	12	11	10	9	8	8	7
	40-59	13	12	11	9	9	8	8
	60 or more	--	--	--	--	--	--	--
4- 7	0-19	13	12	11	9	8	7	7
	20-39	13	12	11	10	9	8	8
	40-59	14	13	12	10	10	9	8
	60 or more	15	14	12	11	10	9	8
8-11	0-19	14	13	11	10	9	8	8
	20-39	15	14	11	10	9	9	9
	40-59	16	14	12	11	10	10	9
	60 or more	17	15	13	11	10	10	10
12-15	0-19	15	14	13	12	11	9	9
	20-39	16	15	13	12	11	10	10
	40-59	17	16	14	12	12	11	10
	60 or more	18	16	14	13	12	11	11
16-20	0-19	17	16	14	13	12	11	10
	20-39	18	17	15	14	13	11	11
	40-59	19	18	15	14	14	12	12
	60 or more	20	19	16	15	14	13	12

APPENDIX B

PREDICTION EQUATION

APPENDIX B. PREDICTION EQUATION

Anagnos et al (Ref 3) conducted a regression analysis to obtain an equation which would satisfactorily predict the tensile strengths of cement-treated crushed limestone and rounded gravel. Since the equation is based only on the results of the experiment which Anagnos performed, its use is valid only for the factors, factor levels, and conditions of his experiment. The factors and levels are presented in Table B1.1 below.

TABLE B1.1. EXPERIMENTAL FACTORS AND LEVELS

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

The prediction equation below utilizes all factors and interactions which produced significant effects at a probability level of 10 percent.

$$\hat{S}_t = -344.7 + 147.9A + 6.799B + 0.6362C - 2.766D$$
$$- 66.83E + 36.70F + 0.4255AD + 19.80AE - 1.956AF$$
$$- 1.426CF + 0.6817DE - 0.7649DF + 7.535EF$$
$$- 17.26A^2 - 2.157E^2 - 0.1049ADE + 2.891AEF$$
$$+ 0.01545CDF - 0.1300DEF \qquad (4)$$

where

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

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

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

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

APPENDIX C

GRADATIONS

APPENDIX C. GRADATIONS (Ref 3)

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

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