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16. Abstract

The instability and pumping response of non-plastic, high silt (and fine sand) soils was investigated. Common reagents, i.e., lime, lime-fly ash, Portland cement, and slag cement were included as admixtures with three high silt (and fine sand) soils. A series of laboratory tests simulated the moisture and loading conditions for 1) subgrade construction operations and 2) longer term, in service support of the completed pavement. Comparisons were based on the performance of mixtures with equal material costs. The improvements were found to vary with the reagent’s character, the mix proportion, and the role required, i.e., construction aid (modification) or in service performance (stabilization).

The reagents act as a drying agent during construction but, for the percentages used, produced only a small reduction in the original moisture content of the natural soil and only small increases in the plastic or cohesive character. For initial moisture contents up to +4 percent wet of optimum, smaller levels of reagents were sufficient to retard or eliminate deformation under low cyclic loads but extremely wet soils (4 to 8 percent of optimum) required larger volumes of reagents.

For long term stability and greater increases in strength, the cements followed by the lime-fly-ash produced the best results. Stabilization mixtures with reagents producing cementicious products (Portland cement) reduced the sensitivity of the soil to moisture changes.

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Identification and Stabilization Methods for Problematic Silt Soils: A Laboratory Evaluation of Modification and Stabilization Additives

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ABSTRACT

The instability and pumping response of non-plastic, high silt (and fine sand) soils was investigated. These soils are commonly encountered in the preparation of the subgrade for highway pavement projects in Louisiana. Common reagents, i.e., lime, lime-fly ash, Portland cement, and slag cement, used in stabilization and modification efforts were included as admixtures with three high silt (and fine sand) soils in the study. A series of laboratory tests simulated the moisture and loading conditions that these soils plus admixtures could experience during 1) subgrade construction operations and 2) longer term, in-service support of the completed pavement. Comparisons were based on the performance of mixtures with equal material costs. The improvements and advantages produced were found to vary with the reagent's character, the mix proportion, and the role required, i.e., construction aid (modification) or in-service performance (stabilization).

The reagents act as a drying agent during construction but, for the percentages used, produce only a small reduction in the initial moisture content of the natural or raw soil and only small increases in the plastic or cohesive character. For initial moisture contents that exceed the optimum value by only a few percentage points (+/- 4 percent wet of optimum), smaller levels of reagents (percent by volume) were sufficient to retard or even eliminate deformation under low cyclic loads but extremely wet soils (+/-8 percent optimum) required larger volumes of reagents to dry.

For long term stability and greatest increase in strength, the cements followed by the lime-fly ash produced the best results. Stabilization mixtures with reagents producing cementicious products (Portland cement) reduced the sensitivity of the soil to moisture changes.

ACKNOWLEDGEMENTS

Significant assistance and information was received from Mark Morvant at the Louisiana Transportation Research Center and the engineering and laboratory staff from the involved DOTD district offices. Their insight and experience provided guidance and focus to the study. Also, the classification and tube suction tests conducted by George Barbu at the University of New Orleans geotechnical laboratory and the cyclic-triaxial tests supervised by George Perkins of Soiltest Engineers, Inc. provided the experimental data necessary for the analysis.

IMPLEMENTATION STATEMENT

The selection of the reagents used should include consideration for compaction and construction support, and continuous in-service support for the pavement during wet seasons.

1. To achieve the compaction requirements and maintain the support of a stable subgrade surface during construction, a lime-fly ash or lime-cement combination should be considered for its ability to provide the advantages for drying a wet subgrade and its lower material costs.
2. A cementing or pozzolanic reagent should be used to improve in-place service performance and future increased moisture resistance.
3. Consideration should be given for utilizing the stabilized subgrade as a sub-base structural component in the design of the pavement.

The selection of the reagent(s) and mix percentages used to treat and/or stabilize the problematic (pumping) silty soils must also consider constructability questions involving blending and compaction. Further research to develop mixture guidelines in optimizing the modification and stabilization of the pumping silts for the reagents used in this study and others is recommended.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

INTRODUCTION

Many areas of Louisiana consist of soils with high silt contents, low strengths, and minimal bearing capacity. Construction traffic on these soils can cause detrimental pumping action when they are wet. These wet subgrades under Louisiana pavements cause both construction and in-service performance problems. These problem soils have had an influence on the Louisiana Department of Transportation and Development (DOTD) standard specification's definition of usable soils, i.e., a maximum of 65 percent silt content for embankments and a maximum of 60 percent for chemically stabilized bases. Soils that do not meet these requirements must be removed and replaced. However, replacement materials are not always readily available and are expensive when they must be hauled any significant distance. The solution to the construction problems that these soils pose has involved excavation and lime treatment. Special provisions are often included in the contract for chemical additives in lieu of undercutting.

The previous research on these soils further refined the description of the pumping problem and guidelines for the identification of problem silt-soil [1]. Secondary importance was given to the identification of alternate methods for stabilization. The study documented field experiences of the DOTD districts and included a testing program to investigate the nature of the problem, the character of the silt materials, and efforts to qualify their performance with modifying and stabilizing agents. Eight soil samples from four of the DOTD districts were used in that laboratory program. The soils were typical of those commonly encountered with a high silt content. Several were acquired from current projects in which pumping problems were occurring.

The basic characteristic-parameters of the natural samples were determined with standard laboratory tests. The response and stability of the natural silts at various moisture levels and compaction efforts was also tested. The susceptibility to pumping of the different samples was reviewed in terms of their physical characteristics. In addition to the silt content percentage, the plastic or cohesive character was noted as being significant during testing. Anomalies were also found to exist between the DOTD's earthwork specifications and the physical properties of the high silt-content soils.

The potential for the modification and stabilization of the problem silt soils was also studied in the initial investigation [1]. Laboratory tests were conducted with consideration of construction and possible post-construction conditions. A limited number of specific additives commonly used were selected considering their ability to dry the subgrade silts for compaction and provide the stability for a working table during the construction of the base and pavement. The additives selected included hydrated lime, Portland cement, and class C fly ash. Limited tests for evaluating long-term stability of the stabilized silt-subgrade with accelerated curing followed by vacuum-saturation conditions were also conducted. The stabilization tests provided qualitative information on the performance of each but did not provide a comparison of the advantages or preference of one reagent over another.

Current DOTD practice allows the contractor the flexibility to bid the job based on the need to treat the problem silts with as much as 10 percent lime by volume. This effort is conducted in order to dry the soil, eliminate the pumping action, and provide a stable subgrade for preparing the base. The permanence of the silt-subgrade during the extended period of construction activities and conditions, and the long-term performance of the subgrade in supporting the completed pavement is not addressed. The only role of the subgrade considered in current pavement design is to provide a working table to support the base during construction.

In order to address the questions concerning a comparison of the performance of other reagents for treating/stabilizing the problem silts and the impact that they may have on pavement design in the future, the investigation was extended to include limited laboratory tests that would address construction needs and long-term performance.

OBJECTIVES

The objectives of this research are to conduct a laboratory comparison of the performance of common modifying and/or stabilizing reagents 1) during construction operations and 2) as support for the in-service pavement.

SCOPE

This continuing investigation is focused on further development of the description of the problems and techniques for modifying and stabilizing soils with high silt content through

1. a laboratory evaluation of the improvements provided by modification and/or stabilization with lime, lime-fly ash, Portland cement, and a slag cement,
2. laboratory tests to simulate pumping conditions occurring with transient construction loads and when the problem silts are at elevated moisture contents, and
3. laboratory tests that address the stability of the subgrade when the pavement is in place and in service.

METHODOLOGY

Method of Investigation

The initial investigation involved a fact finding effort to identify and describe the problems and field experiences of the DOTD districts and contractors, and to develop a testing program for characterizing the silts with respect to their tendency to pump during compaction or when subjected to construction traffic after compaction. A laboratory program was developed to characterize the soils, further refine the description of the pumping problem, and a method was developed for identifying the problem soils in terms of their tendency to pump and evaluate the potential for modification or stabilization.

Testing Program

The original testing program focused on characterization of the pumping soils and the attributes contributing to their instability during compaction activities [1]. A second objective was to consider methods for modifying and stabilizing the natural soils 1) to prevent the pumping during compaction and 2) to improve the long-term performance of the subgrade.

This continuing investigation extends the testing program of the second objective, i.e., modification and stabilization. It involves a study of the selected reagents based on criteria established for the mixtures to be used that would provide a common and equal basis for comparison. The characteristics and performance of the selected mixtures were compared.

Soil Samples

The test specimens used in this investigation were fabricated from soil materials taken from the Lake Charles District 07 U.S. Highway 171 project, the site of the DOTD's Accelerated Load Facility (ALF) in West Baton Rouge, and the Natchitoches K2-1 soil acquired from the Alexandria District 08 that was used in the previous pumping investigation. The US 171 and K2-1 soils consisted of a high silt content with a low plasticity. The ALF soil was composed of 88 percent non-plastic, fine-sand and silt.

Reagents

The reagents used included hydrated lime, lime-fly ash (ASTM Class C), Portland cement, and a slag cement.

Reagents Used For Subgrade Study

Lime-	Hydrated lime (Hi Yield)
Fly Ash-	Class "C" Big River Industries
Cement-	Type 1 Portland (Lonestar)
Slag Cement-	Aucem (Lonestar) 50/50blend 50% Portland/50% slag

A basis for comparing different percentages of the various admixtures had to be established. The performance requirements and the comparison of mixture designs had to be based on specifications using a measure common to all. Thus, the mixture or percentages of reagents used were based on the material cost currently permitted in construction bids for the preparation of subgrades in the problem silts, i.e., 10 percent lime by volume. Thus, the comparison of the physical tests would be based on the performance of the mixtures of equal material costs and test conditions.

The mixtures used were selected as a being equivalent to the bulk costs of 10 percent lime by volume. The bulk unit costs of lime, fly ash, Portland cement, and slag cement at the time the mixtures were established were $65/ton-lime, $30/ton-fly ash, $75/ton-portland cement, and $70/ton-slag cement (50% slag/50%cement). The equivalent percentages based on construction practice and used in the tests were 10 percent lime by volume, 4 percent lime plus 7 percent fly ash, 3.2 percent portland cement, and 3.8 percent of 50/50 slag-cement, Appendix A.

Classification Tests

Gradation tests (DOTD TR 407) and Atterberg tests (DOTD TR428) were conducted on all samples. The soils were classified according to the AASHTO (DOTD TR 423 and ASTM D3282), the Unified Soil Classification System (ASTM D2487), and the Louisiana DOTD TR 423-89 textural classification chart.

Preparation and Compaction of Test Specimen

Laboratory compaction curves, optimum moisture, and maximum dry density of the soils were established using the standard Proctor compaction method (DOTD TR 418 Method - ASTM D698 and AASHTO T99, 12,375 ft-lbf/ft^3 or 590 kN-m/m^3).

Test specimens, with and without the reagents, were prepared using the standard

Proctor compaction method. However, in order to simulate the field conditions of a wet subgrade during compaction/ construction, test specimens for the cyclic load tests were compacted at moisture contents that were four and eight percent in excess of the optimum moisture content for the natural soil. The soil was mixed with water and allowed to slake for approximately one hour before adding the reagents. After the reagent mixtures were added, they were mixed and slaked for approximately one hour. The specimens were molded using the standard Proctor compaction effort. The specimens used in tests simulating construction conditions were tested immediately.

All stabilized specimens were cured under ambient conditions for 28 days. The curing period permitted any possible cementitious improvements and simulated long-term performance in service with the pavement. The testing then subjected the 28-day cured specimens to saturated conditions to simulate wet weather or high moisture situations.

Test specimens with the various chemical agents were also prepared for unconfined strength tests. These specimens were molded with a spring-loaded plunger and the Harvard Miniature Compaction Apparatus (described in ASTM D4609). The apparatus consists of a mold 1.3125 inches in diameter and 2.816 inches long with a volume of 1/454 cubic feet. The weight of the entire soil specimen produced is equal to the unit weight of the soil in pounds per feet cubed. Harvard compaction employs a kneading action in molding the specimens.

Undrained Strength Tests

Unconfined compressive strength tests (ASTM D2166 or AASHTO 208) were conducted on the 28-day cured, stabilized soil at the existing moisture content of the cured specimen and those subjected to vacuum saturation. The long-term stability or durability of the stabilization efforts was evaluated with the vacuum-saturation test included in ASTM C 593. After curing, test specimens were de-aired in vacuum for 30 minutes followed by total inundation in a saturation chamber. They were allowed to soak in the water-filled chamber for one hour. The vacuum-saturated specimen was then tested in the unconfined compression test.

Cyclic Triaxial Compression Tests

Cyclic triaxial tests, similar to ASTM D3999, were conducted to simulate transient wheel traffic on the silts. A chamber pressure of two psi simulating an overburden pressure was used. Test specimens were then subjected to a shearing stress equivalent to the anticipated wheel loads as a cyclic deviator stress, i.e., compression and extension loading. The cyclic loading ranged from 600 psf (4.2 psi) to 90 psf (0.625 psi) in an effort to duplicate an on-and-off 18 kip wheel load at the subgrade depth. The effectiveness of the treatment or stabilization effort was evaluated on the occurrence and extent of continuing deformation (creep) of the specimen under cyclic load.

The testing simulated field conditions of a wet subgrade during compaction/ construction and those of an in-service (saturated) stabilized subgrade. Test specimens, with and without the reagents, were compacted at four and eight percent wet of the optimum moisture content to simulate wet field conditions during construction.

Simulation of Construction Conditions - The test specimens simulating construction were compacted and tested immediately. In most cases, the specimens were tested at the “as molded” moisture contents. However, some of these were also saturated prior to conducting the cyclic triaxial test. In some cases, the drainage lines were left open to allow flow in or out of the test specimen. In other cases, the drainage lines were closed. The specimen moisture content did not change in the tests run with open drain lines on the non-saturated specimen. Thus, due to the rapid loading of the load cycles, the test mode is generally thought to be unconsolidated-undrained, UU. However, opportunity for drainage in and out of the sample with pore pressure release was possible on the open-drain tests.

Wet, Long-Term Pavement Service – The 28-day, stabilized test-specimens were saturated, then consolidated and tested in undrained conditions. In some cases the drainage lines were left opened as discussed for the “as molded” tests. The test mode is generally considered to be consolidated-undrained, CU, although drainage was possible in some tests.

Tube Suction Test

Since the resilient modulus of soil and granular layers is highly dependent on the moisture content, a moisture equilibrium model to account for the water accumulated in the subgrade and granular layers as a function of capillary moisture movement is required to evaluate the effect of a stabilized subgrade as a moisture cutoff or capillary break. A testing methodology has been developed which provides a performance-based measure for identifying subgrades/bases susceptible to moisture and for evaluating the effectiveness of stabilization treatments [2]. Research conducted by the Texas Transportation Institute has focused on using electrical properties for classification of strength properties, and it has produced the Tube Suction and Dielectric Test method to more directly measure the moisture sensitivity of aggregate and soil materials (and frost susceptibility in cold climate areas subjected to freeze-thaw cycles). The dielectric value (DV) is a measure of the volumetric moisture content and the state of molecular bonding in a material. Low DV indicates tightly absorbed and well-arranged water molecules and better strength properties. DV greater than 16 ms/cm indicates the presence of substantial "free" moisture. The Tube Suction Test was developed by the Finnish National Road Administration and the Texas Transportation Institute to determine the moisture susceptibility of granular base materials. The Tube Suction Test has been adopted to measure the effectiveness of stabilization efforts to reduce the moisture sensitivity of stabilized soils.

The test consists of monitoring the capillary rise of moisture within a 150-mm diameter by 200-mm high cylinder of compacted soil, Figure 1. A probe is used to measure the dielectric constant at the surface of the sample. Measurements of the dielectric constant are made over 14 to 21 days. The poorest performing soils are those that rapidly reach saturation and exhibit high surface dielectric values.

The dielectric constant is a measure of the "free" or unbound water. Water molecules adsorbed within a soil are distributed in layers around solid particles in an electrical capture zone. Capillary water molecules beyond this zone are considered unbound and can migrate within the soil. Results from studies demonstrate the value of dielectric constant influences both strength and deformation properties of base course aggregates. Soil suction is a measure of the soil's affinity for water. Permeability controls the moisture increase and migration within the aggregate layer. The higher the unbound water is, the higher the soil's dielectric value.

A graph of surface dielectric versus time is used in order to determine the performance classification. The dielectric values of dry aggregate particles generally are between four and six and the dielectric value of air is one. The values are on a low range for tightly bound water, about three or four, but much higher for unbound water. Aggregates with final dielectric values less than 10 demonstrate superior performance as base materials compared with aggregates for which the values are between 10 and 16.

In addition to conducting the test as described above, surface dielectric readings of the "as compacted" soil were also taken to measure the differences between the natural and treated soil.

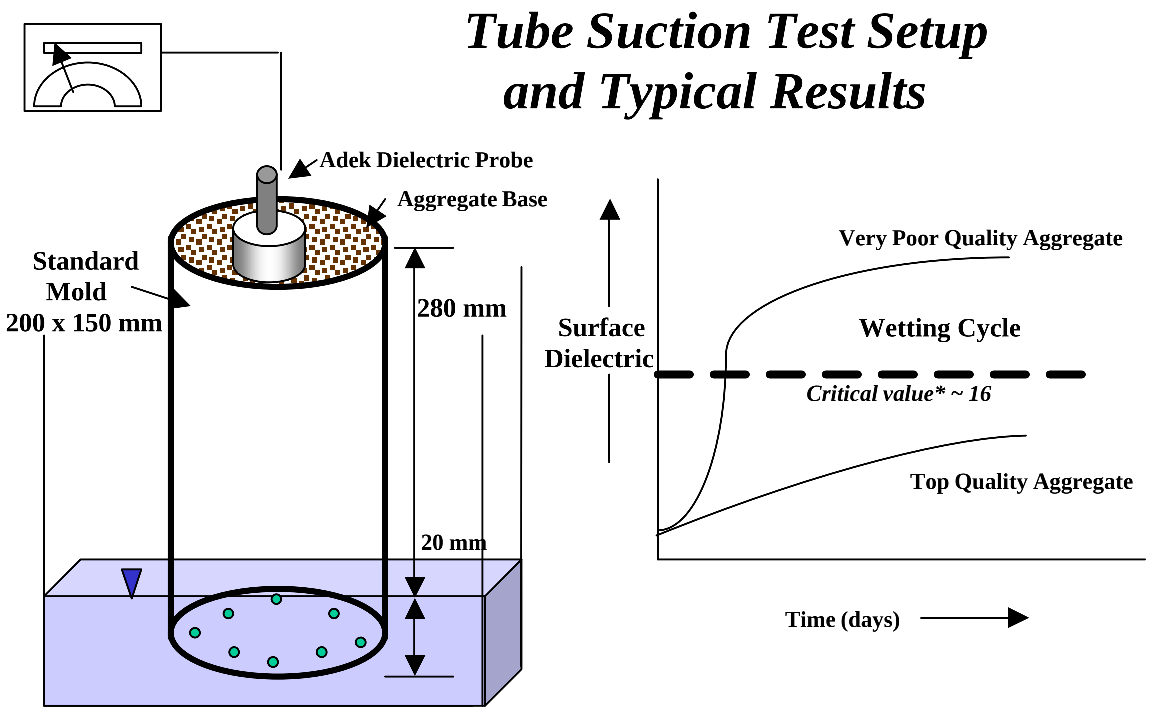

Figure 1
Tube suction test and typical results

DISCUSSION OF RESULTS

Classification Tests

A summary of the gradation for each of the soils tested in this study is shown in Table 1.

Table 1
Gradation characteristics of soils tested

SOIL	**% SAND**	**% SILT**	**% CLAY <2mm**
Highway US 171	14	75	11
Natchitoches K2-1	24	60	16
ALF	49	39	12

The US 171 and Natchitoches K2 soil had high silt contents in excess of 50 percent. The ALF silt content was 35 percent, which is less than the 50+ percent usually associated with a pumping soil. However, 99+ percent of the ALF soil passed the number 40 sieve. The high sand content of the ALF soil (49 percent) was a fine sand smaller than the number 40 sieve size (<0.42 mm). The combined fine-sand-silt content for the ALF soil was 88 percent. The fine-sand-silt content of the US 171 and Natchitoches K2 was 89 and 84 percent, respectively. The ALF is identified as border line loam- to sandy-loam and the US 171 and NatchitochesK2 are silty-loam soils according to the textural classification chart (DOTD TR 423-89). As noted in the previous study, the pumping problem is associated more so with a size range (fine-sand to silt) and the plastic character than with a specific soil type, i.e., silt. The term “silty” is commonly used with fine materials having a PI of 10 or less [3].

The results of the Atterberg Tests (liquid limit [LL] and plastic limit [PL]) conducted to determine the Plasticity Index (PI) of all the soils used in this investigation are provided in Table 2. The PI of each soil is less than 10. The low plasticity combined with high silt contents (including fine sands) identifies these soils as having a high potential to pump when compacted [1].

