EVALUATION OF STRUCTURAL PROPERTIES OF LIME STABILIZED SOILS AND AGGREGATES

VOLUME 3:
MIXTURE DESIGN AND TESTING PROTOCOL FOR LIME STABILIZED SOILS

PREPARED FOR THE NATIONAL LIME ASSOCIATION

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I. INTRODUCTION

Lime stabilization provides structural improvement to many soils and aggregates. This is well documented in the literature which is summarized in Volumes 1 and 2 of this study. To be confident that a lime stabilized soil layer can function as intended in a pavement designed by a mechanistic-empirical approach, it is necessary to determine strength and stiffness properties. Furthermore, it is necessary to demonstrate durability. These key properties are addressed by the following mixture design and testing protocol (MDTP):

- **Classify Soil and Determine Lime Demand.**
- **Fabricate, Cure, and Soak Samples**.
- **Determine Strength and Stiffness.**

The purpose of this study is to evaluate this MDTP.

This report is divided into six sections. The introduction is followed by a description of the MDTP. Section three presents testing results and compares them to expected properties (as defined in the synthesis of pertinent literature--see Volumes 1 and 2). Conventional unconfined compressive strength (ASTM D 5102) and conventional resilient moduli (AASHTO T 294-94) tests were evaluated for three typical candidate soils for lime stabilization. These tests followed accelerated curing and moisture conditioning.

The fourth section of the report assesses two new testing methods to provide expedient and reliable moisture sensitivity and resilient moduli data. Section five presents findings and recommendations.

Appendix A presents a plan for implementing the MDTP in conjunction with a study currently underway with the Mississippi Department of Transportation. This study will also produce lime stabilization design/analysis examples for possible use in the 2002 AASHTO Design Guide.

II. METHODOLOGY

The recommended MDTP is described below:

1. ***Classify Soil and Determine Lime Demand*** -

   Classification: This process is used to screen the soil for potential for reactivity with lime. The U.S. Air Force Soil Stabilization Index System (SSIS, 1976) determines a soil to be a candidate for lime stabilization if the soil has at least 25% passing the 75 micron sieve and has a plasticity index (PI) of at least 10. The screening criteria also limit organics to less than 1% by weight and soluble sulfates to less than 0.3% unless special precautions are taken (Little, 1996).

   Approximate Lime Demand: Perform the Eades and Grim pH test (ASTM D 6276) to determine lime demand. This protocol approximates the amount of lime required to provide a long-term pozzolanic reaction that will maximize the probability of providing acceptable long-term strength, resilient properties, and durability.

2. ***Fabricate, Cure, and Soak Samples*** (to mimic field conditions and the effects of moisture) -

   Fabricate and Cure: The moisture/density relationship is a required part of the mix design. It determines the target moisture content for sample fabrication. Samples are prepared for strength testing and moisture sensitivity testing at optimum moisture content with a tolerance of 1% (plus or minus). All soils are cured for 7 days at 40ºC in plastic bags to retain sufficient moisture. This recommended curing period is short enough to be feasible for mixture design purposes yet long enough, and at a sufficient temperature, to provide reasonable approximations of long-term cure (ultimate strength) under ambient field conditions. This accelerated curing protocol was based on the literature summarized in Volume 1, Table A2.

Soak: The sample is subjected to capillary soak for 24 to 48 hours prior to strength testing. This represents the moisture state under reasonable pavement conditions.

3. ***Determine Strength and Stiffness*** - Unconfined compressive strength is determined using ASTM D 5102. This study confirms that unconfined compressive strength can approximate design parameters such as flexural strength, deformation potential, and stiffness (resilient modulus). This approach can be used for most designs.

   For high volume designs, however, stiffness (i.e., resilient modulus) should be measured directly. This study demonstrates that a rapid triaxial test (RaTT) can be used instead of the more time-consuming and material-intensive AASHTO T 294-94 test.

III. COMPARING SHEAR STRENGTH, RESILIENT MODULUS, AND MOISTURE RESISTANCE OF TYPICAL LIME-STABILIZED SOILS TO EXPECTED VALUES FROM THE LITERATURE

A. RESILIENT MODULUS AND UNCONFINED COMPRESSIVE STRENGTH TESTS

AASHTO Method T 294-94 is the generally accepted protocol for resilient modulus testing for granular and fine-grained soils and aggregates. The method consists of a conditioning phase and a testing phase. The resilient modulus is determined as a function of stress state. However, the protocol is relatively time and material intensive and is not generally amenable to standard mixture designs. Nonetheless, the resilient modulus is an essential property for structural design/analysis.

