Evaluating the Performance of Soil-Cement and Cement-Modified Soil for Pavements: A Laboratory Investigation

by Tom Scullion, Stephen Sebesta,
John P. Harris, and Imran Syed

RESEARCH & DEVELOPMENT BULLETIN RD120

Concrete Thinking for a sustainable world
PCA Portland Cement Association

Abstract: This report presents the findings on an extensive laboratory testing study to identify new approaches to improving the performance of soil-cement bases and cement-modified soils in pavements. Current soil-cement design procedures are based solely on 7-day Unconfined Compressive Strength (UCS) criteria, but high base strengths are no guarantee of satisfactory long-term pavement performance. In this project a laboratory study was undertaken to determine the optimal cement content for three marginal Texas base materials. Recommended cement contents are based on balancing conflicting criteria from the following four performance related tests: a) UCS, b) Shrinkage, c) Moisture Susceptibility, and d) Abrasion Resistance. A new test method called the Tube Suction Test (TST) is introduced for assessing the moisture susceptibility of soil-cement materials. The TST is shown to correlate well with the existing wet-dry and freeze-thaw durability tests.

The TST was also used to measure the moisture susceptibility of two clay soils which were treated in the laboratory with both lime and cement. The effects of both the level of pulverization and the method of adding the stabilizer (dry vs. slurry) were studied. The major finding was that the properties of the CMS were strongly dependent upon the mixing procedure. The use of cement slurries produced the best lab properties. The results showed that the slurry was effective in treating the soil with mixing times up to 4 hours and without mixing remained workable for up to 30 minutes without impacting flow properties.

Keywords: cement modified soils, design, moisture susceptibility, pavement bases, soil-cement, strength, Tube Suction Test.

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Portland Cement Association
5420 Old Orchard Road
Skokie, Illinois 60077-1083
USA
Phone: 847.966.6200 Fax: 847.966.9781
www.cement.org

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Research and Development Bulletin RD120

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[1]Research Engineer, [2]Assistant Transportation Researcher, [3]Associate Research Scientist, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, USA, [4]Project Engineer, Thomas L. Brown Associates, Washington, DC, USA.

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official view or policy of the Texas Transportation Institute (TTI) or the Portland Cement Association (PCA). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge of the project was Tom Scullion, P.E. #62683.

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INTRODUCTION

In 1998, a research project was initiated between the PCA and the Texas Transportation Institute entitled "Improving the Performance of Soil-Cement and Cement-Modified Soils." The objectives of this project were to investigate several key issues in stabilizing pavement base and subgrade materials with cement. These objectives were to:

- Develop a laboratory testing protocol that allows selection of the optimum cement content for soil-cement (S-C) bases that satisfies both strength and shrinkage cracking criteria.
- Investigate new laboratory tests for both durability and moisture susceptibility of S-C bases.
- Improve understanding of the differences between cement-and-lime modified high-PI soils with a focus on the permanency of stabilization.
- Determine the effectiveness of cement slurry application to soil under laboratory conditions.

The results anticipated from the study included:

- Recommended laboratory testing procedures for selecting optimum cement content for soil-cement/cement-treated bases.
- Recommended level of pulverization for permanent effectiveness of cement-modified clay soil for use in subgrade improvement.
- Recommended criteria and limitations for slurry application of cement to soils (for use in either soil-cement or cement-modified soil applications).

The results of this study can be used by pavement engineers at state departments of transportation, local transportation agencies, and consulting engineers for public and private pavement projects for improving the performance of their pavements through proper material selection, design, and construction of soil-cement bases and cement-modified soil subgrades.

Chapters 2 through 5 of this report focus on the issue of evaluating and developing laboratory test procedures for selecting the optimal cement content for soil-cement bases (objectives 1 and 2 and result 1) and are organized as follows:

- A literature review (Chapter 2) summarizes current design criteria and issues: strength, shrinkage, durability, and moisture susceptibility.
- A laboratory testing program using procedures to define the strength, shrinkage, and durability of S-C materials, along with tentative acceptance criteria, is outlined in Chapter 3. Marginal base aggregates from three districts of the Texas DOT are selected for testing.
- The results of the testing program are given in Chapter 4.

- Chapter 5 provides a detailed analysis of the data and, based upon the research findings, makes recommendations for the tests and acceptance criteria for use in defining the optimal cement content.

The following four appendices also are included which present:

A) Results from a mineralogical evaluation of the three aggregates used in this study
B) The protocol for the Tube Suction Test (TST)
C) Details on the test procedures used
D) Comparison of the TST with traditional durability tests

Chapters 6 through 9 of this report focus on evaluating the laboratory performance of plastic soils modified with both lime and cement (objectives 3 and 4 and results 2 and 3). Researchers investigated the impact of both different levels of soil pulverization and the method of mixing the stabilizer with the soil. The layout of these chapters is as follows:

- Chapter 6 describes the two soils used in this study. This includes the Atterberg limits and unconfined compressive strength data on the raw soil. The impact of both lime and cement on the Atterberg limits also will be discussed.
- Chapter 7 presents the impact of different levels of pulverization on the laboratory properties of samples treated with both cement and lime. In this initial series of tests, the stabilizer was mixed with the soil in a relatively dry state, after which the amount of moisture required to bring the sample up to optimum moisture content was added. The samples then were compacted and cured for 7 days prior to testing.
- Chapter 8 presents an evaluation of how different methods of adding stabilizer to the soil impact the laboratory properties. The three methods of adding the stabilizer were:
    - mixing cement with dry soil (soil < 5% moisture); then adding moisture to reach Optimal Moisture Content (OMC),
    - mixing cement with moist soil (soil at 10% moisture); then adding moisture to reach OMC, and
    - mixing cement slurry with damp soil.
- Chapter 9 presents the conclusions and recommendations for cement-modified soils

The following four additional appendices are included which presents:

E) Chemical analysis of soil
F) Effect of slurry mixing time on laboratory properties
G) Evaluation of slurry settling time with no agitation
H) Sample preparation and testing methods

Chapter 2

LITERATURE REVIEW OF SOIL-CEMENT BASES

Soil-cement first was used as an engineered material in a joint research project between the South Carolina State Highway Department and the Portland Cement Association in the early 1930s. In 1935, PCA began an extensive effort to develop scientific control methods to produce uniform, durable mixtures of portland cement and various soils. As a result of this work, the moisture-density test (ASTM D558/AASHTO T134), the wet-dry test (ASTM D559/AASHTO T135) and the freeze-thaw test (ASTM D560/AASHTO T136) for soil-cement mixtures were developed and adopted as standards. For many years state and local highway departments utilized these tests, along with PCA acceptance criteria, to determine optimum moisture content, maximum dry density (standard proctor), and minimum cement content.

Standard compressive strength tests also were developed to make and cure soil-cement specimens (ASTM D1632) and to test for unconfined compressive strength (ASTM D1633). However, compressive strength testing was viewed as a supplementary test to the wet-dry/freeze-thaw durability tests and was not originally developed to determine cement content. Both PCA and highway agencies developed correlations between strength and durability. Highway agencies, after developing experience with the compressive strength vs. durability relationship, often would specify a minimum 7-day compressive strength for a particular soil type in lieu of the standard durability tests. Agencies preferred the compressive strength test primarily because it required less lab equipment and less laboratory technician interaction with the samples, and could return results in one week instead of one month (the approximate time frame needed to run the durability tests).

In response to the need for faster testing procedures, PCA developed the “shortcut test” for sandy soils, which correlates durability with compressive strength for sandy soils within a specific gradation range. This test requires only the determination of soil gradation and 7-day compressive strength, using cement factors recommended in the procedure nomographs.

Today, most agencies use compressive strength as the main/sole criterion from which to select cement content. Unfortunately, unlike the set standards for cement content developed in the freeze-thaw/wet-dry tests or the “shortcut” test, there are no industry standards for compressive strength. Thus a variety of strength requirements developed across the country, from a low of 200 psi in Louisiana to 500-750 psi in Texas to 800 psi in Arizona. The basis for many of the “high” compressive strength requirements (greater than 500 psi) may be Figure 1, or similar locally developed graphs. This graph shows that approximately 95% of all soil samples with < 50% passing the #200 sieve also will meet durability (freeze-thaw/wet-dry) requirements if a 7-day compressive strength of 750 psi is achieved. This also means that if a 750 psi criterion is chosen, the minimum cement content *exceeds* the cement content actually needed to pass the durability tests for 95% of the samples—i.e. 95% of the materials were “overstabilized.”

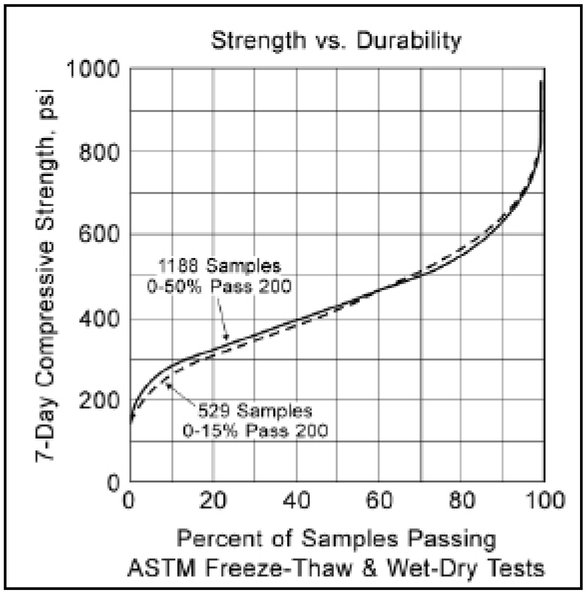


Figure 1. Relationship between strength and durability (PCA).

At the time many of these standards were adopted (20 to 40 years ago), "overstabilizing" soil-cement was thought to be a "conservative" approach that saved testing time and cost at the expense of higher than necessary cement contents for many soils or aggregates. The implication on durability was thought to be, if anything, positive, as more cement would strengthen the soil or aggregate materials and make them more durable. However, more recent research has indicated that "overstabilizing" and achieving a high 7-day compressive strength actually can be detrimental to long-term performance of a cement-stabilized base. Selecting the "optimal" cement content is now viewed more as a balancing act where enough cement must be selected to achieve adequate strength and durability, but not too much cement since that contributes to wide shrinkage cracks and overly rigid bases which can produce continued cracking and faulting.

Hundreds of thousands of lane-miles of soil cement have been placed since its inception in the 1930s, much of it lasting more than 20 years without significant maintenance. However, all soil-cement has not been problem-free. The problems with S-C pavement bases frequently are traced to the fact that these bases are designed for optimum strength, which from field performance studies does not necessarily correlate with optimum long-term performance. Current design procedures for selecting optimum stabilizer content normally are based solely on unconfined compressive strength. In many DOTs, a minimum strength of between 500 and 750 psi is required after 7 days. While this level of cement results in an extremely strong base, it does not necessarily guarantee acceptable long-term pavement performance. The most frequently heard concern is shrinkage cracking. This problem typically is observed as transverse cracks with a spacing of between 3 and 60 feet. These cracks in themselves are not necessarily a structural problem, but they often deteriorate, resulting in unacceptable riding quality. In some instances, these cracks lead to secondary problems when moisture enters the lower pavement layers. In several documented cases (Scullion and Harris, 1998), this moisture led to base disintegration. The cause of shrinkage cracking was studied extensively in the 1960s and 70s and was found to be related to the shrinkage of the fine aggregate fraction, the amount of water used during placement, and a lack of adequate curing (George, 1972).

The main focus of the S-C research conducted in this project was to evaluate alternatives to strength-based design procedures. When designing S-C bases, it is important to optimize both shrinkage and durability in addition to strength. New test procedures were evaluated for each. It is hoped that long-term performance will be improved by reducing cement content while maintaining adequate durability. This study included the use of a simple laboratory shrinkage test to assess if the S-C base will be prone to severe shrinkage cracking. Another series of tests were to determine if the base materials will be prone to durability and moisture-related deterioration. The fundamental issue is, *"Is there a set of laboratory test procedures which can be used on any aggregate source to determine the required cement content for optimum long-term pavement performance?"*

In the remainder of this section, a summary is given on current design and laboratory testing procedures. This includes a review of criteria developed for strength, durability, and shrinkage tests. This will be followed by an outline of the laboratory testing plan undertaken in this project.

CURRENT S-C DESIGN CRITERIA

PCA Procedure

The Portland Cement Association (1971) provided a systematic approach to the determination of cement requirements for soil-cement bases. The procedures and relevant test methods are listed in Figure 2. In this procedure, the mix design is governed by both strength and durability requirements on the soil-cement samples made with a predetermined range of cement contents. The wet-dry test (ASTM D559) and freeze-thaw test (ASTM D560) are the recommended test methods for evaluating durability.

Criteria for satisfactory performance of the soil-cement materials in the durability tests are listed in Table 1. These requirements apply only to base course materials. It was suggested that the freeze-thaw and wet-dry criteria are not suitable for subgrade stabilization evaluation (Epps, Dunlap, and Gallaway, 1971). Cement contents sufficient to prevent weight loss less than the values indicated after 12 cycles of wetting-drying-brushing or freezing-thawing-brushing are considered adequate to produce a durable mixture. The strengths and weaknesses of the brush test will be discussed later in this report. This test is not commonly run by DOTs.

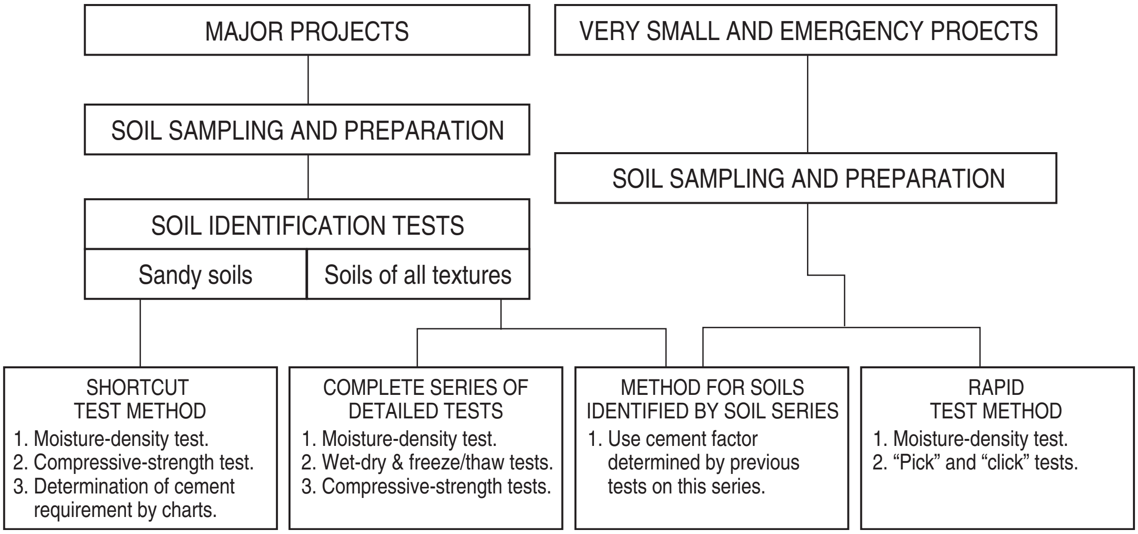


Figure 2. Soil-cement laboratory testing methods (PCA, 1971).

Table 1. Durability Requirements for Cement-treated Base Materials (Terrel, 1979)

Soil Classification		Maximum allowable weight loss after 12 cycles of wet-dry or freeze-thaw test (%)
AASHTO	Unified	
A-1 A-2-4, A-2-5 A-3	GW, GP, GM, SW, SP, SM GM, GC, SM, SC SP	14
A-2-6, A-2-7 A-4 A-5	GM, GC, SM, SC CL, ML ML, MH, OH	10
A-6 A-7	CL, CH OH, MH, CH	7

* Additional criteria:

1. Maximum volume changes during the test should be less than 2% of the initial volume.
2. Maximum water content during the test should be less than the quantity required to saturate the sample at the time of molding.
3. Compressive strength should increase with age of specimen.

Unconfined compressive strength usually is measured in accordance with ASTM D1633. Typical ranges for soil-cement materials are given in Table 2.

Table 2. Typical Ranges of Unconfined Compressive Strength of Soil-cement (Epps, Dunlap, and Gallaway 1971)

Soil Type	Saturated Compressive Strength* (psi)	
	7-day	28-day
Sandy and gravelly soils: AASHTO groups A-1, A-2, A-3 Unified groups GW, GC, GP, GF SW, SC, SP, SF	300-600	400-1,000
Silty soils: AASHTO groups A-4, A-5 Unified groups ML, CL	250-500	300-900
Clayey soils: AASHTO groups A-6, A-7 Unified groups MH, CH	200-400	250-600

* Specimens moist-cured 7 or 28 days, then saturated in water prior to strength testing.

U.S. Army Corps of Engineers

The U.S. Army Corp of Engineers (USACE) developed their mix design criteria in accordance with both durability and strength requirements (ACI, 1990). The USACE durability and strength criteria for cement stabilization are given in Table 3 and Table 4, respectively.

Table 3. USACE Durability Requirements

Type of soil	Maximum allowable weight loss after 12 cycles of wet-dry or freeze-thaw test (%)
Granular, PI < 10	11
Granular, PI > 10	8
Silt	8
Clays	6

Table 4. USACE Unconfined Compressive Strength Criteria.

Stabilized layer	Minimum strength at 7 days (psi)	
	Flexible pavement	Rigid pavement
Base course	750	500
Subbase course or subgrade	250	200

Department of Transportation (DOT) Criteria

DOTs typically base their design criteria on the PCA guidelines. However, most focus on compressive strength alone. The rationale is that if sufficient strength is obtained, then durability as measured by abrasion resistance will not be a problem.

In the 1960s, the California Division of Highway proposed using strength criteria in mix design. For base materials, the mix design initially was based on a minimum compressive strength of 850 psi at 7 days. Experience with this high strength requirement revealed that severe problems caused by shrinkage cracking may occur. Therefore, the minimum unconfined compressive strength requirement was reduced to 750 psi at 7 days. Other agencies proposing unconfined compressive strength criteria at this time were: Texas DOT (500 or 750 psi), Road Research Laboratory in United Kingdom (250 or 400 psi, depending on traffic volume), U.S. Air Force (300 psi), and Iowa DOT (450 psi) (Hitek, 1998).

The Texas DOT constructed many miles of highway in the 1960s with S-C bases designed to meet the 750 psi criteria. However, as experienced in California, in several instances unsatisfactory performance was obtained primarily because of secondary problems relating to shrinkage cracking. Several of the Texas districts abandoned S-C bases because of the observed performance problems; many changed to lime or lime/fly-ash stabilization. In recent years, S-C bases have made a resurgence; however, the design criteria have changed significantly. The focus in recent years has been on reduced strength S-C bases, with 7-day strength criteria in the range of 200 to 300 psi (Wimsatt, 1998).

Other Recent Research Findings

Many agencies have accepted unconfined compressive strength as the mix design criteria for soil-cement materials. Though the mix design procedures adopted in different agencies are very similar, test specifications and strength requirements are somewhat different. A recent research study conducted by Mississippi researchers (Hitek, 1998) gives a good summary of various strength requirements adopted in different agencies. For comparison, Hitek converted each strength requirement to the equivalent strength for the same test condition. Although the specific applications and environments are not specified in the comparison, the converted values of strength requirements are spread widely with a range of 120-1160 psi at 7 days. This range clearly illustrates that there is currently little agreement in the highway community on what target strength to aim for when designing S-C bases.

Summary

Unconfined compressive strength is the most widely referenced property for the mix design of soil-cement base materials. This test will be used as one of the four tests in the laboratory test program. The overall goal is to arrive at a S-C design to minimize reflection cracking and also have acceptable strength and durability criteria. Lower strengths in the order of 200 psi are acceptable if and only if, the durability criteria also are met.

METHOD OF MINIMIZING SHRINKAGE CRACKING

The major performance problems found with soil-cement materials are related to shrinkage cracking. Fine, widely spaced shrinkage cracks are not a structural problem, but in some cases, these cracks become wider and more closely spaced. In documented instances poor performance has been related to secondary problems which initiate around wide shrinkage cracks. A wide crack can result in:

- Moisture infiltration, causing pumping of the subgrade layer and loss of support for the soil-cement layer above.
- Faulting of the soil-cement layer because of loss of subgrade support.
- Moisture-induced deterioration of the soil-cement layer at the joint, causing an even wider crack and subsequent joint raveling.
- Loss of aggregate interlock at the crack, resulting in loss of pavement continuity and reduced pavement capacity.

In this section, the shrinkage cracking mechanism is discussed together with methods of minimizing its severity and extent.

The shrinkage of soil-cement materials results from the loss of water by drying and from self-desiccation during the hydration of cement. The magnitude and rate of shrinkage of soil-cement materials are influenced by several factors, including mix proportions and the properties of materials. Generally, fine-grained materials containing high fine contents exhibit greater shrinkage than coarse-grained materials. Restraints on the shrinkage cause the development of shrinkage stress, and subsequent cracking will occur when the shrinkage stress exceeds the tensile strength of the material. Therefore, the occurrence of shrinkage cracks depends not only on the degree of restraints provided, such as the subbase friction, but also on the time-dependent material properties, such as shrinkage potential, tensile strength, and extensibility. The final crack width is mainly dependent upon the ultimate shrinkage strain and crack spacing. The ultimate shrinkage is, therefore, one of the important characteristic properties of soil-cement materials.

The literature shows that efforts to minimize the shrinkage cracking problem have focused in the following areas: a) material selection and mix design, b) use of additives, c) curing, and d) specific construction techniques.

Material Selection and Mix Design

Based on research and field work completed in Queensland, the Australian code of practice for soil-cement base applications recently was changed (Caltabiano and Rawlings, 1992). Changes included recommendations on the gradation of raw materials as well as the use of linear shrinkage as an indicator of shrinkage potential. It was noted that the crack patterns in the field after the introduction of these specifications were at the regular 16- to 23-ft intervals, but the crack widths were notably finer. These new material specifications included:

- Linear shrinkage of raw soil passing the #40 sieve: 2.5% maximum
- Plasticity index: 4% maximum
- Introduction of a fly-ash blend cement
- Percentage of fines passing #200 sieve: 7.0% maximum
- Linear shrinkage of cement-treated base material should not exceed 250 microstrains after 21 days.

Several researchers also have used special cement, other than ordinary Portland Type I cement, to attempt to reduce shrinkage strains in soil-cement materials. The use of fly-ash blend low-shrinkage cement was introduced in the revised Australian specification for soil-cement base materials. Researchers in Georgia conducted a laboratory study using expansive cement for base stabilization (Barksdale and Vergnolle, 1968). Based on limited laboratory tests, the use of an expansive cement resulted in a definite general reduction and, in some instances, elimination of shrinkage cracking in comparison to the materials treated with type I cement.

Curing

Effective retention of moisture in soil-cement materials, especially at early ages, is important to minimize shrinkage and the corresponding cracking problems. Good curing prevents the drying that causes shrinkage and also promotes strength gain through cement hydration. Kuhlman (1994) recommended that a curing emulsion be applied to the newly constructed soil-cement base and maintained intact for a minimum curing period of 7 days. He asserted that this is the best means of minimizing shrinkage cracks after the soil-cement has been compacted and finished. He also recommended direct asphalt paving on the soil-cement base within one day after placement. By direct surfacing, no cracks form in the cement-treated base because of the immediate moisture cutoff. The Netherlands uses 6 to 12 in. of mixed-in-place soil-cement bases with 10% cement, and with a 2- to 2.5- in. asphalt surfacing (Kuhlman, 1994).

On the other hand, Norling (1973) recommended a delay in placement of the surface as long as practical to minimize surface cracking. Delaying placement of the bituminous surface provides time for much of the total shrinkage of the base to occur before the surface is placed. This process should result in less shrinkage of the base after the surface is placed and less reflective cracking through the hot mix surface layer.

Construction

The upside-down design and construction has been used in New Mexico, South Africa, Arizona, and British Columbia (Williams, 1986). This method adds an untreated granular layer between the soil-cement base and AC surface as an interlayer to minimize and delay reflective cracking, although it does not control the shrinkage cracking in the stabilized layer.

Interest also has been expressed in predetermining the crack pattern of soil-cement bases in preference to waiting for unacceptable crack patterns. This involves saw cutting the surface of the new base at regular intervals. Several promising results have been reported with this approach (Bonfinger and Sullivan, 1971, and Pretorius, 1970). However, the predetermined crack spacing should be associated with sufficient understanding of the strength and stiffness of soil-cement base materials, conditions for shrinkage stress development, and corresponding cracking potential. Fatigue behavior of the soil-cement base with traffic loading also should be incorporated in the predetermination of the optimal crack spacing. Pretorius (1970) suggested that since little or nothing can be done to prevent shrinkage cracking, it is best contained by introducing saw cut joints as is regularly done with jointed concrete pavements. Williams (1986) commented that saw cutting of new surfaces may be cost prohibitive.

Rather than saw cutting pavements, the Austrian agencies (Litzka and Haslehner, 1995) have initiated a program of precracking the soil-cement layer early in its life. This can be achieved by either permitting traffic to use the pavement 24 hours after construction or loading the pavement with a vibratory roller between 24 and 72 hours after placement. Litzka and Haslehner (1995) reported that five passes of the roller led to satisfactory results, creating a microcrack network which eliminated the development of larger shrinkage cracks. It was reported that back-calculated moduli of the layers, as computed from surface deflections, corresponded very well with the assumed design value. The early application of loads was one of the factors (Syed and Scullion, 1998) attributed to the good cracking performance of recycled pavements in Texas. This reconstruction process was done under traffic, which means that at the end of each day, the completed section was sealed with a two-course surface treatment and then opened to traffic. Of the 20 sections monitored, none exhibited the traditional shrinkage crack patterns. This precracking approach does appear to have merit, and it is currently under study within the Texas and Mississippi DOTs.

Summary

As can be seen from the preceding discussion, the causes and the severity of shrinkage cracking are complex. The final crack pattern is dependent not only upon material properties but also upon curing and construction techniques. The literature is somewhat confusing, with some agencies recommending immediate sealing and overlaying of bases and others recommending delayed surfacing. This may be traced to the fact that each agency has its own characteristic base materials and unique environment. The construction techniques, such as precracking, are not widely used, but the initial reported success certainly deserves further consideration.

As far as what can be done in the laboratory testing phase of this project to minimize cracking potential, it appears that the Australian recommendations on a maximum allowable shrinkage strain are worth further investigation. Consequently, the procedure and criteria proposed by Caltabiano and Rawlings (1992) have been included in this test program.

TRADITIONAL DURABILITY/ABRASION TESTING

In S-C bases for highway applications, traditional durability testing generally is concerned with abrasion resistance. The most widely used test is the Brush Test described below.

Brush Tests

The two tests most commonly recommended for durability testing of S-C bases are ASTM D559 for resistance to wetting and drying and ASTM D560 for resistance to freezing and thawing. Under ASTM D559, the weight loss of cement-stabilized material under wire brushing is determined after 12 cycles of wetting and drying, and a similar technique is used for 12 cycles of freezing and thawing.

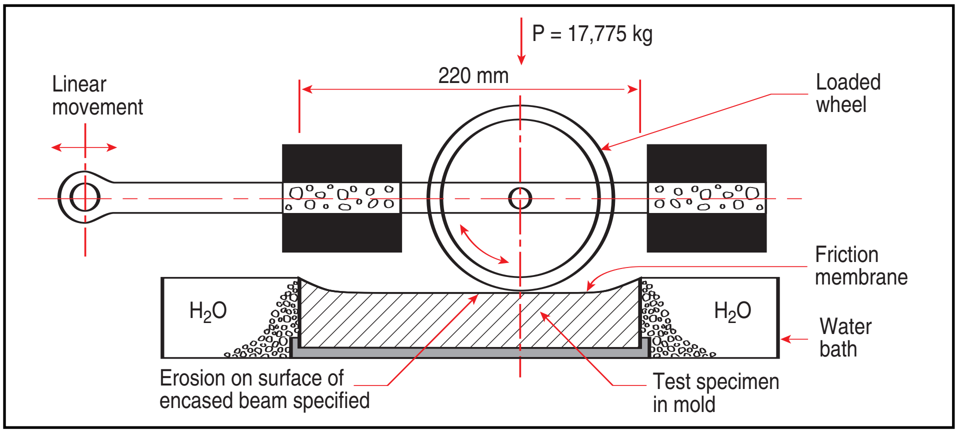
Work done by PCA found that only about 20% of the samples with a compressive strength of 300 psi would pass the laboratory freezing and thawing test, whereas about 70% of the samples would pass with a compressive strength of 500 psi. They observed a correlation between compressive strength and percentage of samples passing laboratory freezing and thawing tests. This relation, shown earlier in Figure 1, can be used to select a minimum compressive strength to achieve some degree of protection against freezing and thawing. However, freezing and thawing damage is primarily a function of pore structure and saturation level, so the relation to strength may be coincidental. Certain factors that yield higher strength, such as higher cement contents and higher density, also decrease pore size and reduce permeability. This makes a sample more difficult to critically saturate. While higher strength may improve durability, strength alone is no guarantee of durability.

Most wet-dry durability brush tests also take considerable time to complete (12 cycles wet-dry takes approximately six weeks). A further drawback of the current wet-dry durability test is that the brush is hand-held, with a specified force to be applied on the brush. An in-depth study by Samson (1986) has shown that the reproducibility of the wet-dry brushing test used in South Africa is poor because of inappropriate brushing techniques adopted by different laboratories.

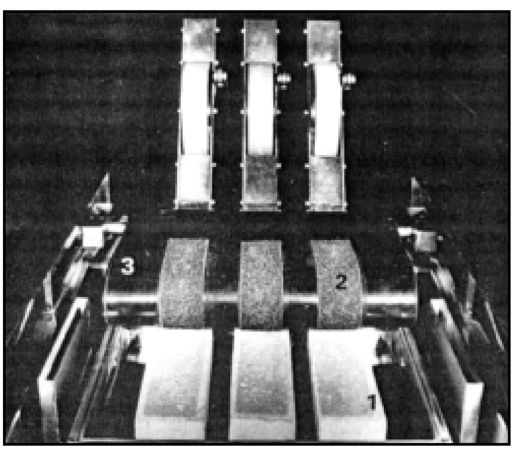
Erosion Test/South African Wheel Tracking Test

The brush test is the most widely recommended durability test for S-C materials in the United States; however, other tests have been recommended around the world. These include rotational shear and water jetting tests (Van Wijk and Lovell, 1986). An excellent review of the strengths and weaknesses of these tests was made by De Beer (1989). Based on the limitations of the current tests, he reported the development of a new test called the South African wheel tracking test for assessing the erodibility of lightly cementitious materials. The aim of the developers was to more closely simulate the stress conditions under thin surfacings by heavy truck loads. The test setup and measurement techniques are shown in Figure 3.

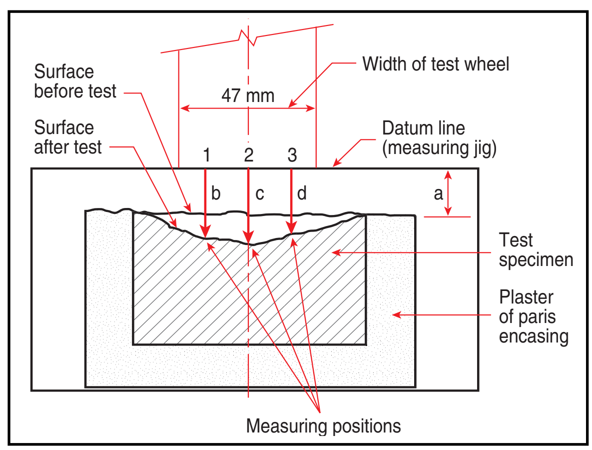
The aim of the wheel tracking test is to identify fine-grained materials that are susceptible to erosion so that they may be avoided or modified. In this test, three rectangular specimens are submerged in water and covered with a rough neoprene membrane. The membrane has a contact texture of very rough sandpaper. A 17.775 kg wheel with a beveled rim is rolled over the sample to erode the surface. After 5000 repetitions, the depth of erosion is measured at 15 points on the specimen surface. The erosion index is expressed as the mean of the average depth of erosion for the three specimens. This test reasonably simulates the actual erosion action that occurs in the stabilized base layer in the presence of water. In the South African test, an accelerated curing procedure was developed that enabled the entire test to be completed in seven days.



A. Test Setup



B. Equipment + Samples



C. Measuring Erosion

Figure 3. South African wheel tracking device for measuring erosion of stabilized materials (De Beer, 1989).

Van Blerk and Scullion (1995) used this test to study the durability problems experienced by soil-cement base material in Texas. They also measured the shrinkage of the test specimens prior to the wheel tracking test. As anticipated, higher cement contents resulted in more shrinkage.

Summary

The South African wheel tracking device is available at the Texas Transportation Institute. It is believed to be most effective in evaluating lightly stabilized, fine-grained materials. If the base material contains large aggregates (>12 mm), then the wheel tends to ride on the large aggregates rather than deteriorating the cement matrix. This test is included in the work to be conducted on this study. An additional benefit is that the same specimen can be used to monitor both the shrinkage and erosion resistance of the stabilized material. Both shrinkage and erosion resistance are important considerations when evaluating the consequences of reduced cement contents.

MOISTURE SUSCEPTIBILITY

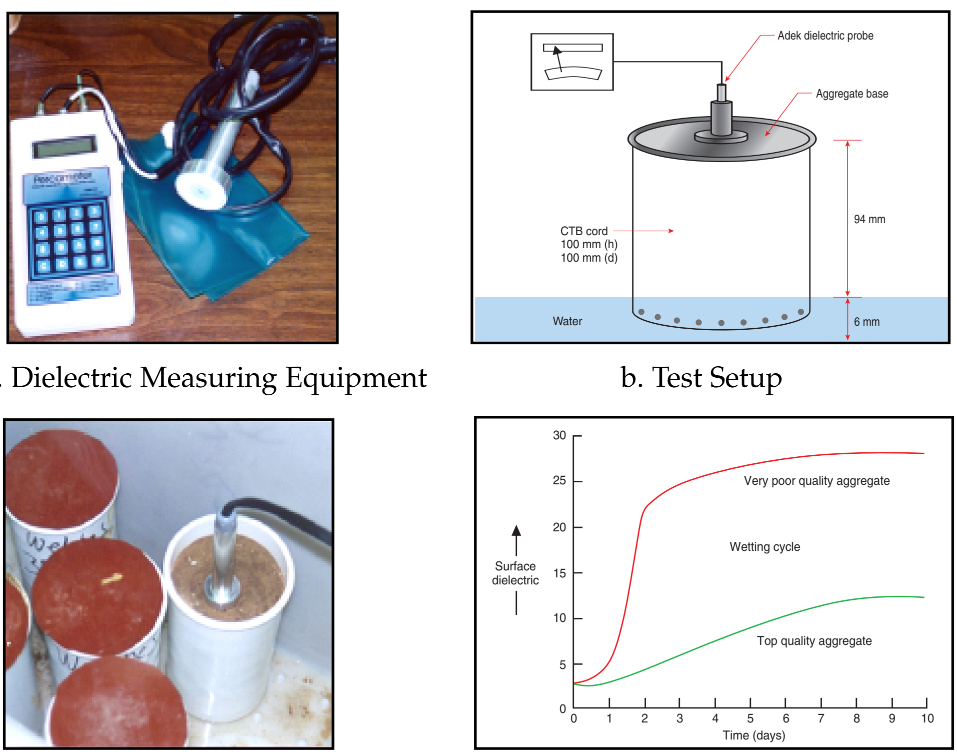
The permanency of stabilization is a major concern with all stabilizing materials. Most DOTs have experienced problems with stabilizers "disappearing" after a few years in service. While this is a common concern with lime and lime/fly-ash stabilized layers, there also have been several documented cases of permanency problems with soil-cement base layers. Typically, these durability problems have been found not to be related to abrasion resistance but to chemical reversals of the stabilization process. In most cases, these reversals are associated with moisture intrusion and movement within the stabilized layer. In this section of the report, a summary will be presented of some of the reported work and field observations. This has led the Texas Transportation Institute to develop a new test procedure called the Tube Suction Test (TST), which also is described. The detailed TST test protocol is presented in Appendix B.

Moisture Susceptibility

Field performance studies conducted in Texas found that most soil-cement bases were performing well. However, a small percentage were found to be experiencing severe durability problems early in their life. Often, the problems arise from design practices; for example, base constructed using two different materials (Scullion and Harris, 1998) have not performed well. On one project the first lift of the base was constructed using cement-treated recycled material (6 in.), and the top 6-in. S-C layer was constructed with virgin limestone aggregate. As measured in the laboratory, these layers had significantly different shrinkage and thermal expansion properties. In the field it was found that the two layers debonded and shrinkage cracks in the upper layer reflected through the asphalt surfacing layer. Moisture entering these cracks was trapped at mid-depth in the S-C layer, contributing to accelerated deterioration of the base by leaching of the cementitious materials and the formation of new (less stable) phases. This moisture, combined with the mechanical loading, accelerated base deterioration. In other forensic investigations, moisture became trapped within the soil-cement layer either because of clay-contaminated fine material or via the use of highly absorptive coarse aggregates. These studies in Texas concluded that the observed durability problems were more related to chemical changes within the stabilized layer caused by moisture intrusion than the classical abrasion durability problem.

Tube Suction Test

In the past five years, the Texas Transportation Institute has been evaluating a new test procedure for identifying problem base aggregates. Scullion and Saarenketo (1997) proposed a test to identify poorly performing unstabilized base materials by measuring their capillary rise and surface dielectric values. The test setup for the TST is shown in Figure 4. It involves compacting a 6 x 8-in. sample at optimum moisture content in a concrete cylinder mold with a series of small diameter holes drilled in its base. The sample is dried in a 40 °C room for several days, and then the capillary rise of moisture is monitored with a dielectric probe, which measures the dielectric properties of the surface of the sample. High surface dielectric measurements indicate suction of water by capillary forces. The mineralogy of the fines contributes to the affinity for water. The dielectric itself is the measure of the unbound moisture within the base. It is this "free" moisture rather than the bound moisture which is thought responsible for poor performance under applied vehicle loads and poor resistance to freeze thaw-cycling. Studies have been underway in both Texas and Finland to relate the laboratory and field performance of materials classified by the TST. Laboratory studies conducted by Saarenketo, Scullion, and Kolisoja (1998) found that materials ranked poorly by the TST also had poorer load-bearing capability as measured by their resilient modulus and permanent deformation properties. In addition, Guthrie and Scullion (2000) reported that poorly ranked materials were also highly susceptible to frost damage. Based on Texas and Finnish studies, tentative criteria have been established for unstabilized base material: if the surface dielectric exceeds a value of 10, then that material may not perform well under heavy traffic loads in areas which are subject to freeze-thaw cycling. A failure level of 16 has been proposed. Materials exceeding this value should be considered for chemical stabilization.



a. Dielectric Measuring Equipment

b. Test Setup

c. Surface Measurement

d. Typical Results

Figure 4. Tube Suction Test (Scullion and Saarenketo, 1997) (a. IMG15465, c. IMG154466).