Table 2

Atterberg tests and plasticity of soils

SOIL	LIQUID LIMIT LL	PLASTIC LIMIT PL	PLASTICITY INDEX, PI
Highway US 171	17	15	2
Natchitoches K2-1	25	22	3
ALF	22	21	1

Classification

All of the soils classify as a silty-loams with a Unified Classification of ML (ASTM D 2487) and as an A-4 soil using the AASHTO classification (ASTM D 3282).

Compaction of Natural Soil

The standard proctor compaction method (ASTM D 698) was used to determine the compaction characteristics of the natural soil, i.e., maximum dry density ($\gamma_{d\ max}$) and optimum moisture content (ω_{opt}), Table 3. The values used for molding test specimens are given in Table 3.

Table 3

Compaction characteristics used in molding test specimens

Soil	Optimum Moisture w_{opt} , % dry solids	Maximum Dry Density $g_{d\ max}$, pcf
Highway US 171	12.5	110.6
Natchitoches K2	14	111.1
ALF	14.7	106.8

Plasticity and Drying Effects with Reagents

In treating the soil, the addition of reagents can possibly offset the moisture effects during compaction (pumping) by drying and altering the plastic character. The effect that the reagents used in this study had on the plastic properties of the soils was investigated. Varying quantities of lime and Portland cement were mixed with the US 171 soil and the PI was determined for each (Figure 2). The PI of the reagents-soil mixtures increased slightly over that of the natural or raw soil. However, the change was small for these soils and there appears to be a limit on the PI increase even with increased amounts of reagent added.

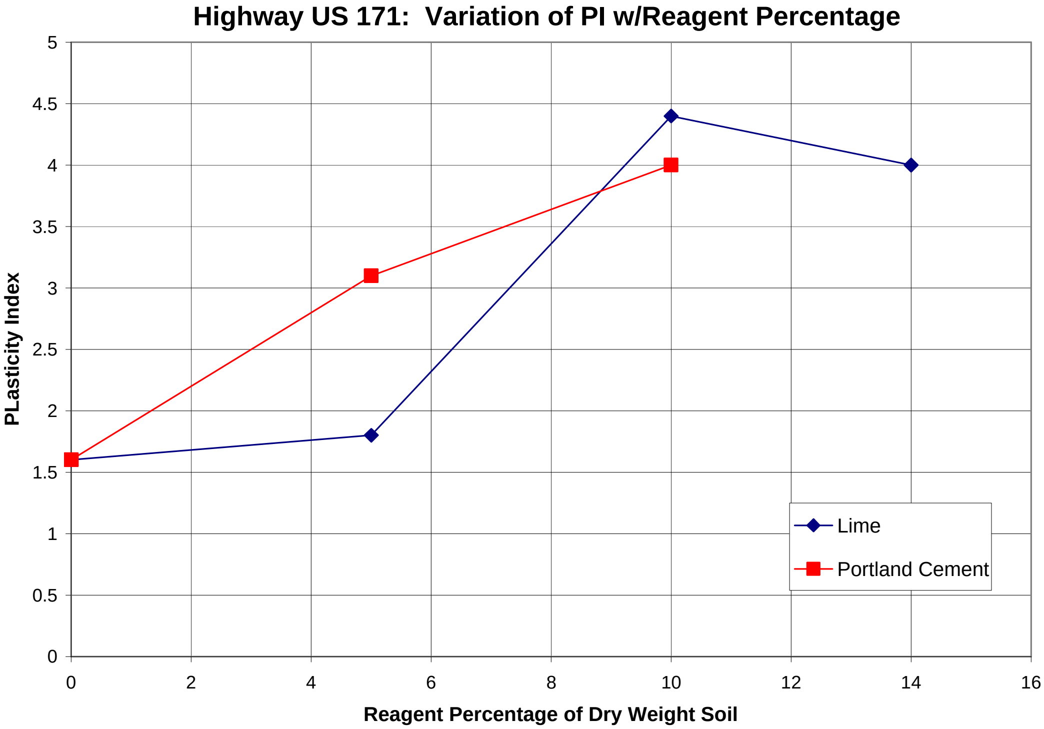

Figure 2

Variation of plasticity index with lime and Portland cement percentages

In an effort to eliminate the pumping that occurs in these soils when wet, the DOTD has permitted the contractor to use as much as 10 percent lime by volume to help dry the material. Although the quick lime (CaO) has more drying potential, the hydrated lime has been the type specified. The decrease in moisture content for the Natchitoches K2 and the US 171 soil-admixtures subjected to standard (proctor) compaction in this study were measured, Table 4. For the percentages of reagents used the changes were small. The change (reduction) in moisture content ($\Delta\omega$) for the lime and the lime-fly ash mixtures 0ranged from -1.6 to 2.3 percent. The smaller percentages of Portland cement and slag-cement decreased the compacted specimens by 0.6 and 0.7 percent moisture content. Theoretical estimates on the extent of drying provided by different percentages of reagents would require assumptions on the unit weight achieved by the compaction effort and the density of the admixture.

Cyclic Triaxial Tests

Cyclic triaxial load tests were conducted on the soil samples to evaluate the load-displacement, response (pumping) of the natural soil and the soil-reagent mixtures subjected to transient loading. The test conditions were selected in an effort to simulate the conditions for construction and longer performance when subjected to seasonal periods of increased moisture. In order to measure improvements provided by the additive reagents during construction, the soils were compacted and molded into specimens at elevated moisture contents, i.e., approximately four percent and eight percent above the natural soil's optimum moisture content for proctor compaction. The cyclic triaxial tests were conducted on the "as molded" specimens in the unconsolidated-undrained (UU) mode.

Table 4

Moisture contents measured in compacted soil-admixtures

SOIL TYPE	REAGENT	MOISTURE CONTENT PRIOR TO MIXING REAGENT (%)	MOISTURE CONTENTENT AFTER MOLDING W/REAGENT (%)	DRYING EFFECT CHANGE IN MOISTURE CONTENT (-Dw, %)
Natchitoches K2-1	Lime	19.0	17.3	1.7
		18.9	17.2	1.7
	Lime/Fly Ash	20.1	18.1	2.0
		18.8	17.0	1.8
	Cement	18.2	17.6	0.6
		17.7	17.1	0.6
	Slag Cement	19.8	19.1	0.7
US 171	Lime	18.2	16.6	1.6
		22.6	20.5	2.1
	Lime/Fly Ash	17.9	16.2	1.7
		22.5	20.2	2.3
	Cement	17.3	16.7	0.6
		20.6	20.0	0.6
	Slag Cement	17.2	16.6	0.6
		21.3	20.6	0.7

To evaluate the stabilized performance of the soil mixtures, the specimens were molded with the proctor compaction technique and cured at ambient conditions for 28 days. At the end of the 28-day cure, the specimens were saturated and tested in the unconsolidated-undrained mode.

Natchitoches K2-1 Soil. The K2 soil was included in the earlier program of study focused on characteristics and identification of the pumping soils. The natural K2 test specimen was compacted +4.3 percent of the optimum moisture as determined in the standard proctor compaction test. It was tested "as molded" in the UU mode with a triaxial confining pressure of two psi to simulate construction conditions in which the natural soil would be wet of the optimum moisture content and more susceptible to pumping. The results produced a strain increase or creep of approximately three percent with 301 undrained load cycles (Figure 3b). A comparison of the test results for all of the reagents and mixtures considered in the tests simulating construction conditions is shown in Figure 4. The test results for each of the admixtures used is provided in graphs in the Appendix B. As can be seen in Figure 4b, all of the reagents and mixture percentages used (with the exception of the slag-cement) eliminated the creep under cyclic load for the "as molded" specimens (construction simulation). The slag-cement mixture decreased much of the creep, however. It should also be noted that the resulting moisture content of the different mixes did vary. The lime, lime-fly ash, and portland cement specimens' moisture contents were +3.3, +4.1, and +3.6 percent of optimum, respectively. The slag-cement specimen had a molded moisture content of +5.1 percent of optimum.

The stabilized, in-service performance of the prepared subgrade soil was simulated using 28-day cured specimens of the mixtures of reagents. After curing, the specimens were saturated and tested in the unconsolidated-undrained mode of the triaxial compression test (σ_3 = 2 psi) under cycled and continuous axial loading. The cycled loading did not produce any strain creep for any of the mixtures used with this soil, Figure 5b. The stress-strain curves, Figure 5a, demonstrate a significant increase in specimen strength over that of the natural soil for some of the mixtures. For the percentages used, the greatest gain was produced by Portland cement (117 psi), followed by the lime-fly ash (85 psi), lime (61.5 psi), and the slag-cement (43.5 psi) was fourth.

Accelerated Load Facility (ALF) Soil. The pumping "silts" used in the first set investigation (McManis, et al, 2001) were more permeable than the non-pumping more clayey materials. However, they still had a relatively low permeability (probably on the order of 10^{-5} cm/sec) and behaved in an essentially undrained manner under cyclic loading. Unlike the more clayey soils (PI>10), they did exhibit high creep under cyclic loading, indicating that they were susceptible to "pumping." The ALF soil is actually a silty-sand with a plasticity index of 1. It had a permeability of approximately 1 to $5x10^{-4}$ cm/sec. Thus, two modes of testing were used in conducting the cyclic triaxial test on the ALF soil, Figure 6.

UU Test Once the specimen was in its chamber, the drain valve was opened briefly to allow the lateral pressure to become effective against the confining membrane. This brief period (seconds) was not sufficient to consolidate the specimen to its effective

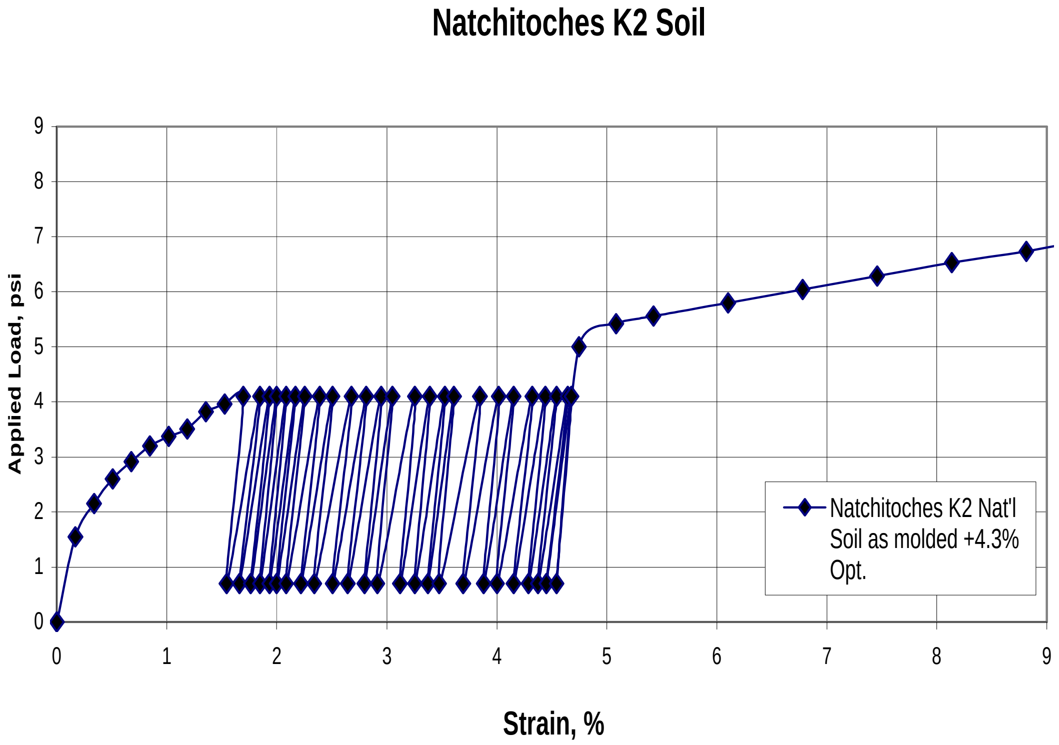

Figure 3a

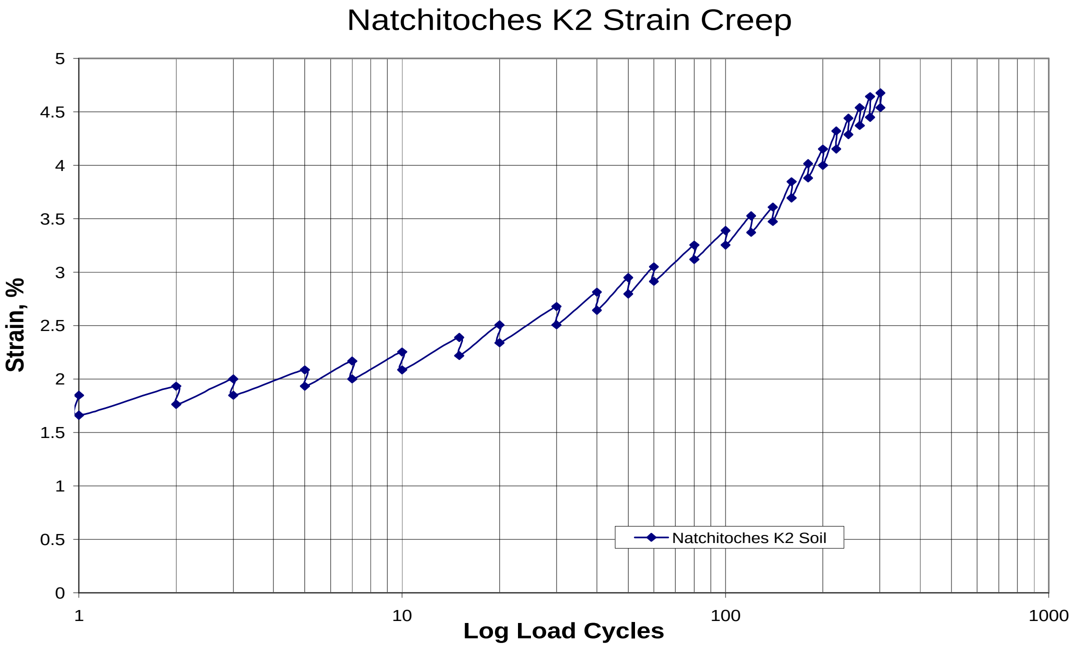

Figure 3b

Figure 3
Natchitoches K2 soil cyclic unconsolidated-undrained triaxial test results:
a. applied load stress vs strain and b. strain creep vs no. of load cycles

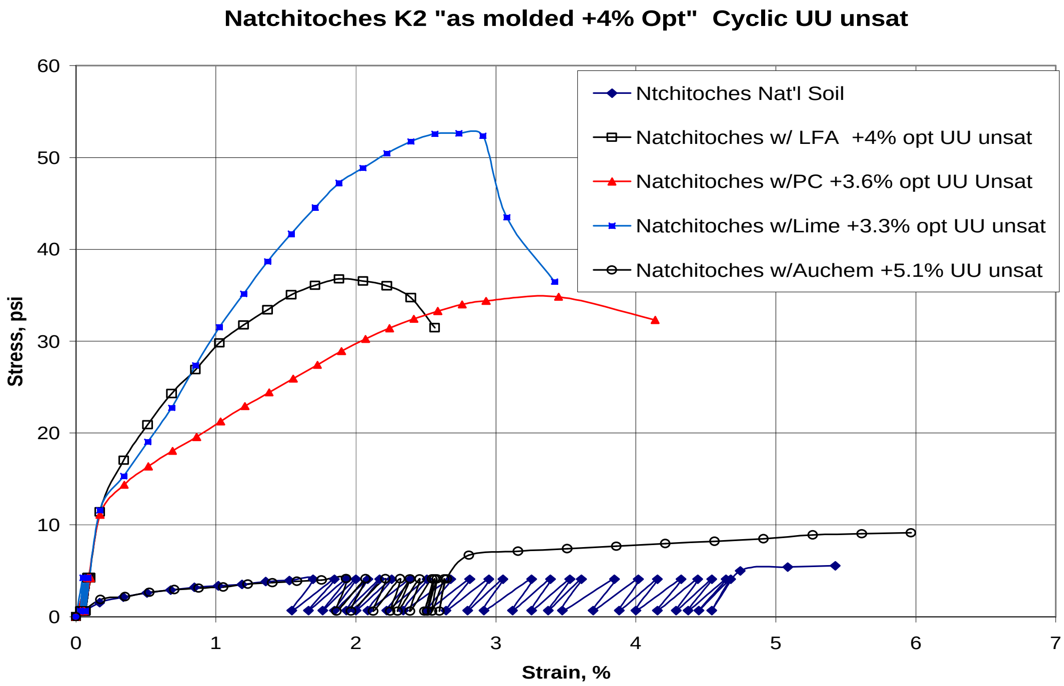

Figure 4a

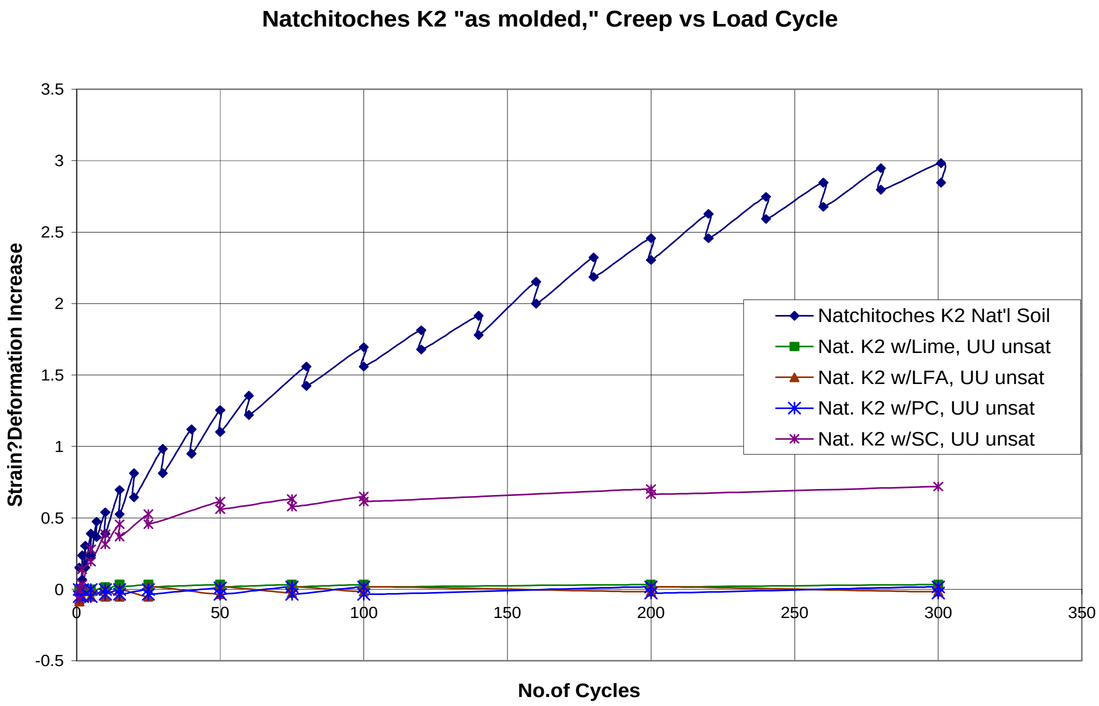

Figure 4b

Figure 4
Cyclic unconsolidated-undrained (UU) triaxial tests conducted on Natchitoches K2 soil-admixture specimen "as molded" +4 percent of optimum