ASTM Method D 5102 is the generally accepted method for unconfined compressive strength measurement of lime-treated soils.

Three soils typical of those stabilized with lime to serve as subbases or bases were tested in this study. Unconfined compressive strengths and resilient moduli were determined following a capillary soak. The capillary soak was designed to simulate the critical moisture state of the layer in the pavement system. The soil properties and testing results are presented in Table 1.

Table 1. Summary of Unconfined Compressive Strength (ASTM D 5102) and Resilient Moduli (AASHTO T 294-94) Testing

Soil ID		Description	Plasticity Index[1]		Unconfined Compressive Strength[2], kPa		Resilient Modulus[2] at Deviatoric Stress of 41kPa, MPa	
			without lime	with lime	without lime	with lime	without lime	with lime
D-16	D-16L	Moderately plastic silty clay (L=with 5% hydrated lime[3])	24	4	145	2,765	79.2	275
D-37	D-37L	Moderately plastic tan clay (L=with 5.5% hydrated lime[3])	29	9	280	2,980	52.5	625
B-1	B-1L	Heavy clay (L=with 6% hydrated lime[3])	38	10	160	2,275	35.6	210

[1] Determined after 24 hours of mellowing for stabilized soils.
[2] All soils cured for 7-days at 40°C in plastic bags filled with water and subjected to capillary soak prior to strength testing.
[3] The optimum lime demand for each soil was determined using the ASTM D 6276 pH test.

Each of the three soils evaluated were candidates for lime stabilization because they had 75 micron fractions in excess of 25% and plasticity indices greater than 10. The lime demand for each soil was determined by the ASTM D 6276 (pH test). All soils were cured for 7 days at 40°C in plastic bags to retain sufficient moisture for the curing process. This is a reasonable period of accelerated cure because previous studies have demonstrated that it promotes a strength that is representative of a long-term cure (approximately one month at typical annual average temperatures of approximately 23°C) - see Table A2 of Volume 1.

All soils were subjected to capillary soak prior to strength and resilient modulus testing. Low to moderate plasticity soils were soaked for 24 hours; high plasticity soils for 48. The capillary soak protocol consists of moisture soak through a porous stone at the base of each sample and an absorptive wrap placed around the circumference of the sample. The porous stone and the fabric wrap are placed in contact with water throughout the capillary soak process. (Soaking unstabilized samples often resulted in disintegration or severe loss of strength.)

The AASHTO T 294-94 resilient modulus testing protocol for type 2 designs consists of a conditioning period followed by subjecting the sample to various deviatoric stresses (ranging from 14 to 69 kPa) for confining pressures of 41, 21, and 0 kPa, respectively. A deviatoric stress of 41 kPa is typical within the subgrade and is used to identify a single resilient modulus. This value of deviatoric stress is typically used to establish the “knee” in the resilient modulus versus deviatoric stress curve.

The results in Table 1 demonstrate the following:

- Each soil is reactive with lime, creating an appreciable improvement in unconfined compressive strength (increases greater than 350 kPa) following the addition of lime and accelerated curing.
- The structural improvement provided by the increase in shear strength and resilient properties following capillary soak are quite significant and represent good structural improvement [Volume 2, Table A2].

B. EFFECT OF MOLDING MOISTURE CONTENT AND COMPACTION ON COMPRESSIVE STRENGTH

The protocol used for mixture fabrication for unconfined compressive strength testing and for resilient modulus testing described in the preceding subsection is modified compaction according to AASHTO T 180 or ASTM D 1557. Some agencies use AASHTO T 99 or ASTM D 698 (standard compaction). The compaction energy for standard compaction is approximately 22% of modified. The literature demonstrates that compaction energy has a large effect on strength of both unstabilized and stabilized fine-grained soils. The literature also demonstrates that molding moisture has a significant effect on strength and resilient properties. The effects of compaction energy and molding moisture on three soils are summarized in Table 2.

Table 2. Effect of Compaction Energy and Molding Moisture Content on Unconfined Compressive Strength (Following 24-Hours of Capillary Soak).

Soil ID		Unconfined Compressive Strength, Modified Compaction Energy, kPa						Unconfined Compressive Strength, Standard Compaction Energy, kPa	
		1% Below Optimum		Optimum Moisture Content		1% Above Optimum		Optimum	
without lime	**with lime**	**without lime**	**with lime**	**without lime**	**with lime**	**without lime**	**with lime**	**without lime**	**with lime**
D-37	D-37L	225	2,725	280	2,980	120	2,235	124	1,395
D-16	D-16L	140	2,458	145	2,765	70	1,935	105	1,293
B-1	B-1L	155	2,150	160	2,275	85	1,820	50	1,195

The data in Table 2 illustrate that strength and modulus values are highly sensitive to molding moisture content. Thus, this testing protocol requires testing samples (for strength and resilient modulus) at optimum moisture content (for maximum density). The data in Table 2 also clearly demonstrate that stabilization not only improves strength and stiffness values but also reduces the sensitivity of strength to the effects of moisture.