This test was recently extended and modified for testing stabilized base materials. In the modified procedure, the specimens of stabilized materials are first cured for 7 days prior to the dry back. They then are placed in 0.25 in. of deionized water. Recent work at TTI has linked the TST results to poorly performing stabilized bases in Texas. If moisture can flow into the stabilized layer from surface cracks or from wet subgrades, then deterioration may occur. Due to the metastable nature of many of the mineral phases associated with chemical stabilization, water movement can leach alkali metals and alkaline earth metals, decreasing the strength of the stabilized material. Calcium hydroxide, one of the principal constituents in both lime and cement-stabilized materials, has a very high solubility in pure water and may be leached rather rapidly. Once the water evaporates, ions in solution start precipitating as soluble salts (e.g., thenardite and gypsum).

Susceptibility of stabilized materials to the ingress of moisture is not addressed in the current laboratory testing methods and specifications. Research done by McCallister and Petry (1991), Scullion and Harris (1998), and Syed and Scullion (1998) suggests that if water can migrate in these chemically stabilized bases, chemical reactions can be triggered. Sometimes this may lead to reversal of stabilization. Syed and Scullion (1998) reported that migration of water into the soil-cement base caused the cement matrix to be leached out, and clean aggregates were left behind. As part of this project, a study was conducted to correlate the TST and brush test for assessing S-C durability (Syed, 2000). A summary of the findings are shown in Appendix D. It was found that there is a strong correlation between the two test methods. Syed's studies included an evaluation of different sample sizes. The best correlation was achieved with a standard sample size of 4 in. diameter by 4.5 in. high. The mere fact that water can migrate through stabilized materials is sufficient to initiate the development of secondary chemical compounds. Often, these secondary compounds are detrimental to the stabilized pavement layer and lead to the deterioration and subsequent loss of strength.

Summary

The TST shows potential for indicating the moisture susceptibility of soil-cement bases. In our experience durability problems usually are related to moisture ingress or cycling in the base layer. The affinity of the base to moisture can be measured readily in this test. This test therefore is included in the laboratory test program.

Chapter 3

LABORATORY TEST PROGRAM FOR SOIL-CEMENT BASES

INTRODUCTION

The task of selecting the type and amount of stabilizer in order to upgrade a marginal base material is far from a simple matter. Strength-based design procedures, which require a minimum unconfined compressive strength after 7 days curing, frequently result in very stiff bases that shrink and crack. Every district within the Texas Department of Transportation (TxDOT) can point to overstabilized projects which have performed poorly. The trend in recent years has been to reduce these strength requirements and hope for adequate durability. The concern with this approach is that too little stabilizer will be used, and several case studies have been conducted where the benefits of the stabilizer disappeared after a few years in service. Selection of the optimal stabilizer content for any base is indeed a balancing act. The base must have sufficient strength to carry the imposed traffic loads, it must provide adequate durability so that its properties are not severely impacted by moisture and temperature changes, and it must have volume stability so that it does not excessively shrink and develop severe shrinkage cracks.

In this report three marginal TxDOT bases are evaluated in the laboratory, at a range of stabilizer contents, in the following series of tests:

- Soil-Cement Compressive Strength Test (TxDOT Method 120-E)
- TST for Moisture Susceptibility
  (specifications under preparation by TxDOT, see Appendix B)
- Wheel Tracking Test for Erosion Resistance (South African Method, De Beer, 1989)
- Shrinkage measurements on S-C (modified TxDOT method)

Criteria have been proposed for each test. The ultimate aim is to select the stabilizer type and content that meets these often-conflicting requirements.

A secondary study correlating the Tube Suction Test to traditional durability tests (wet/dry and freeze/thaw) also was conducted. This information is presented in Appendix D.

MATERIALS USED

In selecting base course aggregates to include in this study, the following factors were taken into consideration:

- The aggregate should be a marginal material which normally would be stabilized in normal TxDOT usage
- The aggregate may have had performance problems in the past
- The TxDOT district expressed an interest in this study and indicated that they would be interested in the results

Accordingly, the following aggregates were selected for inclusion in the study:

- **Recycled Concrete Material** (Houston District)
  Houston is one of the major users of S-C in the state of Texas. They have expressed concerns about shrinkage cracking and durability of several projects built in the late 1980s. In the past, the major aggregate used was good quality crushed limestone, but in recent years, they have changed over to recycled concrete. This is a new material with which they have limited experience. It normally is stabilized with cement and used beneath Continuously Reinforced Concrete Pavements (CRCP) or as the base layer for flexible pavements.
- **Caliche Material** (Pharr District)
  Caliche is lower quality limestone material, which is used extensively in south Texas. Under normal operations, this material is stabilized with lime and used as a base layer in flexible pavements. However, a major concern expressed by the district is that after several years in service, the lime seems to “disappear.” Cement typically is not used with this material.
- **River Gravel** (Yoakum District)
  River gravels have been used for many years in Texas in both base and hot mix applications. The Yoakum District does not have a lot of good quality materials and prefers to upgrade locally available marginal materials. The district has experience with a wide range of stabilizers including cement, lime, and asphalt, although lime is now widely used. It was noted that lime stabilization has caused excessive shrinkage cracking in the past, and the district is interested in evaluating alternate stabilizers.

Details of the mineralogy of each aggregate is given in Appendix A. The fine clay fraction has a major impact on material performance. The crushed concrete was found to have have 0.86% fine clay consisting of a combination of illite, smectite, and kaolinite. The caliche was found to have 1.47% fine clay, largely smectite. Smectite has a high surface area and is known to be a highly expansive mineral; this is clearly one of the problems with this aggregate. The Yoakum river gravel was relatively “clean” with 0.37% fine clay which was dominated by kaolinite.

Cement Stabilization

The cement-stabilized materials were then put through six different testing procedures, each at a 1.5%, 3%, and 4.5% level of cement stabilization. These tests were performed with each aggregate stabilized with portland type I cement, portland type IIP (pozzolan) cement, and at the calculated optimal lime content of 1.5%. The Lime Association’s recommended Eades and Grim pH test was run on these materials and each had a required lime content of 1.5%. This is also the lime content the Pharr District had been using in the caliche material.

TESTING METHODS AND TARGET SPECIFICATIONS

As a baseline, the untreated materials were tested for water susceptibility (TST) and compressive strength both before and after the TST.

For the stabilization studies each test specimen was molded at optimal moisture, then put through the following test procedures. The six testing procedures are summarized as follows (a step-by-step process for each procedure is given in Appendix C):

- **21-day Control**: Specimens cured 21 days in wet room, then tested for Unconfined Compressive Strength (UCS). This is a control test, where this strength is compared with that measured after moisture conditioning in the TST.
- **7-day Cure TST**: Specimens compacted at Optimal Moisture Content (OMC), cured 7 days in wet room, dried 4 days in a 40 °C room, put through TST, which lasts 10 days, then tested for UCS. Throughout the TST the "free moisture" reaching the surface of the sample is monitored with a dielectric probe.
- **10-day Soak**: Specimens compacted at OMC, cured 7 days in wet room, dried 4 days, submerged in water 10 days, then tested for UCS. This soak test has been used extensively around the world to check for moisture-induced deterioration in stabilized materials. It is included here to compare its results with those obtained in the TST.
- **7- then 21-day UCS**: Specimens compacted at OMC, cured 7 days in wet room, tested for UCS just past failure, put back in wet room 14 more days, then retested for UCS. The 7-day strength is the standard TxDOT criteria; the retest has been used to check for rehealing of the material.
- **28-day Cure TST**: Specimens cured 28 days in wet room, dried 4 days, put through TST, then tested for UCS. This was included to evaluate if the 7 days curing was adequate for all stabilizer types, particularly the lime.
- **Shrinkage Test**: 75 x 75 x 450 mm-beam specimen molded and cured 1 day in wet room. Gauge studs then were attached and measurements were taken over a 20-day period for shrinkage data.
- **South African Wheel Tracking Test**: Following the shrinkage test the beam specimen was cut to 270-mm length, cast in plaster-of-paris, and soaked in water until no more gain in weight was observed. This test consists of trafficking the soaked specimen with 5000 passes of a loaded wheel. This equipment is known as the South African Wheel Tracking Machine; it is used to obtain an erosion index, L (De Beer, 1989).

Target Specifications

The specifications desired for these marginal materials to meet after stabilization are taken from a variety of sources, ranging from TxDOT to research done at TTI and other agencies around the world:

- UCS: minimum of 200 psi for 7-day control samples (TxDOT)
- UCS after TST: at least 80% of 21-day control UCS
- UCS after 10-day soak: at least 80% of 21-day control UCS
- TST: final surface dielectric value after the 10-day test of less than 10 (Saarenketo and Scullion, 1997)
- Shrinkage: less then 250 microstrains after 21 days curing (Caltabiano and Rawlings, 1992)
- South African Wheel Tracking: erosion index less than 1 mm after 5000 load repetitions (De Beer, 1989)

The 21-day control strength was measured in order to compare it to the compressive strength of the sample which has gone through the tube suction, which takes 21 days to complete (7 days curing, 4 days drying, and 10 days in actual suction testing). The goal is therefore to compare if the moisture ingress has any impact on compressive strength.

It must be emphasized that the test sequence proposed in these studies is more extensive than could be run under normal design operations. The extended test sequence is to permit the research team to evaluate test variables such as length of cure and other additional issues such as the degree of rehealing. It also will permit the researchers to establish the minimum test sequence for future studies.

LABORATORY TEST RESULTS FOR SOIL-CEMENT BASES

TEST RESULTS FOR THE UNTREATED MATERIALS

Optimal Molding Moisture

Optimal molding moisture was determined according to Test Method Tex-113-E. The optimal molding water content and corresponding maximum dry densities for the untreated materials found are shown in Table 5:

Table 5. Optimal Moisture Content and Density Results

Aggregate	Optimal Molding Moisture (% dry basis)	Maximum Dry Density (lb/cf)
Caliche	10	126.5
Rec. Concrete	10.5	123.5
River Gravel	7	139

Gradation

A sieve analysis (Figure 5) was performed on each aggregate with sieve sizes of 1-3/4, 1-1/4, 3/4, 1/2, 3/8, No. 4, No. 10, No. 40, No. 80, No. 100, and No. 200.

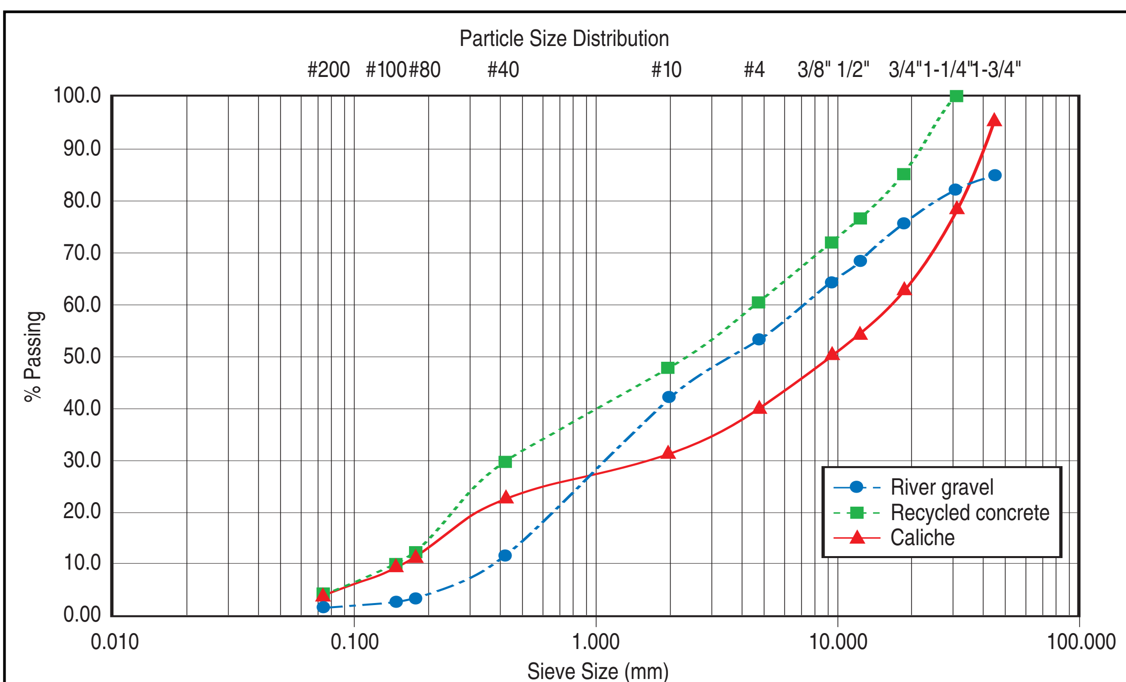


Figure 5. Gradation of base materials.

Atterberg Limits

The Atterberg limits were determined for the Yoakum gravel base material, and its Plasticity Index (PI) was found to be negligible. The Pharr caliche and recycled concrete had PIs of 15 and 13 respectively, both above TxDOT's acceptable value for a base material of 10. As discussed in Appendix A, the high PIs are caused by the high clay contents of these bases.

TST on Raw Material

The TST was performed on each of the untreated base materials to obtain a baseline for their moisture susceptibility, based on the surface dielectric measurements (Figure 6). At the end of the 10-day test, only the river gravel exhibited acceptable performance. The proposed criterion is that nonsusceptible material will have a final dielectric of less than 10. Materials with a final dielectric of more than 16 should be considered for stabilization. If moisture is available then these bases will act as sponges, resulting in lower load-bearing capacity and less resistance to environmental cycling. The beginning and ending dielectrics of the aggregates, along with the surface dielectric readings over the course of the test, are shown in Table 6. Also included is the final moisture content of the specimen after the completion of the TST and this moisture content as a percent of the optimal molding moisture. The caliche had a final moisture content almost 3% above optimum (12.9% vs. 10%). This is attributed to the large percentage (almost 1.5%) of high surface area clay (smectite) in the material. Clearly, when moisture is available this material would be highly susceptible in its raw state.

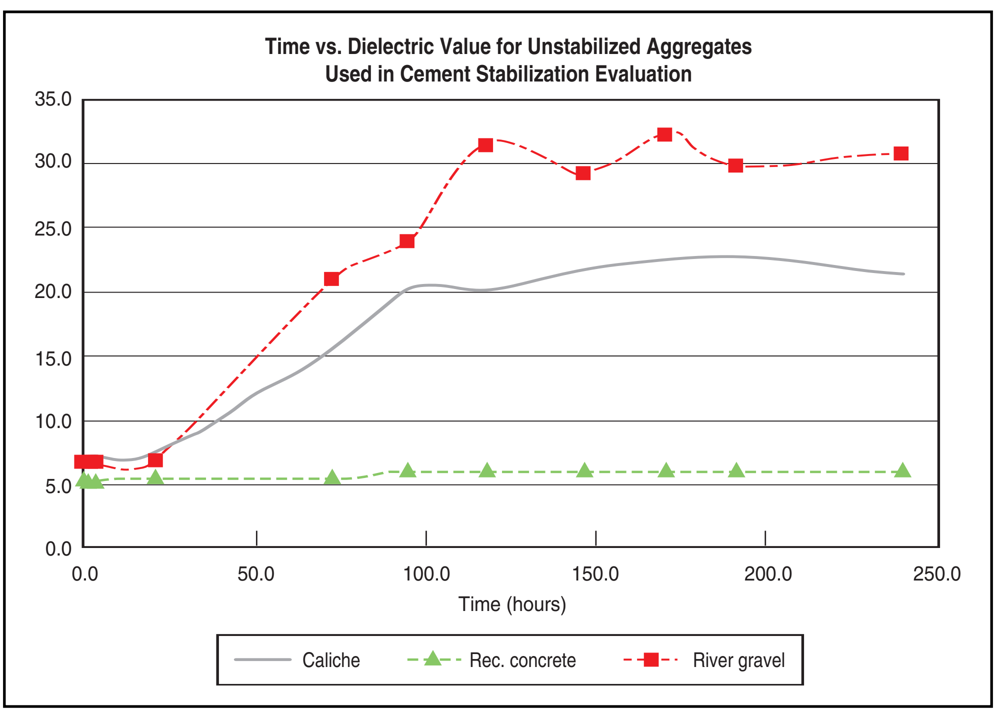


Figure 6. Results from TST on untreated materials.

Table 6. Initial TST Results on Raw Materials

Sample	Initial Dielectric	Final Dielectric	Final Moisture Content (%)	Final Moisture Content as % of OMC
Caliche	6.7	21.4	12.9	129
Rec. Concrete	6.4	30.9	12.6	114
River Gravel	5.3	6.0	5.2	74

Unconfined Compressive Strength Before and After TST

In order to get an indication of the influence of moisture on the engineering properties of each raw base material, unconfined compressive strengths were determined on two different specimens: one at optimal moisture content and one that had undergone the TST. During the TST the sample is dried for 4 days and then allowed to soak water for 10 days via capillary rise. The before strength is used by TxDOT as acceptance criterion, and a minimum value of 35 psi often is recommended for Class 1 material. The before and after strength results (in psi) are shown in Table 7.

Table 7. Unconfined Compressive Strengths Before and After Capillary Rise

Aggregate	UCS Before TST (@ OMC)	UCS After TST
Caliche	38	28
Rec. Concrete	35	48
River Gravel	16	52

It is interesting to note that the caliche showed a 26% loss in strength after undergoing the capillary rise, while the recycled concrete and river gravel showed strength gains of 37% and 225%, respectively. The strength gain in the river gravel is explained by the fact that the specimen first is dried before being started in suction testing, and this aggregate wicked only a small amount of moisture during the test. The moisture content of the river gravel after dry back was at 4.6%; it rose to 5.2% at the end of the test, well below the initial compaction moisture of 7%. Hence, the post-suction specimen was relatively dry when the strength was measured, which explains the strength increase after the TST.

The cause of the strength increase in the recycled concrete is not known, as this aggregate absorbed considerable water during suction testing, which would lead to the belief that its strength should go down (this specimen went from 8.2% after dry back to 12.6% moisture, with the optimal moisture of 10.5%). It may be that this old concrete is re-cementing in the presence of water. More work is needed in this area.

STABILIZATION TEST RESULTS FOR EACH AGGREGATE TYPE

Pharr Caliche

Results for Strength and Moisture Susceptibility Testing. The results from the strength and moisture susceptibility (dielectric) testing of the caliche base material for each stabilizer type are shown in Tables 8, 9, and 10. The type I cement results are shown in Table 8. The UCS values at each stabilizer level are high for this material. With 1.5% cement the 7-day strength was 319 psi; this failed sample was placed in a moisture room and after 21 days it was retested and found to have regained strength with a measured UCS of 321 psi. The 21-day strength after a continuous cure was 506 psi. The after TST strength (7 days cure, 4 days dry back, 10 days capillary) was 400 psi; and the strength after 10-days soak (7 days cure, 4 days dry back, 10 days submerged) was 468 psi. The sample that was moist-cured for 28 days, then subjected to the TST, had a UCS value of 344 psi. The dielectric results for the 1.5% cement level are shown at the bottom of this figure: Both the 7-day and 28-day cure samples failed the dielectric test with a final dielectric of 21.8 and 30.1, respectively.

Table 8. Peak UCS Strengths (psi) and Beginning and Ending Surface Dielectrics for Pharr Caliche Stabilized with Portland Type I Cement

Cement Content	21-day Cure (psi)	7-day Cure Tube Suction Samples (psi)		10-day Soak (psi)	7 then 21-day UCS		28-day Cure Suction Samples (psi)	
					7-day (psi)	21-day (psi)		
1.5%	506	400		468	319	321	344	
3%	586	682		607	441	565	672	
4.5%	759	1095		994	540	646	713	
		Initial E	Final E				Initial E	Final E
1.5%		7.4	21.8				6.7	30.1
3%		7.0	8.0				6.2	8.0
4.5%		5.6	6.0				6.0	6.6

Table 9. Peak UCS strengths (psi) and beginning and ending surface dielectrics for Pharr Caliche Stabilized with Portland Type IP Pozzolan Cement

Cement Content	21-day Cure (psi)	7-day Cure Tube Suction Samples (psi)		10-day Soak (psi)	7 then 21-day UCS		28-day cure Suction Samples (psi)	
					7-day (psi)	21-day (psi)		
1.5%	424	245		94	249	290	135	
3%	573	577		352	587	522	386	
4.5%	761	824		688	534	603	806	
		Initial E	Final E				Initial E	Final E
1.5%		6.2	22.4				5.9	25.7
3%		6.2	14.1				5.8	20.5
4.5%		6.4	6.5				6.6	7.7

Table 10. Peak UCS Strengths (psi) and Beginning and Ending Surface Dielectrics (Where Applicable) for Pharr Caliche Stabilized with 1.5% Lime

Lime Content	21-day Cure (psi)	7-day Cure Tube Suction Samples (psi)		10-day Soak (psi)	7 Then 21-day UCS		28-day Cure Suction Samples (psi)	
					7-day (psi)	21-day (psi)		
1.5%	442	202		260	200	242	257	
		Initial E	Final E				Initial E	Final E
1.5%		7.7	22.8				5.9	27.7

The results shown in Table 8 were used to evaluate the study criteria proposed earlier. For each aggregate type and stabilizer level, the criteria are summarized in Table 20 (type I cement) and Table 21 (type IP cement). At this 1.5% cement level, the sample failed the dielectric criterion (>10) and the retained strength (UCS after TST/21 day cure). The computed ratio was 79% (400/506), just below the criterion of 80%.

In this limited time test the high dielectrics did not immediately impact sample strength. However, as discussed earlier in this report, materials which fail the TST will potentially be subjected to wetting and drying cycles in the field and these materials are judged to be susceptible to durability problems. Indeed, the caliche materials used in this study were thought to be prone to durability problems.

From Table 8 it is also interesting to compare the 7- and 21-day UCS values on the same samples. These samples were tested past failure at 7 days and then placed back in the moist room. For each sample the 21-day strength was higher than the 7-day strength, indicating rehealing of the base. This rehealing phenomena has been reported for lime and lime fly-ash stabilized base materials, but cement-stabilized materials clearly exhibit the same property. This property is highly significant in support of the precracking technique discussed in Chapter 2. It has been reported from Austria that bases that are rerolled 1 and 3 days after placement show minimum shrinkage cracking and an initial strength loss, but then a strength gain with time.

In terms of the 7-day versus 28-day cure before testing, there does not appear to be any significant benefit of the longer cure. In terms of the dielectric test, the conclusions are similar.

The results shown in Table 9 are for the type IP pozzolan cement. This time both the 1.5% and 3% cement levels failed the dielectric criteria. The strength values at the 1.5% level also failed both the retained strength criteria. Only the 4.5% cement level passed all criteria.

Only one level of lime stabilization (1.5%) was used in this study; this is the level recommended by the Lime Association's design procedure, and it is also the value currently used by TxDOT district to treat this material. As with the low levels of cement, this material failed the TST at the 1.5% lime level. It also failed most of the retained strength tests (see Table 20). The sample cured for 28 days had a higher UCS value (257 psi) as compared to the 7-day sample (200 psi). However the dielectric classifications were similar at this stabilizer level; it failed the test after both the 7- and 28-day cure.

Results for Shrinkage and Erosion. The shrinkage and wheel tracking results are shown below in Table 11.

Table 11. Results from Beam Shrinkage and Wheel Tracking Test on Pharr Caliche

	Portland Type 1 Cement		Portland Pozzolan Cement	
Percent cement	Shrinkage after 21-days (microstrains)	Erosion index after 5000 load passes (mm)	Shrinkage after 21-days (microstrains)	Erosion index after 5000 load passes (mm)
1.5	511	0.74	0	0.58
3	-67	0.20	67	0.30
4.5	489	0.24	-178	0.22

Note: A negative shrinkage means the sample expanded.

From the test procedures on the beam samples it was found that 3% type I cement performed acceptably with regard to both shrinkage and erosion. At 1.5% and 4.5% levels of stabilization with type I cement, erosion amounts in the wheel tracking test were also less than the proposed maximum level of 1 mm for base material, but shrinkage after 21 days curing was beyond the Australian specifications of less than 250 microstrains. With the Pozzolan cement stabilization, the caliche performed acceptably in both shrinkage and erosion at all stabilization levels tested.

The results shown in Table 11 are representative of other data sets collected in this study. The following two observations were made:

- The type IP Pozzolan cement in general exhibited less shrinkage than the regular type I cement.
- For type I cement, a U-shaped curve was found relating cement content to final shrinkage. In most cases 3% cement level produced a minimum shrinkage. Higher shrinkage with higher cement contents was anticipated from the literature survey. However, at very low cement contents higher shrinkage levels were found; it may be that at this level the base still has some attributes of an unstabilized granular base material.

Summary Results for the Pharr District's Caliche Aggregate. The best performance with the caliche came from stabilization with 3% type I cement or 4.5% pozzolan cement. Specimens with these levels of stabilization met all of the target specifications. Strength was not a problem; however, the cement was required for the caliche to perform acceptably in the TST for moisture susceptibility. From this it appears that the type I cement does a better job of preventing moisture from permeating the sample. In general specimens treated with type I cement also had higher strengths than those stabilized with the same percentage of pozzolan cement. However, the type IP cement performed better in the shrinkage test.

Samples stabilized with low levels of lime only met a few of the specified requirements. The lime samples passed the 7-day strength requirement but failed the Tube Suction and retained strength test. The implication is that if lime is used with this material in an area where moisture is available (from surface or subgrade), then this material may exhibit a significant loss in strength with time.

Recycled Concrete

Results for Strength and Moisture Susceptibility Testing. Tables 12, 13, and 14 show the test results for strength and moisture susceptibility. The Houston recycled concrete results indicate that stabilization with type I cement yields substantially higher strengths as compared to the type IP pozzolan cement in the testing procedures performed. With the recycled concrete the raw material failed the TST (see Table 6) but all levels cement stabilization samples passed the test. The 1.5% cement was adequate to markedly improve both strength and the moisture susceptibility; this low level passed all criteria (see Table 12).

Table 12. Peak UCS Strengths (psi) and Beginning and Ending Surface Dielectrics for Houston Recycled Concrete Stabilized with Portland Type I Cement

Cement Content	21-day Cure (psi)	7-day Cure Suction Samples (psi)		10-day Soak (psi)	7 then 21-day UCS		28-day Cure Suction Samples (psi)	
					7-day (psi)	21-day (psi)		
1.5%	354	596		433	329	442	409	
3%	491	653		653	429	461	708	
4.5%	589	822		425	525	595	865	
		Initial E	Final E				Initial E	Final E
1.5%		5.8	5.9				4.9	5.2
3%		6.5	6.1				4.9	5.0
4.5%		5.7	5.8				5.5	5.6

Table 13. Peak UCS Strengths (psi) and Beginning and Ending Surface Dielectrics for Houston Recycled Concrete Stabilized with Portland Type IP Pozzolan Cement

Cement Content	21-day Cure (psi)	7-day Cure Suction Samples (psi)		10-day Soak (psi)	7 then 21-day UCS		28-day Cure Suction Samples	
					7-day (psi)	21-day (psi)		
1.5%	294	284		234	246	271	201	
3%	479	474		362	391	458	522	
4.5%	528	600		476	444	515	709	
		Initial E	Final E				Initial E	Final E
1.5%		5.3	5.6				5.1	6.4
3%		5.8	5.8				4.9	5.4
4.5%		5.9	6.1				5.3	5.6

Table 14. Peak UCS Strengths (psi) and Beginning and Ending Surface Dielectrics for Houston Recycled Concrete Stabilized with 1.5% Lime

Lime Content	21-day Cure (psi)	7-day Cure Suction Samples (psi)		10-day Soak (psi)	7 then 21-day UCS		28-day Cure Suction Samples (psi)	
					7-day (psi)	21-day (psi)		
1.5%	288	137		218	201	237	196	
		Initial E	Final E				Initial E	Final E
1.5%		5.6	30.1				4.3	17.7

At the 1.5% level the lime treatment appears to be less effective than the cement with this material. The strength gains were adequate but the sample failed the TST.

Results for Shrinkage and Erosion. The test results are shown below in Table 15. Only the beam specimen with 3% portland type I cement had shrinkage results under the proposed maximum of 250 microstrains after 21 days curing. In addition, the erosion index obtained at the 1.5% and 3% levels of stabilization with type IP Pozzolan cement exceeded the proposed criteria for the wheel tracking test. As part of the procedure, specimens are soaked until saturated before the test is begun. The failure of these specimens in this test is probably indicative of a possibility of failure under wet conditions.

As with other materials tested, the shrinkage results for the type I material are U-shaped in that the minimum is achieved at 3%. It was thought that increased cement content would result in increased shrinkage. This appears to be the case at the higher content levels but not at the low levels. The reason for this is not known with certainty. However, it is proposed that at the low cement level the material still possess some properties of the raw material.

Table 15. Results from Beam Shrinkage and Wheel Tracking Testing on Recycled Concrete

	Portland Type I Cement		Portland Pozzolan Cement	
Percent Cement	Shrinkage After 21 Days (microstrains)	Erosion Index After 5000 Load passes (mm)	Shrinkage After 21 Days (microstrains)	Erosion Index After 5000 Load Passes (mm)
1.5	933	0.50	-356	1.10
3	111	0.44	-333	1.34
4.5	556	0.73	-356	0.22

Note: A negative shrinkage means the sample expanded.

Summary Results for Recycled Concrete. The recycled concrete performed best by meeting all of the target specifications with 3% portland type I cement stabilization. With pozzolan cement, a 4.5% level of stabilization met all target specifications. Shrinkage and potential shrinkage cracking would be a concern with higher levels of type I cement. The pozzolan cement samples in fact did not show any shrinkage with the recycled concrete. At each cement level the sample showed an expansion in the range of 330 to 360 microstrain.

River Gravel

Results for Strength and Moisture Susceptibility Testing

The results are shown in Tables 16, 17, and 18. The river gravel with 4.5% type I cement passed all of the target specifications. The 3% type I cement and 4.5% pozzolan cement levels passed all specifications except the retained strength after the 10-day soak. The raw material and cement-stabilized materials all passed the dielectric criteria.

Table 16. Peak UCS Strengths (psi) and Beginning and Ending Surface Dielectrics for Yoakum River Gravel Stabilized with Portland Type I Cement

Cement Content	21-day Cure (psi)	7-day Cure Suction Samples (psi)		10-day Soak (psi)	7 then 21-day UCS		28-day Cure Suction Samples (psi)	
					7-day (psi)	21-day (psi)		
1.5%	306	149		92	233	313	168	
3%	441	415		199	327	478	347	
4.5%	606	591		318	349	533	564	
		Initial E	Final E				Initial E	Final E
1.5%		5.2	5.5				4.7	4.9
3%		5.3	5.0				4.9	4.9
4.5%		5.2	4.9				4.8	5.0

Table 17. Peak UCS Strengths (psi) and Beginning and Ending Surface Dielectrics for Yoakum River Gravel Stabilized with Portland Pozzolan Cement

Cement Content	21-day Cure (psi)	7-day Cure Suction Samples (psi)		10-day Soak (psi)	7 then 21-day UCS		28-day Cure Suction Samples (psi)	
					7-day (psi)	21-day (psi)		
1.5%	178	82		67	113	153	56	
3%	297	230		187	232	266	219	
4.5%	361	327		238	263	335	378	
		Initial E	Final E				Initial E	Final E
1.5%		4.5	11.3				4.5	6.6
3%		4.8	4.7				4.5	4.9
4.5%		4.4	4.5				4.7	4.9

Table 18. Peak UCS Strengths (psi) and Beginning and Ending Surface Dielectrics for Yoakum River Gravel Stabilized with 1.5% Lime

Lime Content	21-day Cure (psi)	7-day Cure Suction Samples (psi)		10-day Soak (psi)	7 then 21-day UCS		28-day Cure Suction Samples (psi)	
					7-day (psi)	21-day (psi)		
1.5%	79	50		32.5	42	62	35	
		Initial E	Final E		% Strain		Initial E	Final E
1.5%		4.5	5.0		0.51		4.0	6.5

As found with cement, the lime stabilizer passed the dielectric criteria, but the strength gains with this low level of lime were negligible. As shown in Table 7 the UCS of the raw materials after the TST was 52 psi; however, a value of only 50 psi was measured under the same conditions with the sample containing 1.5% lime. It appears that this material is not a good candidate for low levels of lime stabilization.

Results for Shrinkage and Erosion. As shown in Table 19 all specimens from the Yoakum gravel passed the shrinkage criteria except for the specimen stabilized with 1.5% pozzolan cement. In the wheel tracking test, samples stabilized with 1.5% of either type of cement were found to be highly erodible. These specimens had erosion indexes of 4.76 and 3.47 mm for type I and pozzolan cement, respectively, which is well above the 1 mm criterion. At the 3% and 4.5% level of stabilization, all samples performed acceptably with respect to both the shrinkage and the erosion criteria.

Table 19. Results from Beam Shrinkage and Wheel Tracking Testing on Yoakum Gravel

	Portland Type 1 Cement		Portland Pozzolan Cement	
Percent Cement	Shrinkage After 21 days (microstrains)	Erosion Index After 5000 Load passes (mm)	Shrinkage After 21 Days (microstrains)	Erosion Index After 5000 Load Passes (mm)
1.5	222	4.76	267	3.47
3	155	0.49	-67	0.50
4.5	111	0.31	222	0.40

Note: A negative shrinkage means the sample expanded.

Summary of Test Results for the Gravel Material. All stabilizer levels failed the 10-day soak criteria. However, the 3% and 4.5% type I cement passed all the other tests, including the retained strength after the TST. The river gravel used in this test sequence was judged not to be moisture susceptible, as both the raw and treated samples passed the TST. The question raised is which soak test is most representative of field conditions. It is proposed that the capillary rise conditions used during the TST are a better conditioning test and that the 10-day soak is too severe.

SUMMARY RESULTS FOR THE TREATED MATERIALS

After performing the specified testing procedures on the base materials, it is possible to evaluate the effects of stabilization on the engineering properties. The critical issue is whether the stabilized aggregate passed the specifications given in Chapter 3 (Laboratory Test Program). Summary results are given in Tables 20 and 21.

In general, the portland type I cement provided better results than did the pozzolan cement or the optimal lime content with regard to strength gain and moisture susceptibility. The advantage of the pozzolan cement appears to be in the shrinkage area, where both the caliche and crushed concrete showed substantially less shrinkage at the equivalent cement content. In general, however, a higher level of stabilizer was required with the pozzolan cement than with the type I cement in order to meet all of the target specifications.

With the optimal lime content, only the river gravel passed the specifications for the TST. None of the lime samples had strengths of at least 80% of their 21-day curing strength after undergoing the TST or the 10-day soak.

Table 20. Summary of Testing Results for Target Specifications; Specimens with Type I Cement (and Optimal Lime for Comparison)

Aggregate	7-day Control	7-day Cure TST		10-day Soak	7 then 21-day UCS	28-day Cure TST		Shrinkage	Wheel Tracking
	UCS>200	Final E<10	UCS>80%	UCS>80%	UCS>200	Final E<10	UCS>80%	<250 microstrain	Erosion <1mm
Caliche 1.5% Cement	Yes	No (21.8)	No (79%)	Yes	Yes	No (30.1)	No (68%)	No (511)	Yes
Caliche 3% Cement	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Caliche 4.5% Cement	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No (489)	Yes
Caliche 1.5% Lime	Yes	No (22.8)	No (46%)	No (59%)	Yes	No (27.7)	No (58%)		
Rec. Concrete 1.5% Cement	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No (933)	Yes
Rec. Concrete 3% Cement	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Rec. Concrete 4.5% Cement	Yes	Yes	Yes	No (72%)	Yes	Yes	Yes	No (556)	Yes
Rec. Concrete 1.5% Lime	Yes	No (30.1)	No (48%)	No (76%)	Yes	No (17.7)	No (68%)		
River Gravel 1.5% Cement	Yes	Yes	No (49%)	No (30%)	Yes	Yes	No (55%)	Yes	No (4.76)
River Gravel 3% Cement	Yes	Yes	Yes	No (45%)	Yes	Yes	No (79%)	Yes	Yes
River Gravel 4.5% Cement	Yes	Yes	Yes	No (52%)	Yes	Yes	Yes	Yes	Yes
River Gravel 1.5% Lime	No (42 psi)	Yes	No (63%)	No (41%)	No (42 then 62 psi)	Yes	No (44%)		

Note: Data in parentheses are the observed values when a material did not meet the corresponding target specification.

Table 21. Summary of Testing Results for Target Specifications; Specimens with Pozzolan Cement (and Optimal Lime for Comparison)

Aggregate	7-day Control	7-day Cure TST		10-day Soak	7 then 21-day UCS	28-day Cure TST		Shrinkage	Wheel Tracking
	UCS>200	Final E<10	UCS>80%	UCS>80%	UCS>200	Final E<10	UCS>80%	<250 microstrains	Erosion < 1mm
Caliche 1.5% Cement	Yes	No (22.4)	No (58%)	No (22%)	Yes	No (25.7)	No (32%)	Yes	Yes
Caliche 3% Cement	Yes	No (14.1)	Yes	No (61%)	Yes	No (20.5)	No (67%)	Yes	Yes
Caliche 4.5% Cement	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Caliche 1.5% Lime	Yes	No (22.8)	No (46%)	No (59%)	Yes	No (27.7)	No (58%)		
Rec. Concrete 1.5% Cement	Yes	Yes	Yes	Yes	Yes	Yes	No (68%)	Yes	No (1.10)
Rec. Concrete 3% Cement	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No (1.34)
Rec. Concrete 4.5% Cement	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Rec. Concrete 1.5% Lime	Yes	No (30.1)	No (48%)	No (76%)	Yes	No (17.7)	No (68%)		
River Gravel 1.5% Cement	No (113 psi)	No (11.3)	No (46%)	No (38%)	No (113 then 153 psi)	Yes	No (31%)	No (267)	No (3.47)
River Gravel 3% Cement	Yes	Yes	No (77%)	No (63%)	Yes	Yes	No (74%)	Yes	Yes
River Gravel 4.5% Cement	Yes	Yes	Yes	No (66%)	Yes	Yes	Yes	Yes	Yes
River Gravel 1.5% Lime	No (42 psi)	Yes	No (63%)	No (41%)	No (42 then 62 psi)	Yes	No (44%)		

Note: Data in parentheses are the observed values when a material did not meet the corresponding target specification

Based on the performance indicators used in this study, the best performing aggregate/stabilizer contents are:

- Caliche with 3% type I cement (met all target specifications)
- Recycled concrete with 3% (or less) type I cement (met all target specifications)
- River gravel with 4.5% type I or pozzolan cement (met all specifications except one strength specification)

RECOMMENDATIONS FOR THE THREE MARGINAL MATERIALS

On the positive side, increases in cement content provided increases in unconfined compressive strength, decreases in moisture susceptibility (as measured by the TST), and higher abrasion resistance. However, increases in cement content above 3% also caused an increase in specimen shrinkage and a reduction of the strain at the break. With regard to the three marginal base materials tested in this study, the following conclusions are made.