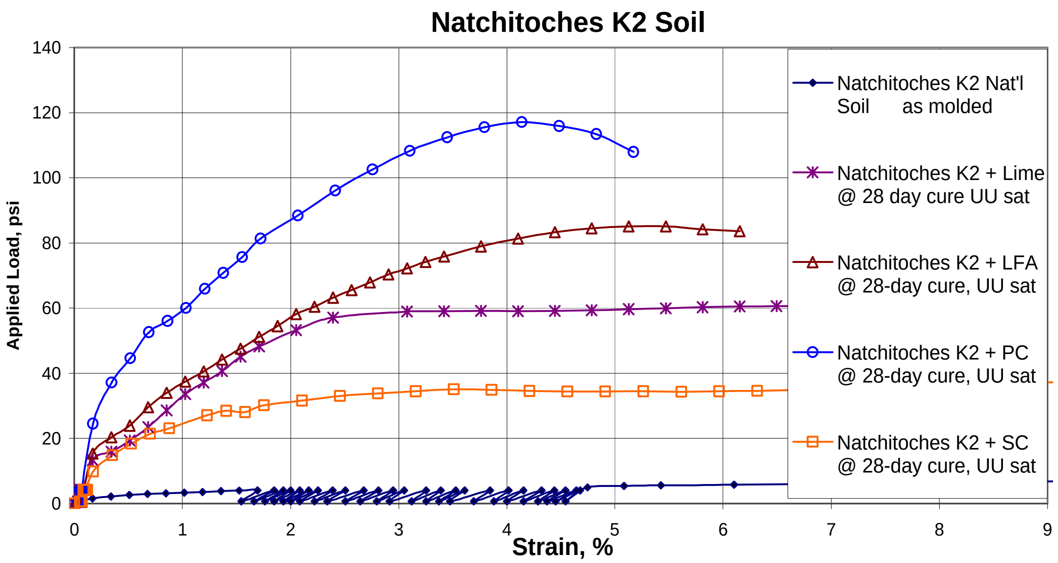

Figure 5a

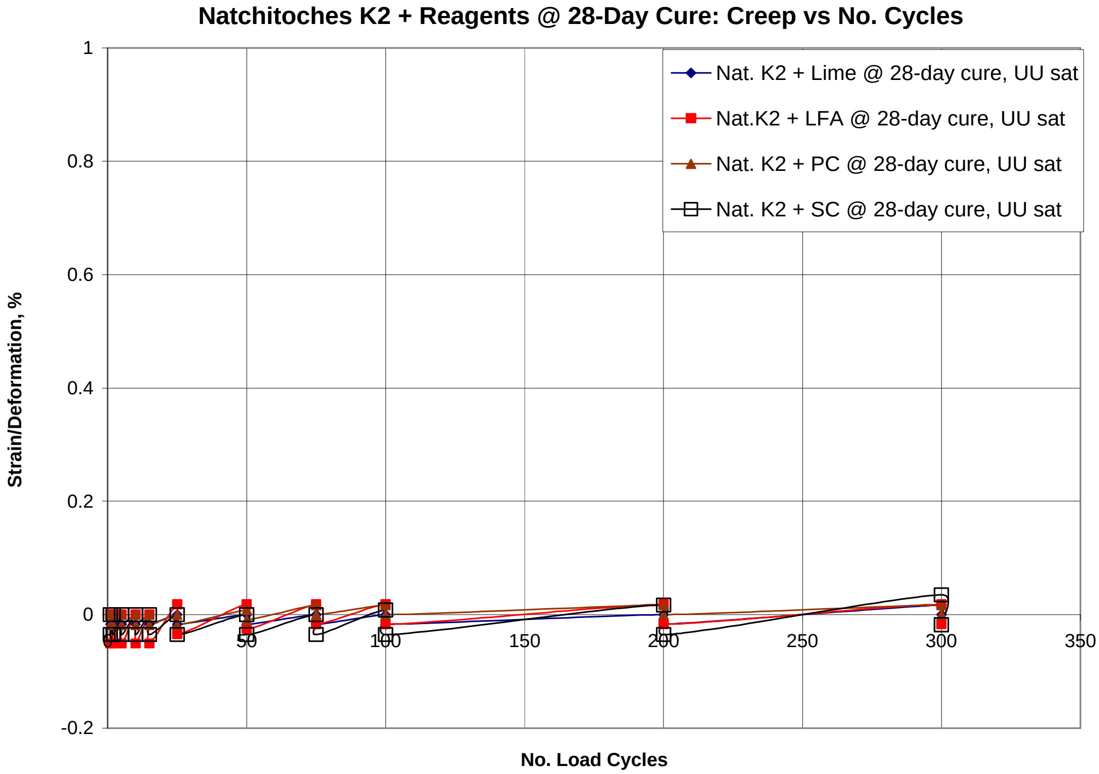

Figure5b

Figure 5
Cyclic unconsolidated-undrained (UU) triaxial tests conducted with Natchitoches K2 soil-admixtures after 28-day curing and with saturation

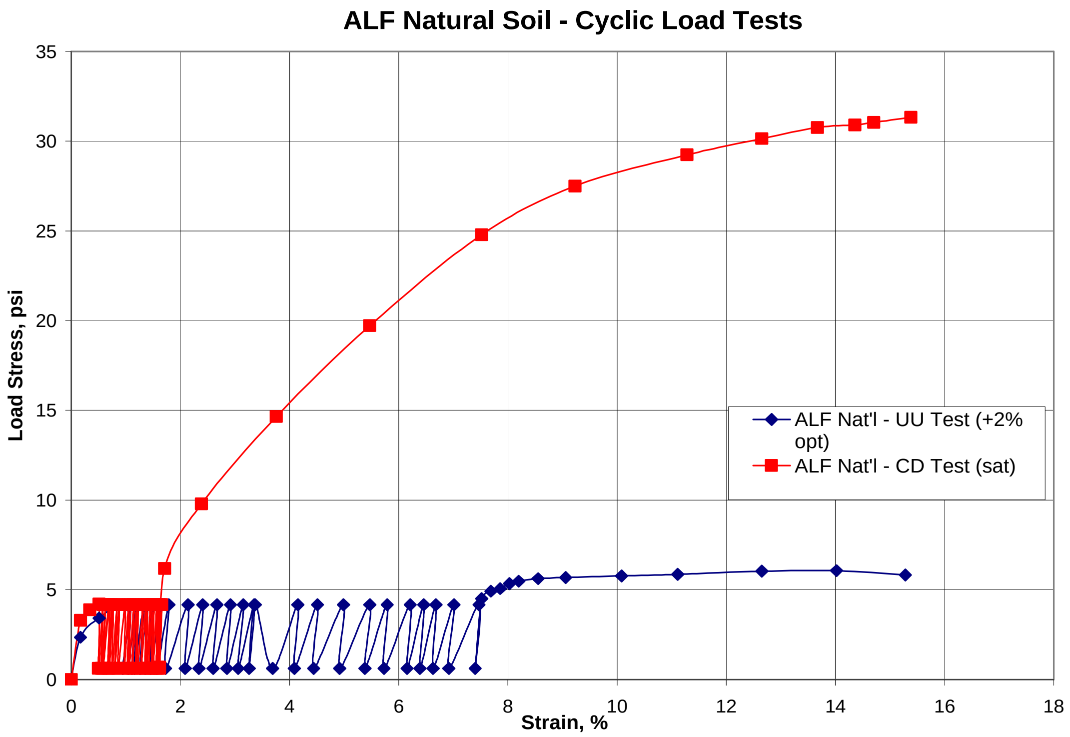

Figure 6a

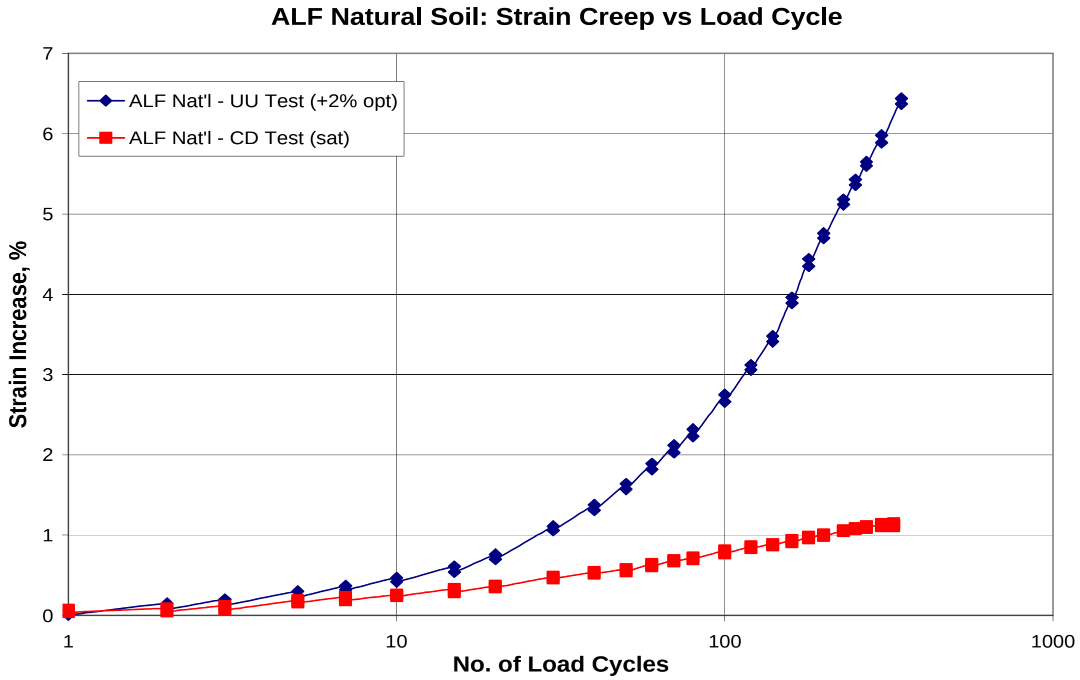

Figure 6b

Figure 6
Cyclic triaxial tests conducted on the natural ALF soil

lateral pressure. The drain valve was then closed, and the cyclic test conducted in a truly unconsolidated-undrained (UU) manner. This test is considered representative of the undrained (rapid load application) cyclic behavior of the ALF soil as compacted.

<u>CD Test</u> A second specimen was artificially saturated using the back pressure saturation method. Pore-pressure dissipation strips were not used due to the high permeability of this material. The specimen was then fully consolidated under its effective pressure. The chamber pressure was 56 psi and the back (pore-water) pressure was 54 psi yielding an effective pressure of two psi. The cyclic test was conducted with the drain valves open. With a material having this high permeability, the conditions during the test were essentially drained. This test is considered representative of the drained (slow load application) cyclic behavior of the ALF compacted soil when saturated. The beneficial effects of some level of drainage and pore-pressure dissipation can be seen in the two different tests. The reduction in the creep deformation produced and the decrease in the creep rate with drainage is significant.

The testing program used for the ALF soil with admixtures is outlined in the following:

1. <u>Construction Simulation.</u> The specimens were molded at four percent wet of optimum moisture content and tested unconsolidated-undrained, UU.

2. <u>Construction Simulation.</u> The specimens were molded at optimum moisture content, saturated, consolidated, and tested undrained, CU.

3. <u>Stabilized In-Service Simulation.</u> Molded four percent wet of optimum and cured for 28 days. Tested unconsolidated-undrained, UU

4. <u>Stabilized In-Service Simulation.</u> The specimens were molded at optimum moisture, cured for 28 days, saturated, and tested consolidated-undrained, CU.

The test results for the above field simulations (construction and in-service pavement support) are presented graphically for comparison of the different reagents under the different test conditions. The performance of the “as molded” soil mixtures can be seen under undrained loading in Figure 7 for conditions simulating construction conditions. Similar test results were also produced in Figure 8 for conditions that might simulate a situation where the subgrade has been successfully compacted, but where changing moisture (saturation) and construction traffic produce conditions that promote pumping. In both cases, the cyclic creep was reduced or eliminated in the slag-cement,

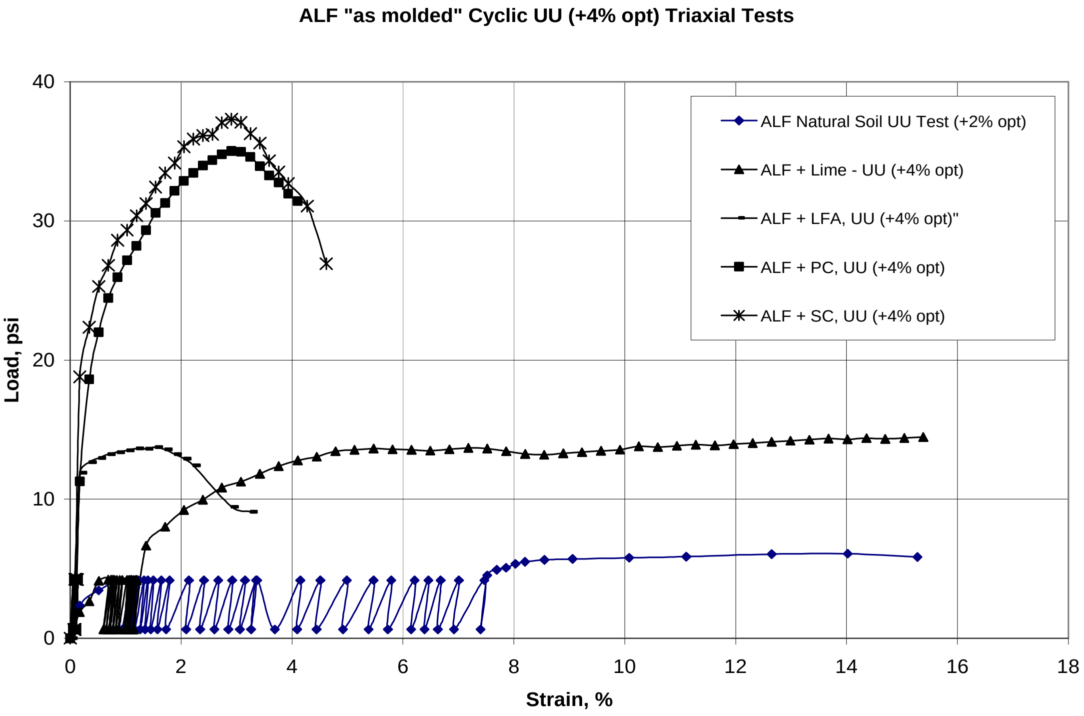

Figure 7a

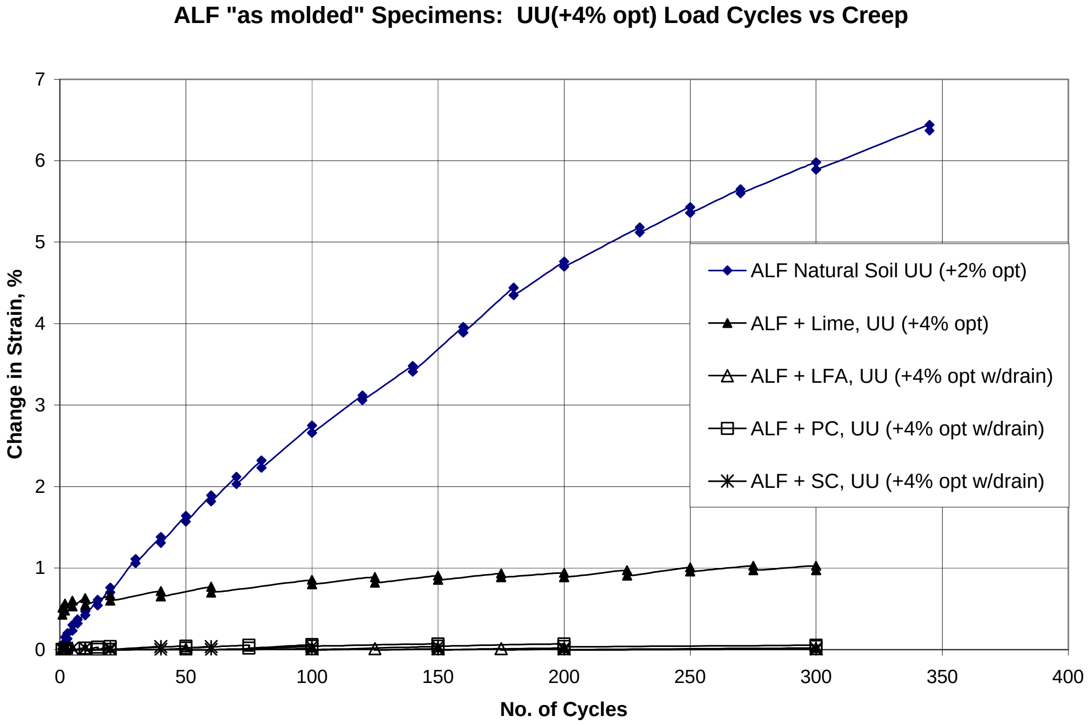

Figure 7b

Figure 7
Cyclic unconsolidated-undrained (UU) triaxial tests conducted on “as molded” ALF specimens four percent wet of optimum moisture content

Portland cement, and lime-fly ash mixtures. The undrained strength gain was greatest with the Portland cement and slag cement. The lime was not as effective. This strength increase is to be expected with the more sandy nature of the ALF soil, however.

Comparisons of the stabilized ALF tests for the 28-day cured specimens under UU and CU are presented in Figures 9 and 10, respectively. All of the cured admixtures appear to have eliminated most, if not all, of the deformation creep under cyclic load. The gain in strength produced with the slag-cement and portland cement specimens were again significant, i.e., 154 psi and 102 psi, respectively. Again, the advantages of the cements and pozzolanic lime and fly ash mixture are evident.

The performance of each reagent mixture under the different test scenarios is provided graphically in the Appendix B.

Highway US 171 Soil. Pumping has been cited as a problem in construction activities for the highway US 171 projects. The test conditions used in conducting the cyclic triaxial tests on the Highway US 171 soil specimens included two levels of wet soil in simulating construction conditions and saturation for the long term performance of the stabilized (post 28-day cured) specimens. All tests were conducted as unconsolidated-undrained (UU).

The response of the US 171 soil to cyclic loading is presented in Figure 11. Actually, the creep deformation produced on the specimen at a 3.1 percent wet of optimum does not seem very significant. That level of moisture may be marginal in producing a pumping condition. However, at the higher +6.8 percent of optimum moisture level, the corresponding deformation with load cycles was very large. The strain corresponding to the cycling load was eight percent strain with only 124 load cycles.

The performance of the reagents and mixtures used with specimens molded approximately at a moisture content that is plus four percent wetter than optimum is presented in Figure 12. These tests simulate the construction issues of pumping with a soil that is too wet. The lime-fly ash and the lime mixtures appear to do a better job of drying the soil and eliminating the pumping for these mix percentages. The same can be seen in the UU cyclic tests at the higher, plus eight percent optimum moisture (Figure 13). The slag-cement and the Portland cement were almost ineffective at the higher moisture level (plus eight percent). The slag-cement performed the least in preventing the “construction” at the level of percentage mix used (3.8 percent slag-cement and 3.3 percent Portland cement by volume). The percentages used were for comparison based on economic costs of reagents being equal and these low levels for the cements would be unrealistic for field operations.

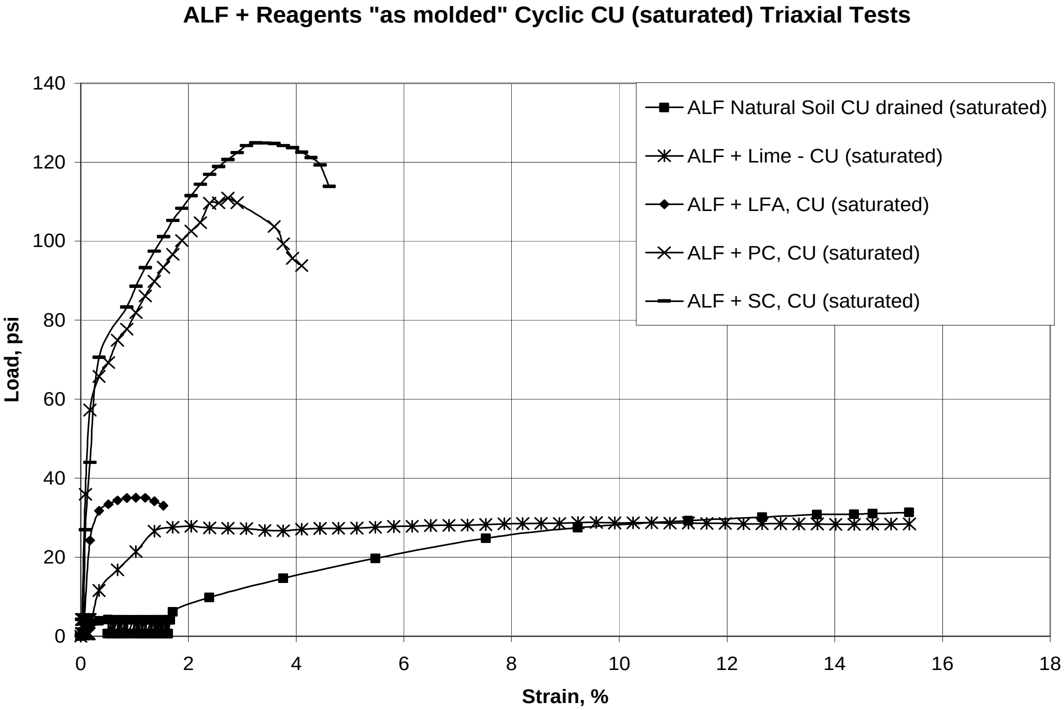

Figure 8a

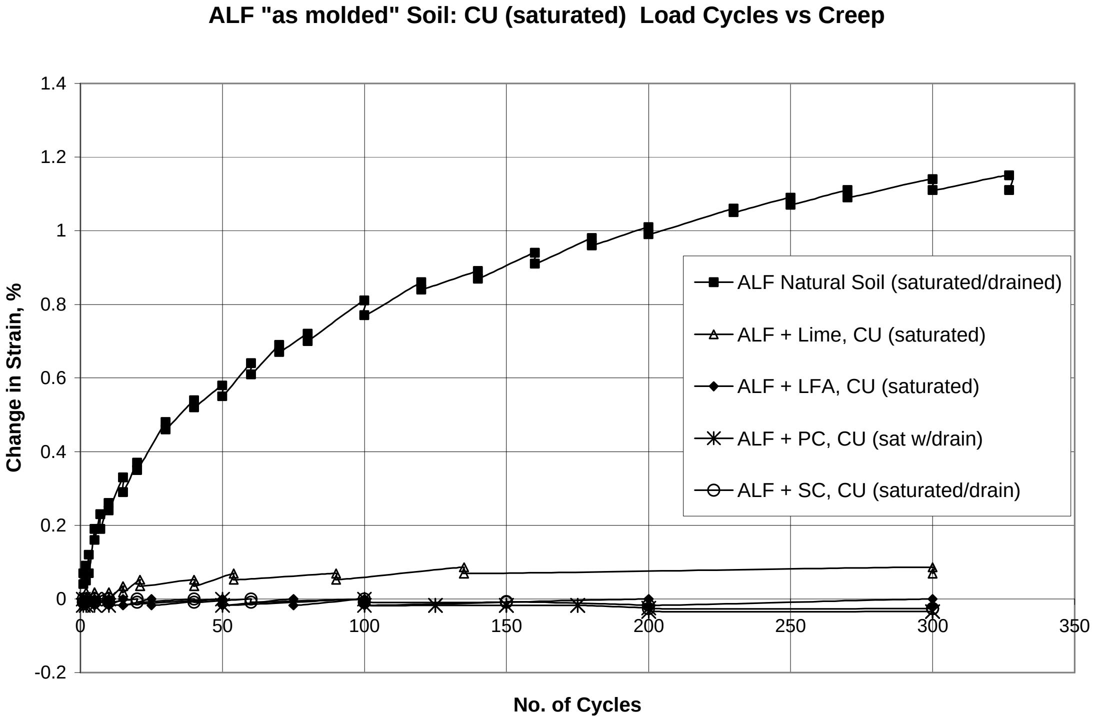

Figure 8b

Figure 8

Cyclic consolidated-undrained (CU) triaxial tests conducted with saturated mixtures of ALF and reagents