The results also illustrate that modified compaction (AASHTO T 180) clearly defines the optimum lime content. Modified compaction is easily achieved with conventional field equipment, and the strength achieved is substantially greater than when standard compaction used. Some agencies use standard compaction on high plasticity soils to minimize problem swell pressures. Lime stabilization will reduce plasticity (and concomitantly swell pressures) to benign levels, however. Thus modified compaction is recommended to more clearly define the optimum lime content, although standard compaction may be used.

IV. EVALUATION OF NEW TEST METHODS

A. EVALUATION OF THE RAPID TRIAXIAL TEST (RaTT) METHOD OF RESILIENT MODULUS TESTING

The AASHTO T 294-94 test method subjects a specimen to sixteen stress stages or regimes. The first stress regime is a conditioning stage in which a minimum of 500 to no more than 1,000 axial pulses are applied. Each of the remaining stress stages apply 100 axial loading pulses to the specimen. The values of confining and deviator stress for each regime are defined by the AASHTO T 294-94 test method.

RaTT Testing Methodology

The Rapid Triaxial Test (RaTT) is one instrument that embodies the requirements of AASHTO T 294-94. It was selected as a candidate for the level 2 MDTP because it offers an efficient method for determining resilient properties of the lime-stabilized soil. It is being used by the International Center for Aggregates Research (ICAR) and by the University of Illinois for unbound aggregate base course testing. The RaTT device provides a more efficient and rapid means than T 294 of determining resilient and permanent deformation properties of granular and fine-grained materials. It also has unique capabilities of measuring radial displacements simultaneously with axial displacements and of pulsing stresses in either the axial or radial directions. This device or a similar device will likely be recommended for aggregate and soil characterization associated with the 2002 AASHTO Design Guide.

The RaTT is pneumatically operated and provides independent control of axial and lateral stresses applied to a specimen during testing. The design of the RaTT hardware allows cylindrically-shaped specimens (normally 100 mm diameter and 100 mm height) to be quickly and conveniently mounted into the system for testing. Lateral stress is applied to the specimen by controlling the pneumatic pressure applied to the membrane in contact with the wall of the specimen. Axial stress is applied to the specimen from an actuator mounted in a reaction loading frame. Feedback servo-control is used for the accurate generation of both the lateral and axial stresses.

The compacted sample must be trimmed within close tolerance because test height has a critical impact on precision and accuracy. Rubber membranes surrounding the sample within the cell minimize end effects and allow use of a one-to-one height to diameter sample.

Once the sample is fabricated and placed within the cell, the complete time for resilient modulus testing across the entire range of stress states to which the specimen is subjected is about 45 minutes.

RaTT Testing Results

Three soils were subjected to RaTT resilient modulus testing: a low plasticity soil (LB1 with PI = 12), a moderate PI soil (MB1 with PI = 25) and a high plasticity soil (HB1 with PI = 35). The results of unconfined compressive strength (ASTM D 5102) and RaTT resilient modulus testing for these soils appear in Table 3.

These results support the following findings:

1. The RaTT resilient modulus test device provides repeatable and realistic resilient moduli for level 2 mixture design and evaluation.

2. Complete soaking (for as long as 48 hours) is needed to simulate moisture effects fully.[1]

3. Lime stabilization produces substantial improvements in unconfined compressive strength and resilient modulus based on testing using the RaTT.

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[1] The resilient moduli data summarized in Table 3 are based on two different capillary soak periods: 24 and 48 hours. Originally, 24 hours was specified for this testing. However, upon observation of the samples during testing, it was apparent that the moisture rise in the highly plastic clays was incomplete (i.e., not all the way to the top of the 100 mm sample). However, the moisture rise was complete at the end of 48 hours. Because 24 hours is not enough for soils with PI above 25, for higher PI soils the moisture conditioning capillary soak period should be extended until it is apparent that the moisture has "wicked" to the top of the sample. The shorter (100 mm high) RaTT samples facilitate a shorter soaking period than conventional AASHTO T 294 testing.

Table 3 Summary of Compressive Strength and RaTT Resilient Modulus Testing on Selected Soils (With and Without Lime).