Caliche/(Pharr District)

The untreated base material did not do well in either the strength test or TST. The material has a high affinity for moisture and lost 26% of its strength during the TST. Minerological studies indicated that this material contained substantial (1.5%) smectite clay. This material is clearly a good candidate for chemical stabilization.

This material is currently treated with 1.5% lime but performance problems have been reported by TxDOT within some instances, the lime being reported to "disappear after a few years." The results from the lime stabilization studies were not encouraging based on the TST results. The samples met the 7-day strength requirement but failed the moisture susceptibility test with a final dielectric of 22.8. It is thought that if this lime-treated material was to be used in a location with a high water table, high rainfall, or a clay subgrade area, then the base could be prone to wetting and drying cycles. This has been shown in several case studies to cause a reduction in base strength with time.

Based on the criteria proposed in this study, the optimum stabilization treatment would be 3% type I cement. At this level all criteria would be met. The 7-day strengths were over 440 psi and, as measured by the TST, it was not moisture susceptible with a final dielectric of 8.0. The shrinkage was also negligible and very little abrasion was measured.

Recycled Concrete/(Houston District)

The untreated material had a high affinity for moisture but surprisingly showed a 37% strength gain from before and after the TST. Most materials that fail this test show a significant strength loss. The unusual results may be because the crushed concrete still retains some self-cementing properties and the availability of moisture accelerated this process. What is not known is a) will this strength gain be reversed with repeated wet-dry cycles? or b) is this phenomenon found with other recycled concrete? The indication from other tests at TTI is that recycled concrete is a variable material and that this beneficial strength gain cannot be guaranteed long-term. The affinity for moisture is thought to be caused by the presence of the old mortar in the crushed concrete.

In the stabilization studies this material responded very well to the addition of small levels of cement. At the 1.5% cement level the strength increased from 35 to 329 psi after 7 days curing, and the final dielectric reduced from 30.9 to 5.9. The only failure at the 1.5% level was the high shrinkage of 933 microstrain, well above the failure level of 250 microstrain. The shape of the shrinkage versus cement content curve is not fully understood at this time. For the type I cement the curve shows a minimum shrinkage at around 3% cement. Above this minimum an increase in cement causes an increase in shrinkage. This has been reported by other researchers; however, the shrinkage at low cement levels possibly is related to the fact that the material may not be fully stabilized at this level and still retains some of the characteristics of a granular material.

The level is the 3% type I cement. However, one cause for concern with this material may be that high levels of cement could cause problems. The shrinkage increased significantly when moving from 3% to 4.5% cement. As a final recommendation the district should use no more than 3% type I cement with this material; consideration should be given to using less. A value of 2% should be considered.

River Gravel/(Yoakum District)

The UCS and Tube Suction results were very interesting for the raw material. At optimum moisture content this low PI material had a very low strength (16 psi), well below the value quoted in the TxDOT specifications of 35 psi. However, this material performed very well during the TST; after the 4-day dry back and 10-day capillary rise the strength increased to 52 psi. Which strength is more representative of the eventual field strength for this material? The implication here is that if this material is to be used deep in the pavement structure or beneath a significant thickness of hot mix then it may not require stabilization.

The concern with this material is that it has low cohesion and high erodibility so that if it is to be used as a base layer, then stabilization is recommended. From the results given in this report this material is not moisture susceptible. However, at the low stabilizer levels it had poor retained strength and was highly erodible in the wheel tracking test. This material failed the 10-day soak criterion at every cement content. However at 3% type I cement and the 4.5% pozzolan cement, it passed all other criteria. At the 3% level the strengths after the TST were similar to the strengths in the control 21-day samples (415 psi versus 441 psi). The results from the stabilization testing indicated that the district should consider 3% type I cement for this material.

Chapter 5

ANALYSIS OF TEST RESULTS AND RECOMMENDATIONS FOR SOIL-CEMENT BASES

SUMMARY

This chapter will examine the data for relationships between cement content and performance, the effect of cement type on performance, the ability of soil-cement to autogenously heal, and the merits of each testing method used, and finally will recommend test methods and criteria for each method. As expected, increases in cement content yielded higher compressive strengths, less susceptibility to moisture, higher retained strengths after being exposed to capillary rise, and less erosion in the wheel tracking test. In shrinkage, many of the specimens showed a bowl-shaped cement content versus shrinkage curve in which there was some level of cement where shrinkage was minimized.

A definitive effect of cement type on compressive strengths was not seen, as the strengths from specimens treated with type IP pozzolan cement were less than those treated with type I cement on two of the aggregates but about the same or greater for the other aggregate. Regarding retained strength after exposure to wetting, specimens treated with type I cement generally performed better than specimens treated at the same cement level with type IP.

All of the cement-treated specimens which exhibited autogenous healing properties. Specimens failed at 7 days were found to regain strength to a level typically between 100% and 150% of their 7-day compressive strength. The pozzolan cement did not seem to offer an advantage in regaining more strength.

Regarding testing methods, higher unconfined compressive strength generally was accompanied by better performance in the other tests, except for shrinkage. As shown in Appendix D the Tube Suction Test was found to be well correlated to the traditional wet-dry and freeze-thaw tests for durability. In addition, it was observed that specifying the strength of the sample after the Tube Suction Test to be at least 100% of the 7-day strength yields virtually the same acceptance decision as requiring the strength after the Tube Suction Test to be at least 80% of the 21-day strength, plus has the added benefit of requiring one less sample. Therefore, a new testing protocol that balances cement content with strength, durability, and economy is suggested.

EFFECT OF CEMENT CONTENT

Unconfined Compressive Strength

As expected, increasing cement content yielded increased 7- and 21-day strengths of the samples. Figure 7 illustrates this with the data from the type I cement. For the marginal aggregates tested, relatively small amounts of cement from 1.5% to 4.5%—were able to increase the UCS to greater than the 200 psi 7-day criterion. In all cases, these were dramatic increases from the unconfined compressive strengths of the unstabilized materials.

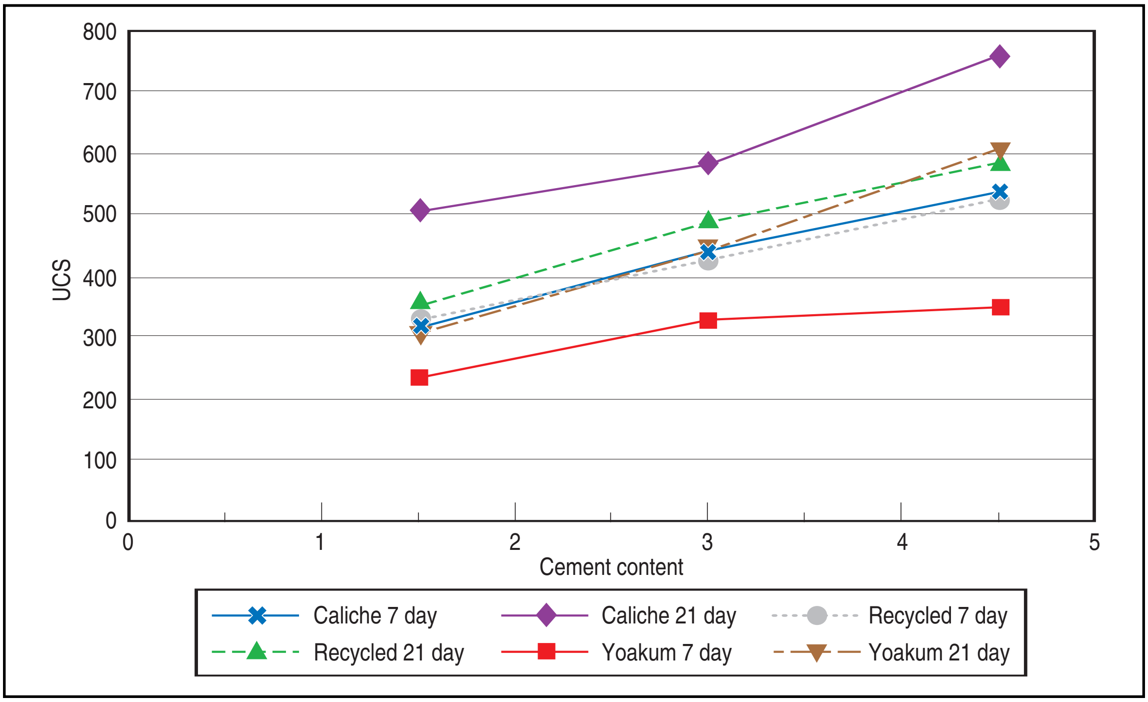


Figure 7. Positive trend between cement content and UCS.

The average increase from 7- to 21-day UCS was 35.5% for all samples. Aggregate type seemed to make a significant difference in 7- to 21-day UCS gain. The average percentage gain for the caliche, recycled, and gravel materials was 49.0%, 15.9%, and 43.8%, respectively (see Table 22).

Table 22. Percent Increase from 7- to 21-day UCS

Aggregate	Cement Type	1.50%	3%	4.50%	Avg: Cement Type	Avg: Aggregate
Pharr Caliche	I	58.6%	32.9%	40.6%	44.0%	
Pharr Caliche	IP	70.3%	-2.4%**	42.5%	56.4%	49.0%
Houston Recycled Concrete	I	7.6%	14.5%	12.2%	11.4%	
Houston Recycled Concrete	IP	19.5%	22.5%	18.9%	20.3%	15.9%
Yoakum River Gravel	I	31.3%	34.9%	73.6%	46.6%	
Yoakum River Gravel	IP	57.5%	28.0%	37.3%	40.9%	43.8%
Avg: All Data						35.5%

** Data excluded from averages because of strength decrease.

Moisture Susceptibility

In nearly every cement type/aggregate combination, increasing cement content decreased the dielectric reading of the 7-day cured sample and thus decreased the moisture susceptibility of the sample (see Figure 8). In all cases, a relatively low cement content—between 1.5% and 4.5%—was able to significantly decrease the moisture susceptibility of the sample to below the recommended dielectric reading of 10. It is postulated that the cement tends to stabilize the active clays within the sample so that, with increasing cement, it becomes more difficult for moisture to rise through capillary action. In only one case—Yoakum with type IP at 1.5% cement—did cement content significantly increase the dielectric reading of the sample. In this case the raw soil, which had a final dielectric value below 10 in the unstabilized state, increased to 11.3 with 1.5% type IP cement, but then was reduced to less than 5 at the 3% and 4.5% cement levels. This aggregate and cement type at 1.5% cement also experienced low compressive strengths (< 200 psi at 7 and 21 days) and exhibited low retained strengths of the soaked samples (< 80% of 21-day cured sample). This suggests that for some materials, too low a cement content may not only result in low strengths, but also may make the material more susceptible to moisture.

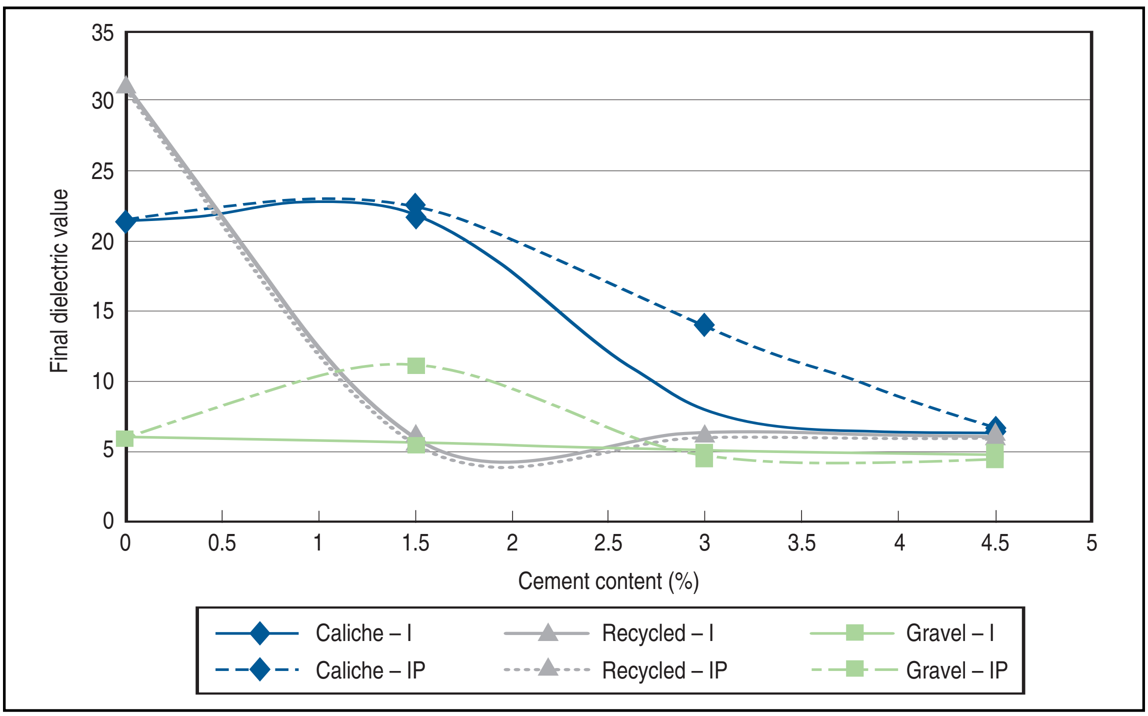


Figure 8. Cement content vs. TST results.

Retained Strength

In all cases of cement type and aggregate combinations—except type I with the recycled concrete material—increasing cement contents tended to improve the percent of strength retained. This might indicate that for most materials, the increased moisture available during soaking (either TST or 10-day immersion) more fully hydrates the cement, allowing it to retain a higher percentage of strength than a lower percentage of cement.

Many of the cement/aggregate combinations actually gained strength after soaking (i.e., >100% UCS retention). This may indicate that cement, to a point, can improve the saturated strength of a stabilized base material (possibly because of continued hydration). Figure 9 shows the retained strength (7-day TST UCS/21-day UCS) for the aggregates.

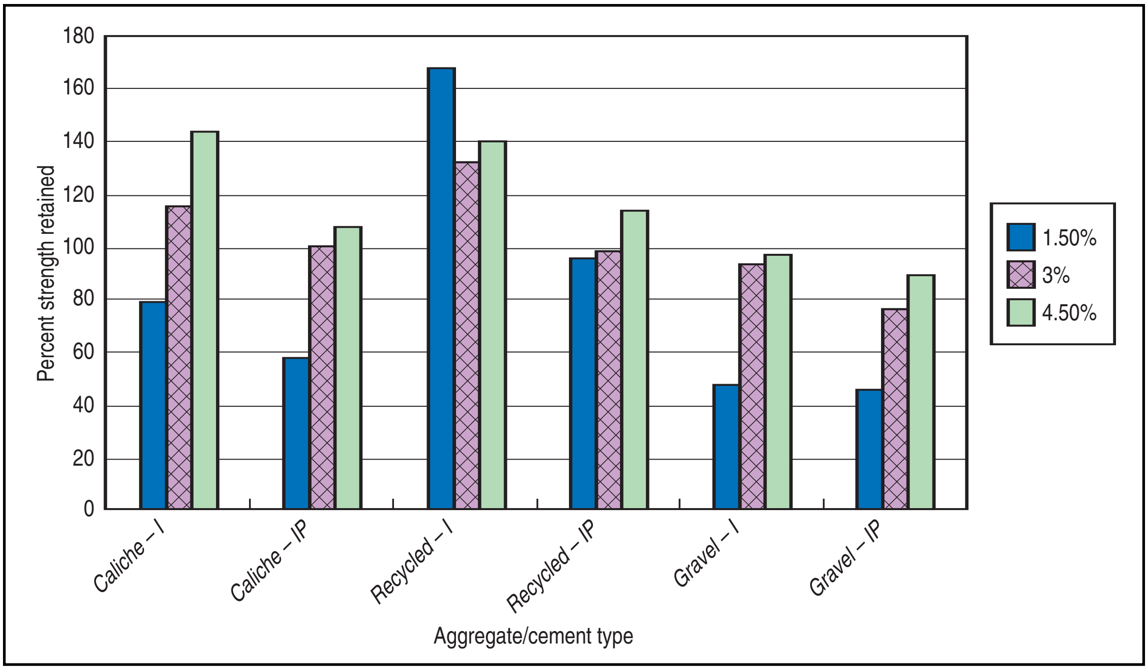


Figure 9. Retained strength increases with increasing cement content.

Shrinkage

At treatment levels from 1.5% to 4.5% cement for the aggregates tested, shrinkage was not positively correlated for all cases with increasing cement content. This runs counter to "conventional wisdom," which contends that increased cement content leads to increased shrinkage (see Figure 10). For many of the samples (Pharr/type I, recycled concrete/type I, Yoakum/type IP), an optimum (minimum) shrinkage level was reached at a level below the 250 microstrain level targeted at an intermediate cement content. For these samples, shrinkage was significantly higher for both the 1.5% and 4.5% cement levels. This may indicate that at very low cement contents (in these cases, the 1.5% level), the shrinkage characteristics of the parent material (possibly due to fine materials in the aggregate) dominate. At higher cement contents (in these cases, the 4.5% level), the effects of increased cement content may tend to increase shrinkage because of increased drying and self-dessication during hydration. However at an "optimum" level (in these cases, 3%), shrinkage is significantly reduced (in some cases to near zero). For the samples which did not exhibit the bowl-shaped curve, shrinkage tended to decrease slightly or stay about the same with increased cement contents.

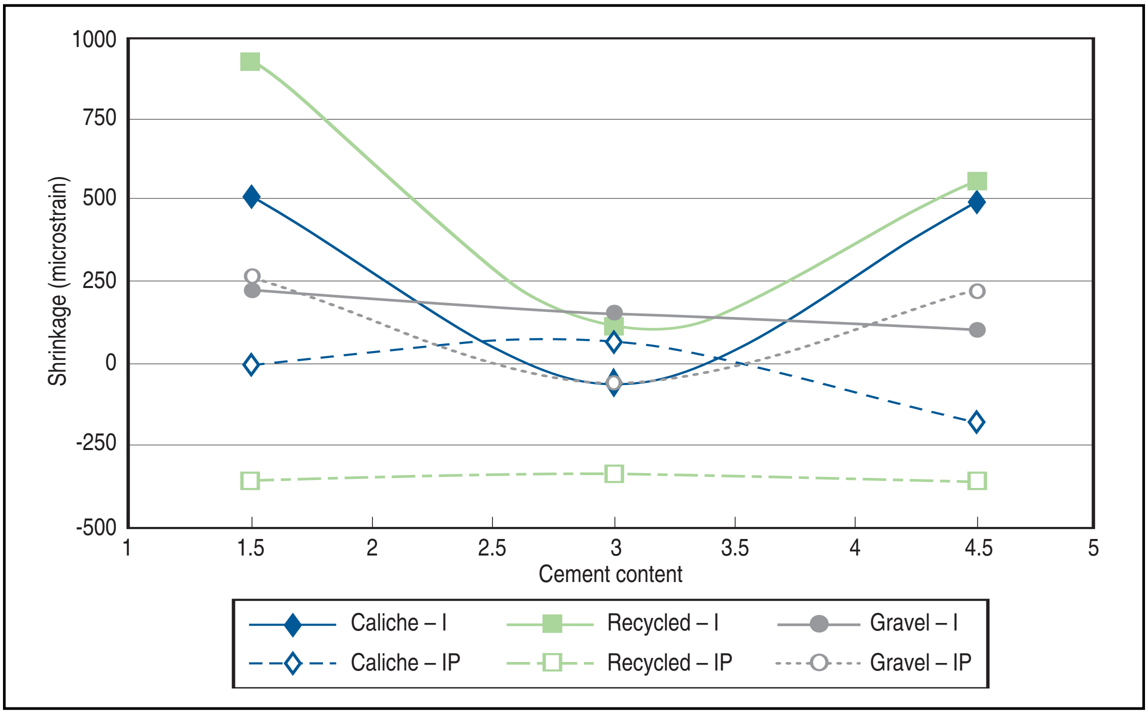


Figure 10. Cement content vs shrinkage.

Several of the samples exhibited slight "negative shrinkage" (i.e., expansion) up to the 350 microstrain level. This is not necessarily a concern, as the small expansion strains will induce compression on the order of 200 to 700 psi (assuming modulus of elasticity between 600,000 and 2,000,000 psi and elastic behavior, [PCA, 1970]). Any slight crushing of the material initially would likely heal autogenously (see discussion below) as the cement would continue to hydrate. It also may help induce a "microcrack" network similar to the externally generated network postulated when post-rolling after 1-2 days is included as part of the construction process. High cement contents, even if they don't increase shrinkage—and they probably do—will nonetheless increase the widths of shrinkage cracks, since the cracks will be spaced a further distance apart than lower cement-content materials. This would be detrimental to pavement performance as was discussed in Chapter 2.

Wheel Tracking

The wheel tracking test, as expected and illustrated in Figure 11, indicated that the erosion index decreased as cement content increased. Cement—at levels between 1.5% and 4.5% depending on the aggregate—decreased the erosion index of all the aggregates to less than the target value of 1 mm. The Yoakum aggregate is of particular note in this test, as it demonstrates the value of having multiple evaluation criteria for determining cement content (and for assessing raw materials for use as base). The Yoakum material demonstrated a high erodability at a low cement content (at 1.5%, erosion index is 3.5 mm and 4.8 mm for type I and IP, respectively). The raw material was not placed in the wheel tracking device because the test is for stabilized materials. However, the raw material has a very low UCS (16 psi), and lime-stabilized material has been observed to result in excessive shrinkage cracking. This in-service cracking observed also may be due to degradation/failure of the material under load and moisture conditions, as 1.5% lime—which the Texas DOT Yoakum District uses—gains a 7-day strength of only 42 psi. This material is of note because the dielectric reading indicated it was not moisture susceptible in the raw or (most) stabilized states. However, because of the low strengths, this material appears to require stabilization to ensure durability as a base material. Essentially it is a nonplastic material with low cohesion and may be relatively unstable under load, even if not moisture susceptible. Just a small increase in cement—from 1.5% to 3.0%—reduced the erosion index by almost 90%.

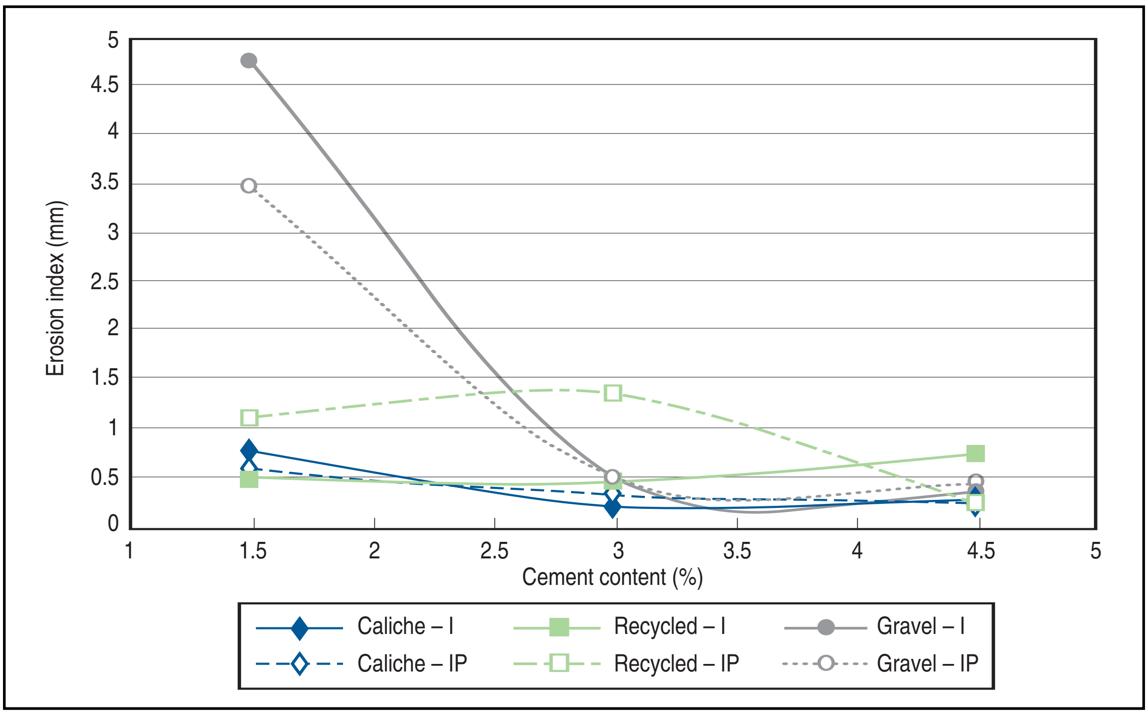


Figure 11. Cement content vs. erosion index.

EFFECT OF CEMENT TYPE

Two cement types were examined in this study: type I and type IP (pozzolan). The type IP was chosen because previous researchers have indicated that inclusion of a pozzolan cement could help decrease shrinkage. The following conclusions can be ascertained when examining the data.

Unconfined Compressive Strength

For the recycled concrete and Yoakum aggregates, compressive strength decreased for type IP cement, when compared to type I, at 7 and 21 days for all cement contents. For the Pharr aggregate at the 3% and 4.5% cement contents, type IP compressive strength either was greater than, or about the same as, the type I cement. The Yoakum aggregate exhibited the greatest decrease in strength when the IP cement was used: between 24.6% and 51.5% reduction. On average, for all samples, the reduction in strength was 16.1% for the 7-day test and 18.1% for the 21-day test. These data are shown in Table 23.

Table 23. Percent Change in UCS between Type I and Type IP Cement

Aggregate	UCS Test	1.5%	3.0%	4.5%	Average
Pharr Caliche	7 day	-21.9%	33.1%	-1.1%	3.4%
	21 day	-16.2%	-2.2%	0.3%	-6.1%
Houston Recycled Concrete	7 day	-25.2%	-8.9%	-15.4%	-16.5%
	21 day	-16.9%	-2.4%	-10.4%	-9.9%
Yoakum River Gravel	7 day	-51.5%	-29.1%	-24.6%	-35.1%
	21 day	-41.8%	-32.7%	-40.4%	-38.3%
Average, All Aggregates					-16.1%
					-18.1%

The percent increase from 7-day to 21-day compressive strength generally was higher with the type IP than with the type I cement. This higher strength gain at later ages might be expected from a pozzolanic cement, as the presence of the pozzolan tends to lower short-term compressive strength but increase later age strength. In the time frame tested, though, the 21-day strengths for IP cement were still lower despite the higher rate of strength gain. It is unclear whether or not longer-term tests (e.g., 60 or 90 days) would have yielded higher strengths for the IP cement than the type I.

Moisture Susceptibility

Both type I and IP cements tended to produce similar results in the Tube Suction tests (see previous Figure 8). As cement content increased, moisture susceptibility decreased. The threshold dielectric level of 10 was reached at the same type I and IP cement content for the Pharr and Yoakum aggregates. The recycled concrete needed slightly higher cement content for the IP cement versus the type I cement to reach a final dielectric value of less than 10 (4.5% and 3.0%, respectively).

Retained Strength

In almost every case the type I cement retained a higher percentage of its 21-day strength (when tested after the TST or after a 10-day soak) than the type IP cement (see previous Figure 9). The principal exception to this was the Yoakum aggregate comparing 10-day soak strengths to 21-day strengths, where the IP cement retained a higher percentage of strength. However, in virtually every case, the type I cement produced higher absolute strengths after the TST and 10-day soak procedures than the type IP cement.

Shrinkage

The IP cement provided some benefit with regard to shrinkage. For each aggregate type, the IP cement resulted in the lowest overall level of shrinkage (or slight expansion) when all cement contents are considered (see previous Figure 10). When comparing the shrinkage generated at a specific cement content, the microstrain from the type IP may be more or less than that from the type I cement. However, the minimal shrinkage was obtained for each aggregate with the type IP cement.

The IP cement also generated some "negative shrinkage" (expansion). The reasons for this are unclear but may include generation of higher levels of slightly expansive cementitious hydration products, or it may be due to slight swelling of the sample due to moisture. Regardless, the use of IP cement at an optimal level can help decrease shrinkage of a cement-stabilized material and should be considered, especially if the parent material is known to have a propensity for high shrinkage.

Wheel Tracking

The wheel tracking test produced almost identical results for the type I and IP cements when used on the Pharr and Yoakum aggregates (see previous Figure 11). Slightly more cement was required, however, for the type IP with the recycled aggregate to reach the threshold level of 1 mm, than the type I cement (4.5% and 3.0% cement, respectively).

AUTOGENOUS HEALING

Cement was found to have autogenous healing properties—the ability of a stabilizer to continue to generate cementitious compounds after cracking/failure, which improves strength and bonds cracks—after samples were taken to a compressive failure condition. For laboratory testing, treated specimens were failed at 7 days in UCS, allowed to cure for an additional 14 days, then retested for UCS. Table 24 quantifies the percentage of strength regained by autogenous healing.

Table 24. Strength Regained in Autogenous Healing

Aggregate	Cement	Test Comparison	1.5%	3.0%	4.5%	Average
Pharr Caliche	I	7-Day UCS*	100.6%	128.1%	119.6%	116.1%
		21-Day UCS**	63.4%	96.4%	85.1%	81.7%
Pharr Caliche	IP	7-Day UCS*	116.5%	88.9%	112.9%	106.1%
		21-Day UCS**	68.4%	91.1%	79.2%	79.6%
Houston Recycled Concrete	I	7-Day UCS*	134.3%	107.5%	113.3%	118.4%
		21-Day UCS**	124.9%	93.9%	101.0%	106.6%
Houston Recycled Concrete	IP	7-Day UCS*	110.2%	117.1%	116.0%	114.4%
		21-Day UCS**	92.2%	95.6%	97.5%	95.1%
Yoakum River Gravel	I	7-Day UCS*	134.3%	146.2%	152.7%	144.4%
		21-Day UCS**	102.3%	108.4%	88.0%	99.5%
Yoakum River Gravel	IP	7-Day UCS*	135.4%	114.7%	127.4%	125.8%
		21-Day UCS**	86.0%	89.6%	92.8%	89.4%
Average, All Aggregates/Cement	I & IP	7-Day UCS*	121.9%	117.1%	123.7%	120.9%
		21-Day UCS**	89.5%	95.8%	90.6%	92.0%

* (21-day rehealed specimen UCS)/(7-day UCS) x 100

** (21-day rehealed specimen UCS)/(21-day UCS) x 100

7-day Specimen Comparison

In almost all cases, the autogenously healed specimen regained at least 100% of its 7-day strength. The lone exception was the Pharr caliche using 3% type IP cement, which retained 89% of its 7-day strength. However, the 7-day strength of this specimen was the highest 7-day strength of all the Pharr materials (and all other aggregates for that matter); thus it had an unusually high 7-day strength. On average, for all aggregates and cement types and contents, the rehealed specimens retained 121% of the 7-day strength, with a range from 101% to 153% retained (neglecting the aforementioned Pharr/I/3% specimen).

21-day UCS Specimen Comparison

In most cases, the autogenously healed specimens, approached, but did not exceed, the 21-day UCS strength. In a few cases the autogenously healed specimens actually exceeded the 21-day UCS; however, no particular trends regarding this occurrence are apparent. Generally, all specimens that were failed in compression at 7 days and then rehealed gained strength back to a level between the 7- and 21-day strengths and sometimes exceeded the 21-day strength.

Effect of Aggregate Type

Aggregate type seemed to have some effect on the level of 7-day strength regained. The Yoakum aggregate had the highest level of strength regained, on average, for both the type I and type IP cements (144% and 126%, respectively). This was followed by the recycled aggregate (118% and 114%), then the Pharr aggregate (116% and 106%). This same trend did not occur when comparing the 21-day UCS with the autogenously healed samples.

Effect of Cement Type

The pozzolan cement did not seem to offer an advantage in regaining a higher percentage of 7- or 21-day strength, and, in fact, on average had a slightly depressing effect on percent retained. This is notable because a pozzolanic cement might be expected to regain a higher percentage of its 7-day strength, as the pozzolanic reactions occur at later ages, and might help "repair" the failed cylinder to a greater extent. This did not seem to occur with the specimens tested.

Implications for "Precracking"

One of the reasons for investigating autogenous healing was to demonstrate that soil-cement has significant reserve binding capacity, which enables it to generate new cementitious bonds even after some of the initial bonds have failed through overloading. This is the situation that would occur if a completed soil-cement base were re-rolled after 24 to 48 hours with a vibratory roller. In doing so, it is postulated that much of the initial shrinkage stress would be relieved through a distributed network of very fine cracks, resulting in significantly reduced propensity for wide, discrete shrinkage cracks and subsequent reflective cracking. Some of the cementitious bonds would fail, and immediately after post-rolling, the soil-cement would have a lower strength. However, as the autogenous healing tests suggest, all of the initial strength should be regained and exceeded (in our test, all of the 7-day strength was regained, which is even further beyond the time frame of 24-48 hour post-rolling). This implies that if post-rolling were to be performed on a soil-cement base, then the 7-day minimum UCS noted in a specification would be achieved and exceeded by the post-rolled section (although in a timeframe which might be more than 7 days after initial construction).

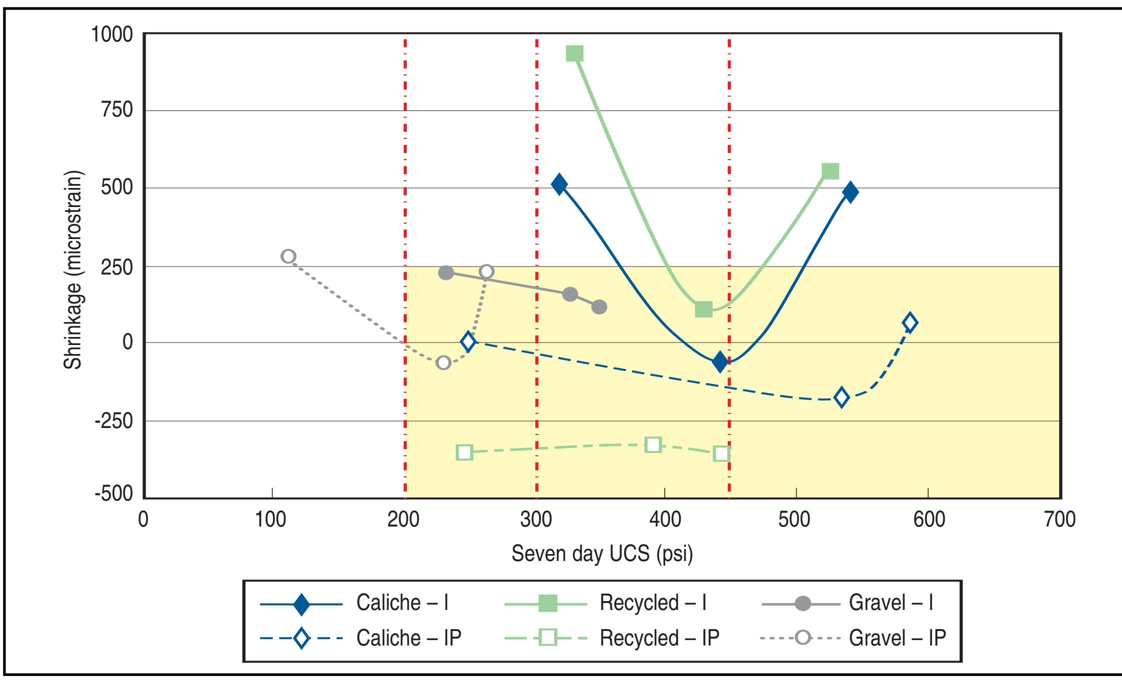
TESTING METHODS AND RECOMMENDATIONS

The principal objectives of this project were to investigate new testing protocols that, for a particular aggregate/soil, would determine an appropriate level of cement stabilization to provide adequate strength and durability without overstabilizing the material. Overstabilization may cause failure through increased shrinkage, wider reflective cracks, moisture infiltration, subgrade pumping and loss of support, reduction of load transfer between cracked sections, and pavement faulting.

Unconfined Compressive Strength

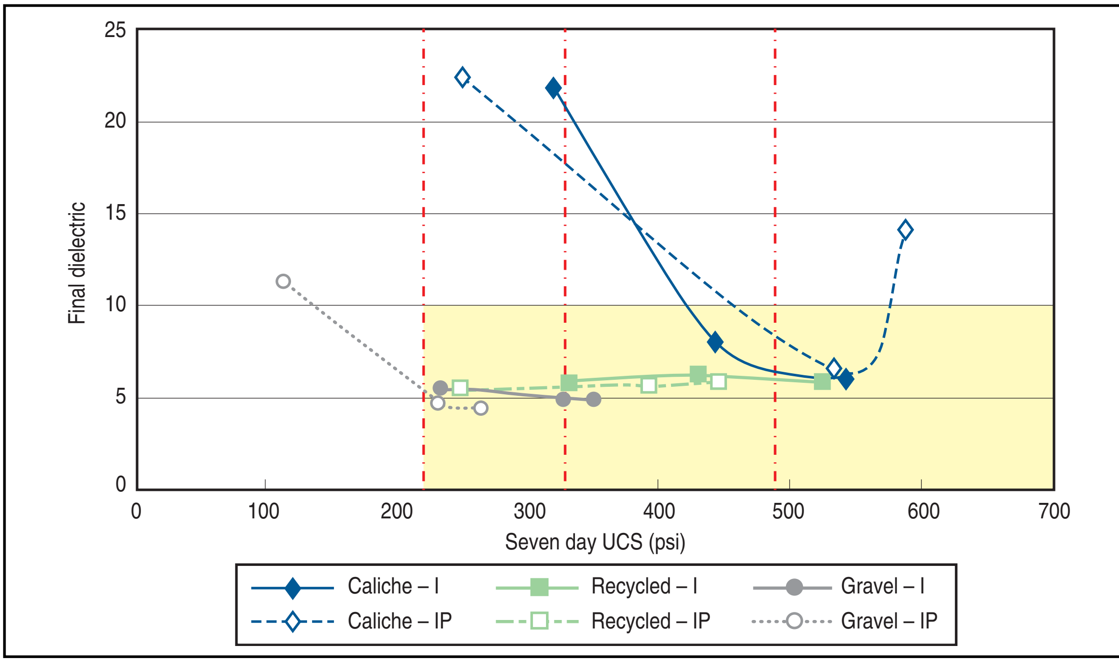
UCS is an important criterion in soil-cement because it provides an indication of load resistance and also is, to some extent, correlated with durability. The general trend for the data, for all tests except 20-day beam shrinkage, is that increased compressive strength will beget improved properties. The shrinkage test, as has been previously pointed out, often produced a bowl-shaped graph when plotted against cement content and corresponding 7-day UCS (since cement content and UCS have a strong positive correlation). Placing a 200 psi minimum on 7-day UCS would include all the shrinkage minima shown in Figure 12. A minimum UCS of 300, as proposed by George, would exclude the minimum shrinkage condition for the Yoakum IP series.