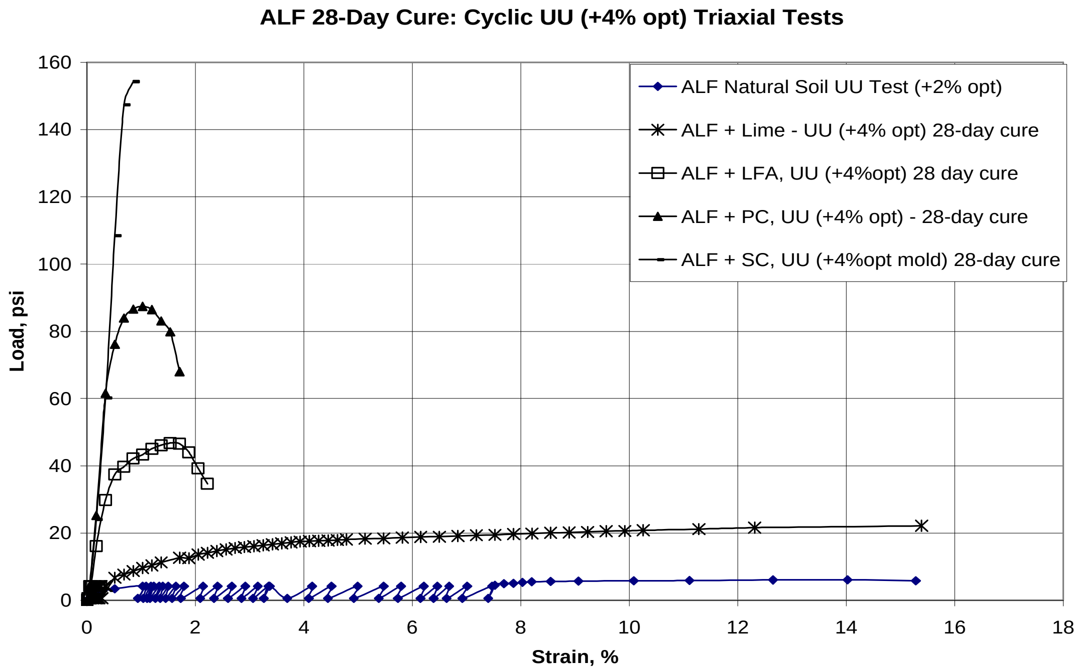

Figure 9a

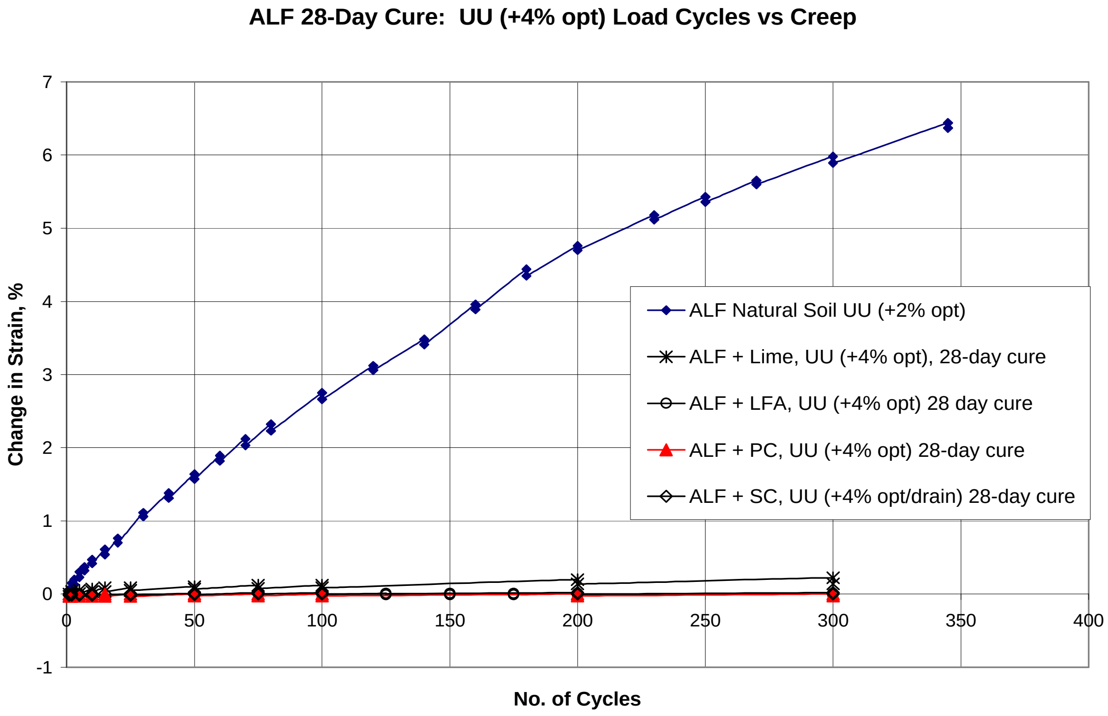

Figure 9b

Figure 9
Cyclic unconsolidated-undrained (UU) triaxial tests conducted with specimens of ALF-reagent mixtures after a curing period of 28 days

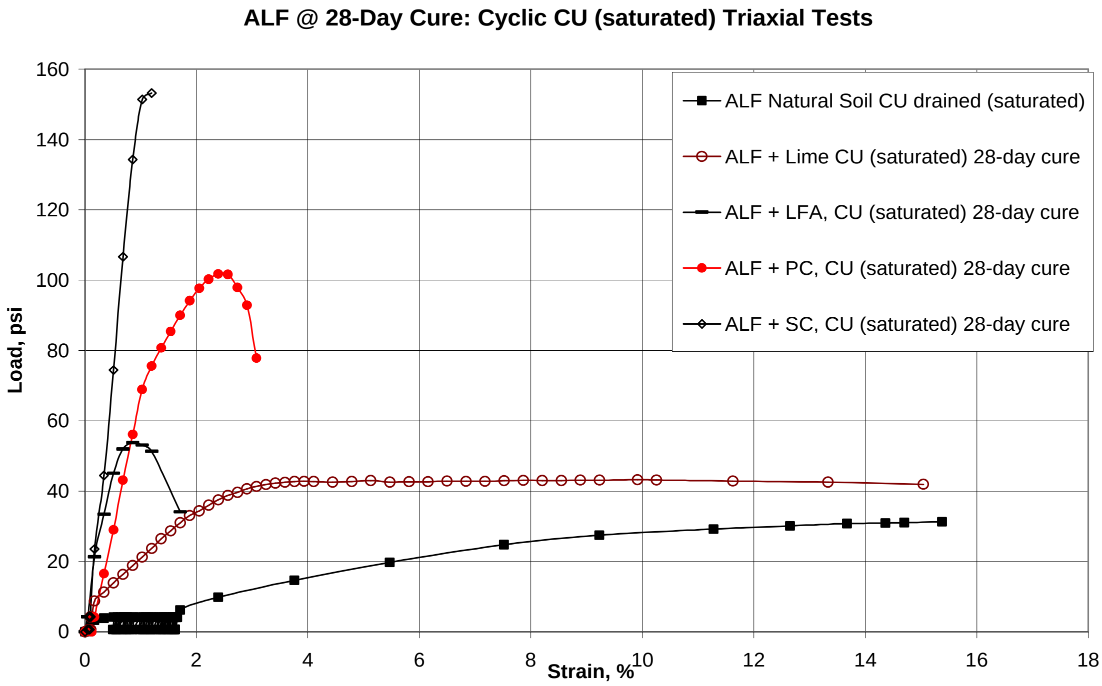

Figure 10a

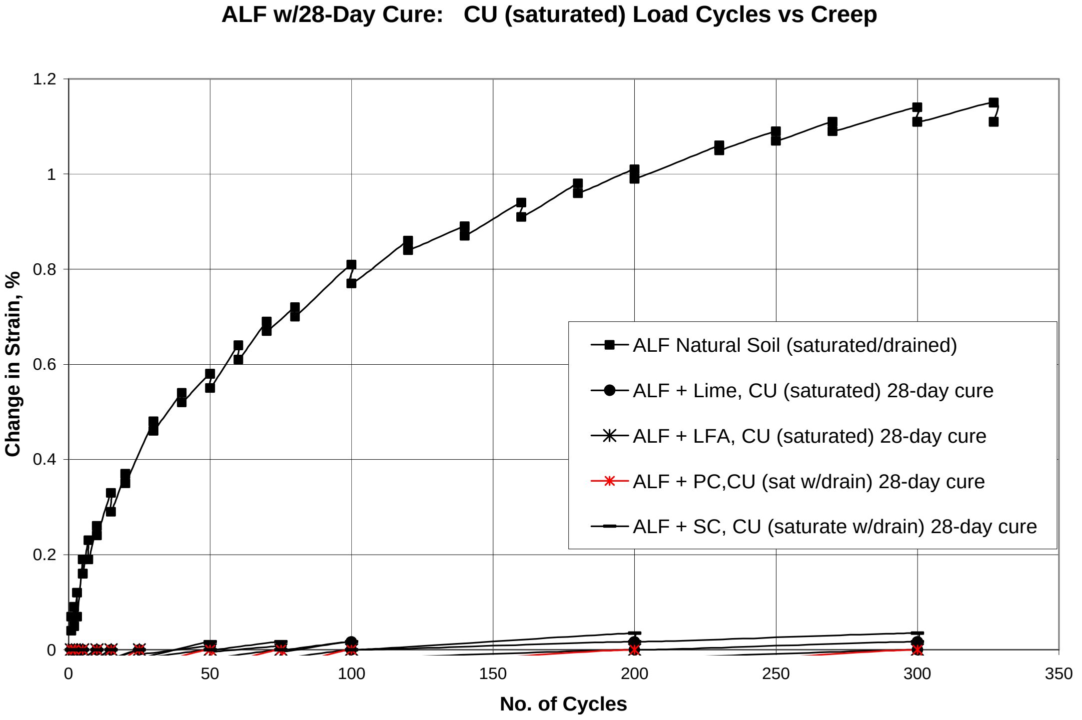

Figure 10b

Figure 10
Cyclic consolidated-undrained (CU) triaxial tests conducted on ALF-reagent mixtures after a curing period of 28 days

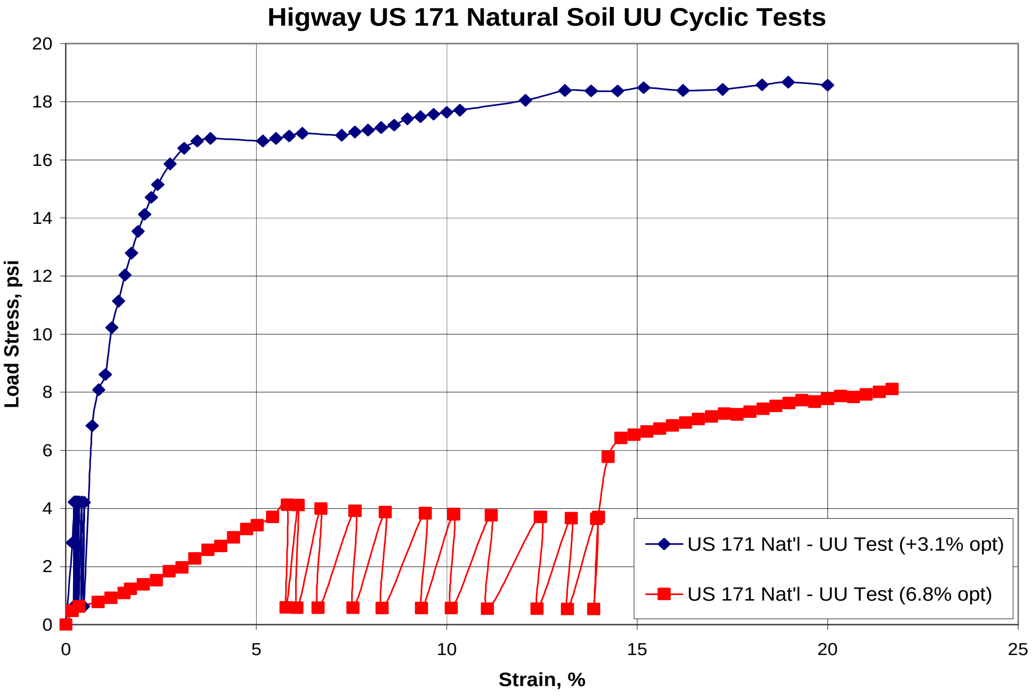

Figure 11a

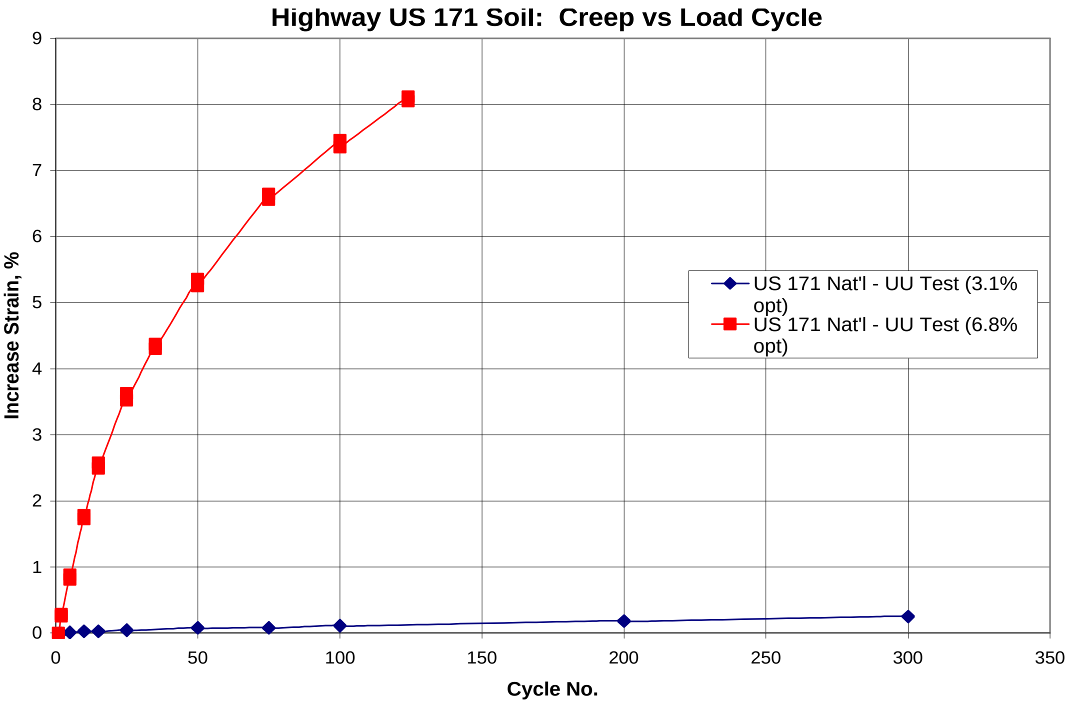

Figure 11b

Figure 11
Cyclic unconsolidated-undrained (UU) triaxial tests conducted on Highway US 171 subgrade soil at moisture levels above optimum

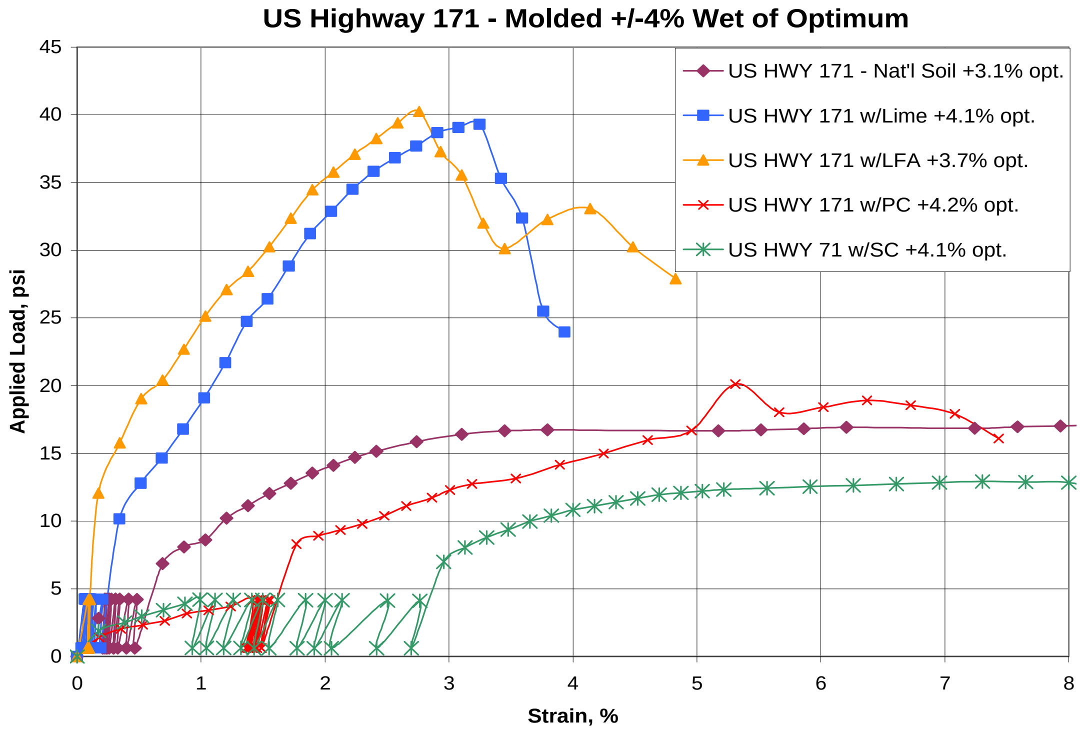

Figure 12a

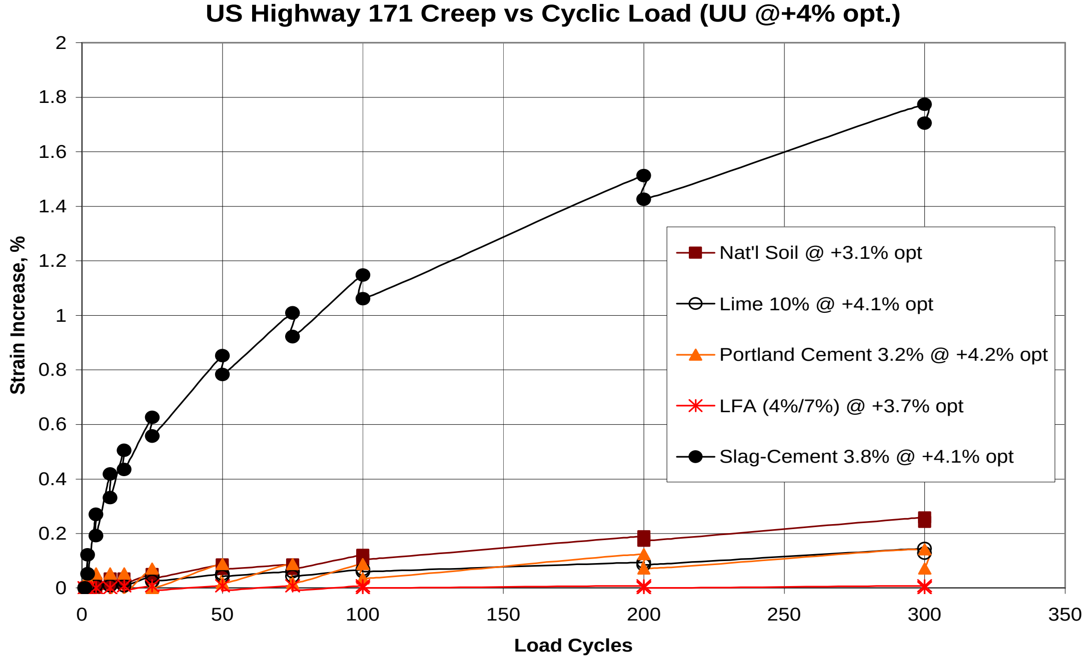

Figure 12b

Figure 12
Cyclic unconsolidated-undrained triaxial tests conducted on "as molded" Highway US 171 and admixtures at four percent wet of optimum