A minimum UCS of 450 psi would exclude minimum shrinkage conditions for Yoakum IP, Recycled I, Pharr I, and possibly Yoakum I (which had not yet reached a minimum in the series).

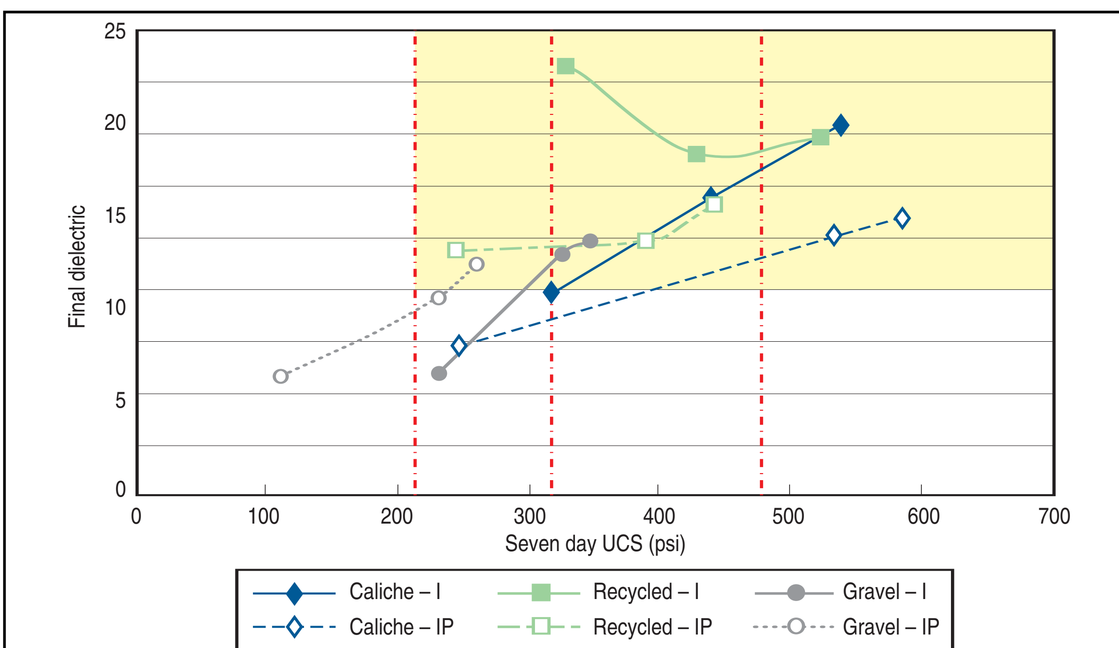


Note: Shaded area is acceptance region.
Figure 12. 7-day UCS vs. beam shrinkage.

Additionally, a 450-psi criterion would exclude many samples that meet TST limits (Figure 13) and retained strength (Figure 14). Given the fact that the 450-psi criterion was proposed for coarse-grained materials—the category for each of these aggregates—this criterion seems to be too severe, as it excludes many aggregate/cement combinations that appear to be durable and have minimum shrinkage. Clearly, a lower (200 or 300 psi) criterion would help ensure that the minimum shrinkage condition is not excluded, as was illustrated in Figure 12. However, given the fact that field strengths tend to have a higher degree of variability and tend to be lower than corresponding lab strengths with identical materials, a 300-psi criterion may be a more practical limit, with a safety factor for some low field strengths. Therefore, it is proposed to change the initial criterion assumption from 200 to 300 psi (George's "fine-grained soil" criterion).



Note: Shaded area is acceptance region.
Figure 13. 7-day UCS vs. final dielectric value in the TST.



Note: Shaded area is acceptance region.
Figure 14. 7-day UCS vs. retained strength after the TST as percentage of 21-day UCS.

Tube Suction Test

The TST is a procedure that, in previous studies, has been correlated with poorly performing materials if the dielectric reading, E, is much higher than 10. Additionally, current research has shown strong positive correlations between the traditional wet-dry and freeze-thaw tests originally developed by PCA. Because of these factors, the TST is a good companion test to the UCS, especially since meeting UCS criterion alone does not guarantee that a soil-cement sample will be moisture resistant (and thus resistant to wet-dry/freeze-thaw cycles). This is illustrated in the previous Figure 13, in which the caliche with 1.5% type I and 1.5% type IP samples reached a UCS greater than 300 psi and 200 psi, respectively, but still had a dielectric reading much greater than 10. Two different curing times were used for the TST: 7 days and 28 days. In almost every case, if the samples cured 28 days failed, the corresponding 7-day cured samples failed, thus indicating that the 7-day cure is a long enough timeframe to adequately characterize the moisture susceptibility of a material.

Percent Retained Strength

The comparison of the retained strength of a specimen after either the TST or a 10-day soak (versus the 7- or 21-day strength) is a variable of interest because it helps ensure that the specimen does not lose appreciable strength when placed in a wet or saturated condition. Three "retained strength" conditions were examined:

- Retained strength of the 7-day TST sample divided by the 21-day UCS (80% minimum)
- Retained strength of the 10-day soak sample divided by the 21-day UCS (80% minimum)
- Retained strength of the 7-day TST sample divided by the 7-day UCS (100% minimum)

The first condition has the advantage that the two comparative samples are the same cure age. Also, the TST sample somewhat simulates many field conditions where a subgrade is saturated and "wicks" up water. The second condition is probably the most severe, in that the 10-day soak saturates the sample to the highest degree, and the most strength loss probably would occur. The third condition is advantageous because it ensures that, in a field-simulated condition, the sample will retain at least all of its 7-day strength. Additionally, this condition requires the least number of samples/tests, since a separate 21-day UCS is not required.

In examining the retained strength data shown for the above three conditions for the caliche, recycled, and gravel materials in Figures 15, 16, and 17, respectively, it is apparent that the 10-day soak comparison (condition 2) is the most severe of the conditions. In fact, if the 80% criterion is used for condition 2, all of the Yoakum aggregate/cement combinations would be rejected as none have a retained strength of more than 66%. Additionally, it is interesting to note that conditions 1 and 3 result in virtually the same results with regard to sample acceptance or rejection for all aggregates.

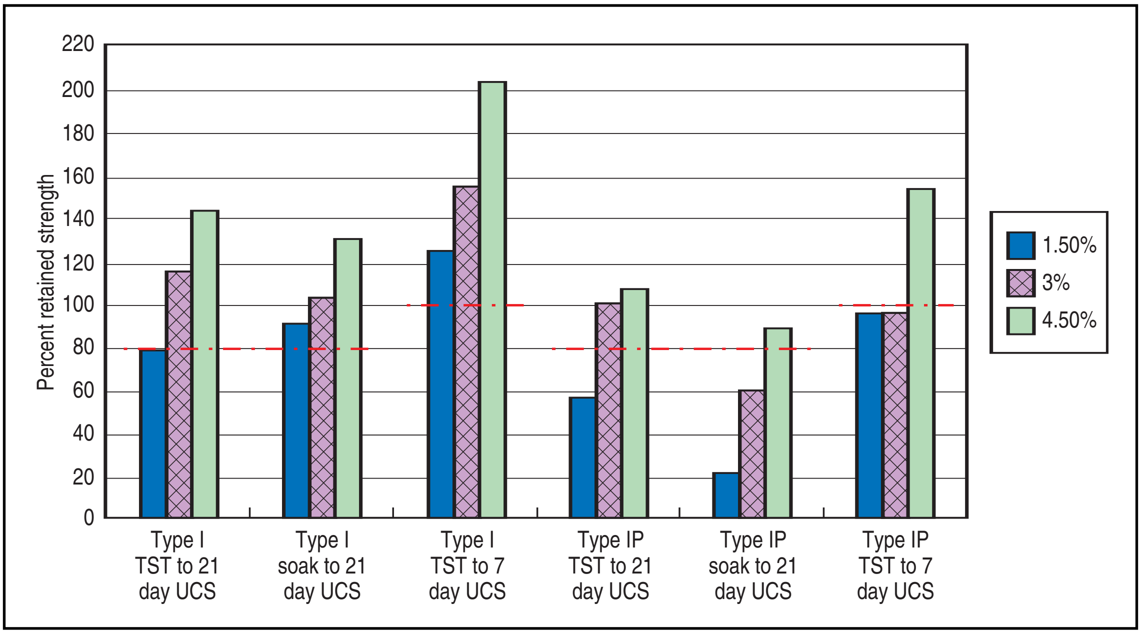


Figure 15. Retained strength results for caliche.

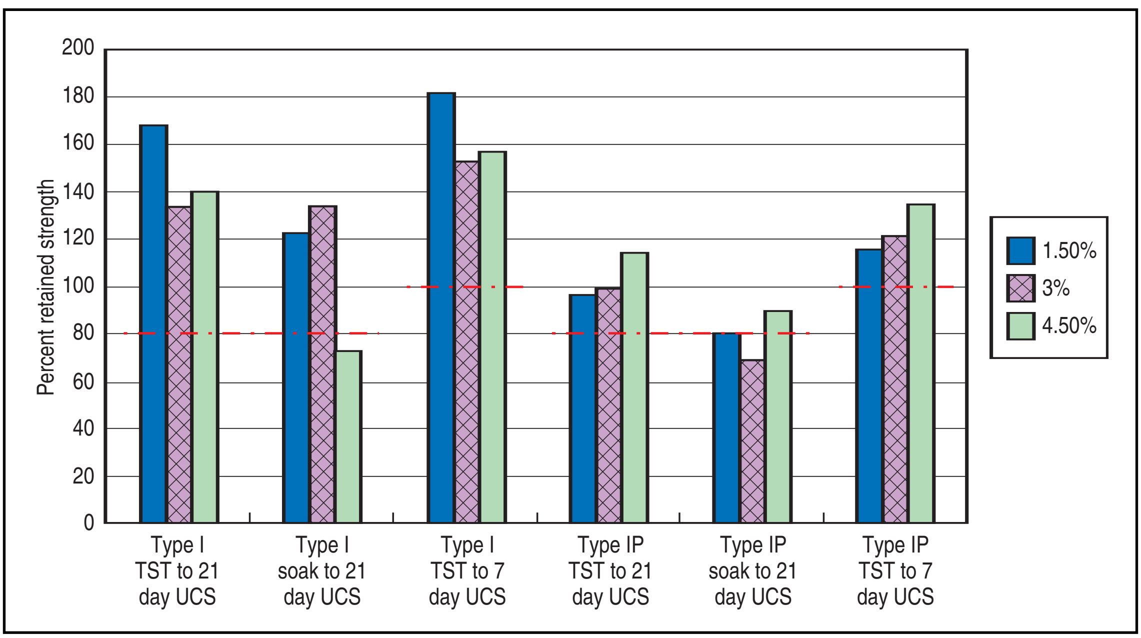


Figure 16. Retained strength results for recycled aggregate.

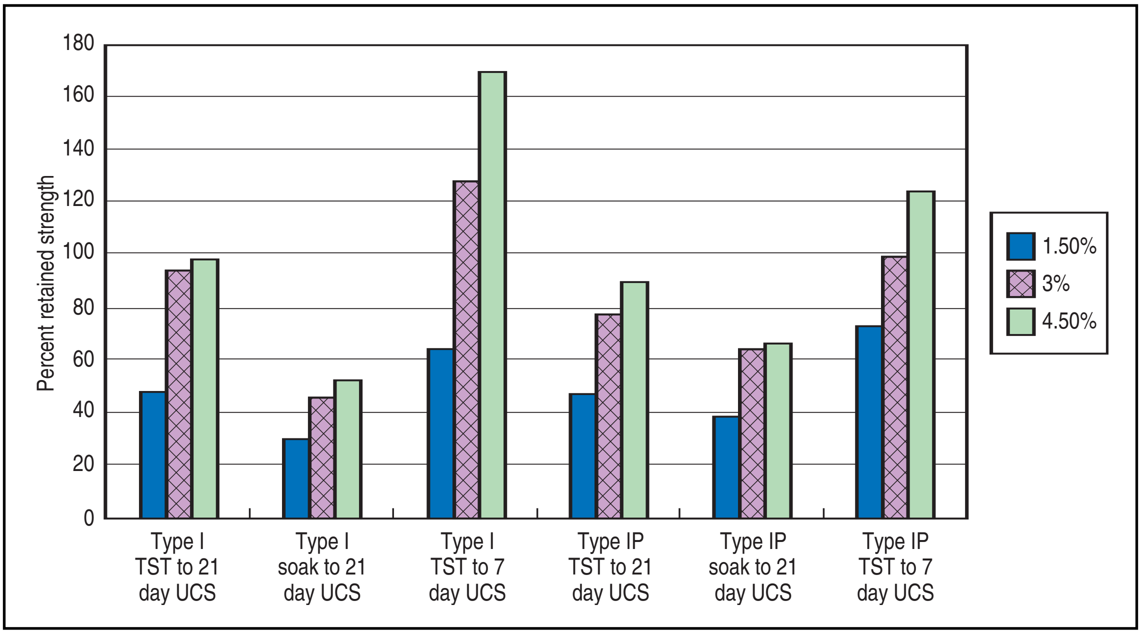
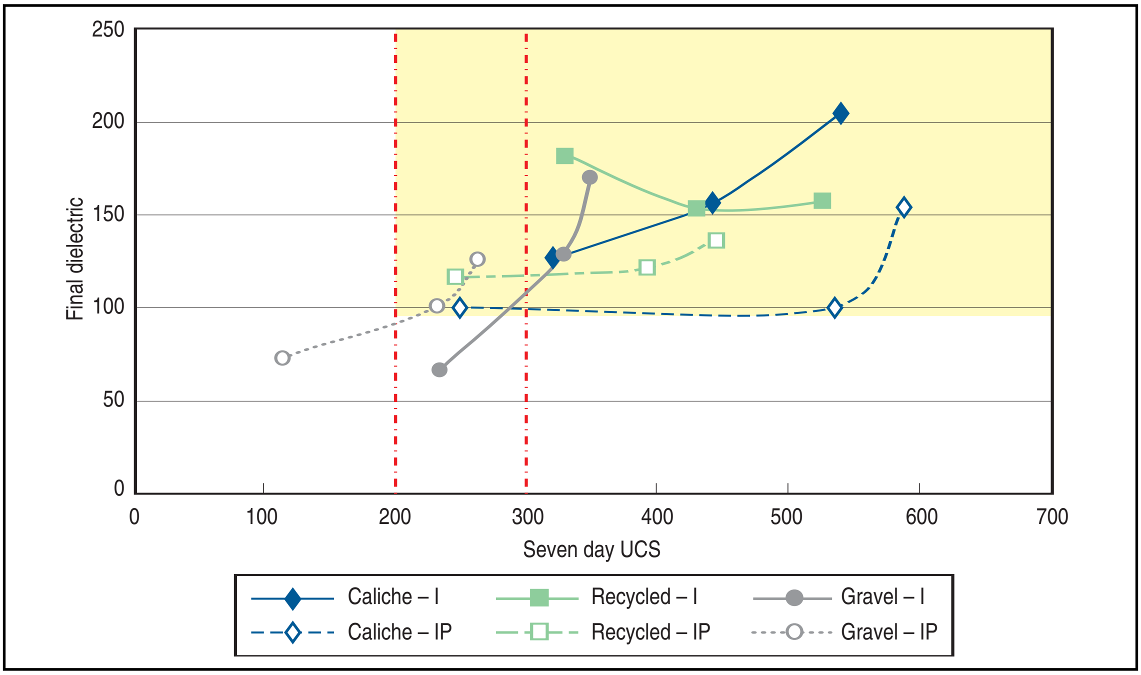


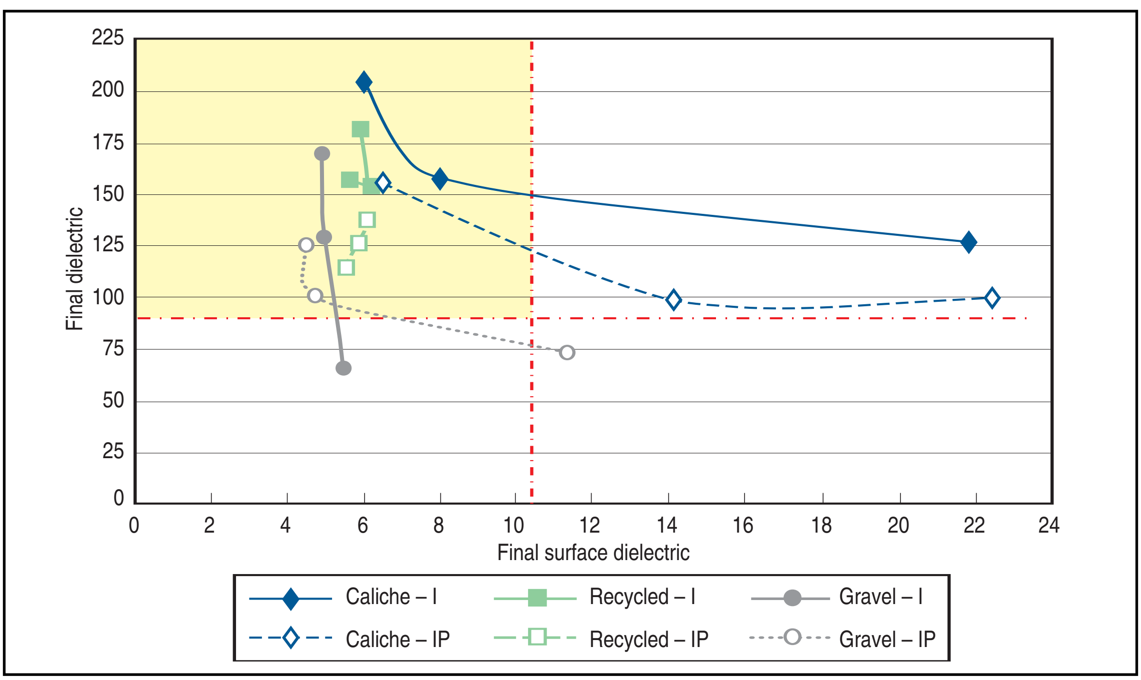
Figure 17. Retained strength results for gravel.

A retained strength criterion can exclude certain samples which are not rejected by other acceptance tests. The previous Figure 14 and Figures 18 and 19 illustrate this point. Figure 14 shows 7-day UCS versus retained strength (condition 1). The shaded quadrant indicates those samples which pass both the retained strength and UCS criteria. Several points fall into the lower right quadrant, which indicates that the samples, although passing the UCS criterion, fail under retained strength. Similarly, Figure 18 plots 7-day UCS versus retained strength (condition 3), in which some specimens that pass the UCS criteria fail in retained strength. Figure 19 shows final dielectric reading versus retained strength (condition 3). Again, two points fall in the lower left quadrant, which indicates that the TST criteria is satisfied but retained strength fails. In further examining the data, there are actually two samples (Yoakum with 1.5% type I and Yoakum with 3% type IP) in which both UCS and TST criteria are satisfied, but retained strength fails.

From a specification requirement perspective, it seems that since conditions 1 and 3 tend to represent a more realistic field condition, and since they produce nearly the same acceptance/rejection decisions, condition 3 should be the recommended choice for specifiers, as fewer samples/tests are required.



Note: Shaded area is acceptance region.
Figure 18. 7-day UCS vs. retained strength after the TST as percentage of 7-day UCS.



Note: Shaded area is acceptance region.
Figure 19. Final surface dielectric vs. retained strength after the TST as percentage of 7-day UCS.

Shrinkage

Shrinkage is important because higher shrinkage tends to beget more and wider shrinkage cracks, which ultimately may reflect through a flexible pavement surface. Previous discussions on shrinkage data have noted that for some of the samples there is a cement content which will produce minimum shrinkage, above and below which shrinkage will be higher (see previous Figure 10). Shrinkage values were wide-ranging, from a high of 933 microstrain to a low (expansion) of -356 microstrain. Even within a single material, small changes in cement content can affect shrinkage dramatically. For instance, the recycled concrete changes from 933 microstrain at 1.5% type I cement to 111 microstrain at 3% type I.

Although shrinkage is clearly highly variable and important to pavement performance, it may be problematic to choose a single shrinkage parameter, such as the 250-microstrain limit recommended by Caltabiano (1992). This is because compressive strength, subgrade friction, and the time-dependence of strength development affect the frequency of shrinkage cracks and their width. For instance, a high shrinkage material with relatively low strength and slow strength development may have more frequent but narrower cracks than a lower shrinkage material with higher strength and faster strength development (a typical situation when comparing a granular material with low, nonplastic fines content with a finer-grained material with plastic fines). With this in mind, George recommended a variable shrinkage limit: 300 microstrain for coarse-grained soils/aggregates and 525 microstrain for fine-grained soils/aggregates. With this said, a higher shrinkage stabilized material which *exceeds* all limits may still be usable and may still be the most economical material. The use of the road (residential versus rural versus mainline) and subsequent construction/curing/surfacing techniques (precracking, intermediate surface treatments, and "upside-down" design) may render that material usable. Therefore it is recommended that shrinkage be an optional criterion. This would allow the specifier to choose whether a particular situation warrants the checking of shrinkage or not.

The previous Figure 12 shows shrinkage versus 7-day UCS, with the shaded area indicating which samples meet both criteria. It can be seen that for each material tested, a mixture can be found that meets both shrinkage and UCS criteria. Each of the materials tested in this research is a "coarse-grained" material; therefore, the 250- or 300-microstrain parameters are appropriate. As the difference between these recommendations is very small, it would probably be acceptable to choose the more liberal of the two (300 microstrain), to exclude fewer samples. However, this would be for coarse-grained materials. A limit of 525 for fine-grained materials can be proposed, but subject to further investigation of finer grained soils/aggregates (which were not included in this study).

Wheel Tracking

The wheel tracking test provides the advantage in determining how a stabilized material holds up under abrasive service conditions. Some soil-cements may have low abrasion resistance, even though other parameters indicate good performance potential. Two aggregate/cement combinations fall into this envelope in the tests: recycled with 1.5% IP and recycled with 3% IP. (However, it should be noted that the 1 mm erosion index was only marginally exceeded: 1.1 mm and 1.3 mm, respectively). Two other materials, although performing poorly in the wheel tracking test (Yoakum with 1.5% I and Yoakum with 1.5% IP), also were excluded because of other tests.

The wheel tracking test suffers from the disadvantage that the test requires a specialized wheel tracking device which is expensive and not commonly available in the United States. Given this fact, and the sense that most of the materials already would be excluded with other tests, the wheel tracking device can be concluded to be principally a research tool, with application only for special studies or unusual soils or aggregates which deserve further investigation.

Testing Method Recommendations

This research study has proposed a series of new and innovative testing procedures to assist in evaluating the impact of varying cement levels on the performance-related engineering properties of aggregate base materials. The concept of considering more than unconfined compressive strength in selecting cement concept is both appealing and practical. Three diverse aggregates were used to study the effects of varying cement levels on strength, shrinkage, and moisture susceptibility (i.e., durability) based on the Tube Suction Test. In addition, criteria for percent of strength retained after exposure to wetting was investigated to ensure a material does not lose significant strength if in a wet condition. Similar trends in the data were seen for all the aggregates tested. Thus, the following criteria are recommended, based on the discussions above, for a new testing protocol that optimizes and balances cement content to achieve adequate strength, durability and economy:

- Unconfined Compressive Strength
  - 7-day UCS ≥ 300 psi
- Moisture Susceptibility
  - Final Dielectric in Tube Suction Test of specimen cured 7 days £ 10
- Retained Strength
  - [(UCS of 7-day cure Tube Suction Test Sample)/(7-day UCS) x 100] ≥ 100%
- Shrinkage (Optional)
  - 20-day beam shrinkage £ 300 in/in microstrain (coarse-grained materials)
  - 20-day beam shrinkage £ 525 in/in microstrain (proposed, fine-grained materials)

Chapter 6

DESCRIPTION OF SOILS USED IN STUDY

The soils used in this study were taken from FM 20 near Seguin, and FM 1343 near Castroville, Texas. The FM 20 soils were part of an upcoming TxDOT reconstruction project. The TxDOT plan was to treat these soils with 6% lime prior to placing the base layer. The concern on this project was permanency of stabilization, as the site was in a river bottom with lots of moisture available. The FM 1343 soil was part of an experimental project constructed by TxDOT to compare in the field the performance of lime and CMS. That field study used 3.5% stabilizer.

CHARACTERISTICS OF THE UNTREATED SOIL

Optimal Molding Moisture

Optimal molding moisture was determined in accordance with Test Method Tex-114-E. Table 25 shows the optimal moisture content (OMC) and corresponding maximum dry densities:

Table 25. OMC and Corresponding Maximum Dry Density for FM 20 and FM 1343

Soil	Optimal Molding Moisture (Percent Dry Basis)	Maximum Dry Density (lb/cf)
FM 20	17.5 percent	110.0
FM 1343	20.0 percent	99.0

Unconfined Compressive Strength at Optimal Moisture

As a baseline, the peak Unconfined Compressive Strength (UCS) was determined for the untreated soils to see what kind of improvement stabilization made to the strength of the soils. Specimens were molded at optimal moisture then immediately strength tested. Researchers used standard pulverization techniques; the criteria were that 100% of the soil passed the 3/4-in. sieve and 60% passed the 1/4-in. sieve. This is standard pulverization recommended by both the Lime Association and TxDOT. Table 26 shows the peak strengths obtained.

Table 26. Untreated UCS for FM 20 and FM 1343

Soil	UCS (psi, at Optimal Moisture)
FM 20	39
FM 1343	37

EFFECT OF LIME AND CEMENT ON ATTERBERG LIMITS

Atterberg Limits

The liquid limit, plastic limit, and plasticity index (PI) were determined for FM 20 and FM 1343 by following Test Procedures TEX-104-E, TEX-105-E, and TEX-106-E. Table 27 gives the Atterberg limits for each soil.

Table 27. Atterberg Limits for FM 20 and FM 1343

Soil	Liquid Limit	Plastic Limit	PI
FM 20	45	17	28
FM 1343	58	21	37

The Atterberg limits also were determined for each soil when stabilized with 3% cement, 6% cement, 9% cement (all type 1), 3% lime, 6% lime, and 3% cement with 3% lime. With cement, dry soil was mixed with cement and the soil wetted until it was just dry of the plastic limit. It was then sealed airtight for 6 hours. After 6 hours, the Atterberg limits were run.

With lime, dry soil was mixed with lime and the soil wetted until it was just dry of the plastic limit. It was then sealed airtight for 24 hours. After 24 hours, the Atterberg limits were run. To test 3% lime with 3% cement, the lime was added as described above. After being sealed 24 hours, the cement was then mixed in and the soil sealed 6 more hours; then the Atterberg limits were run.

Table 28 shows the complete Atterberg limit results. It was found that, with the testing methods described above, cement was just as effective at reducing the Plasticity Index as lime, which Figure 20 illustrates.

Table 28. Atterberg Limits for FM 20 and FM 1343 After Stabilization

FM 20				
Percent Cement	Percent Lime	Liquid Limit	Plastic Limit	PI
0	0	45	17	28
3	0	43	30	13
6	0	43	33	10
9	0	42	32	10
0	3	42	30	12
0	6	41	32	9
3	3	43	33	10
FM 1343				
Percent Cement	Percent Lime	Liquid Limit	Plastic Limit	PI
0	0	58	21	37
3	0	49	32	17
6	0	47	35	12
9	0	48	36	12
0	3	45	28	17
0	6	46	36	10
3	3	49	36	13

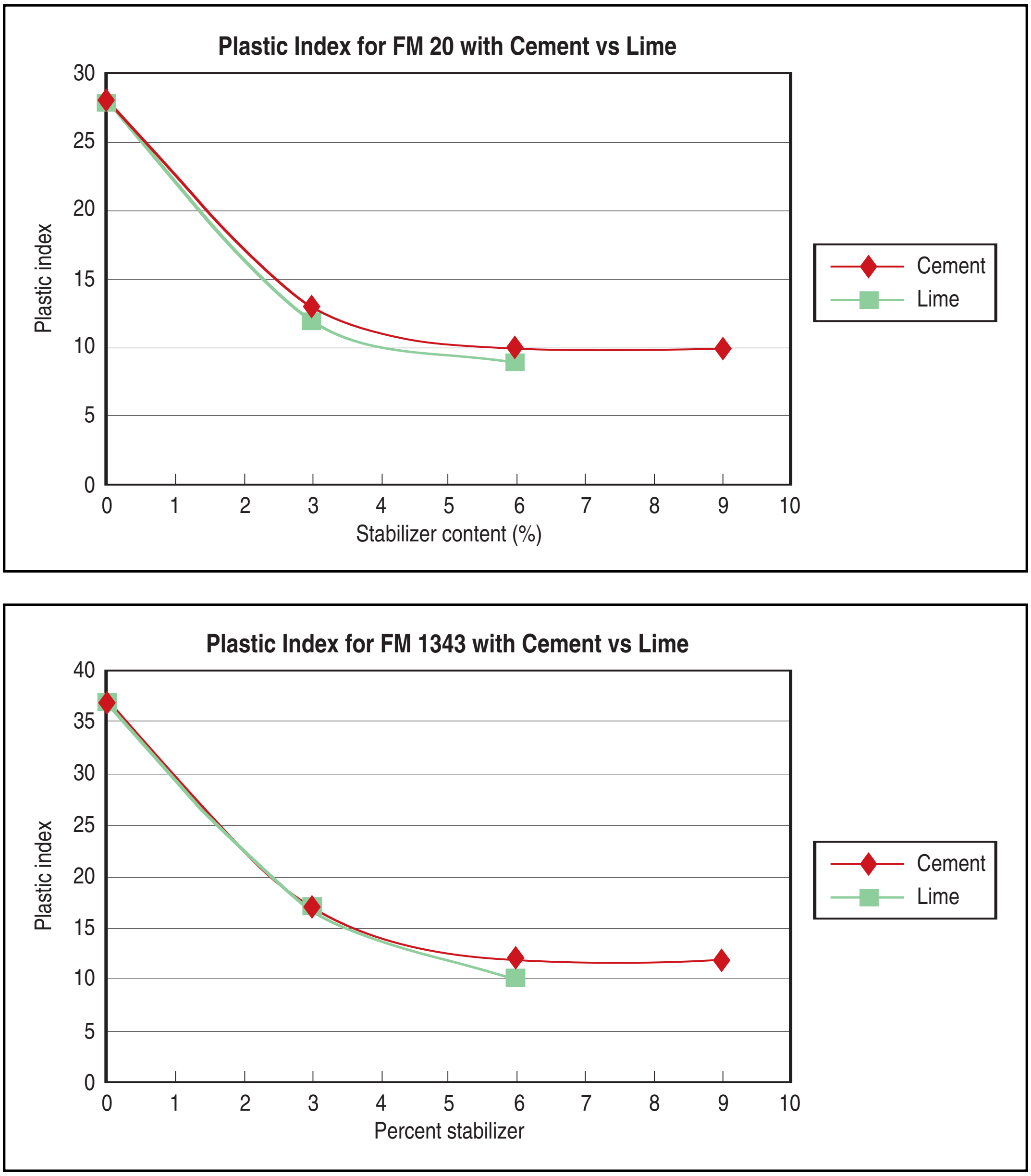


Figure 20. Plastic index of soils after being stabilized.

Chapter 7

LABORATORY PROPERTIES OF SOILS USED IN CEMENT-MODIFIED SOIL STUDY

LEVELS OF PULVERIZATION

Tests were performed on the soils with two different levels of pulverization. The first series of tests was done on soils that were pulverized through a rock crusher. The goal was to obtain a soil where 100% passes the 3/4-in. sieve and 60% passes the 1/4-in. sieve; this is referred to a Level 1 in the text. This is the pulverization level recommended by the Lime Association (Berger, 2000). The second series of tests was performed on soils pulverized to where at least 60% of the material passes the No. 40 sieve (Level 2). This level is much finer than would be anticipated in the field. It was selected to determine if it would substantially improve the performance of primarily the cement-modified soils. The two levels of pulverization are shown in Figure 21, and the gradation curve for the FM 20 soils is shown in Figure 22.

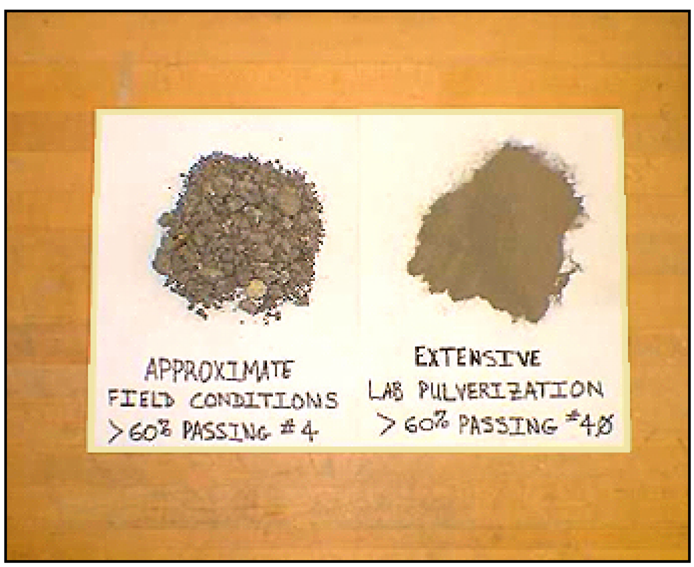


Figure 21. Pulverization levels used in study. (IMG15467)

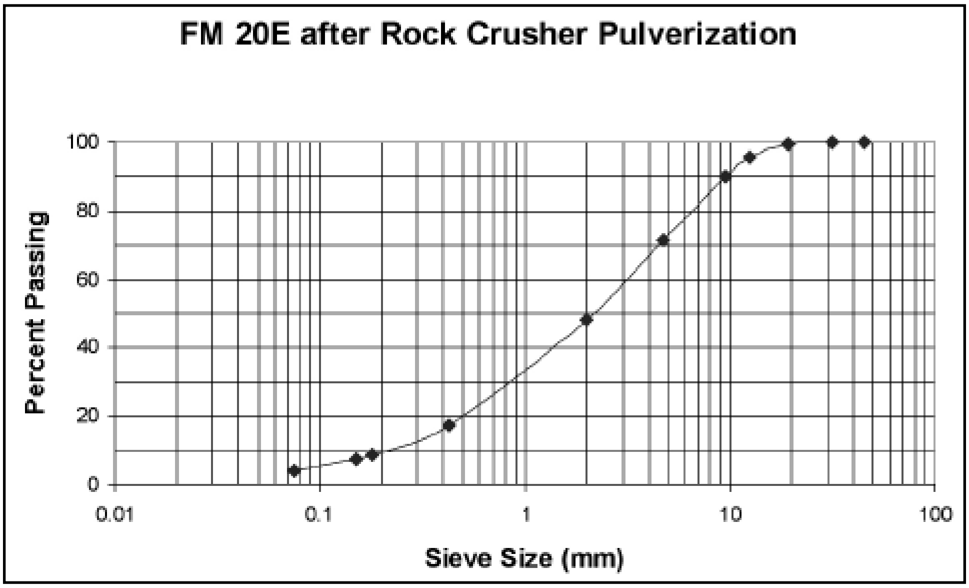


Figure 22. Gradation curve for Level I pulverization.

SAMPLE PREPARATION PROCEDURES

Soil from FM 20 was tested with 6% portland type I cement, 6% lime, and a combination of 3% cement and 3% lime. FM 1343 was tested at stabilization levels of 3% portland type I cement, 6% cement, 3% lime, 6% lime, and a combination of 3% cement and 3% lime.

Soils were mixed in a laboratory mixer as shown in Figure 23. In this study, this is referred to as the dry mixing process, where the dry soil was first mixed with the stabilizer for several minutes, then the required amount of water was slowly added while mixing continued. After all the water was added, the soil was mixed for approximately five more minutes to ensure an even distribution of moisture.

Figure 23. Soil being mixed in laboratory mixer. (IMG15464)

Following mixing, 4-in. diameter by 6-in. tall test specimens were manufactured with a standard proctor (four lifts of 25 blows with a 12 in. drop), as is shown in Figure 24. Samples were wrapped in plastic following production and placed in a 73°F, 100% relative humidity environment for curing.

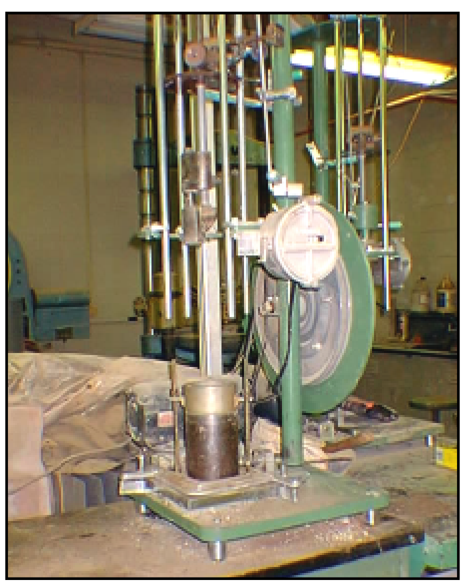


Figure 24. Standard proctor for compaction of 4x6 test specimens. (IMG15477)

TESTING PROCEDURES AND CRITERIA

Samples were then put through the following test procedures:

- 21-day Control: Specimens were cured 21 days in the wet room, then tested for (UCS). After 21 days, this sample was the same age as those put through the TST. The 21-day strength of this sample under ideal curing then could be compared to the sample exposed to moisture in the TST.
- 7-day Cure TST: Specimens cured 7 days in a 100% humidity room and dried 4 days in a 104°F room were put through TST, which lasts 10 days, then tested for UCS. Throughout the TST, the "free moisture" reaching the surface of the sample was monitored with a dielectric probe.
- 7- then 21-day UCS: Specimens cured 7 days in the wet room were tested for UCS just past failure, put back in the wet room for 14 more days, then retested for UCS. The 7-day strength is the standard; the retest after an additional 14 days curing is to evaluate if any substantial rehealing occurs.

The overall performance of the soils between the two different pulverization levels was evaluated to determine if the more finely pulverized soil performed better. The criteria used to evaluate the stabilizer effectiveness were as follows:

- Were the 7-day strengths adequate? The strengths of the treated soil were evaluated by comparison to the strength of the raw soil. A minimum strength gain criteria of 50 psi above the strength of the raw soil was proposed. (Note this is similar to the recommendations of the Lime Association, which recommends 50 psi after 28 days cure, but as will be shown in the test results most samples easily met the criteria after 7 days).
- Was the specimen susceptible to moisture infiltration? The surface dielectric in the TST measured moisture infiltration. Ideally, the treated subgrade materials should have a surface dielectric value of less than 16 at the conclusion of the test. (Note these criteria are tentative at this time. TTI has performed substantial testing on base materials and in that test the acceptable dielectric value is 10. Soils contain higher initial moisture contents and even after dry back at the start of the test dielectric values in excess of 10 are common. The main objective is to create a treated soil that, when subjected to capillary rise, the moisture does not wet the entire sample but stops at some height above the porous stone. It has been noted that when moisture reaches the surface, the dielectric increases above 16).
- Did the specimen sufficiently retain strength after being exposed to moisture in the TST? Strengths after the tube suction test were compared to 7-day curing strengths. The tentative criterion used was that strength after the TST should be at least 80% of the 7-day strength after only curing. (In retrospect, it may be more appropriate to compare the after TST strengths to the 21-day cure strengths. This is because the samples will be the same age at the time of testing; however, in this study, the 21-day strengths were measured on only a few samples).

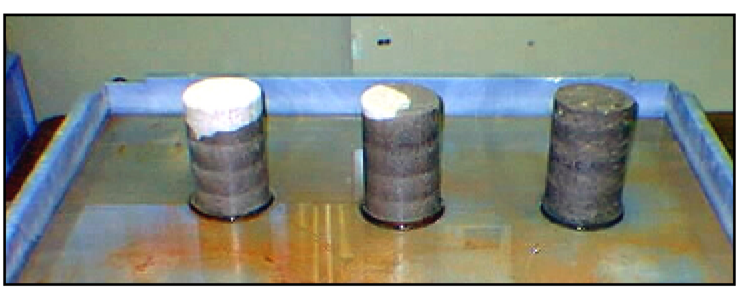
LABORATORY RESULTS FOR FM 20 SOILS

FM 20 Pulverization Level 1 (100% passing 3/4 in.)

Strength and Tube Suction Results. Test results from FM 20 at pulverization level 1 show that for all specimens, the strength values were several times higher than the strength of 39 psi obtained with the untreated soil. All 7-day strength values pass the 50 psi increase criteria; in fact, all samples after the TST also pass this criteria. It was found that a combination of 3 percent cement and 3 percent lime performed the best with respect to maximum strength. However, when subjected to capillary rise all specimens except for the lime stabilized soil experienced a significant loss in strength and had unacceptable final surface dielectric values. The specimen with 6 percent lime had a final surface dielectric value of 13.9 and retained the largest proportion of its 7-day strength after exposure to water and was thus determined to be the best performer. Table 29 shows the results from the tests performed on this soil. A photograph of the specimens during the TST is shown in Figure 25.

Table 29. Peak UCS Strengths (psi) and Beginning and Ending Surface Dielectrics (Where Applicable) for FM 20 Test Samples at Level 1 of Pulverization

Cement Content	Lime Content	21-day Cure	7-day Cure Suction Samples (Percent of 7-day in Parentheses)		7-then 21-day UCS	
					7 day	21 day
6	0	225 psi	106 psi (37%)		289 psi	N/A
0	6	192 psi	134 psi (98%)		137 psi	145 psi
3	3	380 psi	180 psi (50%)		357 psi	218 psi
			Initial E	Final E		
6	0		9.1	22.8		
0	6		9.8	13.9		
3	3		16.5	25.6		



From left to right: 6% lime, 6% cement, 3% cement and 3% lime
Figure 25. FM 20 in Tube Suction Test after 30.5 hours. (IMG15478)

FM 20 Soils at Level 2 Pulverization (60% Passing #40)

Strength and Tube Suction Results. Strengths obtained with FM 20 after pulverization to at least 60% passing the #40 sieve (the actual percent passing No. 40 was 97.8) were substantially higher than with the Level 1 pulverized soil. Surface dielectrics on specimens that underwent TST testing were also much lower. The specimens stabilized with 6% lime and with 3% cement/3% lime performed best with respect to final surface dielectric values.

Figure 26 shows the FM 20 soils at this level of pulverization after 54.5 hours in capillary rise. Beyond this point in time, no significant changes in surface dielectric readings took place.

From left to right: 6% cement, 6% Lime, 3% cement and 3% lime
Figure 26. FM 20 at second level of pulverization in moisture susceptibility testing. (IMG15479)

Although the specimens still absorbed water in capillary rise, as can be seen in Figure 26, their strengths (see Table 6) remained high. Only the cement-stabilized sample lost strength after undergoing the TST test, whereas the specimen stabilized with lime and the specimen stabilized with both cement and lime had higher strengths after undergoing TST testing as compared to their 7-day strength. A 21-day cure UCS test was not done in order to conserve material. Table 30 shows the results from all of the testing on FM 20 at the second pulverization level.

Table 30. Peak UCS Strengths (psi) and Beginning and Ending Surface Dielectrics (Where Applicable) for FM 20 Test Samples at Second Level of Pulverization

Cement Content	Lime Content	7-day Cure Suction Samples (Percent of 7-day strength in Parenthesis)		7-then 21-Day UCS	
				7-day	21-day
6	0	369 psi (64%)		576 psi	289 psi
0	6	334 psi (146%)		228 psi	142 psi
3	3	494 psi (102%)		485 psi	249 psi
		Initial E	Final E		
6	0	12.0	13.6		
0	6	9.6	8.6		
3	3	11.4	9.3		

Improvements over First Level of Pulverization. Of particular interest is to examine the results from the first and second levels of pulverization. At the second level of pulverization, strengths were significantly higher and the specimens also performed better in moisture susceptibility as indicated by their final surface dielectric values. Table 31 shows the final surface dielectrics at both levels of pulverization and the percent increase in strength at the second level of pulverization (where the baseline strengths are the UCS values from the first level of pulverization). Clearly both stabilizers benefitted from the finer gradation of the soils being treated.

Table 31. Improvements in Performance from First Level of Pulverization to Second Level of Pulverization for FM 20.

Percent Cement	Percent Lime	Final ε - 1st Level of Pulverization	Final ε - 2nd Level of Pulverization	UCS Improvement after 7-day Cure	UCS Improvement after TST
6	0	22.8	13.6	99%	248%
0	6	13.9	8.6	66%	149%
3	3	25.6	9.3	36%	174%

LABORATORY RESULTS FOR FM 1343 SOILS

FM 1343 Soils Pulverization Level 1

Strength and Tube Suction Results. As with FM 20, a combination of 3% cement and 3% lime provided the best strength results when cured in a 100% humidity environment then strength tested after 7 days. Similarly, when subjected to capillary rise the samples stabilized with lime performed the best. The specimen with 3% cement and 3% lime performed satisfactorily in the TST with a final surface dielectric of 9.2; however, the strength of the specimen was substantially weakened by the introduction of water. The specimen with 6% lime retained most of its strength after being subjected to capillary rise and had a final surface dielectric value of 7.8, so it was judged to be the best performing. This was the only treatment which met all criteria. Table 32 presents the results from this testing phase for FM 1343.

Table 32. Peak UCS Strengths (psi) and Beginning and Ending Surface Dielectrics (Where Applicable) for FM 1343 Test Samples at First Level of Pulverization

Cement Content	Lime Content	7-day Cure Suction Samples (Percent of 7-day strengths in Parentheses)		7-then 21-day UCS	
				7-day	21-day
3	0	25 psi (14%)		175 psi	112 psi
6	0	58 psi (23%)		254 psi	191 psi
0	3	63 psi (57%)		110 psi	76 psi
0	6	102 psi (82%)		124 psi	81 psi
3	3	97 psi (37%)		265 psi	161 psi
		Initial E	Final E		
3	0	10.3	28.4		
6	0	9.1	24.0		
0	3	9.2	9.4		
0	6	8.2	7.8		
3	3	8.2	9.2		

FM 1343 Pulverization Level 2 (60% Passing #40)

Strength and Tube Suction Results. The results from the second level of pulverization were not as anticipated. The best performing stabilization level with FM 1343 was now the 6% cement. All the other specimens failed the TST and significantly declined in strength after undergoing moisture susceptibility testing. The specimen with 3% cement and the sample with 3%lime completely fell apart when trying to move them and thus could not be strength tested. Table 33 has the UCS and dielectric results for FM 1343 at the second level of pulverization. As with FM 20, no 21-day cure UCS tests were done in order to conserve material for slurry testing.

Table 33. Peak UCS Strengths (psi) and Beginning and Ending Surface Dielectrics (Where Applicable) for FM 1343 Test Samples at Second Level of Pulverization

Cement Content	Lime Content	7-day Cure Suction Samples (Percent of 7-day Strengths in Parentheses)		7-then 21-day UCS	
				7-day	21-day
3	0	N/A – Sample fell apart		310 psi	104 psi
6	0	351 psi (101%)		348 psi	179 psi
0	3	N/A – Sample fell apart		138 psi	59 psi
0	6	57 psi (34%)		167 psi	113 psi
3	3	117 psi (41%)		287 psi	118 psi
		Initial E	Final E		
3	0	10.6	33.1		
6	0	11.4	10.0		
0	3	9.4	34.9		
0	6	9.1	32.5		
3	3	8.8	26.9		

The specimens after the 10-day TST are shown in Figure 27. It can be seen that all but the 6 percent cement and 3 percent cement with 3 percent lime specimens became wet throughout the test specimen. In addition, a corner of the top of the specimen with 6 percent lime had already fallen off from the light pressure put on the specimen when taking surface dielectric measurements.

From left to right: 3% cement, 6% cement, 3% lime, 6% lime, 3% cement and 3% lime
Figure 27. FM 1343 at second level of pulverization after Tube Suction Test. (IMG15482)

Improvements Over First Level of Pulverization

Pulverization of the soil to a much finer level had substantial improvements in the seven-day strength for FM 1343. However, all but the specimen with 6 percent cement performed unacceptably in the TST. This was a strange occurrence, as the lime treated specimens at the first level of pulverization performed well in the TST but failed that same test at the second level of pulverization. Another peculiar finding was that at the second level of pulverization the specimen with 3 percent cement/3 percent lime failed the TST, but at the first level of pulverization it also passed this test. However, the second level of pulverization still led to an increase in strength after the TST for this specimen. The changes in results from the first level of pulverization to the second level of pulverization are shown in Table 34, below.

Table 34. Changes in Performance from First Level of Pulverization to Second Level of Pulverization for FM 1343

Percent Cement	Percent Lime	Final ε - 1st Level of Pulverization	Final ε - 2nd Level of Pulverization	UCS Improvement after 7-day Cure	UCS Change after TST
3	0	28.4	33.1	77 percent	*
6	0	24.0	10.0	37 percent	505%
0	3	9.4	34.9	25 percent	*
0	6	7.8	32.5	35 percent	-44%
3	3	9.2	26.9	8 percent	21%

Specimens with 3% cement and 3% lime at second level of pulverization fell apart before strength testing.

Being that at the second pulverization level all specimens showed substantial strength gains when cured in the 100% Relative Humidity (RH) environment, it is clear that stabilization was progressing. However, when subjected to moisture, all but the sample with 6% cement performed poorly. No complete explanation is available to explain these unexpected results. However, the following two factors are known to have contributed. Firstly, the FM 1343 sample contained substantial rock, which was pulverized in these tests since this would lead to more sand size particles in the soil and thus a smaller proportion of clays for the lime to react with. The second cause is the variability of results with this dry-mixing procedure. Any unreacted lime or cement would have a high affinity for water, which could account for the poor performance of the samples in the TST. This occurrence was evident by the fact that specimens at the second pulverization level with 3% lime and 3% lime/3% cement in them, even with ample water present, contained substantial unreacted lime after the conclusion of the TST, as can be seen in Figure 28.

3% Lime

3% Cement/3% Lime

Figure 28. Unreacted lime in FM 1343 specimens at second pulverization level After the Tube Suction Test. (IMG75484)

Regarding the significant improvement in the performance of the specimen with 6% cement at the second pulverization level, the presence of the rock is again a possible contributing factor. By the pulverization of the rock particles, the PI would be lower and the cement stabilization should perform better. The PI of the FM 1343 soil after pulverization was 34, as compared to 37 before pulverization. In addition, finer pulverization obviously provided more surface area for the stabilizer to react with, and thus the CMS performs better, as was shown with FM 20.

SUMMARY

From the testing involved in this study, it is evident that finer pulverization of the FM 20 soil to better laboratory performance of CMS. When pulverized to finer levels, the strengths of the cement-stabilized specimens are higher; they are less susceptible to moisture and retain more strength after being subjected to water. With FM 20, the finer pulverization led to significant increases in performance in both cement- and lime-stabilized samples. The most drastic improvement was in soil strength after the TST, where the UCS values were 2.5 to 3.5 times higher than UCS values at the original pulverization level.

With FM 1343, finer pulverization led to a significant improvement in the strength values and moisture resistance of cement-stabilized materials. However, the lime stabilization that led to the only acceptable performance of the original FM 1343 soil performed poorly at the finer pulverization level, at least partially because the rock in the soil had been crushed. This led to more sand-sized particles in the material and a lower PI, so it is logical that results from cement stabilization would improve and lime stabilization results would not be as good. However, the PI change was rather small, so there are probably some mineralogical reasons behind the drastic shift in results.

From the FM 1343 testing, it is evident that one must be cautious and not immediately conclude that finer pulverization is better in every circumstance. The results presented indicate that, with a pure soil, finer pulverization is better for cement or lime stabilization since there will be more total surface area of soil particles with which the stabilizer can react. However, if the soil has a substantial amount of rock present, finer pulverization changes the engineering properties of the soil and can actually hurt some aspects of performance when lime stabilization is used. The larger amount of sand particles present when rock is crushed into the soil lowers the PI and reduces the surface areas of clays as a proportion of the total surface area, so the type and amount of stabilizer added may need to be reevaluated. The mineralogy of the rock also could have a significant impact on how the stabilizer performs with fine pulverization. However, it is important to note that lime stabilization performed best on both of the high PI soils at the pulverization level (Level 1), which more closely represented field conditions.

One major concern with the data presented in this chapter is with the adequacy of the dry-mixing process. As shown in Figure 28, substantial amounts of unreacted stabilizer remained in several of the samples. These clearly will have a big impact on the affinity of the material to available moisture. The next chapter gives a comparison of the different mixing procedures on the laboratory performance.

Chapter 8

EFFECT OF SAMPLE PREPARATION PROCEDURE ON LABORATORY PROPERTIES IN CEMENT-MODIFIED SOIL STUDY

INTRODUCTION

The application of a stabilizer by slurry methods has many potential advantages. Lime is frequently applied by slurry to eliminate dusting and improve stabilizer distribution (Little, 1995). The purpose of this analysis was to investigate how the laboratory performance of a high PI subgrade soil is affected by slurry application of cement or lime as compared to dry application. It is believed that better stabilization takes place when the stabilizer is applied in slurry form.

The soil from FM 20 was used for this testing and was pulverized to approximate field conditions (Level 1). This soil has a PI of 28, a plastic limit of 17, and optimal molding moisture of 17.5%. Stabilization levels of 6% cement, 6% lime, and 3% cement with 3% lime were used. The following three mixing methods were used in the evaluation:

- Dry application of the stabilizer to the dry soil, then add molding moisture to reach OMC.
- Dry application of the stabilizer to the soil at 10% moisture, then add remaining moisture to bring water content to optimum.
- Slurry application of the stabilizer to the soil at 10% moisture content, then add remaining moisture to bring water to optimum.

After each of these mixing methods, samples were compacted and cured as described in Appendix H. Then the following tests were performed:

- Unconfined compressive strength (UCS) after 21 days curing
- TST after 7 days curing, followed by UCS determination
- UCS after 7 days curing

A complete description of all the testing procedures is in Appendix H entitled, "Sample Preparation and Testing Methods."

RESULTS OF TREATED MATERIAL

Several duplicate samples also were made, especially with cement stabilization, to verify results. Table 35 contains a summary of all the data. In this table, samples are sorted first by cement content (from highest to lowest), then by the testing procedure, then by peak unconfined compressive strength (from highest to lowest). The end result is that for the same stabilizer content and testing procedure, the samples are ranked from best to worst performing.

ANALYSIS OF RESULTS

The results from testing indicated, especially with cement, that the slurry application leads to the best laboratory performance. The specimens in which the stabilizer was applied dry to dry soil were the worst performing. When stabilized by cement slurry, FM 20 soil had exceptionally high strengths, even after being subjected to capillary rise in the TST, and retained a large proportion of its 7-day strength after being put through the TST. When mixed in dry to a moist soil, cement stabilization still performed well with respect to strength, resistance to moisture, and strength retention. However, when added to a dry soil, cement stabilization resulted in poor strength values, high moisture susceptibility, and low strength retention after being subjected to capillary rise. In terms of the dielectric criteria presented in Chapter 3, both the cement slurry and lime/cement slurry passed the test, whereas when the cement was added to the dry soil, the samples failed the test. The implication here is that in slurry form, a better distribution and hydration of cement is achieved in the soil matrix and no significant unreacted cement is present in the treated soil. From these test results it was found that if cement is added to the soil in slurry form, its laboratory properties will be similar to if not better than lime.

With specimens containing lime, the application method of the stabilizer had a small impact on 7- and 21-day strengths. These specimens did perform better in the TST when the stabilizer was added to a moist soil or by slurry. As with the cement, these specimens also performed the best when stabilized by slurry. One encouraging feature from Table 11 is that when duplicate samples were run, the results from both UCS and TST were reasonable and repeatable.

The next few sections will detail the results from each testing method. For purposes of generating graphs, the results were averaged in instances where duplicate specimens were made.

Table 35. Data collected for Evaluating Soil Performance

Percent Cement	Percent Lime	Mixing Method	Procedure	Final ε	Peak UCS (psi)
6	0	C	21-day UCS	N/A	592
6	0	B	21-day UCS	N/A	523
6	0	B	21-day UCS	N/A	510
6	0	A	21-day UCS	N/A	242
6	0	A	21-day UCS	N/A	225
6	0	C	7-day UCS	N/A	467
6	0	B	7-day UCS	N/A	366
6	0	A	7-day UCS	N/A	289
6	0	C	TST	12.8	475
6	0	C	TST	12.6	467
6	0	B	TST	12.7	381
6	0	A	TST	22.8	106
3	3	C	21-day UCS	N/A	424
3	3	C	21-day UCS	N/A	421
3	3	A	21-day UCS	N/A	380
3	3	B	21-day UCS	N/A	379
3	3	A	7-day UCS	N/A	357
3	3	C	7-day UCS	N/A	337
3	3	C	TST	12.4	483
3	3	B	TST	12.2	444
3	3	A	TST	25.6	180
0	6	B	21-day UCS	N/A	193
0	6	A	21-day UCS	N/A	192
0	6	C	21-day UCS	N/A	190
0	6	C	7-day UCS	N/A	148
0	6	A	7-day UCS	N/A	137
0	6	C	TST	9.3	220
0	6	C	TST	12.1	187
0	6	B	TST	12.8	179
0	6	A	TST	13.9	134

Mixing Methods:
A: Dry stabilizer applied to dry soil
B: Dry stabilizer applied to soil at 10% Moisture Content
C: Stabilizer applied by slurry to soil at 10% M.C.

Unconfined Compressive Strength After 21 Days Curing

The results from the 21-day cure specimens are a good representation of the general nature of the performance of the soils under different stabilization types and application procedures. Figure 29 illustrates that there is a substantial improvement in performance between the specimen stabilized by 6% cement applied dry to the dry soil and 6%cement applied dry to the moist soil. There is then a noticeable, but much less drastic, improvement in performance between stabilization with 6% cement applied dry to the moist soil and 6% cement applied by slurry to the moist soil.

For the stabilized specimens containing 6% lime, the results are essentially the same across all types of preparation methods. The results indicate that the lime-stabilized specimens will get just as strong regardless of the method of application or original moisture content of the soil when simply cured before testing. The specimens with 3% cement/3% lime also showed virtually identical results across the preparation methods, but the slurry sample had a slightly higher strength which may or may not be statistically significant.

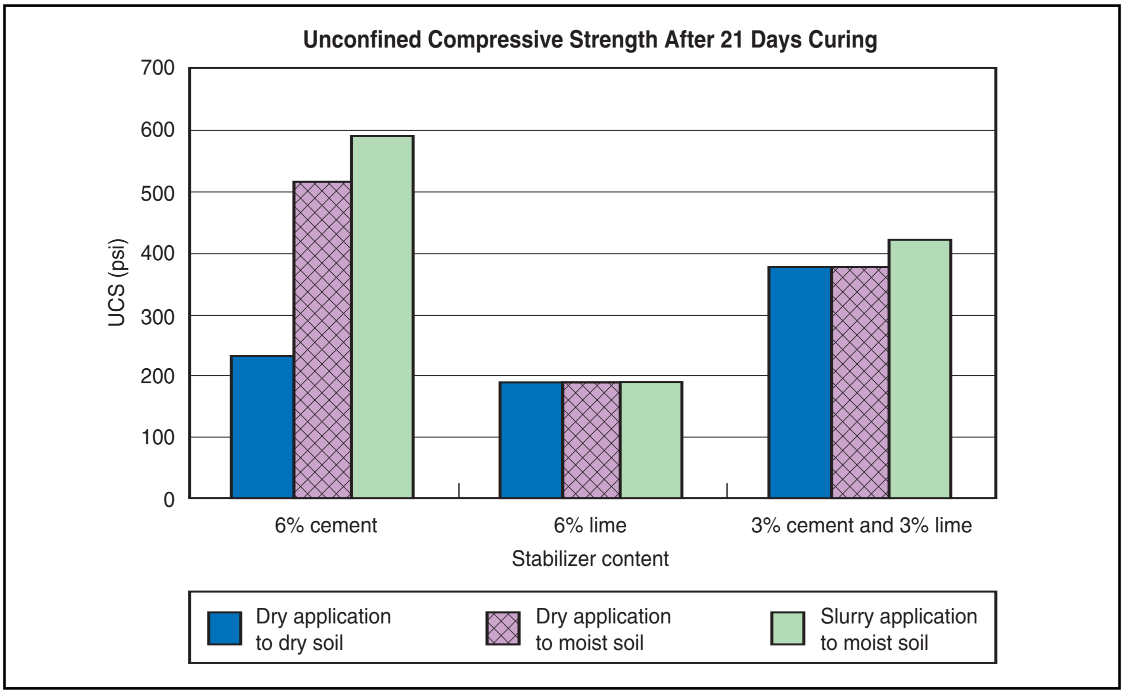
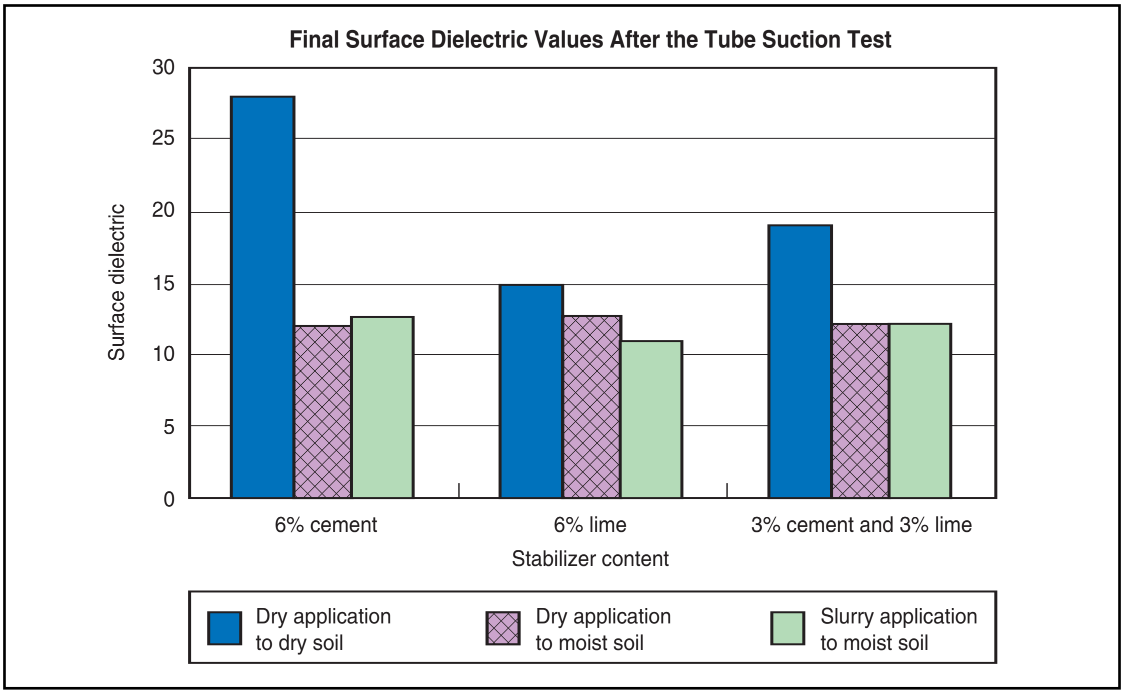


Figure 29. UCS for FM 20 soil after 21 days curing time.

Tube Suction Test After 7 Days Curing, Followed by UCS Determination

These specimens underwent the TST, then were tested for strength at the conclusion of the test. It should be mentioned that all specimens started the test with an initial surface dielectric of approximately 11.0 to 12.0. The tentative failure criterion in the test is a value of 16, which would indicate that moisture has “wicked” through the sample. A soil was judged to have performed acceptably in the test if its surface dielectric value did not rise by more than a few points at the end of the 10-day test. In practice, this means that water must not make it to within approximately 1/2 in. from the surface of the sample in order for the sample to pass the test.

The results from the TST are in Figure 30. When applied dry to a dry soil, cement stabilization did not protect against moisture infiltration, and substantial strength was lost. When applied dry to a moist soil or applied by slurry to a moist soil, the cement-stabilized specimens performed well in the test. With 6% lime applied dry to the dry soil, performance was marginal. With the other two mixing procedures, specimens stabilized by 6% lime passed the test. When stabilized with 3% cement/3% lime, the soil performed acceptably as long as the soil was moist when the stabilizer was applied.



Note: Initial surface e was approximately 11.0 to 12.0 for all samples
Figure 30. Tube Suction Test results for FM 20 soil.

As a visual illustration of the performance of the soils in the TST, Figure 31 shows the cement-stabilized specimens at the completion of the test. It can easily be seen that the specimen stabilized with cement applied dry to the dry soil became wet throughout the sample and the specimen swelled up and cracked. This method of application obviously resulted in poor stabilization. The other two preparation methods with cement stabilization performed acceptably in the test, but the specimen stabilized by slurry application clearly performed the best since it has the least amount of moisture in it.

From left to right: dry application to dry soil, dry application to moist soil, and slurry application to moist soil
Figure 31. Cement-stabilized specimens after the Tube Suction Test. (IMG15485)

The lime stabilized specimens after the TST are in Figure 32. The slurry application of lime also resulted in the least amount of moisture rising into the specimen, and the specimen in which lime was applied dry to dry soil had moisture on part of the top of the specimen. It also was visually noticeable that this sample swelled. As with cement, slurry application of lime led to the best performance in this test.

From left to right: dry application to dry soil, dry application to moist soil, and slurry application to moist soil
Figure 32. Lime-stabilized specimens after the Tube Suction Test. (IMG15486)

Figure 34 shows the specimens with 3% cement/3% lime at the completion of the TST. As with the other stabilizer contents, the poorest performer was when stabilizer was applied dry to dry soil. The specimen where stabilizer was applied to a dry soil also swelled up. Also consistent with all other results is the fact that the best performer was the specimen stabilized by slurry. However, the difference in performance between the two samples where dry stabilizer was applied to a moist soil and the slurry application was quite small.

From left to right: dry application to dry soil, dry application to moist soil, and slurry application to moist soi
Figure 33. 3% cement/3% lime-stabilized specimens after the Tube Suction Test. (IMG15487)

In addition to the ending surface dielectric of the specimens at the completion of the TST, substantial importance is put on the strength of the specimen at the completion of this procedure. A strength value greater than or equal to 80% of the strength after 7 days curing is the target in order for the specimen to be judged as having adequately retained strength after being subjected to capillary rise.

Figure 34 shows the strength values of the specimens at the completion of the TST. This figure illustrates the consistent improvement in performance of the stabilized specimens going across the different stabilizer application procedures. The changes in strength across the mixing procedures correspond to the better resistance to moisture infiltration in the TST. Within each stabilizer content, the specimens that took up less water in the TST always had the higher strengths. Samples containing cement had the most dramatic changes in performance between the mixing methods, whereas lime showed a slight improvement in performance each time the application procedure was changed.

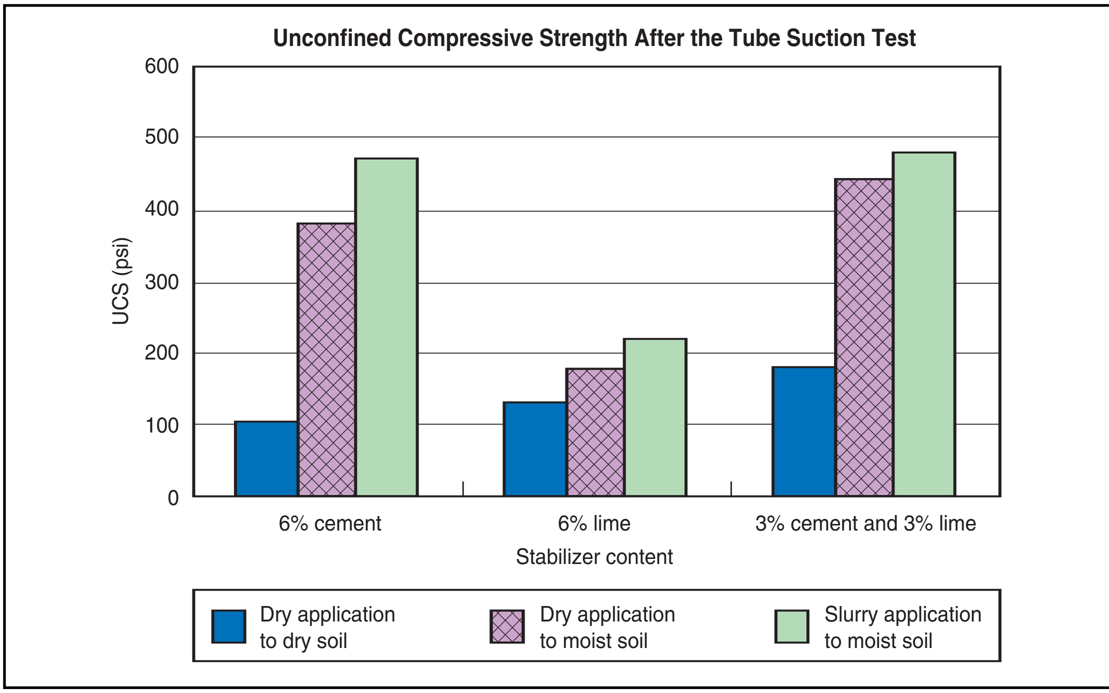


Figure 34. UCS for FM 20 after the Tube Suction Test.

This figure reiterates the fact that, when using cement in soil stabilization, it is important that the soil has some moisture in it to allow for soil breakdown. In the samples containing cement, there is a very large improvement between the results from where stabilizer was applied to dry soil and where stabilizer was applied to moist soil, but the difference in performance is much smaller between dry application to moist soil and slurry application to moist soil.

Figure 35 shows the strengths of the samples after the TST as a percentage of their 21-day curing strength. Specimens containing lime performed best from this evaluation perspective. An interesting finding was that since specimens containing lime had virtually identical curing-only strengths, regardless of the preparation method, the better resistance to moisture infiltration resulting from the application of stabilizers to the moist soil led to some of the specimens that were subjected to capillary rise having higher strengths than their 21-day UCS counterparts. For these cases, the UCS after the TST as a percentage of the 21-day UCS is greater than 100%.

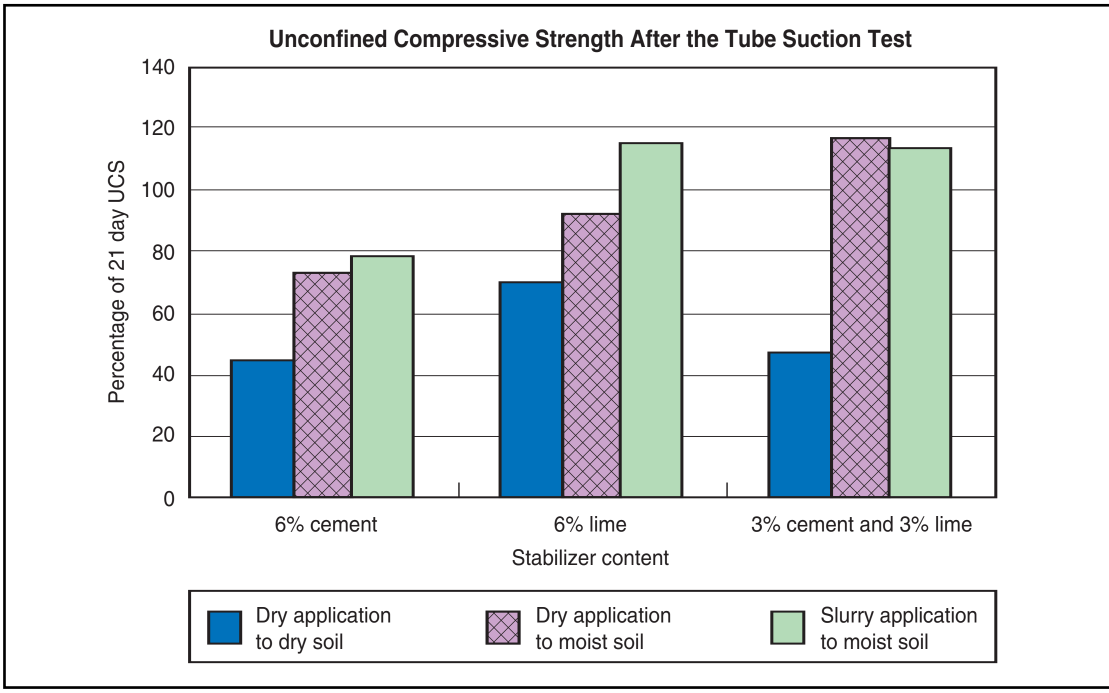


Figure 35. UCS after the Tube Suction Test as a percentage of their 21-day curing strength.

Unconfined Compressive Strengths after 7-Days Curing

As with the 21-day cured specimens, the performance of the soil stabilized with 6% cement applied by slurry was clearly much improved over its counterparts stabilized by dry applications. Although the 7-day curing strength for when the stabilizer was applied dry to the moist soil was only performed with 6% cement, the results indicate that the performance of the soil was not significantly affected, regardless of the preparation methods, with 6 percent lime or 3% cement/3% lime. This is consistent with the results from the 21-day cured specimens in which the performance of the specimens with 6% lime were almost identical across all three mixing procedures, as were the results from 3% cement/3% lime. These results give further validation that cement stabilization of soils works better when the cement is applied by slurry. The results from the 7-day UCS can be seen in Figure 36.

The moisture susceptibility criterion proposed in Chapter 3 was that the UCS at the end of the TST be at least 80% of the 7-day strength. The results are shown below in Figure 37. The benefits of the slurry application are clear. With the dry application, both the 6% cement and 3% lime/3% cement failed the strength criteria. However, with the slurry, all stabilizers met this retained strength criteria.

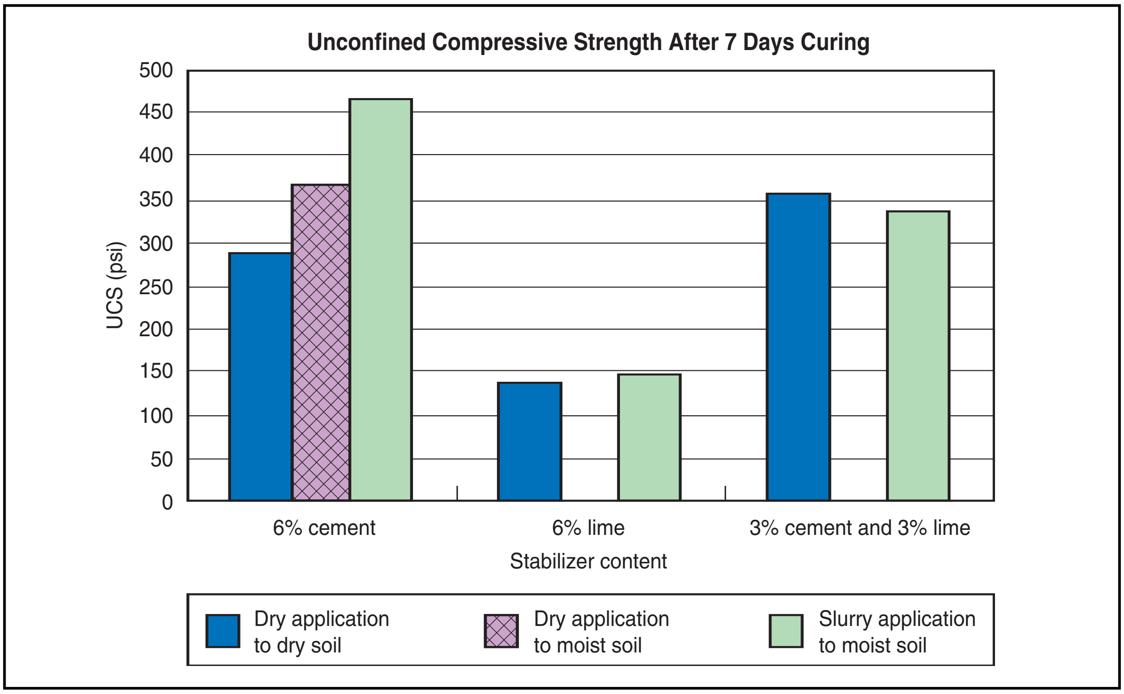


Figure 36. Results from 7-day strength testing.