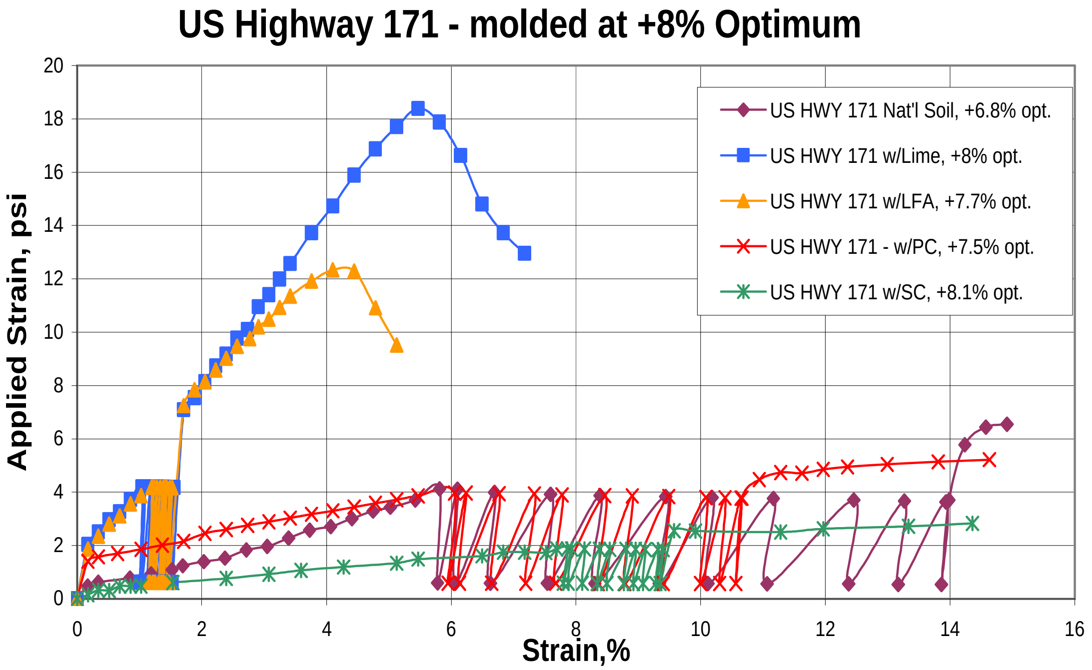

Figure 13a

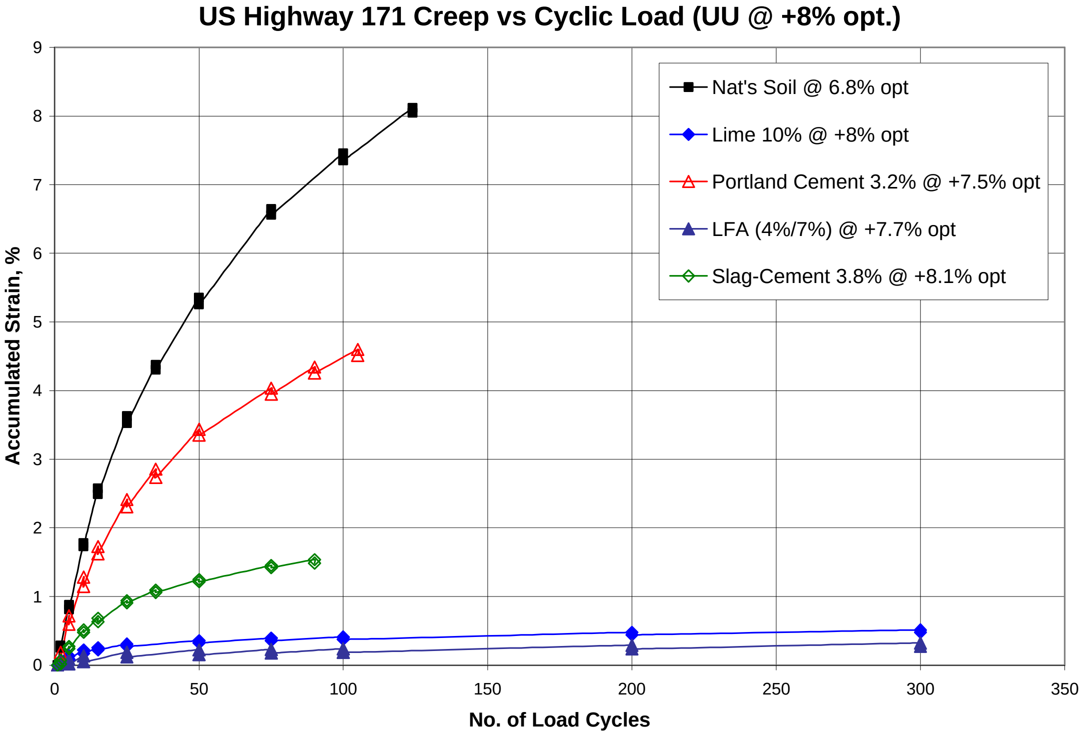

Figure 13b

Figure 13
Cyclic unconsolidated-undrained (UU) triaxial tests conducted with “as molded” Highway US 171 and admixtures after saturation

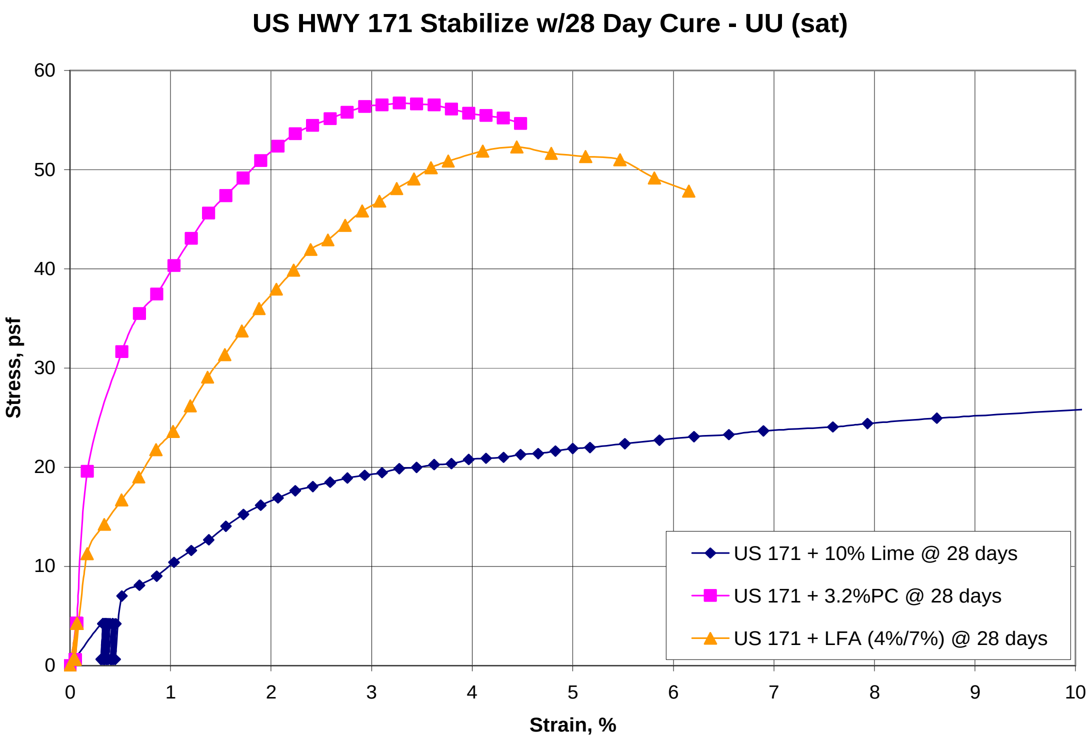
US HWY 171 Stabilize w/28 Day Cure - UU (sat)

Figure 14a

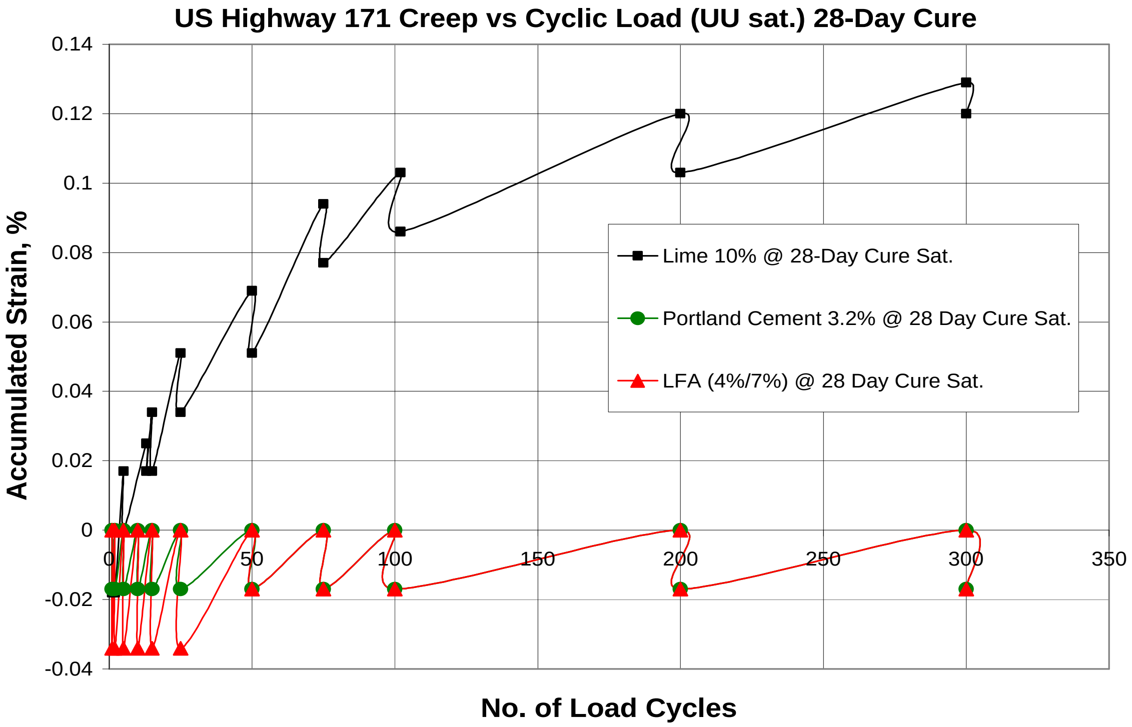
US Highway 171 Creep vs Cyclic Load (UU sat.) 28-Day Cure

Figure 14b

Figure 14
Cyclic unconsolidated-undrained (UU) triaxial tests conducted with Highway US 171 and admixtures after curing for 28 days and with saturation.

The cyclic tests conducted on the 28-day cured (stabilized) specimens are presented in gain was produced by the Portland cement and the lime-fly ash. Although not at the level achieved with the silty, fine-sand ALF soil, both Natchitoches and US 171 did achieve a strength in excess of 50 psi and eliminated the creep.

The different test results for the individual reagents with the US 171 soil are presented graphically in Appendix B.

Durability Tests

A simplified test to evaluate the longer term durability of the admixtures involves subjecting the cured specimens to complete inundation and saturation and comparing their performance to cured specimens not inundated. While this test does not include all the possible environmental or aging factors, it may provide a cursory comparison between different reagents used as admixtures.

Test specimens of the Highway US 171 admixtures (Lime 10 percent, PC 3.2 percent and L4 percent+FA7 percent, all by volume) were molded at OMC (12 percent) and then placed in the humidity room for 28 days curing under ambient conditions. At the end of the curing period, a set of the stabilized specimens was placed in a vacuum saturation chamber and subjected to 30 minutes of de-airing. This was followed by one hour of inundation with water. After this procedure, unconfined tests were conducted on the saturated specimens. Another set of the specimens were tested in unconfined compression without being subjected to vacuum saturation.

The cured mixtures of additives show an improvement in strength over that of the natural soil (Table 5). Even after vacuum saturation, the unconfined strength values, q_u , exceeded or equaled the value for the non-saturated, natural soil. The best results for strength gain with curing occurred with the admixtures that provided the greatest opportunity for the development of cementitious products, i.e., the Portland cement and lime-fly ash. The results of the strength tests show the lime-fly ash as provide slightly better results than the Portland cement. However, the very low percentage of the Portland cement compared to the lime-fly ash admixture should also be kept in mind. With respect to strength loss with inundation, the extent of decreasing strength varied from 50 percent (Portland cement) to 25 percent (lime). Still, the testing population and the percentages of admixtures used were limited and must be considered in any conclusion.

Table 5

Unconfined strength comparisons for cured specimens at the molded moisture vs. cured specimens subjected to vacuum saturation

Soil Mixture	28-Day Cure		Vacuum Saturation	
	q_u , (psi)	Moisture (%)	q_u (psi)	Saturation (%)
US 171(natural)	24.5	12.2		-
US 171+PC 3.2%	44.52	11.8	23.5	0.95
US 171+Lime 10%	33.12	12.4	24.75	0.945
US171+L4%+FA7%	50	11.86	32.8	0.94

Tube Suction Tests

The Tube Suction Test (TST) has been promoted as a means for determining the moisture susceptibility of granular base materials. The test involves a series of surface readings of the dielectric values (DV) for an oven-dried compacted soil as it accumulates capillary water over time. The DV is a measure of the free or unbound water and its implied influence on both the strength and deformation properties of base course aggregates. Permeability controls the moisture increase and migration within the aggregate layer. The higher the unbound water is, the higher the soil's dielectric value. A DV less than 10 indicates better performance as base materials compared with aggregates for which the values are between 10 and 16. A dielectric value (DV) greater than 16 ms/cm is an indication of the presence of substantial "free" moisture.

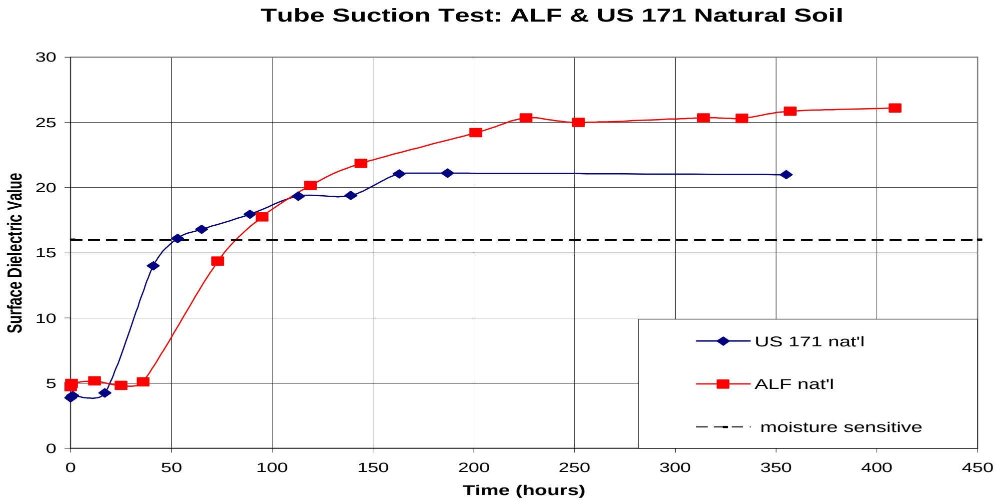

Figure 15

Tube suction test results for the ALF and Highway US 171 soils

A graph of surface dielectric readings versus time is used to determine the performance classification. The results of the TST readings for the natural soils is shown in Figure 15. Both of these soils developed high DV values indicating their susceptibility and sensitivity to moisture.

The Tube Suction Test has also been used to measure the effectiveness of stabilization efforts in reducing the moisture sensitivity of a stabilized soil (after 28-day ambient cure). The TST was conducted with the ALF natural soil and with admixtures of lime and portand cement. Surface dielectric readings of the "as compacted" soil and soil-admixtures were also taken to measure the differences between the natural and treated soil (Table 6). The TST was also conducted with uncured compacted specimen as presented in the table. However, since the normal TST procedures require that the compacted specimens be oven dried at 50° C for five days, the preparations of test specimen approaches that of an accelerated cure. The DV measured for the "as molded" and "28-day cure" columns in Table 6 represent readings taken immediately after molding and at the end of the 28-day cure, i.e., did not include the oven drying. The "max TST" column is the maximum DV value achieved after the specimens were dried in the oven.

Table 6
ALF tube suction tests with stabilized and as molded specimens

ALF	As Molded		28-Day Cure		Max TST
	w (%)	DV	w (%)	DV	DV
Natural soil	12.5	26.3	NA	NA	27.6
Soil + Lime 5% by vol	13.2	23.6	12.6	23.1	25
Soil + Lime 10% by vol.	13.1	21.2	12.6	21	25
Soil + PC 1.75% by vol.	14	15.1	13.5	14.8	10
Soil + PC 3.5% by vol.	13.3	15.8	13	15.6	6.3

The cured Portland cement specimens with the ALF soil greatly reduced their susceptibility to moisture as measured in the TST (Figure 16). The measurements of the dielectric values for the PC specimens produced readings of $\leq$ 10 as compared to the natural ALF soil DV readings of 25. The DV readings in the TST for the lime-ALF soil admixtures with 28-day curing did not change from those of the natural soil. The readings indicate that even with the added lime and after a curing period of 28-days, these specimens would remain potentially sensitive and perform poorly (less pavement support) with increased moisture conditions. Confined by the pavement, the tendency to pump would be diminished. However, the extremely wet conditions in many areas of Louisiana combined with the formation of pavement cracks might produce pumping in the lime "stabilized" subgrade under wheel loading.

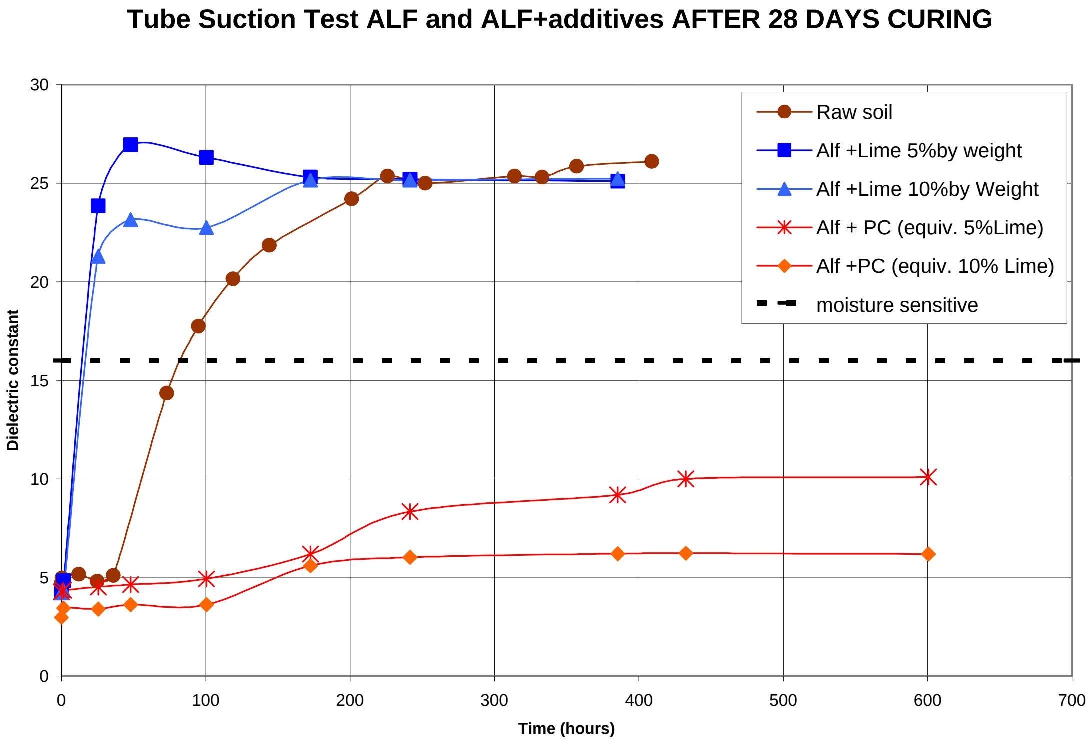

Figure 16

Moisture sensitivity variations produced by admixtures in the TST

Discussion

In the above testing program, the objective was to determine the ability of the reagents to alter the pumping character or instability of these commonly occurring subgrade soils. The extent of drying or the altering of the plastic/cohesive character by adding the reagents was measured. For the percentages used, a decrease in the moisture content (–Δω) ranged from 0.6 to 2.3 percent, with the greatest drying effects occurring with the lime and lime-fly ash. Obviously, the lime and lime-fly ash represent the higher levels of percentages of additives by volume. However, in considering the construction problems associated with trying to achieve a compacted density and post-compaction stability in these soils which may pump a few percentage points above optimum, the lime or lime-fly ash provide drying advantages. It was also noted in the Atterberg tests that a slight increase in the cohesive or plastic character is achieved with additives. Depending on the percentages used, a maximum increase of the natural soil's PI+ three was achieved. Again, this additional cohesive character contributes in suppressing the pumping.