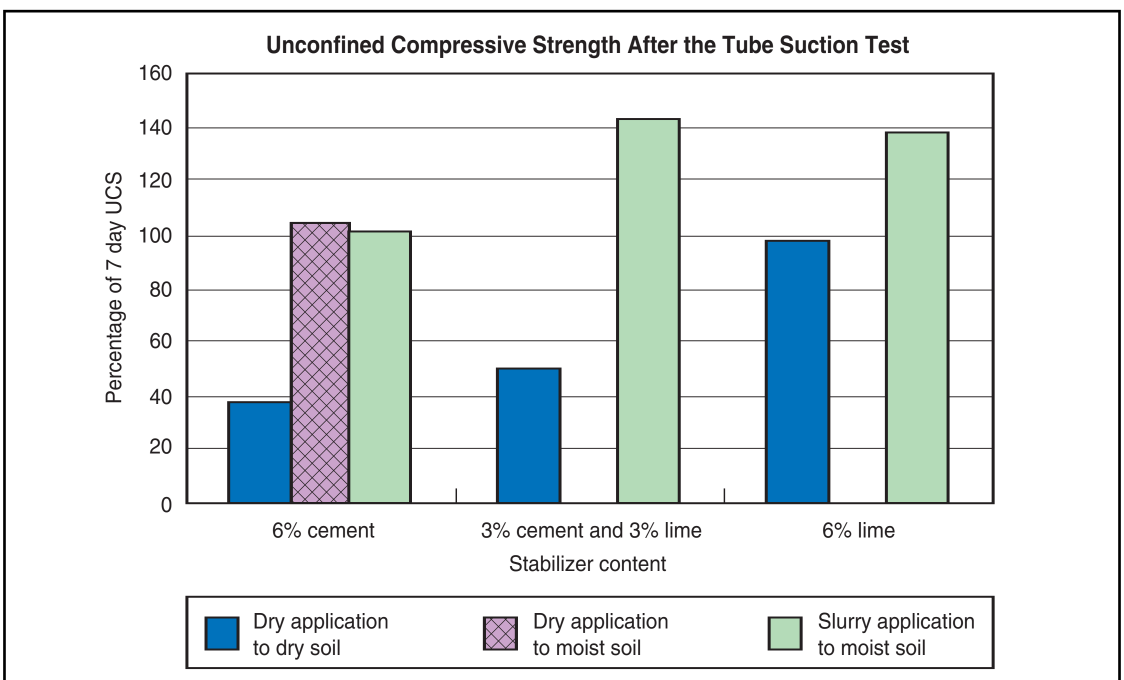


Figure 37. Moisture susceptibility results comparing the strength After capillary rise to the 7-day strength.

SUMMARY AND FUTURE WORK

From the results of this study, it was determined that slurry application of stabilizers to soils results in the best laboratory properties. Cement stabilization was found to be acceptable when applied dry to a moist soil or applied by slurry to a moist soil. Lime stabilization or a combination of cement/lime was found to perform reasonably well regardless of the application method. The stabilized soil that had at least some lime in it also had better strength retention after being subjected to capillary rise, but lower strength values, than the soil stabilized with only cement.

Applying three different stabilization levels to a moderately high PI soil, and using three different mixing procedures, led to four key findings:

- Regardless of stabilizer content, application by slurry led to the best overall performance of the soil with regard to the level of moisture susceptibility and strength retention after being exposed to capillary rise. It was found that stabilization results were worst when the stabilizer was applied dry to a dry soil. Overall results were improved when the stabilizer was applied dry to the soil already containing 10% moisture. The best performance of stabilized soil was when the stabilizer was applied by slurry to the soil already containing 10% moisture.
- With samples stabilized with only cement, slurry application of cement provided the best performance with respect to curing-only strengths, level of moisture susceptibility, and strength retention after being exposed to capillary rise. The performance when cement was applied dry to the moist soil was between that obtained by slurry application and results from dry application of cement to the dry soil.
- With samples containing lime, curing-only strengths were not affected significantly by the different application procedures. However, the level of susceptibility to moisture and strength retention after being exposed to capillary rise was improved when these specimens were prepared with stabilizer being mixed to the soil at 10% moisture, and the best performance was when preparing the stabilized soil with a slurry.
- From these results it appears that cement is a viable alternative for the stabilization of moderately high PI soils. This was evidenced by the fact that, when applied to a moist soil by either dry application or slurry application, the FM 20 soil (PI of 28) had good strength characteristics, good resistance to moisture infiltration, and reasonable strength retention after being exposed to capillary rise.

It is suggested that more research be carried out to investigate why the slurry application of cement is more effective at stabilization. One suggested area of study is to investigate if the degree of hydration of the cement is different between the slurry-stabilized specimens and the specimens prepared by dry application. Two methods have been identified for doing this, one being by measuring chemically bound water and another being through image analysis with a scanning electron microscope (Mouret, 1997). Another topic of investigation should include the distribution of cement throughout the specimen. If slurry stabilization with cement leads to better distribution of cement, then it is logical that the stabilization would be more effective. Consideration also should be given to in-depth research into the reaction mechanisms that take place between the stabilizers and the clays in the soil with the different application procedures, as understanding in this area would greatly aid in determining the reason slurry application leads to the best stabilization.

Chapter 9

CONCLUSIONS AND RECOMMENDATIONS FOR CEMENT-MODIFED SOILS

In addition to the results presented in Chapters 8 and 9, several complementary studies were undertaken to evaluate construction issues related to the use of cement slurries with soils. These are documented in the Appendices to this report. In Appendix F the effect of extended slurry mixing time on laboratory properties was evaluated. In Appendix G a study also was undertaken to determine the settling time with no agitation.

The main conclusions from this study are as follows:

- Cement was shown to reduce the plasticity index of the two soils used in the study. The initial PI of 28 and 37 were reduced to 10 and 12 with the use of 6% cement. This was similar to lime treatment where the final PI's were 9 and 10, respectively.
- The level of pulverization has a large impact on the strength achieved with cement stabilization. Clearly, the finer the pulverization, the higher the ultimate strength.
- The factor with the biggest influence on final soil properties was the method of mixing the stabilizer to the soil. The samples made using the cement slurries had better properties than those made by mixing the raw cement to the dry or moist soil. It was found that even with controlled laboratory mixing at optimum moisture content, the dry mixing techniques left substantial amounts of unreacted stabilizer particles in the soil mass and these had a major impact on the moisture susceptibility results.
- When applied in slurry form, the 3% lime/3% cement and 6% cement produced higher 7- and 28-day strengths than the 6% lime samples. All slurry samples also had adequate moisture susceptibility as measured by the Tube Suction Test and by the retained strength test.
- Extended slurry mixing times were found to not have a major impact on the final strengths of the cement-stabilized soils. High strengths were obtained on samples where the slurry was mixed continuously for 4 hours.
- Settling time and flow studies found that the slurry remained workable for 30 minutes once continuous agitation was stopped. After 30 minutes some settlement in the slurry was observed; a layer of water formed on top of the samples.

In summary, the methodology of selecting stabilizer type and content based on more than simply 7-day unconfined compressive strength appears beneficial. As a minimum it is recommended that a moisture susceptibility test, such as the one developed in this study, be included in the selection criteria. To be a general procedure to be used in all areas it also will be necessary to measure the swell of the treated samples. This is a localized concern where the natural soil contains high levels of natural gypsum. The swell measurement can be included as an extra measurement in the TST where the volume change during dry back and wetting is being monitored.

More research is needed to fully understand the positive reactions that occurred with the slurry application. The chemical reactions that occur between cement paste and natural materials are very complex. The variability of the soil and the relatively low levels of stabilizer mean that it is often difficult to quantify the reaction products with standard chemical analysis techniques such as scanning electron microscopy and X-ray diffraction. As part of this study, a limited amount of work was conducted with stabilizing well-characterized homogeneous clay particles with cement and the results were promising. What needs to be done now is to compare dry versus slurry applications with these experimental materials. With this controlled setup it should be possible to identify the reaction mechanisms and conclusively identify the differences between the dry versus slurry application.

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APPENDIX A
MINERALOGY OF THE THREE BASE MATERIALS

MINERALOGY OF BASES

Minerals present in various size fractions (sand, silt, coarse clay, and fine clay) were determined by techniques outlined in Jackson (1969). The -40 sieve fraction of three base course materials commonly used in this study were examined for mineralogical constituents to try and correlate performance to composition, i.e., chemistry.

The first sample examined was a caliche from the Pharr District. Initially we started with 101.0 g of sample. After chemical pretreatment and size fractionation, there were 65.8 g (65.1%) of sample recovered. The bulk of the sample lost was in the form of calcium carbonate with a minor amount being lost in the form of organic matter and due to inefficient mechanical separation. This sample is composed of 66.3% sand, 22.9% silt, 4.4% coarse clay, and 6.4% fine clay.

The sand size fraction is composed predominantly of quartz with minor feldspar. The silt is quartz and feldspar as well. The coarse clay is composed of quartz, smectite, illite, and kaolinite. The fine clay is predominantly smectite with lesser amounts of illite and kaolinite.

Secondly, recycled concrete from Houston was examined. The most obvious component was asphalt, which was removed during chemical pretreatment. We started with 101.0 g of sample and recovered 80.92 g or 80.1%. The majority of this sample lies in the sand size range with 76.9% (62.2 g) of the sample in this fraction. The rest of the fractions consist of 14.2% (11.5 g) silt, 5.2% (4.2 g) coarse clay, and 3.7% (3.02 g) fine clay.

The recycled concrete is dominated by quartz in the sand fraction with a minor feldspar component. The silt has quartz as the dominant mineral, but it also has feldspars and probably some cement compounds not available in the JCPDS mineral index. The coarse clay is composed of quartz, discrete illite, smectite, and kaolinite. The fine clay is a mixed layer illite/smectite and kaolinite.

The final sample is a river gravel from the Yoakum District. The Yoakum sample yielded the highest recovery with 97.7% recovered. It is composed of 74.7% sand, 10.6% silt, 8.8% coarse clay, and 5.9% fine clay. The sand fraction is coarse-grained and consists predominantly of quartz. The silt is also quartz with some feldspar. The coarse clay is predominantly kaolinite with minor smectite and discrete illite. The fine clay fraction is dominated by kaolinite with a very small amount of illite/smectite.

Smectite is the most reactive constituent in these base course materials so it was decided to determine the cation exchange capacity (CEC) of the coarse and fine clay fractions to try to quantify the smectite concentrations. The CEC was determined by a Ca exchange procedure outlined in Dixon and White (1999). The values listed in Table A1 represent averages of duplicate analyses run for repeatability.

Table A1. Coarse and Fine Clay Fractions of Base Materials CEC Determinations

Sample Name and Size Fraction	Cation Exchange Capacity
Pharr Caliche Coarse Clay	53.78
Pharr Caliche Fine Clay	46.15
Houston Recycled Concrete Coarse Clay	54.54
Houston Recycled Concrete Fine Clay	58.39
Yoakum River Gravel Coarse Clay	15.27
Yoakum River Gravel Fine Clay	22.61
Smectite Standard	93.19

The CEC measurements agree very well with the X-ray interpretation. The Yoakum sample has the lowest CEC because the clay fractions are dominated by kaolinite.

Table A2. Results of Sample Size Fractionation

Sample Name	Size Fraction	Weight %
Pharr Caliche	Sand	66.3
	Silt	22.9
	Coarse Clay	4.4
	Fine Clay	6.4
Houston Recycled Concrete	Sand	76.9
	Silt	14.2
	Coarse Clay	5.2
	Fine Clay	3.7
Yoakum River Gravel	Sand	74.7
	Silt	10.6
	Coarse Clay	8.8
	Fine Clay	5.9

SCANNING ELECTRON MICROSCOPY

The base materials were then analyzed with a JEOL JSM 6400 scanning electron microscope equipped with a Princeton Gammatech energy dispersive spectrometer. Samples were selected on the basis of strength and TST performance. The Pharr caliche with 1.5%

and 3.0% cement was analyzed due to the large difference in physical test performance. The 1.5% cement-stabilized material failed the physical tests and the 3.0% cement passed. There were two characteristic differences in these materials at the microscopic scale. First, the 1.5% cement (Figure A1) sample appeared to be more poorly consolidated than the 3.0% cement (Figure A2). The other noticeable difference was the presence of a large amount of fibrous phases (calcium silicate hydrates?) in the 3.0% cement sample (Figure A3) that was noticeably absent in the sample stabilized with 1.5% cement.

REACTION PRODUCT CHEMISTRY

Thin sections of the various stabilized base materials were made for analysis by electron probe microanalysis (EPMA). This technique is useful for determining chemical reactions that have occurred in samples by examining the position of various elements in unstabilized and stabilized materials. This is accomplished by aiming an electron beam at the sample and recording the intensity of the characteristic's X-ray line of a particular element while the beam is moved across the specimen (Reed, 1996). Elemental maps of selected areas are created to show how different phases (cement paste, clays, and mineral aggregates) interact on a two-dimensional scale.

The Pharr caliche was chosen to be analyzed first because it exhibited the most drastic change in physical properties with stabilization. The 4.5% cement (Figure A4) and the unstabilized samples were chosen to compare chemistry of the samples. After a number of analyses, it was concluded that the cement content was not high enough and the grain size was too small in this very heterogeneous sample to see any reaction products. We then examined the Houston recycled concrete (Figure A5) to try and see a difference. This attempt was unsuccessful as well. We then concluded that using EPMA, XRD, and FTIR to identify reaction products of these very heterogeneous samples would not be possible.

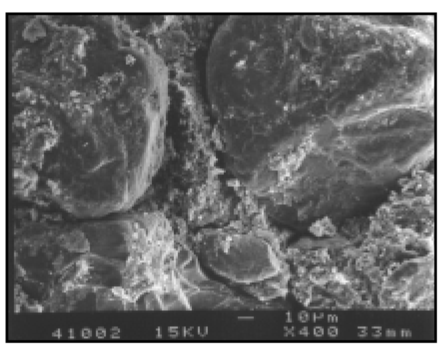


Figure A1. Pharr caliche with 1.5% cement. (IMG15488)

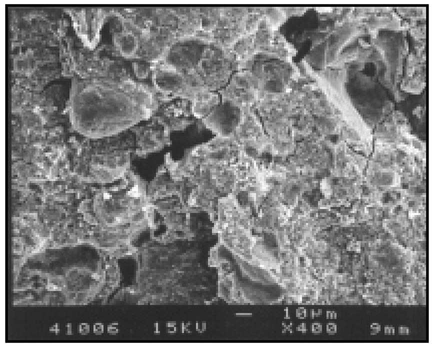
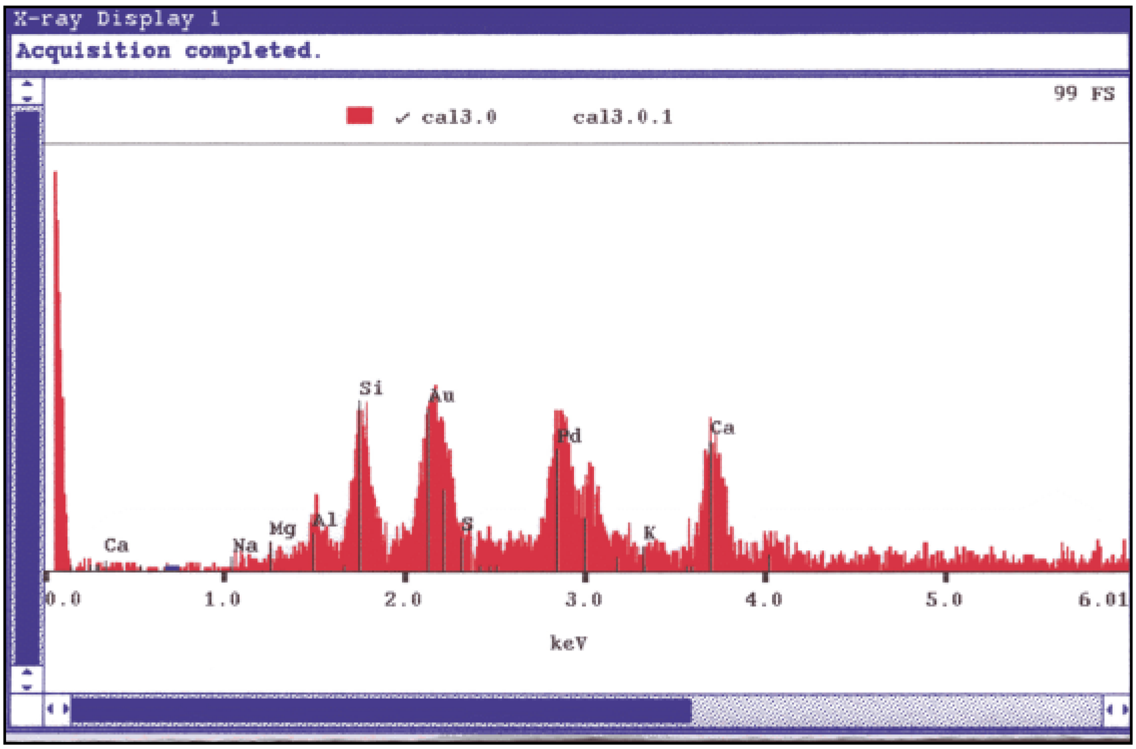


Figure A2. Pharr caliche with 3.0% cement. (IMG15489)



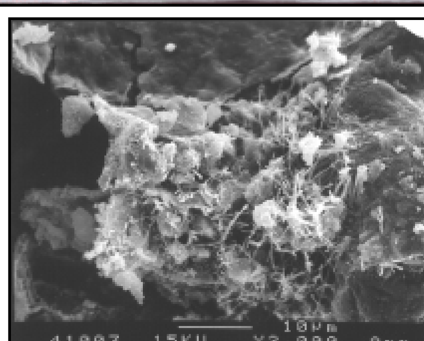
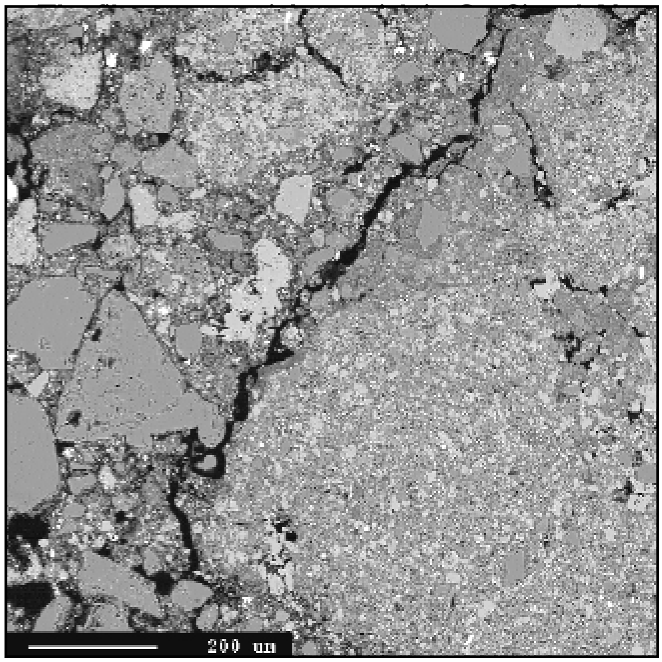
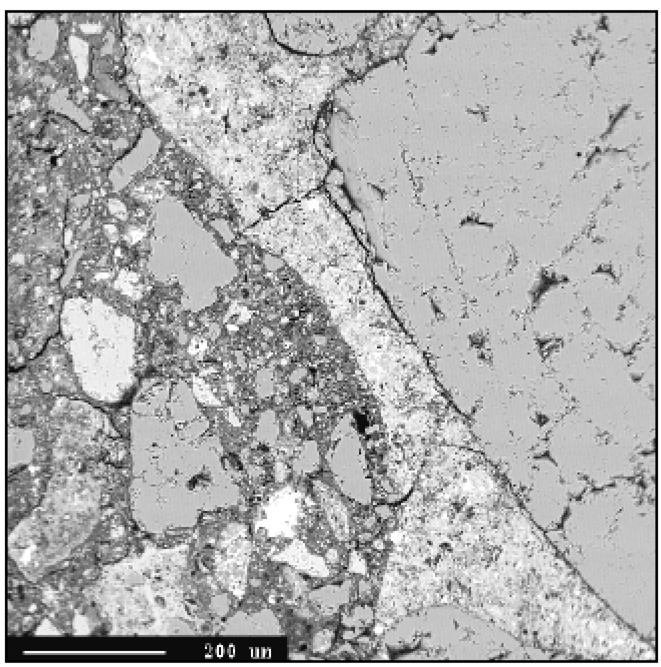


Figure A3. EDS pattern and SEM image of Pharr caliche stabilized with 3.0% cement. (IMG15490)



Note the heterogeneous nature of the aggregates and cement paste.
Figure A4. Backscattered election image of Pharr caliche stabilized with 4.5% cement. (IMG15491)



Note the large quartz grain in the upper right of the image. The cement paste of the original concrete is seen as a lighter band surrounding this large aggregate. The new stabilizer (4.5% cement) is observed as a darker gray material on the left side of the image, 100x magnification.
Figure A5. Backscattered electron image of Houston recycled concrete. (IMG15492)

APPENDIX B
TUBE SUCTION TEST FOR STABILIZED MATERIALS

APPLICATION

Based on the principles of soil suction, moisture ingress, and dielectric permittivity, the TST (TST) is designed to evaluate the moisture susceptibility of aggregates used as base materials in pavements. The Adek PercometerTM, a 50 MHz surface dielectric probe, is employed in the TST to measure the dielectric values of compacted aggregate samples during a monitored exposure to capillary rise conditions in the laboratory. The interpretation of test results is founded on an empirical relationship between the final dielectric value and the expected performance of aggregate base materials in the field. The Adek Percometer is shown in Figure B1.

Figure B1. Adek Percometer. (IMG15505)

Since the stabilized materials may be base or subgrade, the TST protocol for stabilized materials only includes sample testing and data analysis procedures. Standard procedures for sample preparation are to use 6 x 8-in. specimens for base material and 4 x 6-in. specimens for subgrade, using the appropriate TxDOT method for sample preparation. The specimens are allowed to cure for 7 days then dried back 4 days. Base material is dried in a 104°F environment, and subgrade is air dried to prevent excessive cracking.

Sample Testing

- After the four-day dry-back, record the weight of each sample to the nearest gram.
- Use the Adek PercometerTM to take six dielectric readings on the surface of each sample. Five should be around the perimeter of the sample, and the sixth should be in the center. Press down on the probe with a force of about 20 lb to ensure adequate contact of the probe on the sample surface. Some twisting also can be used to seat the probe. Follow this pattern for each sample each time dielectric readings are made. See the attached typical TST data collection form.
- Place each sample in the empty soaking basin. Base materials are placed directly into the basin. Subgrade specimens should be placed on a 4-in. diameter porous stone.
- Use distilled water at 77°F to fill the soaking basin. For subgrade specimens, the water level should be maintained at a depth equal to the height of the porous stone. Previous experience with subgrade soils in this test has indicated the specimens tend to “melt” over time when placed in direct contact with water. The setup for testing subgrades is shown in Figure B2. For base samples, a water depth of 1 in. is maintained. A picture of the setup for testing base specimens is in Figure B3.

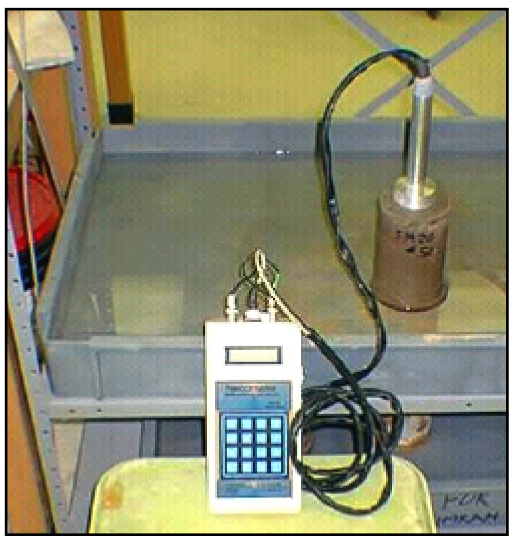


Figure B2. Setup of the TST for subgrade soils. (IMG15506)

Figure B3. Base specimens in the TST. (IMG15507)

- Take additional dielectric readings at time intervals of approximately 24 hours until testing is completed.
- If the water content also is to be monitored through time, the weight of each sample should be recorded at the same or similar time intervals.
- . The test is completed when the elapsed time exceeds 240 hours. Take final dielectric readings and record the final weight.
- If the actual dry density of each sample is to be calculated, place the samples in an oven for drying to constant weight. The oven should be maintained at a temperature of 230°F. Record the dried weight.

Data Analysis

- For each sample at each time interval, discard the highest and lowest dielectric readings. Average the remaining four readings and plot these against time.
- If the weight of each sample also was recorded at each time interval, the water content through time may be calculated for each sample and also plotted against time.
- Other information such as dry density, relative density, and residual moisture within each sample before placement in the water bath also can be calculated and shown in the analysis. See the attached typical TST data analysis sheet.
- Base aggregates whose final, or asymptotic, dielectric values are less than 10 are expected to provide superior performance as base materials in the presence of water. If these aggregates have reasonable strength characteristics, they should be able to withstand both heavy truckloads and environmental stresses. Aggregates with final dielectric values between 10 and 16 are expected to provide marginal performance as

base materials. For inadequately drained base layers, moisture available in the subgrade soils or from the pavement surface may cause poor freeze-thaw resistance and reduced shear strength. Aggregates with dielectric values exceeding 16 are expected to be especially moisture susceptible. In the field, these aggregates are expected to be moist or near saturation and susceptible to forming ice lenses upon freezing. Under a dynamic load, plastic deformation of these materials may occur because of high pore water pressure and low shear strength.

The criteria for soil aggregates are a new area, as subgrade soils often have dielectric values close to or above 10 even when at very low moisture contents. A stabilized subgrade is deemed a good performer if:

- Moisture does not reach the top of the specimen and the final surface dielectric value after 10 days is not significantly different from the original surface dielectric value, and
- The unconfined compressive strength (UCS) of the specimen after undergoing the TST is greater than or equal to 80% of the UCS of a corresponding specimen that was cured in a 100% relative humidity environment for 21 days.

Because little research has been done on dielectric testing of subgrade soils, the most weight in evaluating the soil performance is put on the strength after the TST. In practice, however, most subgrade soils we have tested have not met condition number 2, even when moisture does not rise through the entire specimen. However, the two evaluation parameters, when used together, are useful for identifying the better performer when comparing different stabilizer types and/or contents.

Figure B4 shows a typical data collection form used during the TST. Figure B5 is a typical summary of TST data.

TUBE SUCTION TEST

Data Collection Form

SAMPLE:

Year:

	Dielectric Value																	
Date (mm/dd)																		
Time																		
Mass (g)																		
No. 1																		
No. 2																		
No. 3																		
No. 4																		
No. 5																		
No. 6																		

Comments																		

Figure B4. Typical TST data collection form.

TUBE SUCTION TEST
Data Analysis Report

SAMPLE: **Pharr Caliche Untreated**

SAMPLE PREPARATION

Mold Mass (g)	283
Sample Diameter (in)	6.0
Sample Height (in)	8.1
Sample Volume (ft^3)	0.133

Wet Total Mass (g)	8240
Wet Soil Mass (g)	7957
Dry Total Mass (g)	7517
Dry Soil Mass (g)	7230

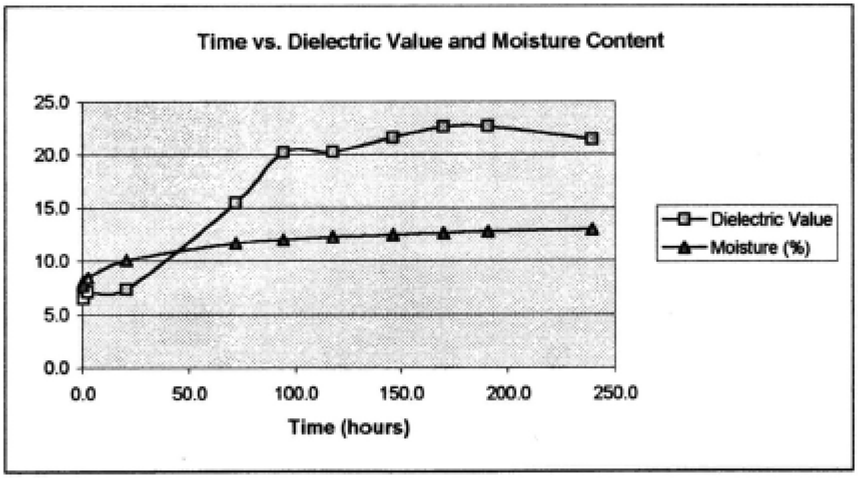
Desired Compaction Moisture (%)	10.0
Actual Compaction Moisture (%)	10.1
Desired Dry Density (lb/ft^3)	123.5
Actual Dry Density (lb/ft^3)	120.3
Relative Density (%)	97.4

SAMPLE TESTING

Time (hr)	0.0	0.5	2.5	20.5	72.0	94.3	117.9	146.4	170.2	190.6	239.5
Total Mass (g)	8064	8096	8122	8242	8358	8378	8397	8414	8426	8434	8446
Soil Mass (g)	7781	7813	7839	7959	8075	8095	8114	8131	8143	8151	8163
Moisture (%)	7.6	8.1	8.4	10.1	11.7	12.0	12.2	12.5	12.6	12.7	12.9

Dielectric Values

No. 1	6.2	6.6	7.3	7.8	16.7	20.8	20.8	20.8	20.1	24.9	22.1
No. 2	6.4	5.7	6.2	6.6	14.1	19.9	20.7	22.0	23.7	20.6	23.6
No. 3	6.7	7.3	7.4	7.4	15.9	19.0	19.9	19.9	20.8	24.2	22.6
No. 4	7.3	6.4	7.4	7.5	15.2	21.3	19.8	23.9	25.8	20.9	17.3
Average	6.7	6.5	7.1	7.3	15.5	20.3	20.3	21.7	22.6	22.7	21.4



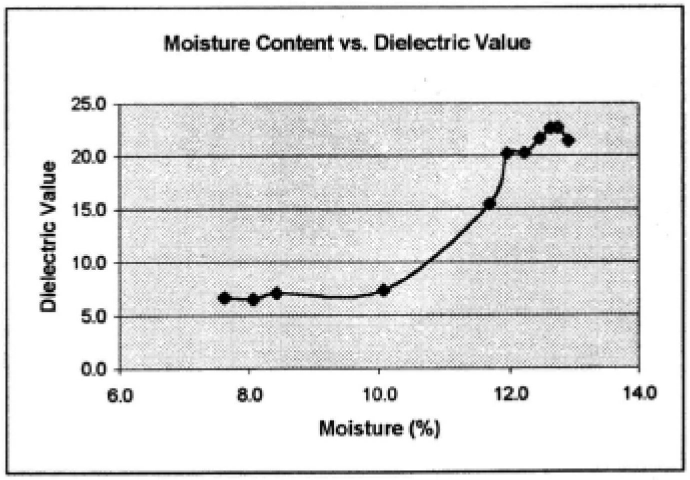


Figure B5. Typical TST data analysis sheet.

APPENDIX C
TESTING PROCEDURES FOR BASE SPECIMENS

The laboratory procedures described below were used as part of the method for investigating and evaluating the performance of the stabilized base materials used in the study. Since this study was aimed at investigating stabilization, and stabilizers react with fines, only material passing the 3/4-in. sieve was used in the base material testing. This created a larger proportion of soil binder in the material and would thus highlight the effects of stabilization more.

The manufacturing procedure for making the samples is from Tex-120-E. As per TxDOT recommendations, all samples in this study were 6 in. in diameter by 8 in. high. Molding procedures for all specimens included the application of stabilizer to the minus #4 fraction, the application of water to the plus #4 fraction, and compaction with 4 lifts of 50 blows per lift with a modified proctor. In addition, the height and circumference of the test specimens were measured throughout the testing phase to try to determine if the specimens were swelling or shrinking.

21-DAY CONTROL

This test was used to obtain the unconfined compressive strength of the specimen after 21 days curing time. This strength value would later serve as a baseline to compare with strengths obtained after the TST.

- Separate aggregate into plus and minus #4 fractions.
- Add stabilizer to the minus #4 fraction and mix.
- Add required molding moisture to the plus #4 fraction and mix.
- Add the minus #4 fraction/stabilizer combination to the plus #4 fraction/water combination and mix.
- Mold the specimen (6 x 8 in.) in 4 lifts of 50 blows per lift; 18-in. drop.
- Extrude the sample and record its weight.
- Take initial height measurements with dial gage measuring jig and circumference measurements with flexible measuring tape.
- Place in 100% humidity environment for 21 days curing.
  -Take height and circumference measurements every 7 days.
- After 21 days curing, take final height and circumference measurements.
- Test for unconfined compressive strength.

7-DAY CURE TST

This test was used to evaluate the specimens' susceptibility to moisture infiltration as measured by the TST. Specimens were allowed to cure 7 days to bring them to the curing conditions typically used by TxDOT before testing, then procedures for the TST were begun. The TST is used as a predictor of material performance in the presence of available water and uses the surface dielectric value as the evaluation method.

- Separate aggregate into plus and minus #4 fractions.
- Add stabilizer to the minus #4 fraction and mix.
- Add required molding moisture to the plus #4 fraction and mix.
- Add the minus #4 fraction/stabilizer combination to the plus #4 fraction/water combination and mix.
- Mold the specimen (6x 8-in.) in 4 lifts of 50 blows per lift; 18-in. drop.
- Extrude the sample and record its weight.
- Take initial height measurements with dial gage measuring jig and circumference measurements with flexible measuring tape.
- Place in 100% humidity environment for 7 days curing.
- Take height and circumference measurements after the 7-day cure.
- Dry sample for 4 days in 104°F room.
- Take height and circumference measurements after the 4-day drying process.
- Run standard 10-day TST for stabilized materials (see Appendix B).
- Take height and circumference measurements after completion of the 10-day TST.
- Test for unconfined compressive strength.

10-DAY SOAK

The purpose of this procedure was to expose the test specimens to the worst-case scenario (they were completely submerged in water for 10 days) after allowing 7 days curing time. Following the submersion period the samples were strength tested.

- Separate aggregate into plus and minus #4 fractions.
- Add stabilizer to the minus #4 fraction and mix.
- Add required molding moisture to the plus #4 fraction and mix.
- Add the minus #4 fraction/stabilizer combination to the plus #4 fraction/water combination and mix.
- Mold the specimen (6 x by 8-in.) in 4 lifts of 50 blows per lift; 18-in. drop.
- Extrude the sample and record its weight.
- Take initial height measurements with dial gage measuring jig and circumference measurements with flexible measuring tape.
- Place in 100% humidity environment for 7 days curing.
- Take height and circumference measurements after the 7-day cure.

- Dry sample for 4 days in 104°F room.
- Take height and circumference measurements after the four-day drying process.
- Soak sample by submerging in water for 10 days.
- Take height and circumference measurements after completion of the 10-day soak.
- Test for unconfined compressive strength.

7- THEN 21-DAY UCS

The purpose of this testing procedure was to obtain the unconfined compressive strength of the stabilized test specimens after 7 days' curing time. This test was chosen because TxDOT uses 7-day strengths when evaluating materials. These specimens also were retested at 21 days to test for "fracture healing."

- Separate aggregate into plus and minus #4 fractions.
- Add stabilizer to the minus #4 fraction and mix.
- Add required molding moisture to the plus #4 fraction and mix.
- Add the minus #4 fraction/stabilizer combination to the plus #4 fraction/water combination and mix.
- Mold the specimen (6 x by 8-in.) in 4 lifts of 50 blows per lift; 18-in. drop.
- Extrude the sample and record its weight.
- Take initial height measurements with dial gage measuring jig and circumference measurements with flexible measuring tape.
- Place in 100% humidity environment for 7 days curing.
- Take height and circumference measurements after the 7-day cure.
- Test for unconfined compressive strength.
- Place sample back in 100% humidity environment for 14 days.
- Test for unconfined compressive strength.

28-DAY CURE TST

These specimens were allowed to cure in a 100% R.H. environment for 28 days before the procedures for the TST were begun. This was done to investigate if allowing longer time for hydration would affect results in the test.

- Separate aggregate into plus and minus #4 fractions.
- Add stabilizer to the minus #4 fraction and mix.
- Add required molding moisture to the plus #4 fraction and mix.
- Add the minus #4 fraction/stabilizer combination to the plus #4 fraction/water combination and mix.
- Mold the specimen (6 x 8-in.) in 4 lifts of 50 blows per lift; 18-in. drop.
- Extrude the sample and record its weight.
- Take initial height measurements with dial gage measuring jig and circumference measurements with flexible measuring tape.

- Place in 100% humidity environment for 28-days curing.
- Take height and circumference measurements after the 28-day cure.
- Dry sample for 4 days in the 104°F room.
- Take height and circumference measurements after the 4-day drying process.
- Run standard 10-day TST for stabilized materials.
- Take height and circumference measurements after completion of the 10-day TST.
- Test for unconfined compressive strength.

APPENDIX D
COMPARING THE TUBE SUCTION TEST TO TRADITIONAL DURABILITY TESTS

This section has been extracted from a thesis by Syed (2000). This complementary study was undertaken to correlate the Tube Suction Test (TST) with the existing ASTM durability tests. The three aggregates discussed in the main portion of the report were tested together with a crushed limestone which was thought to be of higher quality. In conducting these tests the influence of sample size was also studied. The earlier work was conducted on 6-in. diameter by 8-in. high samples, which is standard for TxDOT. In this study a set of samples with the conventional PCA size (4-in. diameter by 4.5-in. high) also were tested. The shorter samples are a more severe test than the standard 8-in. samples. All of the materials were tested in both the untreated and cement-stabilized states. The TST's were conducted as per the test procedure in Appendix B.

Crushed Limestone

Figure D1 shows the TST results for 6 x by 8-in. samples of crushed limestone, and Figure D2 shows the results on 4-inch by 4.5-inch samples. As is evident from Figure D1, the measured surface dielectric constants on all the samples vary between 5 and 7 over the entire time period of the test. There are no statistically significant differences in the surface dielectric constant measurements among the samples or over time. Details of the statistical analysis are presented in Syed (2000).

TST results shown in Figure D2 for the smaller (4 x 4.5 in.) samples of crushed limestone show the surface dielectric constants varying between 14 and 15 after two days for the raw material as compared to values between 6 and 7 measured on the larger sample in Figure D1. Smaller samples of crushed limestone stabilized with 1.5% by weight cement also developed a surface dielectric constant of about 10 rather than values between 6 and 7. The dielectric constants on these two materials rose quickly in the first 48 hours and stayed nearly constant for the remainder of test period.

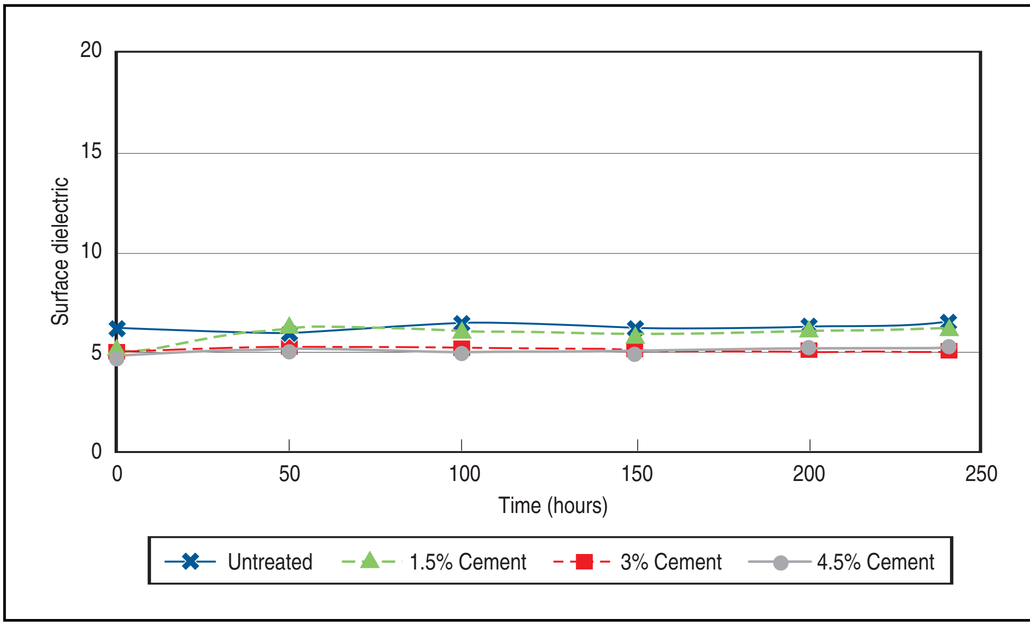


Figure D1. Tube Suction Test on crushed limestone (6 x 8 in.).

Smaller samples of crushed limestone stabilized with 3.0% and 4.5% cement had dielectric values between 6 and 8; however, based on a 95% confidence interval these values are not significantly different than the value of approximately 5 recorded on the larger samples. The surface dielectric constants on these samples were nearly constant for the entire test period.

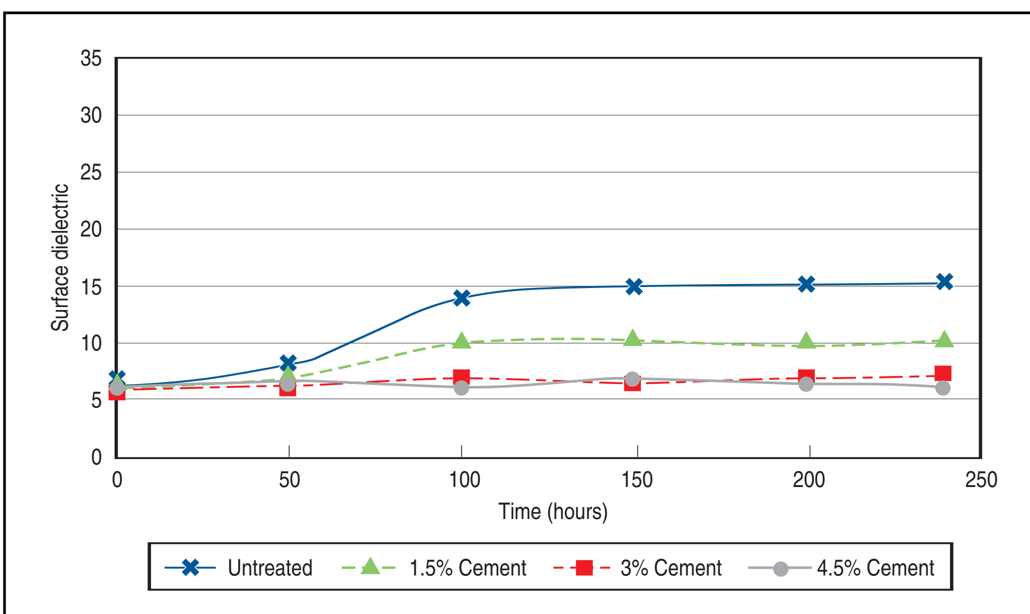


Figure D2. Tube Suction Test on crushed limestone (4 x 4.5 in.).

Pharr Caliche

Figure D3 shows the TST results for 6 x 8-in. samples of the Pharr caliche material. The dielectric values showed a rapid increase in the first 72 hours of the test for the untreated material and the first 48 hours for the material stabilized with 1.5% cement. After the initial rapid increase in the surface dielectric constants, the dielectric values were nearly constant in both the samples. The measured surface dielectric constants on the raw material varied between values of 20 and 23. The Pharr caliche samples stabilized with 1.5 percent cement developed dielectric values between 25 and 30.

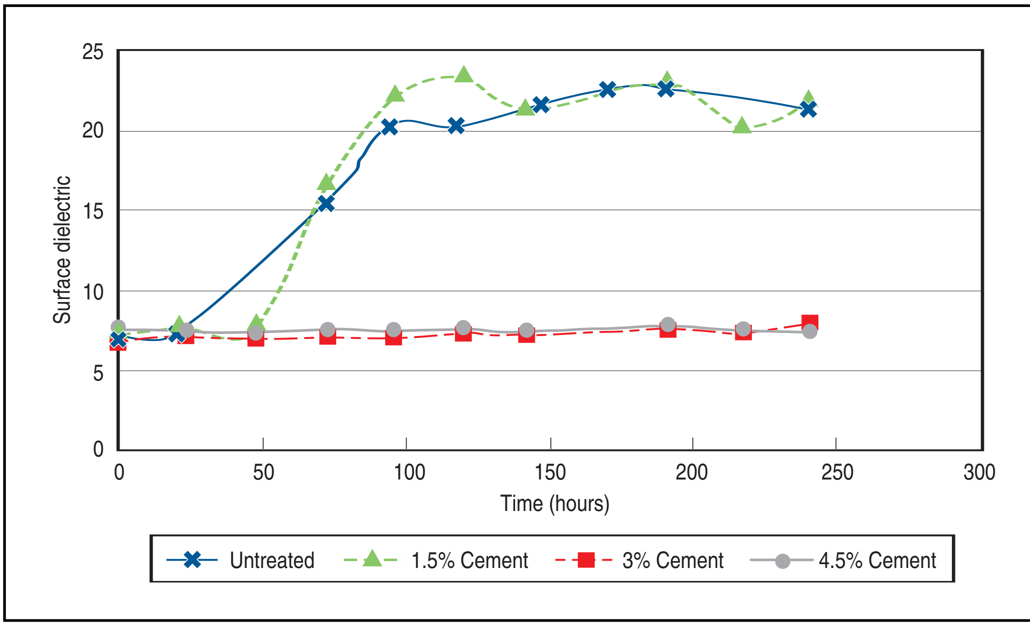


Figure D3. Tube Suction Test on Pharr caliche (6 x 8 in.).

The Pharr caliche samples stabilized with 3.0% and 4.5% cement showed surface dielectric measurements of about 6 and remained constant over the entire duration of the test. Based on a 95% confidence interval, there is no statistically significant difference in the surface dielectric measurements on the Pharr caliche samples stabilized with 3.0% and 4.5% cement. The observation that low levels of cement will make the sample fail faster is interesting; it also was noted on the samples treated with lime.

TST results shown in Figure D4 for the smaller (4 x 4.5 in.) samples of Pharr caliche are similar to the results shown in Figure D4 for the larger samples. The dielectric readings increase rapidly in the first 48 hours for both the raw and the Pharr caliche material stabilized with 1.5% cement. After the rapid initial rise, the surface dielectric constants for the untreated material varied between values of 20 and 24, which based on a 95% confidence interval are not statistically different from the values measured for the larger samples in Figure D4 over the duration of the TST. The surface dielectric constants for the Pharr caliche stabilized with 1.5% cement varied between 20 and 23, which based on a 95% confidence interval is statistically different (lower) than the values for the larger sample in

Figure D4. The surface dielectric measurements on the raw and the material stabilized with 1.5% cement of the smaller sample size were not statistically different based on a 95% confidence interval.

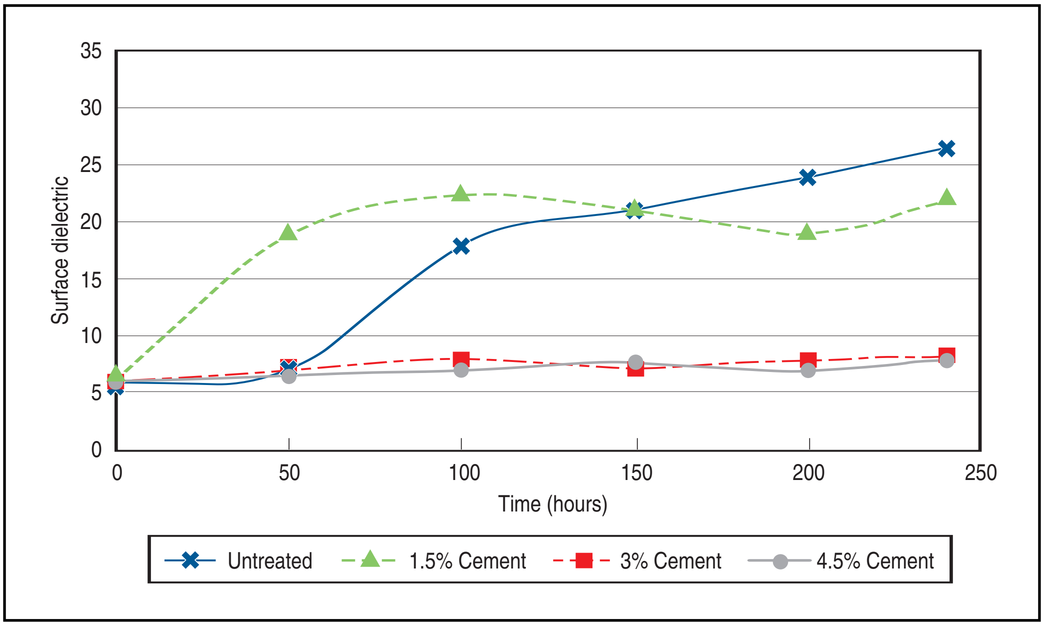


Figure D4. Tube Suction Test on Pharr caliche (4 x 4.5 in.).

Dielectric measurements on the 3.0% and 4.5% cement-stabilized Pharr caliche stayed between 6 and 8 (same as the values for the larger samples in Figure D3) over the entire test period. Based on a 95% confidence interval, there are no statistically significant differences among the dielectric values for the Pharr caliche materials stabilized with 3.0% and 4.5% cement for both sample sizes.

Yoakum River Gravel

Figure D5 shows the TST results for 6 x 8-in. samples of the Yoakum river gravel. The measured surface dielectric constants on all the samples vary between 4 and 6. There are no statistically significant differences among these values.

The TST results for the smaller (4 x 4.5 in.) samples of the Yoakum river gravel are shown in Figure D6. The surface dielectric constants for the 1.5% cement-stabilized river gravel rose rapidly to attain a value of about 14 to 15 (compared with values of about 5 for the larger sample in Figure D5) within the first 24 hours of commencing the TST. Although the 3.0% cement-stabilized river gravel recorded a higher value between 7 and 8 as compared to the value of about 5 recorded for the larger sample in Figure D5, there are no significant statistical differences among these values.

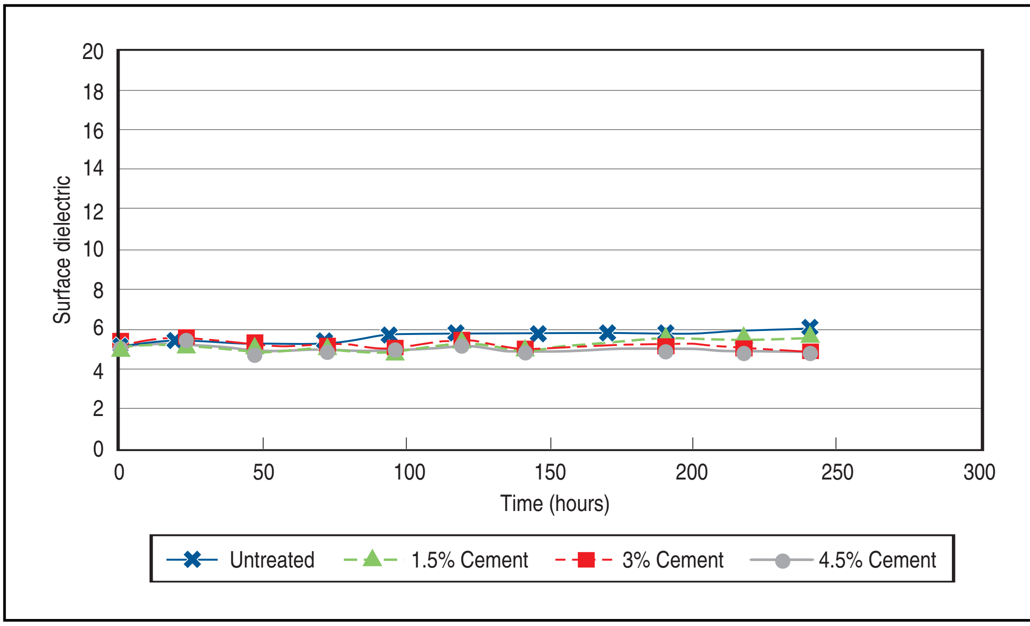


Figure D5. Tube Suction Test on Yoakum river gravel (6 x 8 in,).

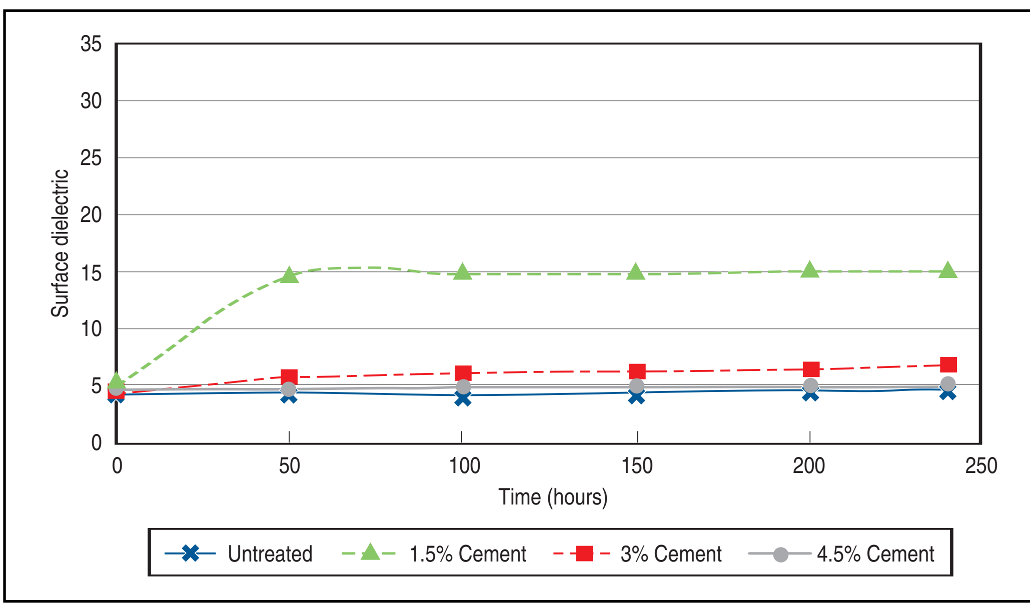


Figure D6. Tube Suction Test on Yoakum river gravel (4 x 4.5 in.).

Dielectric constants of 4 to 5 were measured on the surface of the raw river gravel and on the material stabilized with 4.5% cement. These were similar to those measured on the larger samples shown in Figure D5. The dielectric values on the raw and the river gravel stabilized with 4.5% cement remained constant for the entire duration of the test, and based on a 95% confidence interval, there are no significant statistical differences in the values for the two sample sizes.

Houston Recycled Concrete

Figure D7 shows the TST results for 6 x 8-in. samples of the Houston recycled concrete. The measured surface dielectric constants on the cement-stabilized samples are around 5 and stay constant through the entire duration of TST. However, the surface dielectric constant on the raw material increased rapidly to a value of about 22 within 48 hours of commencement of the TST and to 32 at 96 hours. For the remainder of the duration of TST, the surface dielectric constant measured on the untreated Houston recycled concrete varied between 29 and 33. Based on a 95% confidence interval, there are no statistically significant differences in the surface dielectric values for the samples stabilized with cement or over time.

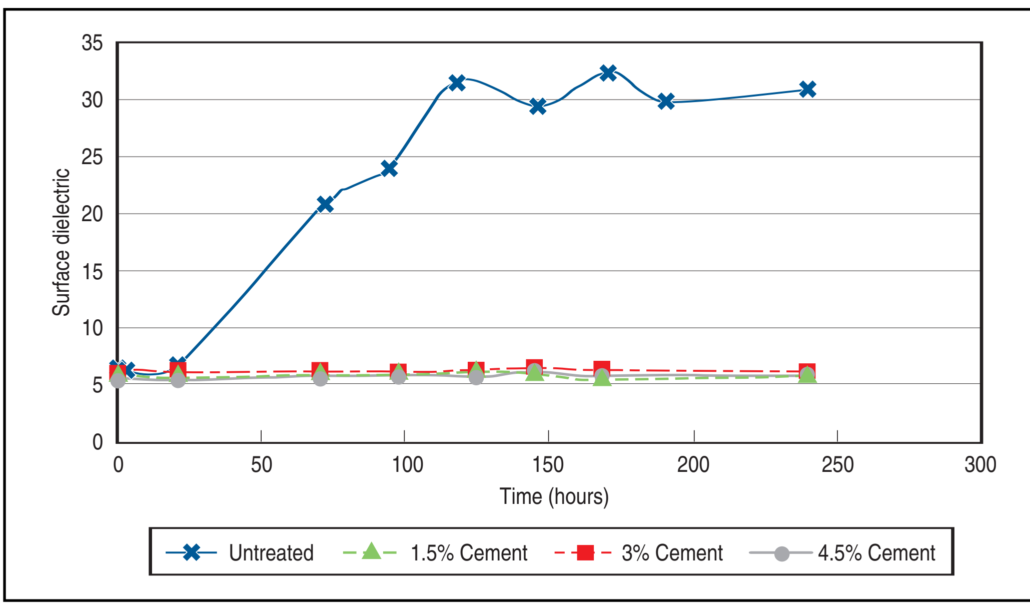


Figure D7. Tube Suction Test on Houston recycled concrete (6 x 8 in.).

The results of the TST performed on the smaller (4 x 4.5 in.) samples of the Houston recycled concrete are shown in Figure D8. Surface dielectric constants rose very rapidly within 24 hours of commencement of TST for the 1.5% and 3.0% cement-stabilized Houston recycled concrete and attained values of 24 and 32, respectively. Over the remainder of the TST, the material stabilized with 1.5% cement reached a constant dielectric value of about 30, whereas the material stabilized with 3.0% cement attained a constant dielectric value of about 25. This is in sharp contrast to the constant dielectric value of about 5 obtained on the surface of the larger samples shown in Figure D7.

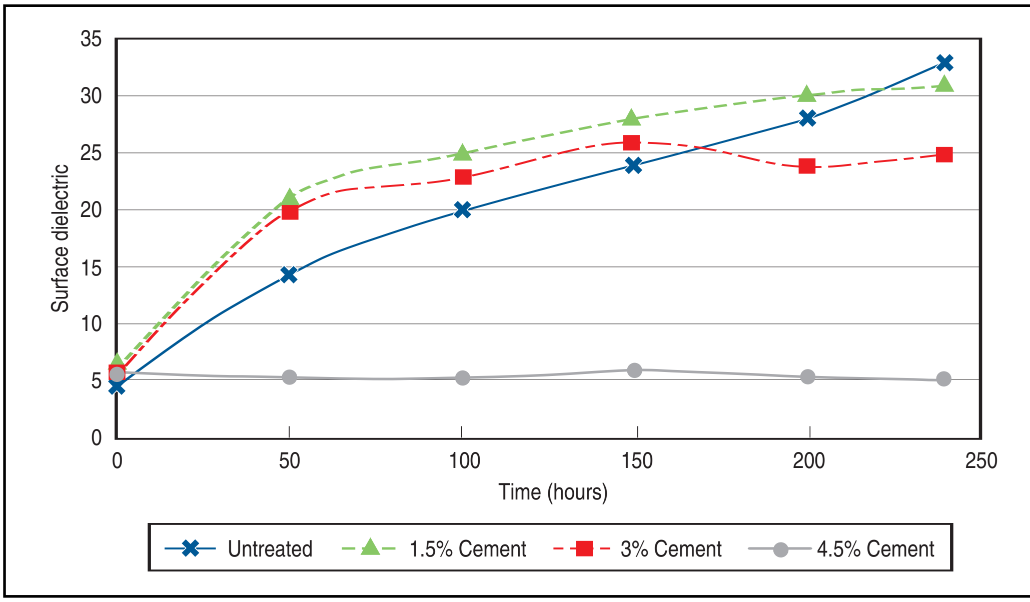


Figure D8. Tube Suction Test on Houston recycled concrete (4 x 4.5 in.).

The raw material showed a constant dielectric value of 5 for the first 24 hours of the TST. Beyond the first 24 hours, the raw material showed increasing surface dielectric constants for the remainder of TST. The surface dielectric constants measured on the smaller untreated sample were statistically different (lower) than those measured on the corresponding larger sample. Surface dielectric constants for the recycled concrete stabilized with 4.5% cement showed a uniform value of about 6 for the entire duration of the test. The test results of the raw and recycled concrete stabilized with 4.5% cement are similar to the dielectric values observed in the larger samples shown in Figure D7 and based on a 95% confidence interval there is no statistically significant difference.

The results from the Houston aggregates clearly demonstrate that the short sample height is a more severe test. The low levels of cement passed with the taller samples but failed with the shorter samples.

ENGINEERING DURABILITY TESTS

Single samples for each mixture design were prepared as per ASTM D558 and subjected to standard brushing, or abrasion resistance, durability tests as specified by ASTM D559 for resistance to wetting and drying and ASTM D560 for resistance to freezing and thawing. The weight loss of cement-stabilized material under wire brushing was determined after 12 cycles of wetting and drying, and a similar technique was used after 12 cycles of freezing and thawing. The weight loss results and the typical durability requirements or maximum permissible weight loss as per PCA (1971) and the U.S. Army Corps of Engineers (1969) are summarized in the following paragraphs.

Crushed Limestone

Table D1 summarizes the freeze/thaw and wet/dry durability tests performed on the crushed limestone aggregate material stabilized with varying levels of cement. All the mixture combinations passed the durability requirements established by PCA. Crushed limestone stabilized with 1.5% cement barely passed the PCA requirements but failed to pass the USACE requirements for freeze/thaw durability. Crushed limestone stabilized with 3.0% and 4.5% cement performed better in the freeze/thaw test than in the wet/dry test.

Table D1. Durability Test on Crushed Limestone

Cement Content	Weight Loss, %		Maximum Permissible Weight Loss, %	
%	Wet/Dry	Freeze/Thaw	PCA	USACE
1.5	10	14	14	11
3.0	6	2	14	11
4.5	6	1	14	11

Pharr Caliche

Table D2 summarizes the freeze/thaw and wet/dry durability tests performed on the Pharr caliche stabilized with varying levels of cement. Pharr caliche stabilized with 1.5% cement failed the durability test requirements of both PCA and USACE. Durability test results for the Pharr caliche stabilized with 3.0% cement is on the border as per PCA and unacceptable as per

Table D2. Durability Test on Pharr Caliche

Cement Content	Weight Loss, %		Maximum Permissible Weight Loss, %	
%	Wet/Dry	Freeze/Thaw	PCA	USACE
1.5	47	21	14	11
3.0	15	3	14	11
4.5	9	1	14	11

USACE. The wet/dry test showed higher than permissible weight loss, but the freeze/thaw test showed acceptable results. Only Pharr caliche stabilized with 4.5% cement passed all the durability requirements of PCA and USACE.

Yoakum River Gravel

Table D3 summarizes the freeze/thaw and wet/dry durability tests performed on Yoakum river gravel stabilized with varying levels of cement. River gravel stabilized with 1.5% cement failed to meet the durability requirements of both PCA and USACE. River gravel stabilized with 3.0% and 4.5% cement met all durability requirements of both PCA and USACE. Mixture combinations undergoing the freeze/thaw test showed lower weight loss as compared to materials undergoing the wet/dry test.

Table D3. Durability Test on Yoakum River Gravel

Cement Content %	Weight Loss, %		Maximum Permissible Weight Loss, %	
	Wet/Dry	Freeze/Thaw	PCA	USACE
1.5	30	19	14	11
3.0	10	6	14	11
4.5	6	3	14	11

Houston Recycled Concrete

Table D4 summarizes the freeze/thaw and wet/dry durability tests performed on Houston recycled concrete stabilized with varying levels of cement. Recycled concrete stabilized with 1.5% cement disintegrated upon the completion of the fourth cycle in the freeze/thaw test. Recycled concrete stabilized with 1.5% and 3.0% cement failed to meet the durability requirements of both PCA and USACE. The recycled concrete material stabilized with 4.5% cement was on the border line for the wet/dry durability requirements of PCA but failed to meet the wet/dry durability requirements of USACE. It did meet the requirement of the freeze/thaw test for both PCA and USACE.

Table D4. Durability Test on Houston Recycled Concrete

Cement Content %	Weight Loss, %		Maximum Permissible Weight Loss, %	
	Wet/Dry	Freeze/Thaw	PCA	USACE
1.5	45	Disintegrated	14	11
3.0	20	16	14	11
4.5	15	2	14	11

Tube Suction Test

In this research work, TST's were performed on two sample sizes, 6-in. diameter by 8-in. high and 4-in. diameter by 4.5-in. high. Durability testing, as previously presented, was performed on cement-stabilized materials as per ASTM D559 and ASTM D560. Table D-5 presents a comparison of the maximum dielectric constants measured in the TST on the two sample sizes with the results of durability testing.

The results summarized in Table D5 suggest that the TST results on 6-in. diameter by 8-in. height samples are not consistent with the TST results on 4-in. diameter by 4.5-in. height samples. In addition, a correlation is evident in terms of high surface dielectric constant values measured on the 4-in. diameter by 4.5-in. samples and poor performance of the cement-stabilized aggregate material in standard durability tests as specified by ASTM D559 and ASTM D560.

Table D5. Dielectric Measurements and Durability Testing

Material	Cement Content, %	Dielectric Constant		Durability Test		
		(152x204)	(102x117)	W/D	F/T	Acceptable
Crushed Limestone	1.5	6.7	10.2	10	14	Yes
	3.0	5.6	7.0	6	1	Yes
	4.5	5.9	8.1	5	0	Yes
Pharr Caliche	1.5	30.1	22.3	47	20	No
	3.0	8.4	8.3	14	3	Yes
	4.5	7.1	7.6	9	1	Yes
Yoakum River Gravel	1.5	5.2	15.2	30	18	No
	3.0	5.2	7.6	9	5	Yes
	4.5	5.2	5.2	6	3	Yes
Houston Recycled Concrete	1.5	5.2	30.7	45	*	No
	3.0	5.2	25.9	20	15	No
	4.5	5.7	6.4	15	2	Yes/No

W/D: Percent soil-cement loss recorded in wet/dry test as per ASTM D559.
F/T: Percent soil-cement loss recorded in freeze/thaw test as per ASTM D560.
*: Sample disintegrated after four cycles.
Test results are acceptable if weight loss is less than 14% (specified by PCA, 1971).

Figures D9 and D10 present the results of the Tube Suction Tests with the ASTM durability tests. Ideally, all data points would fall into the lower left quadrant (passing the criteria of both tests) or the upper right quadrant (failing both tests). In Figure D9 it is evident that the results from the TST with 4 x 4.5-in. test specimens are more consistent with the results from ASTM D559 than the TST with the 6 x 8-in. specimens. There are three cases with the smaller size TST samples in which the TST results did not exactly match the wet/dry results: limestone with 1.5% cement (marginal in the TST but passed wet/dry), caliche with 3% cement (passed the TST but had a weight loss of 14% in wet/dry testing), and recycled concrete with 4.5% cement (passed the TST but failed wet/dry testing). However, all three of these instances were on the border line of the test criteria, whereas the three 6 x 8-inch TST specimens in the upper left quadrant of Figure D9 clearly passed TST criteria but clearly failed ASTM D559. In addition, two more of the 6 x 8-in. TST results are on the border line. The caliche with 3% cement passed the TST but had a weight loss of 14% in ASTM D559. The recycled material with 4.5% cement passed the TST but had a weight loss of 15% in ASTM D559. Clearly then the TST results from the smaller sample size were better predictors of ASTM D559 results.

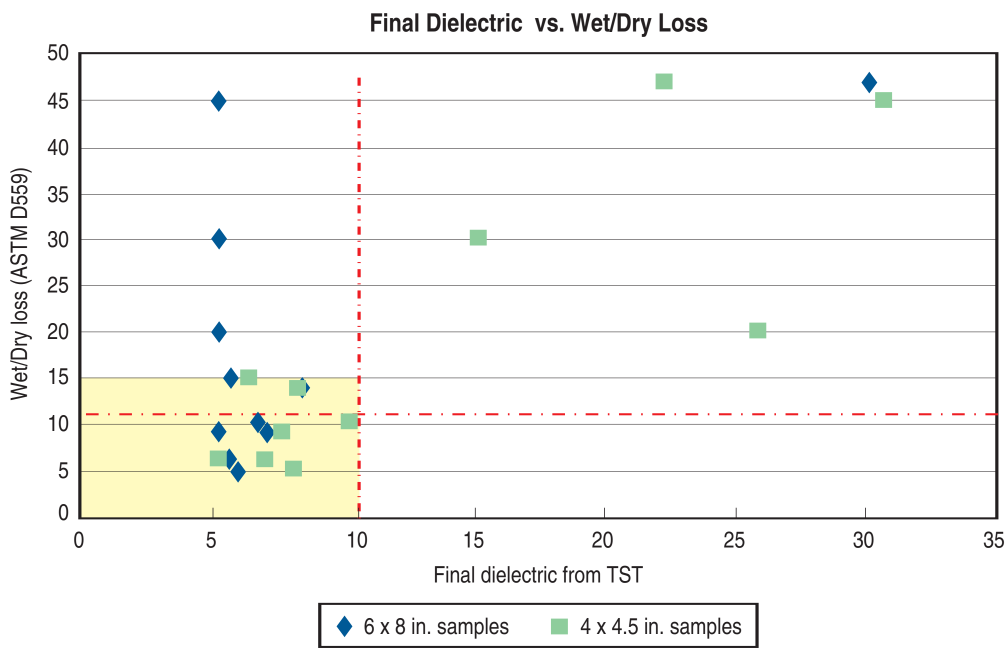


Figure D9. TST results with wet/dry durability test results.
Note: Shaded area is acceptance region.

Figure D10 illustrates that the results from the TST with 4 x 4.5-in. test specimens were reliable for predicting whether a material would pass the freeze/thaw durability test. All of the results from these specimens are either in the lower left or upper right quadrant, indicating that if the material passed the TST it likewise passed the PCA requirements from ASTM D560, and if TST criteria were not met the criteria for durability from ASTM D560 were likewise not met. This was not the case with the 6 x 8-in. TST samples. Three samples (Yoakum with 1.5% cement and recycled concrete with 3% and 4.5% cement) clearly passed the TST but clearly failed the PCA criteria for durability in ASTM D560.

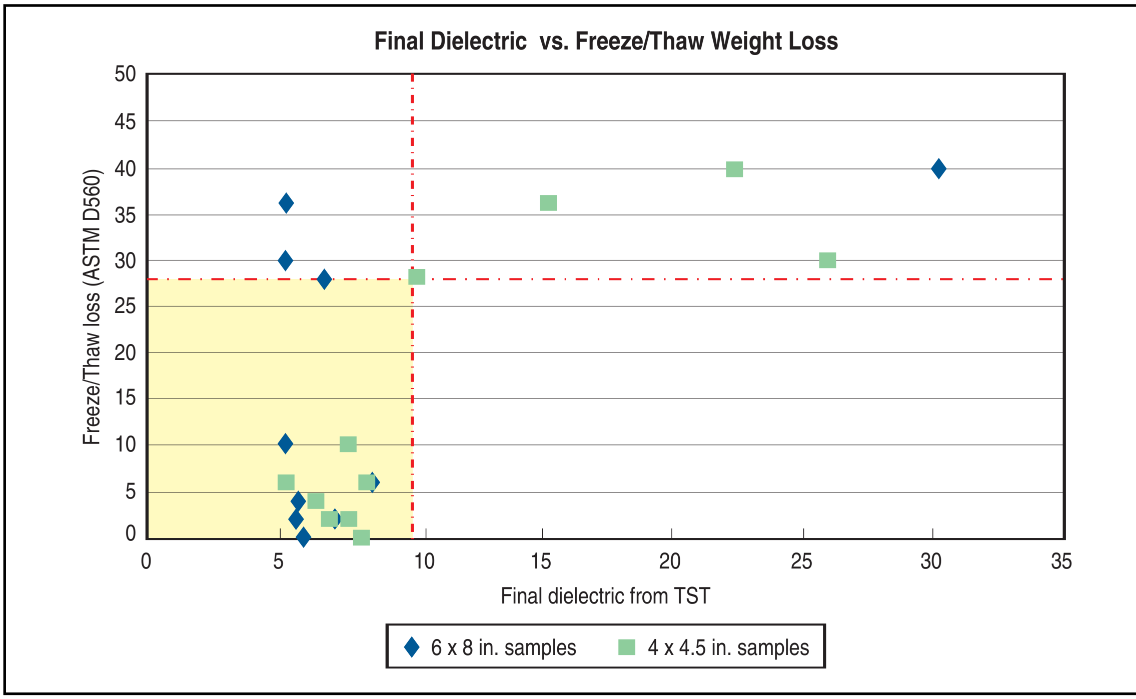


Figure D10. TST results with freeze/thaw durability test results.
Note: Shaded area is the acceptance region.

The data presented above have illustrated that the Tube Suction Test can serve as a reliable substitute for traditional durability testing. If the objective of performing the TST is to replace ASTM D559 and ASTM D560, then a sample size of 4 x 4.5 in. in the Tube Suction Test is recommended. TST results of specimens this size were found to be accurate for determining whether a material would pass or fail the traditional durability tests. If the final dielectric value of the material after the TST was less than 10, then traditional durability testing criteria were met. When the final dielectric value from the TST was greater than 10, criteria for durability were not met. In addition, the TST has the added benefit of eliminating the operator error inherent in the brushing cycles of ASTM D559 and D560. Since the TST results are well correlated to the results of traditional durability tests, the TST is much simpler to perform, and the TST has much less potential for operator error, it is suggested that the TST be considered as a replacement test for ASTM D559 and ASTM D560.

APPENDIX E
CHEMICAL ANALYSIS OF FM 20 SUBGRADE

The mineralogy of soils from FM 20 near San Antonio has been determined using the procedures recommended by Jackson (1969). We started with 50.3 g of air-dried soil in site 1 and recovered 39.5 g (78.5% recovery) after chemical pretreatments. There are 6.9 g of sand, 12.1 g silt, 5.8 g of coarse clay, and 14.7 g of fine clay.

This sample is dark brown, mottled with white calcium carbonate concretions. The USDA/NRCS textural classification for this sample is a clay, with 51.7% of the sample being composed of clay-sized particles, 30.7% silt-sized, and 17.5% in the sand-size range. This sample has approximately 4.7% moisture.

Site 1 from FM 20 reveals the sand size fraction as being composed of quartz, according to the X-ray diffraction pattern. However, if there are other minerals present in concentrations below about 5% then they may not show up in the X-ray results. The silt fraction is composed of quartz with minor feldspar. The coarse clay consists of kaolinite, illite, and smectite. The fine clay is predominantly interstratified smectite/illite and minor kaolinite.

In site 2, we started with 57.0 g of air-dried soil and after the chemical pretreatments, 40.3 g of sand, silt, and clay were recovered. There are 4.5 g of sand, 19.5 g of silt, 3.4 g of coarse clay, and 12.9 g of fine clay. Thirty percent of the material was lost during chemical pretreatments. Material lost or removed includes calcite concretions, organic matter, possible iron sulfides, and manganese oxides.

This sample is light to dark brown, and mottled with white calcium carbonate concretions. The USDA/NRCS textural classification for this sample is a silty clay, with 40.5% of the sample being composed of clay-sized particles, 48.4% silt sized and 11.2% in the sand size range. This sample has approximately 5.6% moisture.

The sand and silt fractions for site 2 consist of quartz with minor feldspar. The coarse clay is composed of smectite, illite, and kaolinite. The fine clay is dominated by smectite, with lower concentrations of illite and kaolinite .

Table E1. Results of Sample Size Fractionation of Subgrade Soils

Sample Name	Size Fraction	Weight Percent
FM 20 Site 1	Sand	17.5
	Silt	30.7
	Coarse Clay	14.6
	Fine Clay	37.2
FM 20 Site 2	Sand	11.2
	Silt	48.4
	Coarse Clay	8.3
	Fine Clay	32.1

SCANNING ELECTRON MICROSCOPY

Physical testing of soil located on FM 1343, west of San Antonio, Texas, revealed a difference in performance between lime and cement stabilization. The material had been pulverized, and we initially thought that cement performed better due to a lowering of the PI due to pulverizing coarse-grained rocks. We checked the PIs, and they were virtually unchanged from the raw soil before pulverization. At this point we decided to use the scanning electron microscope (SEM) at Texas A&M University to look for differences in the stabilized and unstabilized soil.

The 3% lime-stabilized material was compared with the 3% cement-stabilized soil. The only difference observed with the SEM is that the lime (Figure E1) appears to have higher permeability because the soil particles look like they form in small aggregates. The cement-treated soil does not have this appearance (Figure E2). The stabilizer content was too low to see any differences in sample chemistry.

CONCLUSIONS AND RECOMMENDATIONS

From examining natural materials with low stabilizer concentrations, we determined that it was extremely difficult to quantify reactions that may be occurring due to chemical stabilization. We therefore recommend making experimental samples composed of pure materials. These samples then will be stabilized with lime and cement to see what reaction products can be measured.