In the modification/treatment or stabilization study, the mix proportions of the reagents used were selected as being equivalent in terms of the unit material costs at the time. Since current DOTD practice had permitted a construction bid based on 10 percent by volume of lime to be added in compacting the soils that pump, this was the benchmark used for cost and ultimately for performance comparison. It is recognized that this approach did produce unusually small percentages for the Portland cement and slag cement. The inability to adequately mix this low level of additive in the field would probably mandate larger percentages in meeting construction control and economics. Also, the ratio of lime to fly ash for optimizing the pozzolanic reaction may vary from those percentages used. However, performance based on material costs does permit an equivalent basis and the smaller percentages could be controlled in laboratory tests. Thus, the mixture percentages of 1) 10 percent by volume of lime, 2) four and seven percent by volume of lime and class C fly ash, 3) 3.2 percent by volume of Portland cement, and 4) 3.8 percent by slag cement were used.

The three soils included in this program of study were similar in that they exhibited pumping tendencies at moisture levels greater than the optimum moisture content. All of the soils had approximately the same silt-fine sand content that ranged from 84 to 89 percent. Two of the soils, Natchitoches K2 and U.S. 171, had high silt contents of 60 and 75 percent, respectively. The major difference was that the ALF soil was more of a silty-sand consisting of 49 percent fine sand. These material differences and those of the different reagents had an influence on their variation in response to the cyclic loads in terms of deformation and strength.

As noted, all of the natural soils used demonstrated a tendency to creep significantly when wet of optimum and subjected to cyclic loads of 600 psf (4.2 psi) to 90 psf (0.625 psi). In one series of saturated CU tests with the natural (untreated) ALF soil, it was noted that the creep deformation could be reduced with in-place consolidation and some level of drainage. Although noted as being undrained, this test was conducted with the drains open. Because it is a silty-sand, the more permeable ALF soil provided an opportunity for greater drainage under cyclic load than the high-silts—Natchitoches and US 171 soils. However, even though reduced, creep did occur in the ALF CU test.

Other cyclic load tests for the treated or stabilized soils simulated conditions for construction (as molded specimens) and in-place service (long-term performance). Efforts were made to simulate compaction (or post compaction) of the soils plus additives when the soils were four- and eight-percent wet of optimum. In most cases, the added reagents did eliminate or retard the extent of the cyclic deformation for the “as molded” test specimens. There were discrepancies among the different soils with respect to the performance of the different reagents. However, there were also differences in the moisture contents within a test series which was undoubtedly significant in importance to the pumping character of these soils. For example, the natural U.S. 171 soil did not pump when molded at a moisture content of +3.1 percent of optimum (Figure 11). It did pump with the Portland cement, slag cement, and lime (to a lesser extent) when the soil moisture content was approximately five percent above optimum. After mixing and molding, these specimens had a moisture content of approximately five percent above the optimum (Figure 12).

In the "as molded" tests, simulating the treated subgrade's response to construction conditions and operations, the soils with the high silt contents (Natchitoches K2 with 60 percent silt and US 171 with 75 percent silt), seemed to perform better with the lime-fly ash and the lime alone. A reduction or elimination of the continuous deformation with cyclic load and improved ultimate strength of the treated soils can be seen in Figures 4, 12, and 13. This is attributed to greater drying potential provided by the larger volume of reagents and their affinity for water.

The creep with cyclic load was eliminated in the "as molded" tests with the more sandy ALF soil at plus four percent above optimum moisture content and treated with the Portland cement, slag cement, and the lime-fly ash. The lime alone still exhibited a tendency to creep. The greatest strength gain was provided by the cements.

The creep deformation was eliminated or greatly reduced in the cyclic tests conducted with the specimens stabilized with a 28-day curing period. However, the US 171 soil with the lime-alone mixture exhibited a small tendency to pump. The greatest improvements with respect to strength were achieved with the cements and the lime-fly ash pozzolanic mixture. Undrained, saturated 28-day-strengths between 50 and 150 psi were produced with the Portland cement, slag cement, and lime-fly ash.

Tube suction tests suggest that the moisture sensitivity of the cured specimens is reduced in the Portland cement mixture if allowed to cure (Figure 17). The dielectric value readings in the Portland cement did not exceed a DV value of 10. This was not the case for the lime-alone mixture in which the DV that developed over the period of the test was the same as the natural soil, i.e., no increased moisture resistance.

CONCLUSIONS AND RECOMMENDATIONS

The stability and pumping response of high silt (and fine sand) soils commonly encountered in the preparation of the subgrade for highway pavement projects in Louisiana was investigated through a series of laboratory tests. The tests attempted to duplicate the environmental (moisture) and loading conditions that these soils could experience 1) during construction operations and 2) longer term, in service support of the completed pavement. Based on the test results, the following conclusions are made in comparing the modification and stabilization performance of the soils with the mixtures and reagents used:

1. The reagents act as a drying agent during construction but, for the percentages used, produce only a small reduction in the initial moisture content of the natural or raw soil and only small increases in the plastic or cohesive character. For initial moisture contents that exceed the optimum value by only a few percentage points (+/- four percent wet of optimum), smaller levels of reagents (percent by volume) were sufficient to retard or even eliminate deformation under low cyclic loads but extremely wet soils (+/- eight percent optimum) required larger volumes of reagents to dry.
2. For construction purposes, the greater drying potential of the lime and lime-fly ash performed better in eliminating the pumping potential of the predominately high-silt soils. However, the stability of the predominately fine sand in the silty-sand soil was greater with the cements and the pozzolanic mixture of lime-fly ash.
3. To achieve long term stability the greatest increase in strength, the cements followed by the lime-fly ash produced the best results.
4. Stabilization mixtures with reagents producing cementicious products (Portland cement) seem to reduce the sensitivity of the soil to moisture changes.

Recommendations

1. To achieve the compaction requirements and maintain the support of a stable subgrade surface during construction, lime-fly ash should be given strong consideration in its ability to provide the advantages for drying a wet subgrade and its lower material costs.

2. For long-term and increased resistance to seasonal variations with respect to moisture changes, a cementing or pozzolanic reagent should be used to provide the greatest advantages.
3. The selection of the reagents used should include consideration for both
    1) compaction and construction support, and
    2) continuous in-service support for the pavement during wet seasons.

    Lime and/or lime-fly ash, or cement would address both.
4. Consideration should be given for utilizing the stabilized subgrade as a sub-base structural component in the design of the pavement.

The selection of the reagent(s) and mix percentages used to treat and/or stabilize the problematic (pumping) silty-soils, must also consider constructability questions involving blending and compaction.

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APPENDIX A

Cost Basis Comparison

Equivalent Admixtures Based on Unit Cost and 10 Percent Lime by Volume

Lime: $65/ton & γ_{lime} = 35 pcf

Cost/CY = (35 pcf)($65/ton)(1ton/2000#)(27 ft^3/yd^3)
= $30.7125/CY

For 10% Lime by Volume: $3.07125/CY

Basis for comparison

Portland Cement: $75/ton and γ_{PC} = 94 pcf

Cost/CY = (94 pcf)($75/ton)(1ton/2000#)(27 ft^3/yd^3)
= $95.175/CY

Percent PC by Volume: 95.175P_{PC}$ = $3.07125

P_{PC} = 3.22695%

Fly Ash: $30/ton and γ_{FA} = 65 pcf

Cost/CY = (65 pcf)($30/ton)(1ton/2000#)(27 ft^3/yd^3)
= $26.325/CY

Percent FA by Volume: 26.325P_{FA}$ = $3.07125

P_{FA} = 11.6667%

Slag Cement: $70/ton and γ_{SC} = 90 pcf

Cost/CY = (90 pcf)($70/ton)(1ton/2000#)(27 ft^3/yd^3)
= $85.05/CY

Percent Slag Cement by Volume: 85.05P_{SC}$ = $3.07125

P_{SC} = 3.8111%

Percent Lime-Fly Ash: (% by Volume)

For 2% Lime- $(2/10)(\$3.07125) = \$0.61425/\text{CY}$

$$\$26.235\ P_{FA} = \$3.07125 - \$0.61425$$

$$P_{FA} = \underline{9.3654\%}$$

For 3% Lime- $(3/10)(\$3.07125) = \$0.921375/\text{CY}$

$$\$26.235\ P_{FA} = \$3.07125 - \$0.921375$$

$$P_{FA} = \underline{8.1947\%}$$

For 4% Lime- $(4/10)(\$3.07125) = \$1.2285/\text{CY}$

$$\$26.235\ P_{FA} = \$3.07125 - \$1.2285$$

$$P_{FA} = \underline{7.024\%}$$

← **Selected for Study**

For 5% Lime- $(5/10)(\$3.07125) = \$1.535625/\text{CY}$

$$\$26.235\ P_{FA} = \$3.07125 - \$1.535625$$

$$P_{FA} = \underline{5.8533\%}$$

Equivalent Admixtures (% Dry Weight) Based on Unit Cost

from DOTD TR 418-98 Method B

$A = (W_S + W_{add}) / V_T$ Max Dry Wt Density of Soil, pcf

$B = V_{add} / V_T$ Percent by Volume of Additive

$U = W_{add} / V_{add}$ Unit Wt. of Additive, pcf

$C = W_{add} / W_S$ Percent by Weight of Additive

$$C = [(UB/100)/(A - (UB/100))] \times 100$$

$$= [(W_{add}/\cancel{V_{add}})(\cancel{V_{add}} / V_T)]/[((W_S + W_{add}) / V_T) - (W_{add}/\cancel{V_{add}})(\cancel{V_{add}} / V_T)]$$

$$= (W_{add}/\cancel{V_T}) / [(W_S + W_{add} - W_{add})/ \cancel{V_T}]$$

$$= W_{add}/ W_S$$

Computing C and inputing B as percentage (rather than decimal)

$$C = 1 / [(A/UB) - 0.01] \quad \text{by dry weight}$$

$C_{lime} = 1/[(A/(35)(10) - 0.01] =$ Lime % by dry weight

$C_{PC} = 1/[(A/(94)(3.22695) - 0.01] =$ PC % by dry weight

$C_{FA} = 1/[(A/(65)(11.6667) - 0.01] =$ FA % by dry weight

$C_{SC} = 1/[(A/(90)(3.6111) - 0.01] =$ SC % by dry weight

$C_{LFA(4\%-7\%)} = C_{4\%L} + C_{7\%FA} = 1/[(A)/(35)(4) - 0.01]L$
$+ 1/[(A)/(65)(7) - 0.01] =$
$= \%L - \%FA$ by dry weight

APPENDIX B

Cyclic Triaxial Tests with Individual Reagents

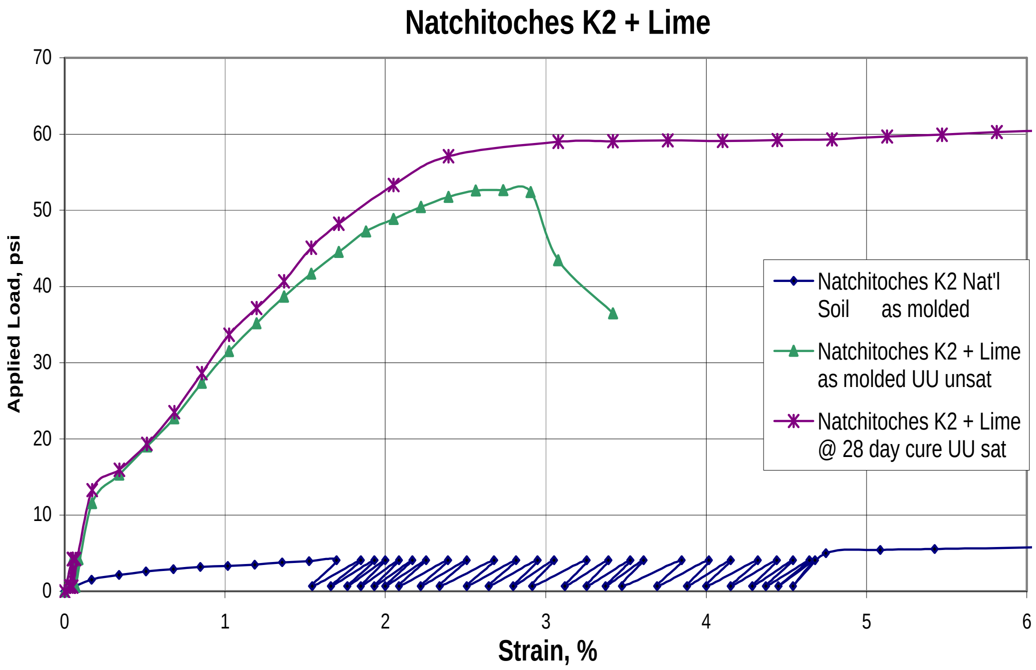

Figure 17
Cyclic triaxial tests with Natchitoches K2 soil and Lime

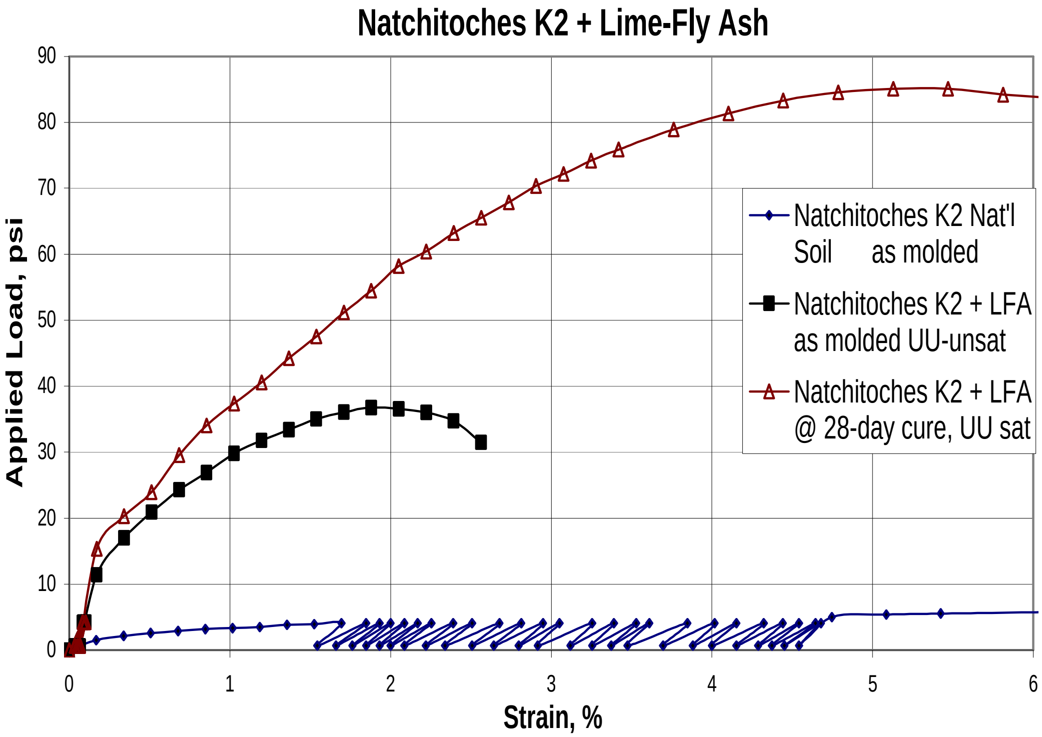

Figure 18
Cyclic triaxial tests with Natchitoches K2 Soil and lime-fly ash

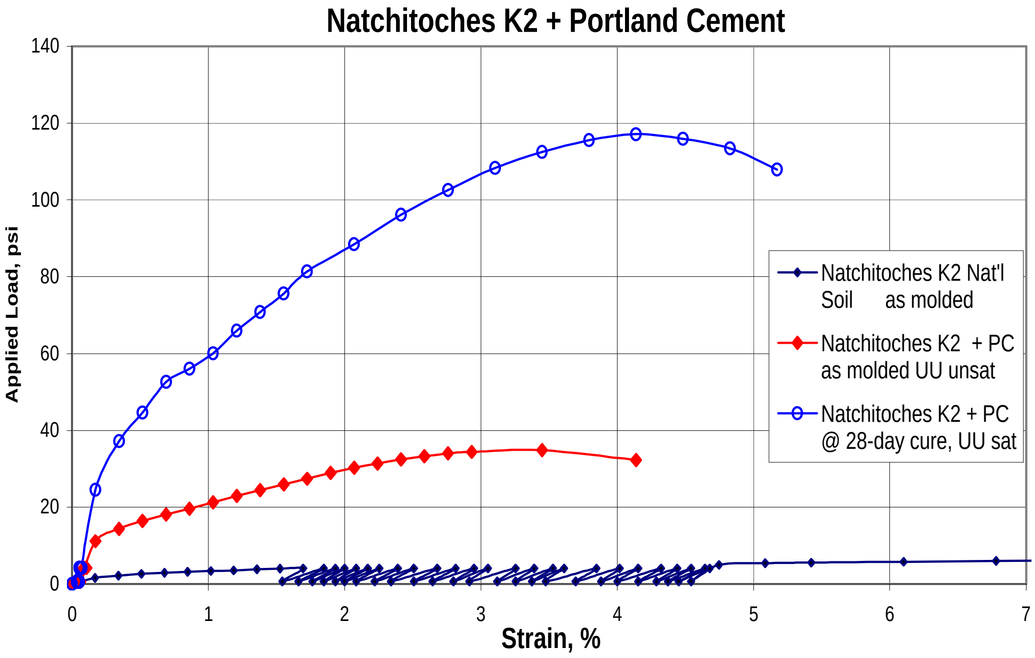

Figure 19
Cyclic triaxial tests with Natchitoches K2 soil and Portland cement

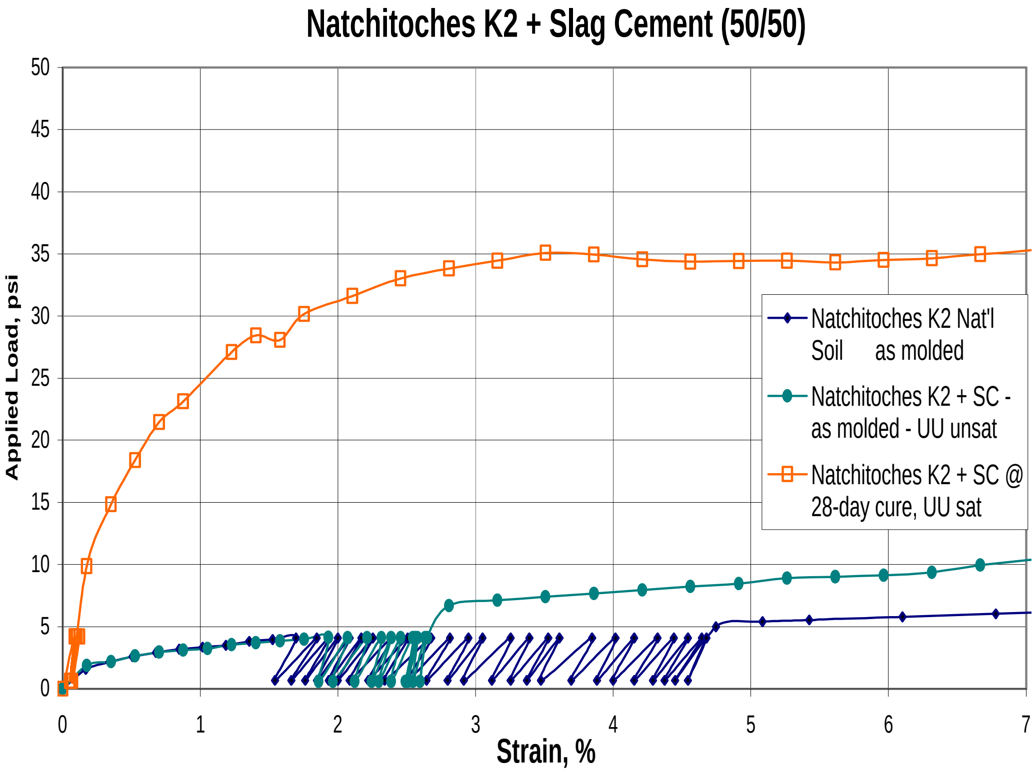

Figure 20
Cyclic triaxial tests with Natchitoches K2 soil and slag cement (50/50)