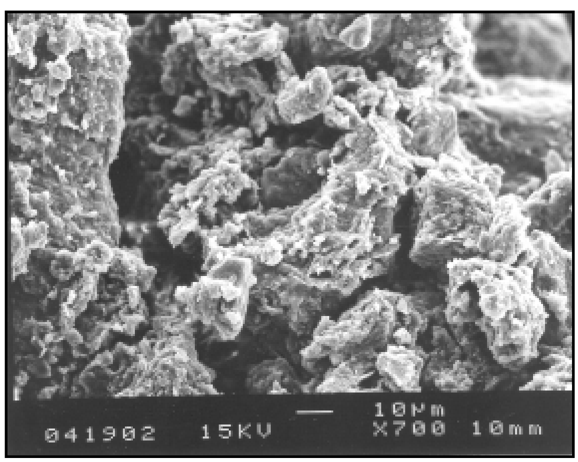


Figure E1. FM 1343 pulverized with 3% lime. (IMG15493)

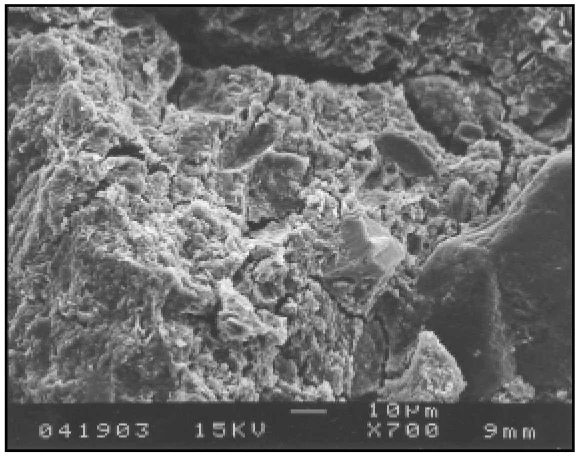


Figure E2. FM 1343 pulverized with 3% cement. (IMG15494)

APPENDIX F
EFFECT OF SLURRY MIXING TIME ON LABORATORY PROPERTIES

INTRODUCTION

This section investigates how cement-modified soil properties are affected by slurry mixing time. In these tests the slurry was continuously agitated before applying it to the soil. By testing in this manner, the cement will not be able to settle out but will have time to start hydrating before being applied to the soil. It is expected that performance will go down with longer time intervals between initial preparation of the slurry and its application.

The soil from FM 20 was used for this analysis. It has a PI of 28 and Level 1 pulverization was used, (100% passing 3/4 in. sieve). Sample preparation was identical to that reported in Chapter 4 for slurry stabilization. The slurry was applied to soil at 10% moisture content, except that specimens were prepared with slurry ages of five minutes, one hour, two hours, and four hours. The soil at 10% moisture content was stabilized with 6% cement and evaluated using 21-day unconfined compressive strength (UCS), moisture susceptibility (TST) followed by UCS determination, and 7-day UCS. The specimens prepared with slurry that was five minutes old before being applied to the soil were used as the baseline in the evaluation.

RESULT

The results from the testing with the different mixing times of the cement slurry are in Table F1. As expected, curing-only strengths declined with longer time intervals between slurry preparation and application. However, the TST results were peculiar in that specimens prepared with a one-hour and two-hour old slurry failed the test, yet the four-hour mixing time sample did not fail this test. However the trend observed was that longer mixing times resulted in the lower strength value at the conclusion of the Tube Suction Test. It is interesting to note that all samples, except the one-hour mixing sample, met the 80% retained strength criteria (after TST/7-day strength).

Table F1. Results from Slurry Age Evaluation

Mixing Time	21-day UCS (psi)	Final ε	UCS after Tube Suction Test (psi)	UCS after Tube Suction Test as Percent of 7-day UCS	7-day UCS (psi)
5 minutes	592	12.7	471	101	467
1 hour	569	30.8	343	72	472
2 hours	539	25.8	379	94	401
4 hours	529	12.8	307	81	379

ANALYSIS OF RESULTS

Unconfined Compressive Strength after 21 Days Curing

With 21 days of curing, the strength of the samples linearly decreased up to the slurry age of two hours then started to level off slightly. There was an 11% decrease in strength between the slurry age of five minutes and slurry age of four hours. This change is not really very drastic. Figure F1 shows the results from the 21 days curing tests.

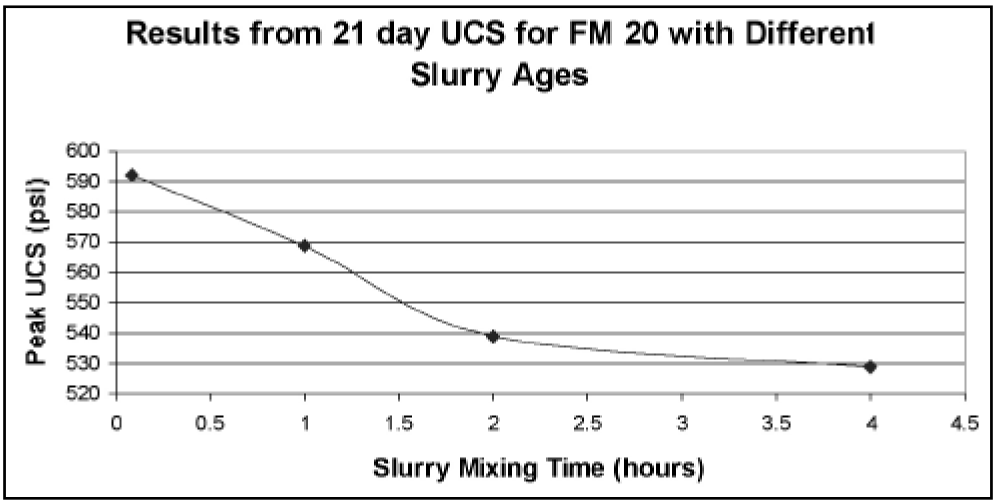


Figure F1. Twenty-one day curing strength values.

Tube Suction Test after 7 Days Curing, Followed by UCS Determination

In the TST, both the one-hour and two-hour old slurries led to unacceptable performance. These specimens became wet throughout the sample and had a greater than 20% loss in strength as compared to the strength after the test when specimens were stabilized by a five-minute-old slurry. With a slurry age of four hours, a 35% loss in strength as compared to the five-minute mixing time resulted, yet the sample prepared with this procedure passed the TST. The reason for this is not known with certainty, as it would seem a loss in strength would indicate poorer stabilization. This sample did, however, draw water much nearer to its surface than the specimen stabilized with slurry that was five minutes old (see Figure F2).

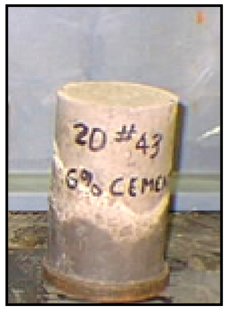


Figure F2. Specimens After the Tube Suction Test stabilized with 5-minute old slurry (left) vs. four-hour old slurry (right). (IMG15496)

Using the five-minute slurry age as a baseline to compare to, the final surface dielectrics are in Figure F3, and strengths after the TST as a percentage of the strengths from the five minute-old slurry are in Figure F4. All of the decreases in performance in the TST with higher slurry age were significant. Losses in strength between 20% and 35%, and decreasing resistance to moisture infiltration mean that cement slurry should be applied to the soil as soon as possible after slurry preparation.

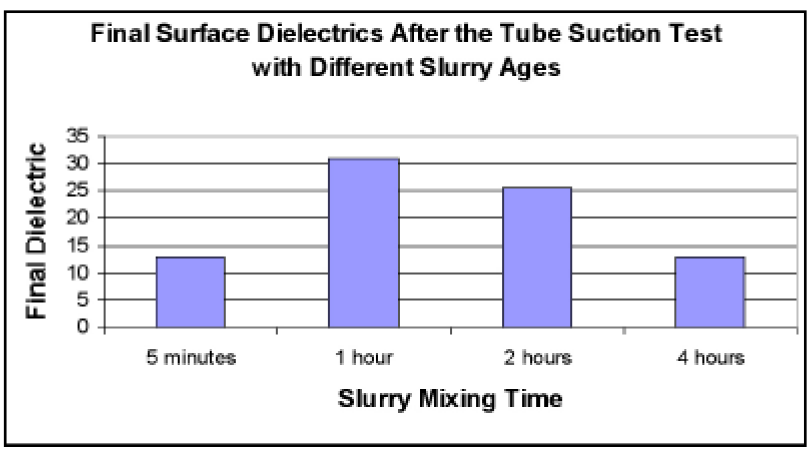


Figure F3. Final surface dielectrics After the Tube Suction Test.

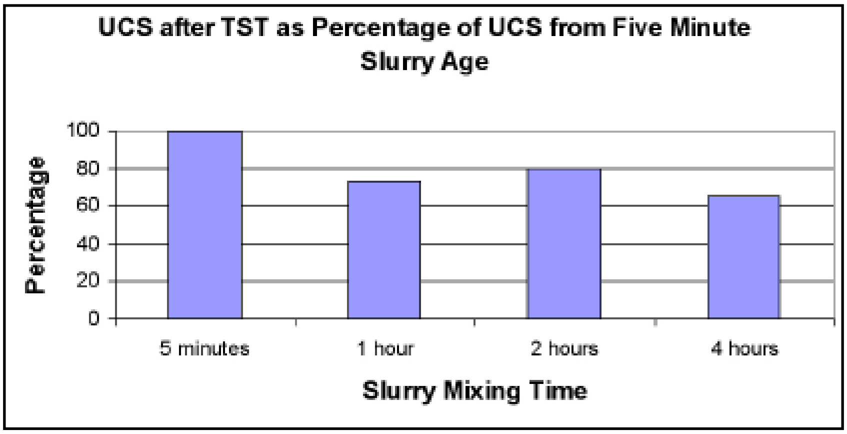


Figure F4. Strengths after the Tube Suction Test as a percentage of strength from the five-minute-old slurry.

Unconfined Compressive Strength after 7 Days Curing

With 7 days of curing, there was basically no difference in strength between samples prepared with a five-minute-old slurry and those prepared with a one-hour-old slurry. At an age of two hours, strength decreased by 14%, and with a slurry age of four hours, strength decreased by 19%. These results are in Figure F5 and appear to indicate that, while still in the early stages of hydration, a one-hour mixing time is acceptable. However, as was indicated by the other two testing procedures employed, which lasted for 21 days, the performance of the stabilization when slurry is mixed for longer continuously drops off.

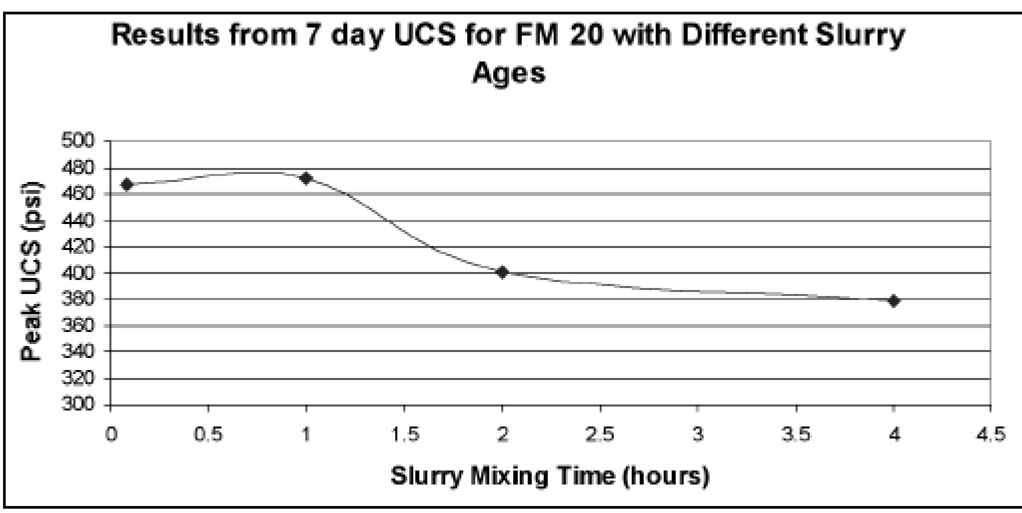


Figure F5. Seven-day cure strength values.

CONCLUSIONS

Based on this analysis, cement slurry should be applied to and mixed with the soil as soon as possible after slurry preparation. However, it is important to point out that even after four hours of continuous mixing, reasonable laboratory properties were obtained. As shown in Table F5, the CMS sample with a slurry, which had been mixed for 4 hours, had a 7-day strength of 379 psi, a 21-day strength of 529 psi, and still retained over 80% of its 7-day strength after the TST. Therefore, for all practical purposes, the laboratory properties were not severely impacted by extended slurry mixing times.

APPENDIX G
EVALUATION OF SLURRY SETTLING TIME WITH NO AGITATION

INTRODUCTION

The aim of this test program was to determine an approximate maximum time interval between the mixing and pumping of unagitated cement slurry. No standard tests were found in the literature to assess this in the laboratory. Therefore, it was decided to run two fairly simple tests on slurries left for different rest periods. These were:

- visual observation, noting the amount of free water at the top of a cyclinder of slurry, and
- a simple flow test, as described below.

To perform the flow test, a 5/16-in. hole was drilled at the bottom of a 4-in. diameter by 8-in. tall plastic mold and corked. A cement slurry of 1626 g consisting of 813 g portland type I cement and 813 g water was mixed and poured into the mold. This was done for settling tests at time intervals of 5 minutes, 15 minutes, 30 minutes, 1 hour, 2 hours, and 19 hours. The mixing procedure for the cement slurry is illustrated in Figure G1.

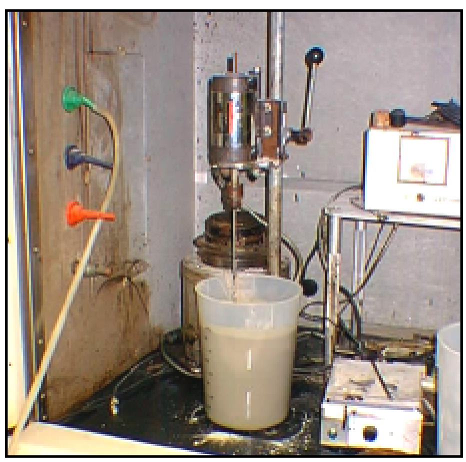


Figure G1. Cement slurry being mixed in preparation for settling time test. (IMG15497)

After the slurry was mixed, poured into the corked mold, and allowed to settle for the appropriate settling test time, the cork was pulled and the slurry allowed to drain on its own into a pan filled with sand. When flow had ceased, the mold was re-corked; the height of the sludge remaining in the mold was recorded (at its highest point), and the weight of the sludge remaining was recorded. Figure G2 is a photograph of the setup for this test, and Figure G3 shows the test in progress.

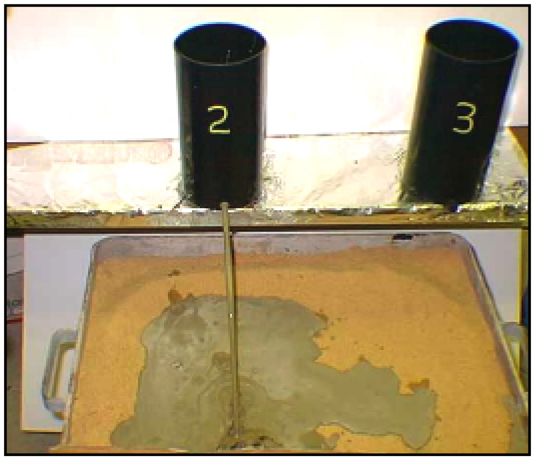


Figure G2. Setup for the cement slurry settling time falling head flow-meter. (IMG15498)

Figure G3. Cement sslurry settling time falling head flow-meter testing in progress. (IMG15499)

RESULTS

The results from the Cement Slurry Settling Time Falling Head Flow-meter indicated that, of the settling times evaluated, 30 minutes was the maximum time interval between mixing and pumping in which acceptable pumping would be expected if the slurry was not agitated after its initial mixing. After settling for one hour, the slurry at the bottom was noticeably thick, and approximately the last third of the slurry to drain out was clearly more watery and diluted. The amount of sludge remaining at the end of the test for the one-hour settling time was also more than double the amount of sludge remaining after 30 minutes settling time. Although this is not evident in the photographs, Figure G4 shows the amount of sludge remaining in the flow-meter test cells with the slurry that had been allowed to settle for 30 minutes versus the slurry that settled for 1 hour. However, as Figure G5 shows, it is obvious that there is an exponential jump in the amount of sludge remaining between the 30 minute settling time and the 1 hour settling time.

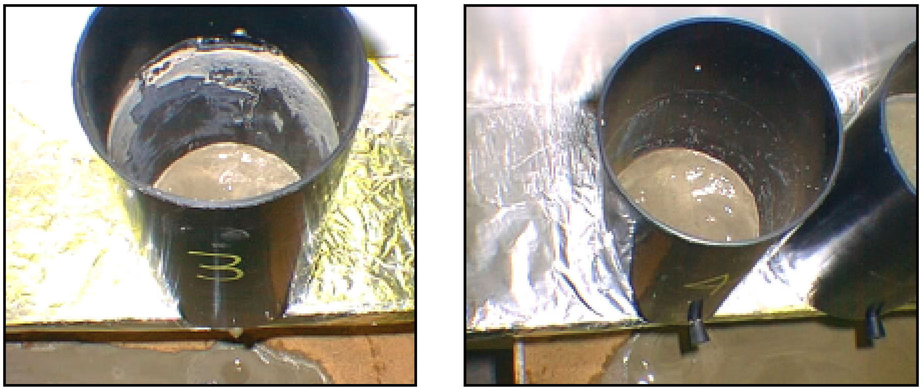


Figure G4. Sludge remaining in test Cells from 30-minute (left) and 1-hour (right) slurry settling time tests. (IMG15500)

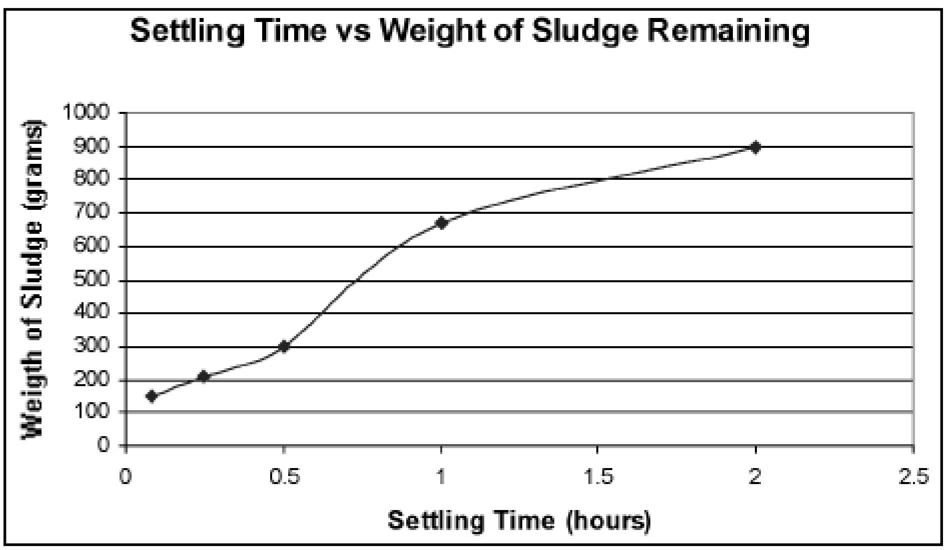
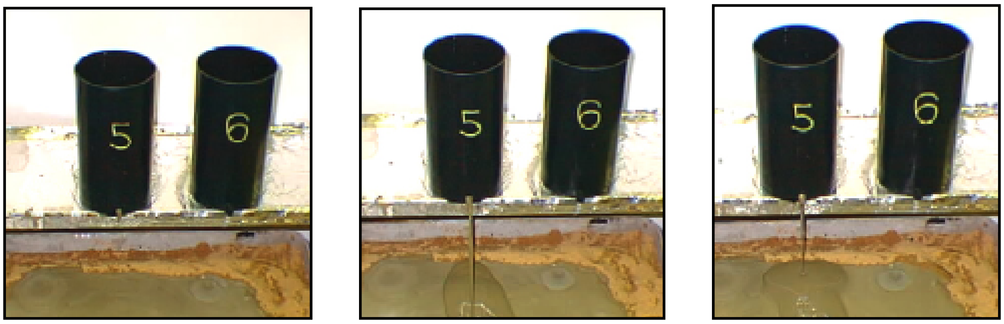


Figure G5. Weight of sludge remaining at the end of the cement slurry settling time falling head flow-meter testing.

With two hours of settling time, the slurry would barely drain at first, then less viscous fluid quickly drained, then more sludge dripped out, then less viscous fluid again, until finally the drain hole clogged with sludge. Two hours with no agitation is definitely too long for a cement slurry to sit. Figure C6 illustrates the flow of the slurry during the testing with two hours of settling time. The complete results from the Cement Slurry Settling Time Falling Head Flow-meter are in Table G1.



Immediately after pulling the plug | Five seconds after pulling the plug | 25 seconds after pulling the plug

Figure G6. Sequence of events for slurry with two hours settling time. Note: Flow stopped after one minute. (IMG15501)

Table G1. Results from the Cement Slurry Settling Time Falling Head Flow-meter

Settling Time	Weight of Sludge Remaining (grams)	Height of Sludge Remaining (inches at highest point)
5 minutes	147	0.5
15 minutes	212	0.75
30 minutes	299	1.2
1 hour	669	1.9
2 hours	899	3.5
19 hours	1599 (27 g lost to evaporation)	--cement set up: no flow took place--

SUMMARY AND SUGGESTED FUTURE WORK

A new test procedure, the Cement Slurry Flow-meter testing procedure, worked very well for evaluating the working time available with a cement slurry, mixed one part portland type I cement to one part water (by weight), when the cement slurry is not agitated. At this mixing ratio, 30 minutes was the maximum time the slurry could be left before pumping, if not agitated. At one hour of settling time, the slurry was starting to separate out into sludge and water, plus the amount of sludge remaining in the flow-meter test cell after 1 hour settling time was more than twice that left from the 30 minute settling time. At two hours of settling time, the slurry was clearly no longer a homogenous mixture, as the fluid coming out of the flow-meter test cell with this settling time would alternate between thick sludge and opaque water.

It is suggested that this test procedure be carried out with a variety of cement water ratios to better investigate the possible situations that could be encountered in the field. Guidelines for the time interval between mixing and application should be established for different cement:water ratios. This would aid contractors when mixing and using cement slurry in the field and help them reduce problems due to settling that may be encountered during pumping.

APPENDIX H
SAMPLE PREPARATION AND TESTING METHODS APPLIED TO DRY SOIL

The procedures described below were used as the starting point for the evaluation of the CMS. For each procedure, stabilizer was applied dry to dry soil in the mixing process. Three testing procedures were used to evaluate the soil performance.

7- then 21-day UCS

The purpose of this testing procedure was to obtain the UCS of the stabilized test specimens after 7 days curing time. This test was chosen because TxDOT uses 7-day strengths when evaluating materials. These specimens were also retested at 21 days to test for "fracture healing."

- Add dry stabilizer to dry soil and mix for 5 minutes in laboratory mixer.
- Bring to optimal moisture content by slowly adding required water to sample while mixing; continue mixing for 10 additional minutes.
- Mold specimen (4¥6) with 4 lifts of 25 blows per lift; 12-in. drop height.
- Trim molded specimen to 6-in. height.
- Weigh specimen plus mold.
- Extrude specimen from mold.
- Place in 100% humidity environment for 7 days curing.
- After 7 days curing, test for unconfined compressive strength.
- Place sample back in 100% humidity environment for 14 more days.
- Test for unconfined compressive strength.

7-day Cure Tube Suction Test

This test was used to evaluate the specimens' susceptibility to moisture infiltration as measured by the TST. Specimens were allowed to cure 7 days to bring them to the curing conditions typically used by TxDOT before testing; then procedures for the TST were begun. The TST is used as a predictor of material performance in the presence of available water and uses the surface dielectric value as the evaluation method (Scullion and Saarenketo, 1997).

- Add dry stabilizer to dry soil and mix for 5 minutes in laboratory mixer.
- Bring to optimal moisture content by slowly adding required water to the sample while mixing, then continue mixing for 10 additional minutes.
- Mold specimen (4¥6) with 4 lifts of 25 blows per lift; 12-in. drop height.
- Trim molded specimen to 6-in. height.
- Weigh specimen plus mold.
- Extrude specimen from mold.
- Place in 100%humidity environment for 7 days curing.

- After 7 days curing, air dry the sample for 4 days (this was to avoid excessive cracking).
- Run standard 10 day tube suction test for stabilized material.
- Test for unconfined compressive strength at the completion of the tube suction test.

21-day Control

Specimens were tested for strength after 21 days to have a baseline to compare strengths to those obtained after the TST. By using 21-day strengths, the specimens from the TST procedure and the 21-day curing procedure are at the same age when strength tested.

- Add dry stabilizer to dry soil, and mix for 5 minutes in laboratory mixer.
- Bring to optimal moisture content by slowly adding required water to the sample while mixing; continue mixing for 10 additional minutes.
- Mold specimen (4¥6) with 4 lifts of 25 blows per lift; 12-in. drop height.
- Trim molded specimen to 6-in. height.
- Weigh specimen plus mold.
- Extrude specimen from mold.
- Place in 100% humidity environment for 21 days curing.
- After 21 days curing, test for unconfined compressive strength.

APPLIED TO SOIL AT 10% MOISTURE CONTENT

The second phase of the testing of the soils was aimed at determining how soil performance was affected when the stabilizer was applied to soil that more accurately reflected field conditions; i.e. already containing moisture. It was suspected that adding stabilizer to a soil that already had moisture in it would result in better performance. We suggest this occurs because dry soil has clods in it that are not broken up when the stabilizer is mixed in, resulting in incomplete distribution of the stabilizer in the sample. By mixing the stabilizer in with a moist soil, clods are broken up, and better distribution should be achieved.

7- then 21-day UCS

The purpose of this testing procedure was to obtain the unconfined compressive strength of the stabilized test specimens after 7 days curing time. This test was chosen because TxDOT uses 7-day strengths when evaluating materials. These specimens were also retested at 21 days to test for "fracture healing."

- Starting with dry soil, slowly mix in the required amount of water to bring the soil to 10% moisture content.
- Place the soil in a sealed plastic bag and allow it to sit for 24 hours to allow moisture to be adsorbed uniformly throughout the soil.
- After the 24-hour soaking period, place the soil in a container for laboratory mixing.

- Add the required amount of dry stabilizer to the soil, and mix for 5 minutes in a laboratory mixer.
- While still mixing, slowly add the remaining amount of water to bring the soil to optimal molding moisture; mix an additional 10 minutes.
- Mold specimen (4¥6) with 4 lifts of 25 blows per lift; 12-in. drop height.
- Trim molded specimen to 6-in. height.
- Weigh specimen plus mold.
- Extrude specimen from mold.
- Place in 100% humidity environment for 7 days curing.
- After 7 days curing, test for unconfined compressive strength.
- Place the sample back in 100% humidity environment for 14 more days.
- Test for unconfined compressive strength.

7-day Cure Tube Suction Test

This test was used to evaluate the specimens' susceptibility to moisture infiltration as measured by the TST. Specimens were allowed to cure 7 days to bring them to the curing conditions typically used by TxDOT before testing, then procedures for the TST were begun. Based on the research of Tom Scullion and Timo Saarenketo, the TST is used as a predictor of material performance in the presence of available water and uses the surface dielectric value as the evaluation method.

- Starting with dry soil, slowly mix in the required amount of water to bring the soil to 10% moisture content.
- Place the soil in a sealed plastic bag and allow it to sit for 24 hours in order to allow moisture to be adsorbed uniformly throughout the soil.
- After the 24-hour soaking period, place the soil in a container for laboratory mixing.
- Add the required amount of dry stabilizer to the soil and mix for 5 minutes in a laboratory mixer.
- While still mixing, slowly add the remaining amount of water to bring the soil to optimal molding moisture, then mix an additional 10 minutes.
- Mold specimen (4¥6) with 4 lifts of 25 blows per lift; 12-in. drop height.
- Trim molded specimen to 6-in. height.
- Weigh specimen plus mold.
- Extrude specimen from mold.
- Place in 100% humidity environment for 7 days curing.
- After 7 days curing, air dry the sample for 4 days (this was to avoid excessive cracking).
- Run standard 10-day TST for stabilized material.
- Test for unconfined compressive strength at the completion of the TST.

21-day Control

Specimens were tested for strength after 21 days to have a baseline to compare strengths to after the TST. By using 21-day strengths, the specimens from the TST procedure and the 21-day curing procedure are at the same age when strength tested.

- Starting with dry soil, slowly mix in the required amount of water to bring the soil to 10% moisture content.
- Place the soil in a sealed plastic bag and allow to sit for 24 hours in order to allow moisture to be adsorbed uniformly throughout the soil.
- After the 24-hour soaking period, place the soil in a container for laboratory mixing.
- Add the required amount of dry stabilizer to the soil and mix for 5 minutes in a laboratory mixer.
- While still mixing, slowly add the remaining amount of water to bring the soil to optimal molding moisture, then mix an additional 10 minutes.
- Mold specimen (4¥6) with 4 lifts of 25 blows per lift; 12-in. drop height.
- Trim molded specimen to 6-inches height.
- Weigh specimen plus mold.
- Extrude specimen from mold.
- Place in 100% humidity environment for 21 days curing.
- After 21 days curing, test for unconfined compressive strength.

APPLIED BY SLURRY TO SOIL AT 10% MOISTURE CONTENT

These procedures were used to investigate the performance of the soil when stabilizer was applied by slurry. Not only does slurry application help eliminate dusting problems, it has been noted that the application of lime by slurry results in better distribution (Little 1995). Since preliminary testing had suggested cement stabilization was more effective when applied by slurry, specimens prepared by slurry were tested for comparison purposes with results obtained through dry application of stabilizer. Cement slurry was 50% cement and 50% water, by mass; lime slurry was 35% lime, and 65% water, by mass.

7- then 21-day UCS

The purpose of this testing procedure was to obtain the unconfined compressive strength of the stabilized test specimens after 7 days curing time. This test was chosen because TxDOT uses 7-day strengths when evaluating materials. These specimens were also retested at 21 days to test for "fracture healing."

- Starting with dry soil, slowly mix in the required amount of water to bring the soil to 10% moisture content.
- Place the soil in a sealed plastic bag and allow to sit for 24 hours in order to allow moisture to be adsorbed uniformly throughout the soil.
- After the 24-hour soaking period, place the soil in a container for laboratory mixing.

- Mix a slurry with the required amount of stabilizer in it, and add it to the soil.
- Mix the soil/slurry combination for 5 minutes in a laboratory mixer.
- While still mixing, slowly add the remaining amount of water to bring the soil to optimal molding moisture; mix an additional 10 minutes.
- Mold specimen (4¥6) with 4 lifts of 25 blows per lift; 12-in. drop height.
- Trim molded specimen to 6-in. height.
- Weigh specimen plus mold.
- Extrude specimen from mold.
- Place in 100% humidity environment for 7 days curing.
- After 7 days curing, test for unconfined compressive strength.
- Place sample back in 100% humidity environment for 14 more days.
- Test for unconfined compressive strength.

7-day Cure Tube Suction Test

This test was used to evaluate specimens' susceptibility to moisture infiltration as measured by the TST. Specimens were allowed to cure 7 days to bring them to the curing conditions typically used by TxDOT before testing, then procedures for the TST were begun. The TST is used as a predictor of material performance in the presence of available water and uses the surface dielectric value as the evaluation method (Scullion and Saarenketo, 1997).

- Starting with dry soil, slowly mix in the required amount of water to bring the soil to 10% moisture content.
- Place the soil in a sealed plastic bag and allow it to sit for 24 hours in order to allow moisture to be adsorbed uniformly throughout the soil.
- After the 24-hour soaking period, place the soil in a container for laboratory mixing.
- Mix a slurry with the required amount of stabilizer and add it to the soil.
- Mix the soil/slurry combination for 5 minutes in a laboratory mixer.
- While still mixing, slowly add the remaining amount of water to bring the soil to optimal molding moisture; mix an additional 10 minutes.
- Mold specimen (4¥6) with 4 lifts of 25 blows per lift; 12-in. drop height.
- Trim molded specimen to 6-in. height.
- Weigh specimen plus mold.
- Extrude specimen from mold.
- Place in 100% humidity environment for 7-days curing.
- After 7 days curing, air dry the sample for 4 days (to avoid excessive cracking).
- Run standard 10-day TST for stabilized material.
- Test for unconfined compressive strength at the completion of the TST.

21-day Control

Specimens were tested for strength after 21 days to have a baseline to compare strengths to after the TST. By using 21-day strengths, the specimens from the TST procedure and the 21-day curing procedure are at the same age when strength tested.

- Starting with dry soil, slowly mix in the required amount of water to bring the soil to 10% moisture content.
- Place the soil in a sealed plastic bag and allow it to sit for 24 hours in order to allow moisture to be adsorbed uniformly throughout the soil.
- After the 24-hour soaking period, place the soil in a container for laboratory mixing.
- Mix a slurry with the required amount of stabilizer, and add it to the soil.
- Mix the soil/slurry combination for 5 minutes in a laboratory mixer.
- While still mixing, slowly add the remaining amount of water to bring the soil to optimal molding moisture; mix an additional 10 minutes.
- Mold specimen (4¥6) with 4 lifts of 25 blows per lift; 12-in. drop height.
- Trim molded specimen to 6-in. height.
- Weigh specimen plus mold.
- Extrude specimen from mold.
- Place in 100% humidity environment for 21 days curing.
- After 21 days curing, test for unconfined compressive strength.

METRIC CONVERSION FACTORS

The following list provides the conversion relationship between U.S. customary units and SI (International System) units. The proper conversion procedure is to multiply the specified value on the left (primarily U.S. customary values) by the conversion factor exactly as given below and then round to the appropriate number of significant digits desired. For example, to convert 11.4 ft to meters: 11.4 x 0.3048 = 3.47472, which rounds to 3.47 meters. Do not round either value before performing the multiplication, as accuracy would be reduced. A complete guide to the SI system and its use can be found in IEEE/ASTM SI-10, Metric Practice.

To convert from	to	multiply by
Length		
inch (in.)	micrometer (µm)	25,400 E*
inch (in.)	millimeter (mm)	25.4 E
inch (in.)	meter (m)	0.0254 E
foot (ft)	meter (m)	0.3048 E
yard (yd)	meter (m)	0.9144
Area		
square foot (ft^2) E	square meter (m^2)	0.09290304
square inch (in.^{2})	square millimeter (mm^2)	645.2 E
square inch (in.^{2}) E	square meter (m^2)	0.00064516
square yard (yd^2)	square meter (m^2)	0.8361274
Volume		
cubic inch (in.^{3})	cubic millimeter (mm^3)	16.387064
cubic inch (in.^{3})	cubic meter (m^3)	0.00001639
cubic foot (ft^3)	cubic meter (m^3)	0.02831685
cubic yard (yd^3)	cubic meter (m^3)	0.7645549
gallon (gal) U.S. liquid**	liter (L)	3.7854118
gallon (gal) U.S. liquid	cubic meter (m^3)	0.00378541
fluid ounce (fl oz)	milliliters (mL)	29.57353
fluid ounce (fl oz)	cubic meter (m^3)	0.00002957
Force		
kip (1000 lb)	kilogram (kg)	453.6
kip (1000 lb)	newton (N)	4,448.222
pound (lb) avoirdupois	kilogram (kg)	0.4535924
pound (lb)	newton (N)	4.448222
Pressure or stress		
pound per square foot (psf)	kilogram per square meter (kg/m^2)	4.8824
pound per square foot (psf)	pascal (Pa)†	47.88
pound per square inch (psi)	kilogram per square centimeter (kg/sq cm)	0.07031
pound per square inch (psi)	pascal (Pa)†	6,894.757
pound per square inch (psi)	megapascal (MPa)	0.00689476
Mass (weight)		
pound (lb) avoirdupois	kilogram (kg)	0.4535924
ton, 2000 lb	kilogram (kg)	907.1848
Mass (weight) per length		
kip per linear foot (klf)	kilogram per meter (kg/m)	0.001488
pound per linear foot (plf)	kilogram per meter (kg/m)	1.488
Mass per volume (density)		
pound per cubic foot (lb/ft^3)	kilogram per cubic meter (kg/m^3)	16.01846
pound per cubic yard (lb/yd^3)	kilogram per cubic meter (kg/m^3)	0.5933
Temperature		
degree Fahrenheit (°F)	degree Celsius (°C)	$t_C = (t_F - 32)/1.8$
degree Fahrenheit (°F)	degree Kelvin (°K)	$t_K = (t_F + 459.7)/1.8$
degree Kelvin (°K)	degree Celsius (°C)	$t_C = t_K - 273.15$
Energy and heat		
British thermal unit (Btu)	joule (J)	1055.056
calorie (cal)	joule (J)	4.1868 E
Btu/°F hr • ft^2	W/m^2 • °K	5.678263
kilowatt-hour (kwh)	joule (J)	3,600,000 E
British thermal unit per pound (Btu/lb)	calories per gram (cal/g)	0.55556
British thermal unit per hour (Btu/hr)	watt (W)	0.2930711
Permeability		
darcy	centimeter per second (cm/sec)	0.000968
feet per day (ft/day)	centimeter per second (cm/sec)	0.000352

* E indicates that the factor given is exact.
** One U.S. gallon equals 0.8327 Canadian gallon.
† A pascal equals 1.000 newton per square meter.

Note:
One U.S. gallon of water weighs 8.34 pounds (U.S.) at 60°F.
One cubic foot of water weighs 62.4 pounds (U.S.).
One milliliter of water has a mass of 1 gram and has a volume of one cubic centimeter.
One U.S. bag of cement weighs 94 lb.
The prefixes and symbols listed below are commonly used to form names and symbols of the decimal multiples and submultiples of the SI units.

Multiplication Factor	Prefix	Symbol
1,000,000,000 = 10^9	giga	G
1,000,000 = 10^6	mega	M
1,000 = 10^3	kilo	k
1 = 1	—	—
0.01 = 10^{-2}	centi	c
0.001 = 10^{-3}	milli	m
0.000001 = 10^{-6}	micro	µ
0.000000001 = 10^{-9}	nano	n

PCA Portland Cement Association

5420 Old Orchard Road
Skokie, Illinois 60077-1083 USA

847.966.6200
Fax: 847.966.9781
Internet: www.cement.org

An organization of cement companies to improve and extend the uses of portland cement and concrete through market development, engineering, research, education, and public affairs work.

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