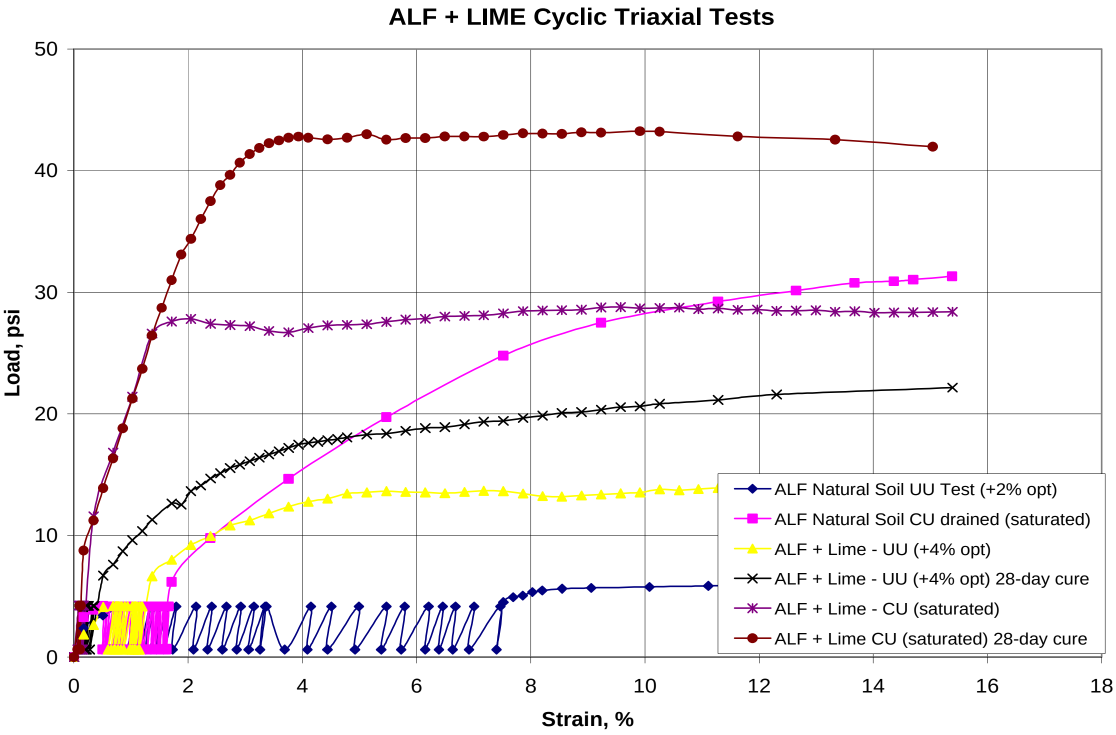

Figure 21
Cyclic triaxial tests with ALF soil and lime

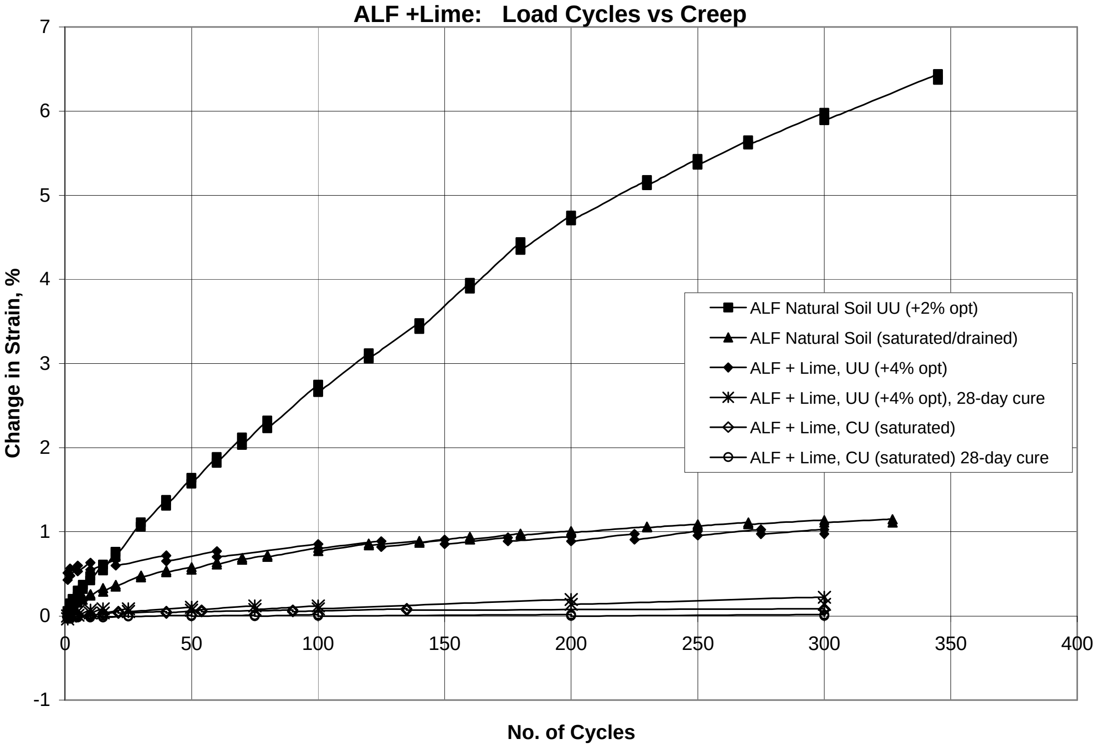

Figure 22
Creep deformation in cyclic tests with ALF and lime

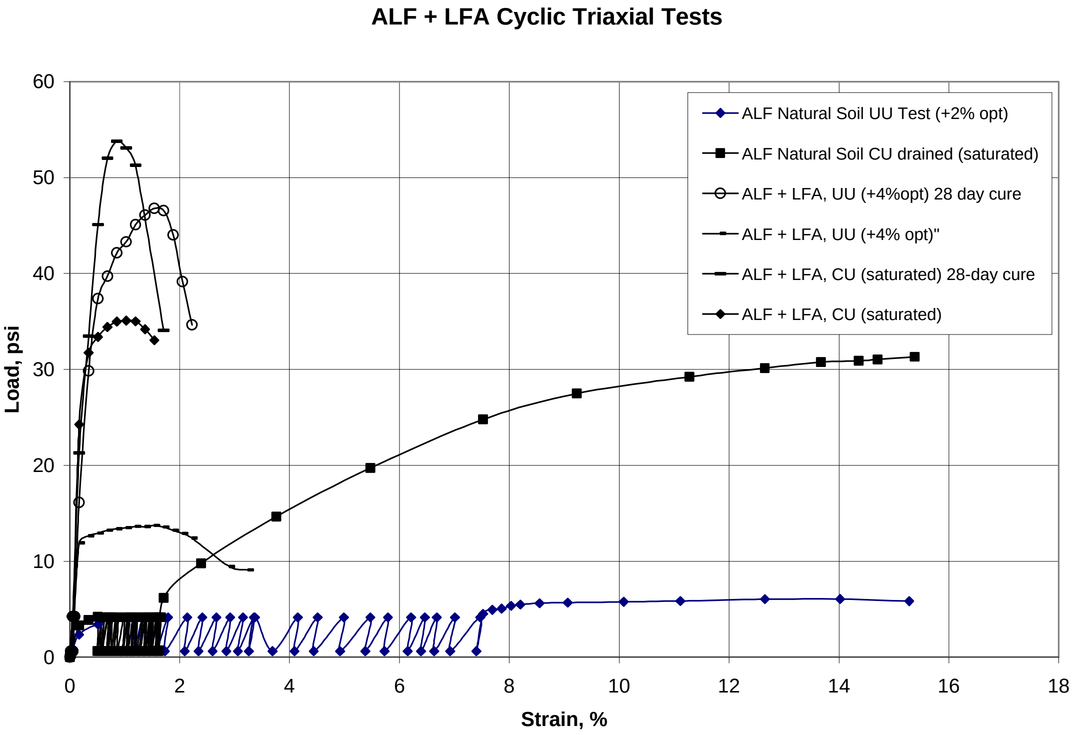

Figure 23
Cyclic triaxial tests with ALF and lime-fly ash

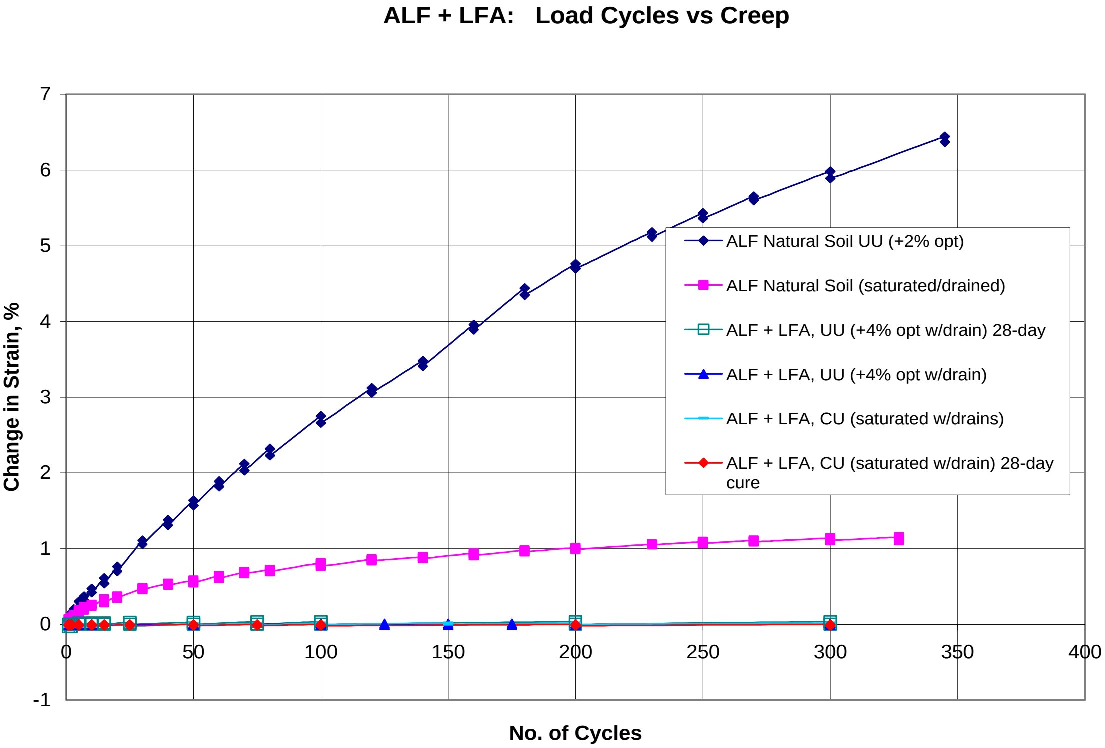

Figure 24
Creep deformation in cyclic tests with ALF and lime-fly ash

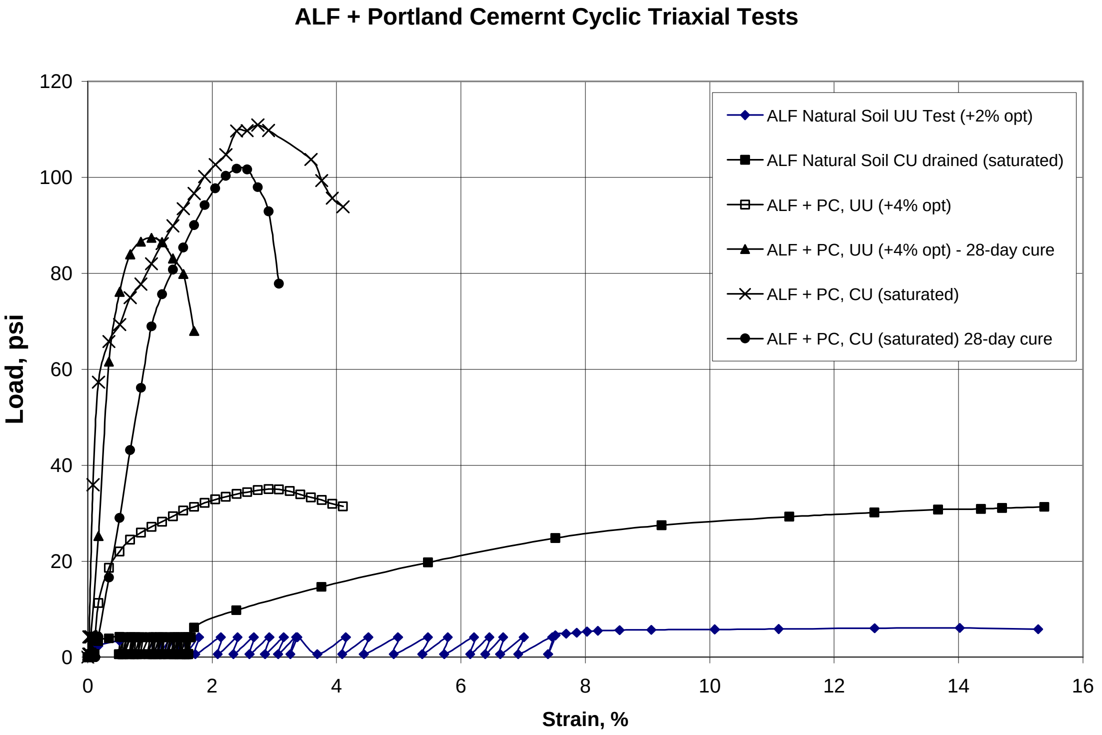

Figure 25
Cyclic triaxial tests with ALF and Portland cement

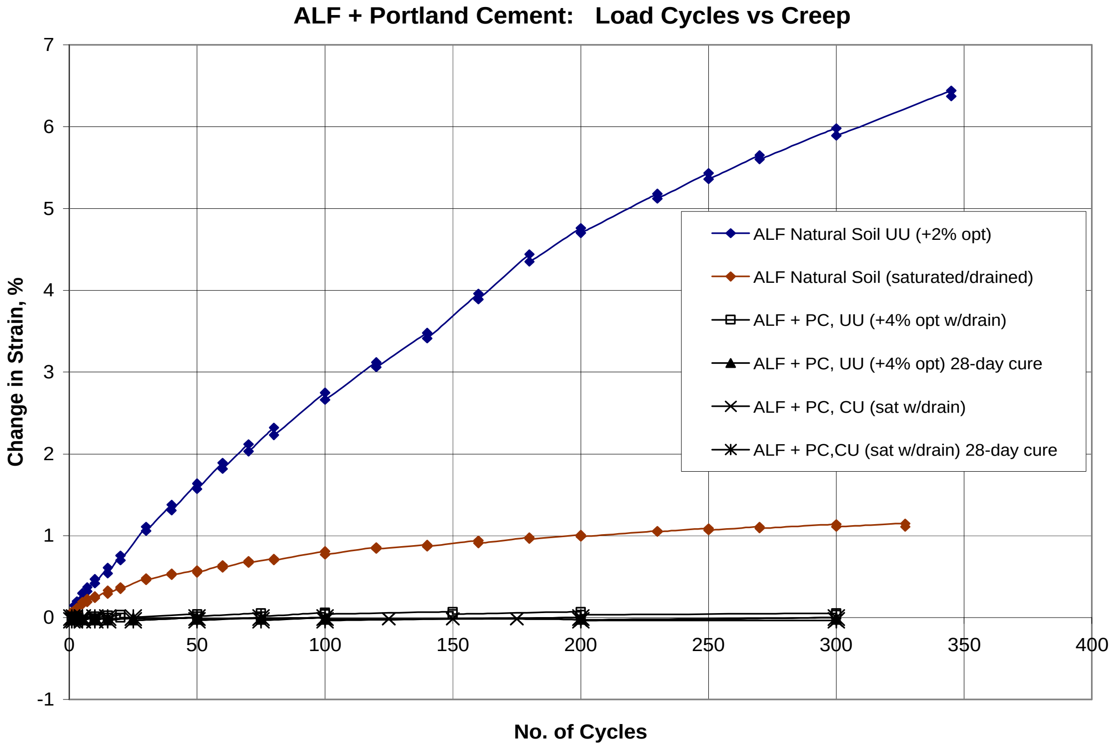

Figure 26
Creep deformation in cyclic tests with ALF and Portland cement

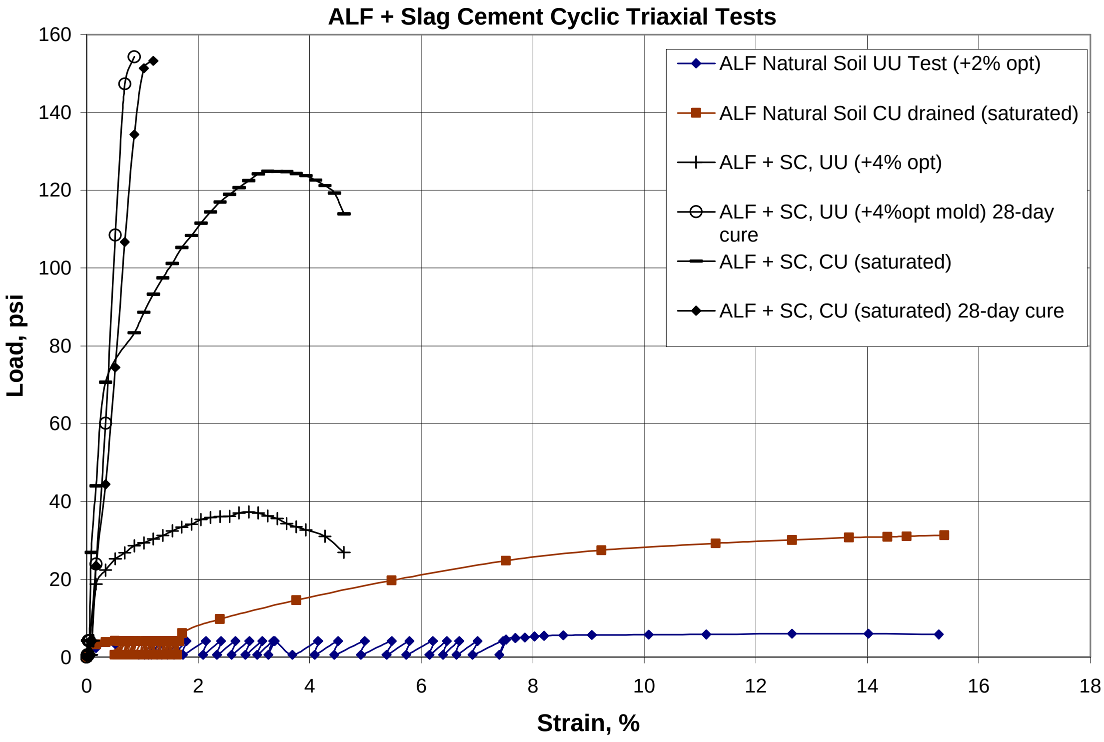

Figure 27
Cyclic triaxial tests with ALF and slag cement

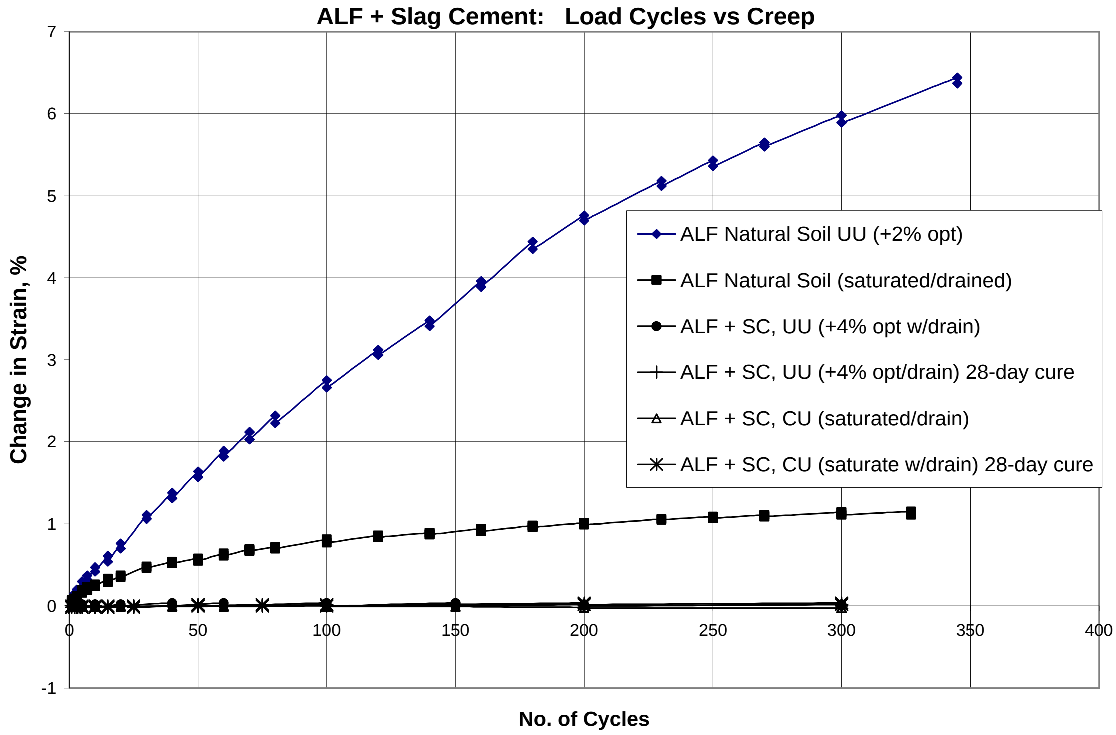

Figure 28
Creep deformation in cyclic tests with ALF and slag cement

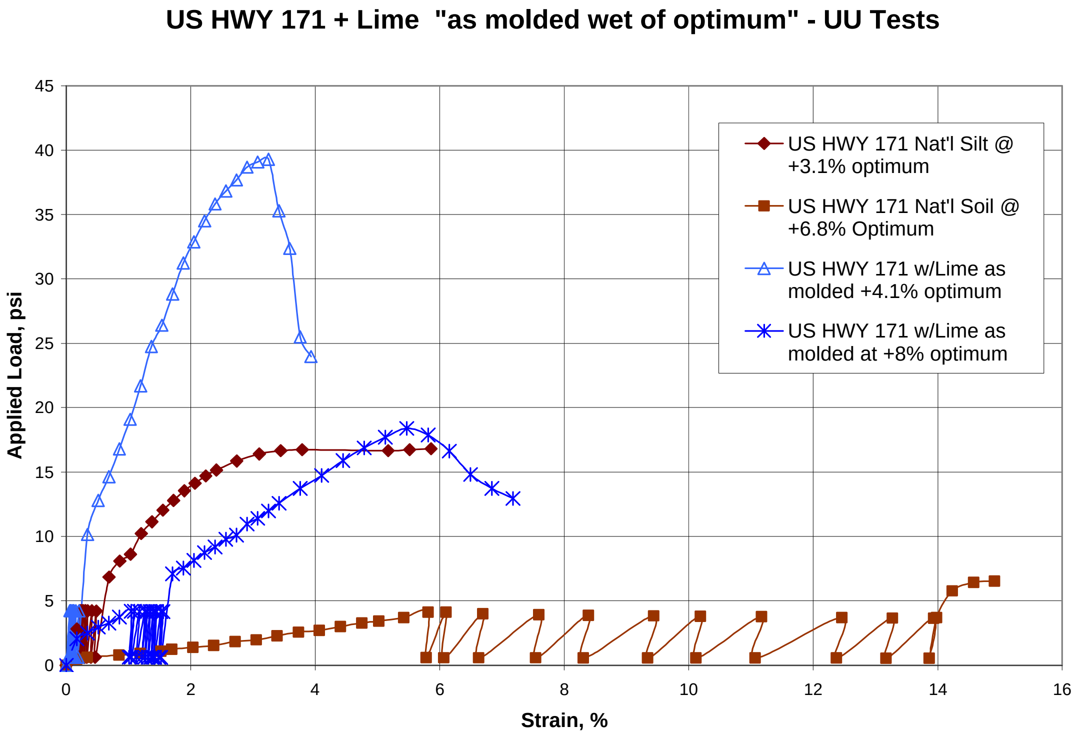

Figure 29
Cyclic triaxial tests with US 171 soil and lime

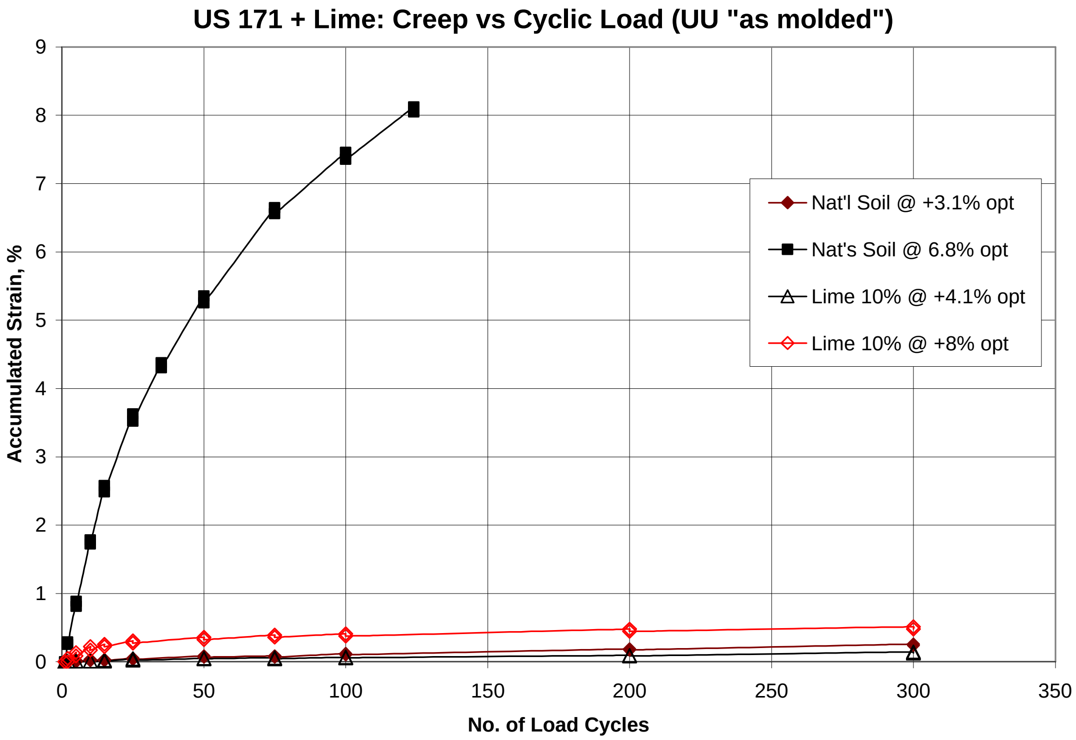

Figure 30
Creep deformation in cyclic tests with US 171 soil and lime

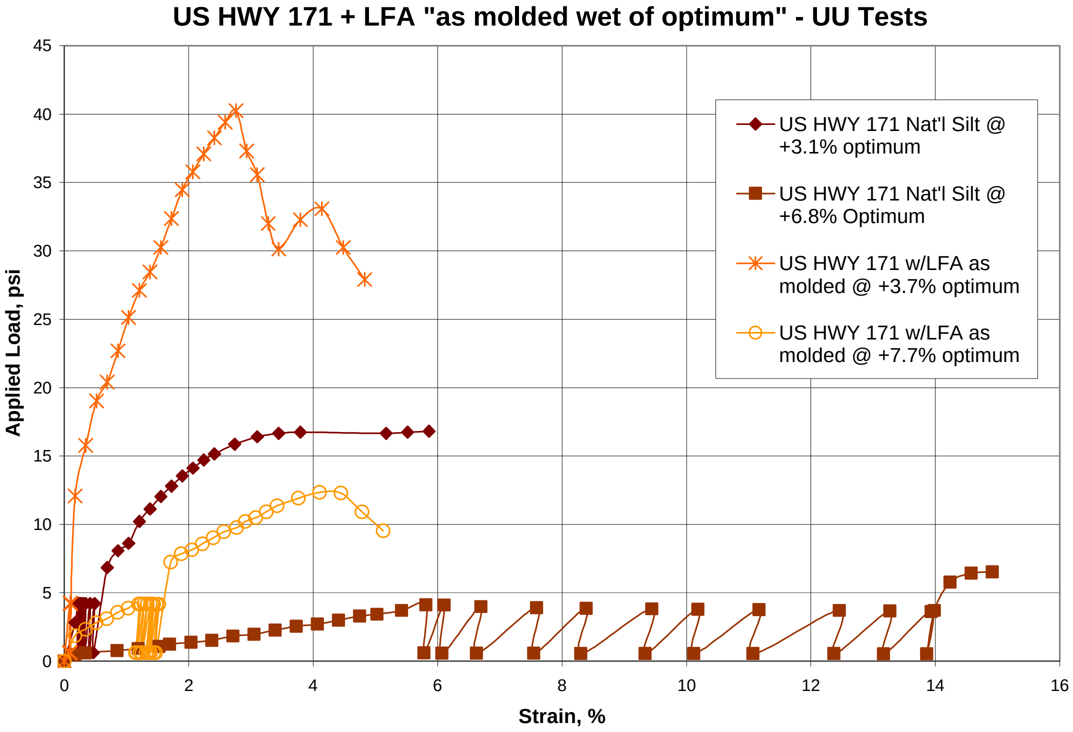

Figure 31
Cyclic triaxial tests with US 171 soil and lime-fly ash

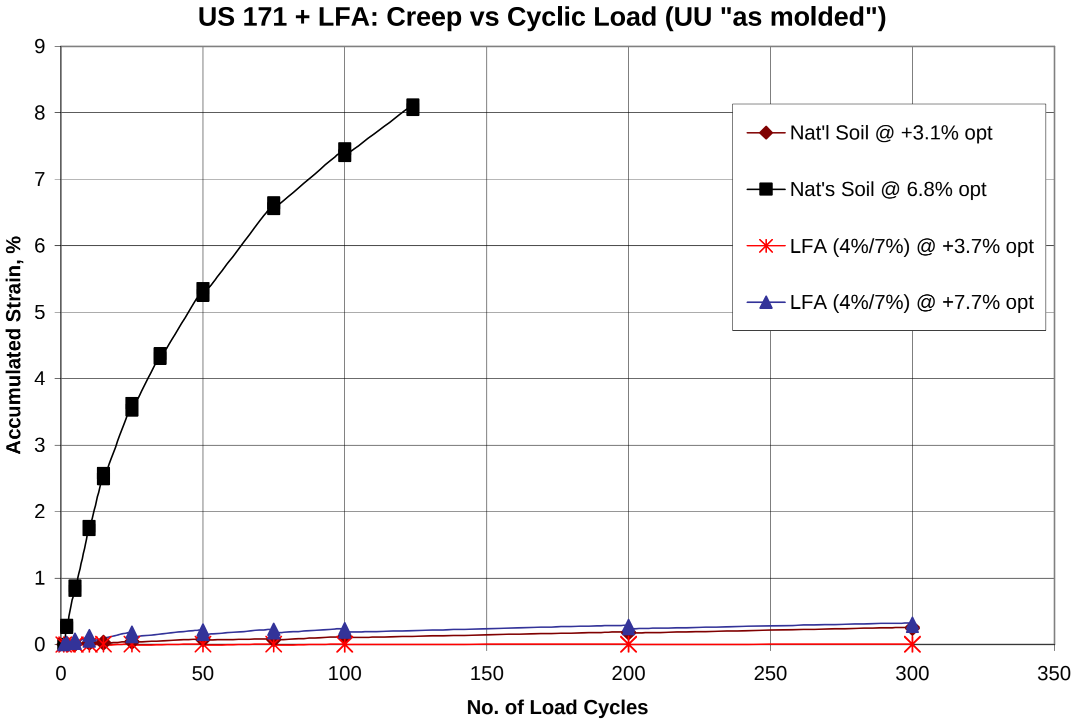

Figure 32
Creep deformation in cyclic tests with US 171 soil and lime-fly ash

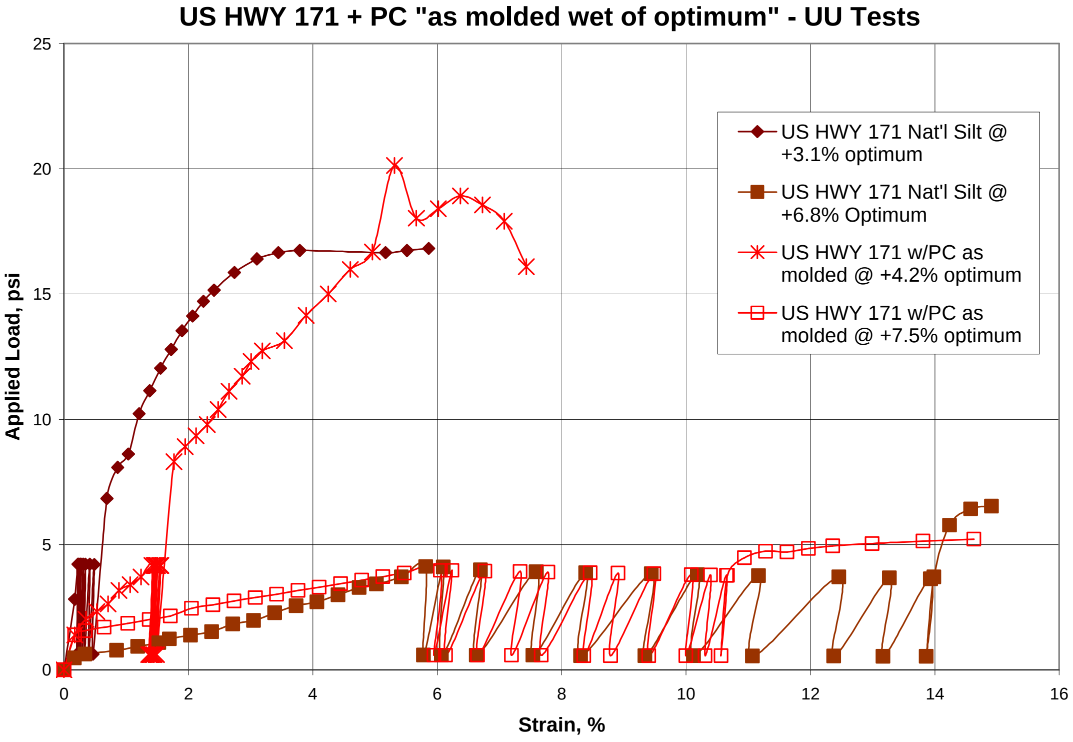

Figure 33
Cyclic triaxial tests with US 171 soil and Portland cement

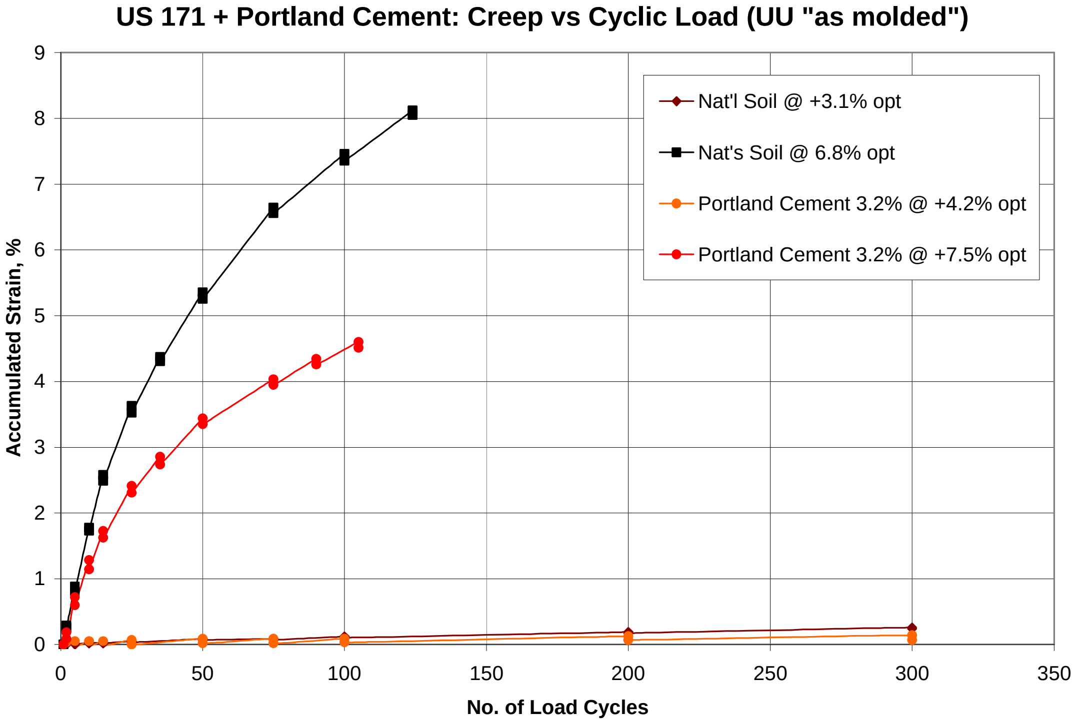

Figure 34
Creep deformation in cyclic tests with US 171 soil and Portland cement.

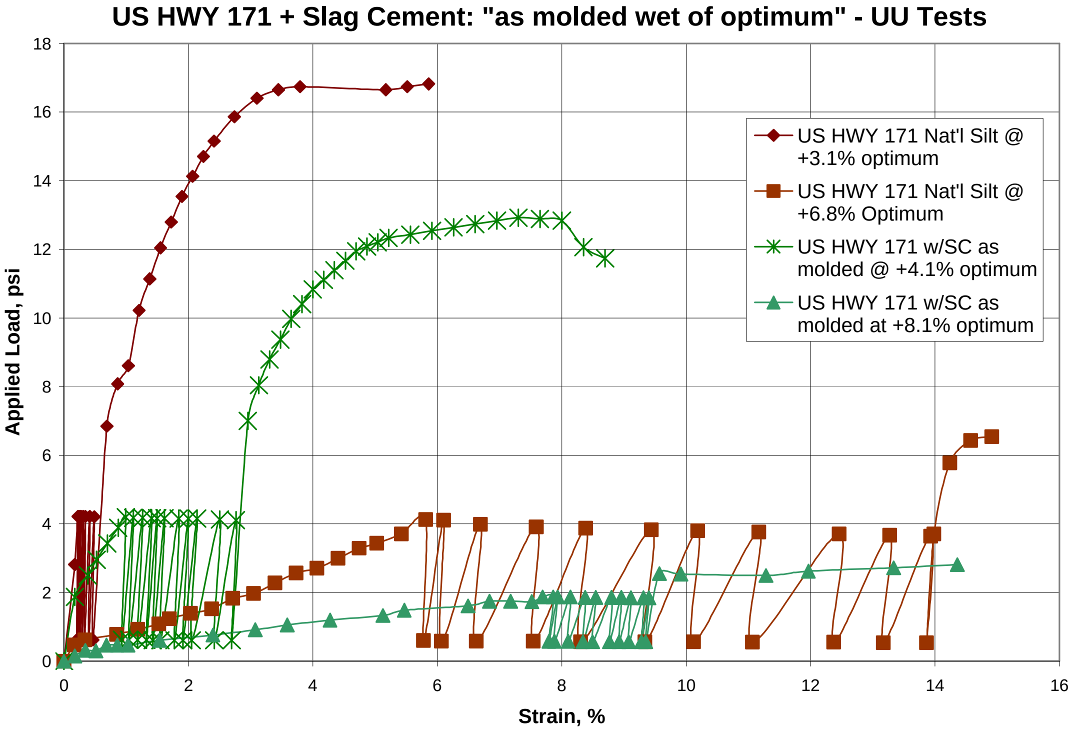

Figure 35
Cyclic triaxial tests with US 171 soil and slag cement

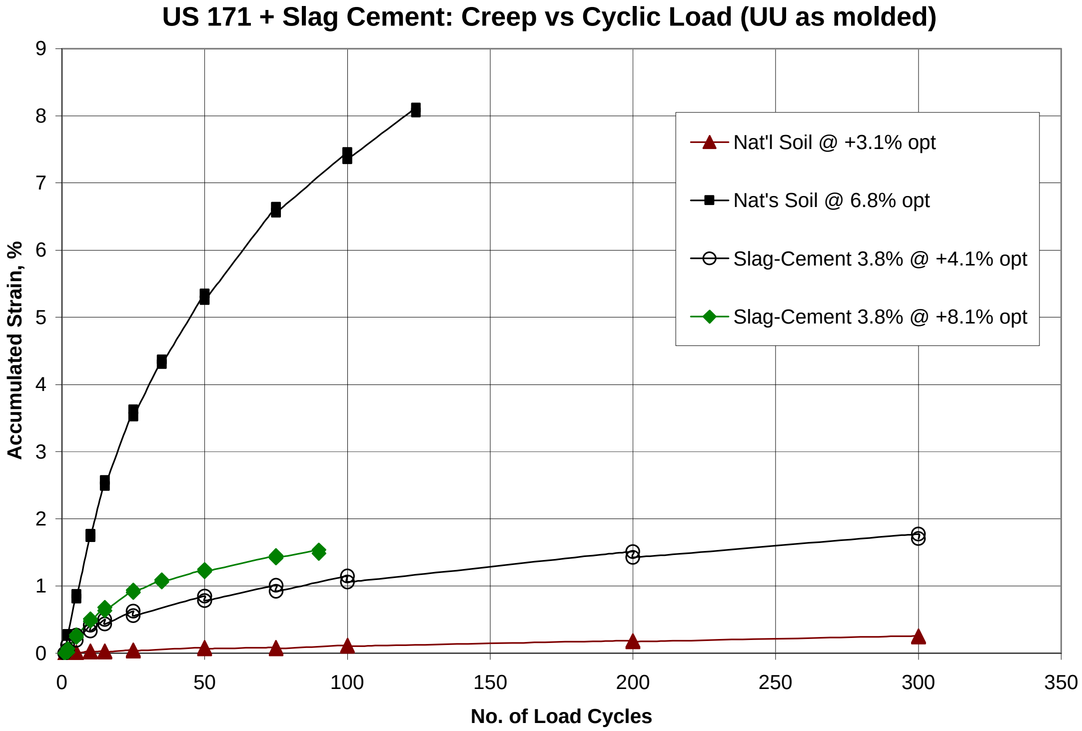

Figure 36
Creep deformation in cyclic tests with US 171 soil and slag cement