Soil I.D.	Unconfined Compressive Strength after 7-day Cure at 40ºC, kPa		Unconfined Compressive Strength after 14-days Cure at 40ºC, kPa		Unconfined Compressive Strength after 14-days Cure and 24-hours of Capillary Soak, kPa		RaTT Resilient Modulus Testing at 100 kPa after Soak, MPa
	Individual	Average	Individual	Average	Individual	Average	
LB1	266	234	343	343	NT[3]	NT[3]	100[1] 12[2]
	217		345		NT[3]		
	217		343		NT[3]		
MB1	882	728	1,596	1,162	854	735	180[1] 85[2]
	721		1,092		693		
	588		798		648		
HB1	1,274	1,113	2,394	1,874	420	294	91[1] NT[2,3]
	1,218		1,873		231		
	840		1,355		252		
LB1 - L (3% hydrated lime)	2,835	2,940	3,528	3,857	2,953	3,212	225[1] 265[2]
	2,660		4,123		3,616		
	3,318		3,927		3,067		
MB1 - L (4% hydrated lime)	3,318	5,215	6,188	6,923	6,517	6,860	645[1] 665[2]
	5,600		7,168		7,371		
	6,727		7,420		6,692		
HB1 - L (5% hydrated lime)	7,308	7,294	8,897	9,399	7,994	7,917	533[1] 533[2]
	7,343		9,369		8,239		
	7,231		9,931		7,504		

[1] Sample subjected to 24 hours of capillary soak prior to resilient modulus testing

[2] Sample subjected to 48 hours of capillary soak prior to resilient modulus testing

[3] NT = Sample not testable (too weak to test)

B. EVALUATION OF THE TUBE SUCTION TEST (TST) METHOD OF MOISTURE SENSITIVITY TESTING

The dielectric value (DV) is a measure of the volumetric moisture content and the state of molecular bonding in a material. Low dielectric values indicate the presence of tightly absorbed and well-arranged water molecules. Granular bases or stabilized bases with low dielectric values normally have better strength properties. Dielectric values that are greater than about 16 indicate the presence of substantial "free" moisture. The electrical conductivity of a material is an indication of the amount of ions dissociated to the free water. A higher electrical conductivity is associated with more ions present in the pore water system.

TST Testing Methodology

The Tube Suction Test (TST) was adapted in this study to measure the effectiveness of lime stabilization to reduce moisture sensitivity of stabilized soils. The TST was developed at Texas Transportation Institute (TTI) to determine the moisture susceptibility of base course aggregates. Applying this procedure to soils is based on the premise that lime will reduce the moisture retention and moisture sensitivity of the clay system. The test is simple to perform and has the potential to be an effective screening test for durability.

The TST is a measure of how much moisture a base will absorb through capillary rise and the state of bonding of the absorbed moisture. The test results are primarily related to the amount and type of clay in the aggregate, and secondarily to the water absorption properties of the coarse aggregate fraction. Proposed base course aggregate materials, which fail this test, would be anticipated to perform poorly under heavy wheel loads and when subjected to freezing and thawing conditions.

Previous research demonstrates the success of lime in DV reduction of caliche and clay bound siliceous aggregates (Table 2, Volume 1). Furthermore, past research shows that lime stabilization of an aggregate base with deleterious fines (i.e., fines that make the base susceptible to moisture) improves moisture resistance and increases shear strength.

TST Testing Results

The TST was performed on the low, moderate, and high plasticity soils previously tested for strength and resilient modulus properties. Tube suction testing was continued until each soil reached an equilibrium DV and/or an equilibrium moisture content. All soils reached this equilibrium level within 311.3 hours of testing. Four independent readings of DV and moisture content were taken at nine different times. Tests were performed on three versions of each soil: (1) untreated, (2) lime-treated with unsealed curing, and (3) lime-treated with controlled curing (seal-cured). In version (3) the lime-treated mixtures were cured for 7-days at 40^0C in a sealed, moisture-controlled environment.

Results of testing are presented in Figures 1 and 2.

- For low-plasticity soils, lime acted as a fine filler and increased the water content after capillary soak. No significant difference was seen in the DV over that of the untreated soil.

- For moderate plasticity and high plasticity soils, lime treatment with seal-curing resulted in slightly lower moisture contents and substantial and statistically significant reductions in DVs. (Unsealed curing caused each soil to gain significantly more water and for the DV to rise significantly.) The results in soils that have been seal-cured are consistent with the strength and resilient moduli data.

The TST has the potential to be an important and convenient supplemental test to be used with strength and stiffness testing to monitor the ability of lime to reduce moisture sensitivity and improve mixture durability. Using the TST test with the testing protocol recommended in future field projects will establish a correlation between changes in DV and changes in moisture damage potential.

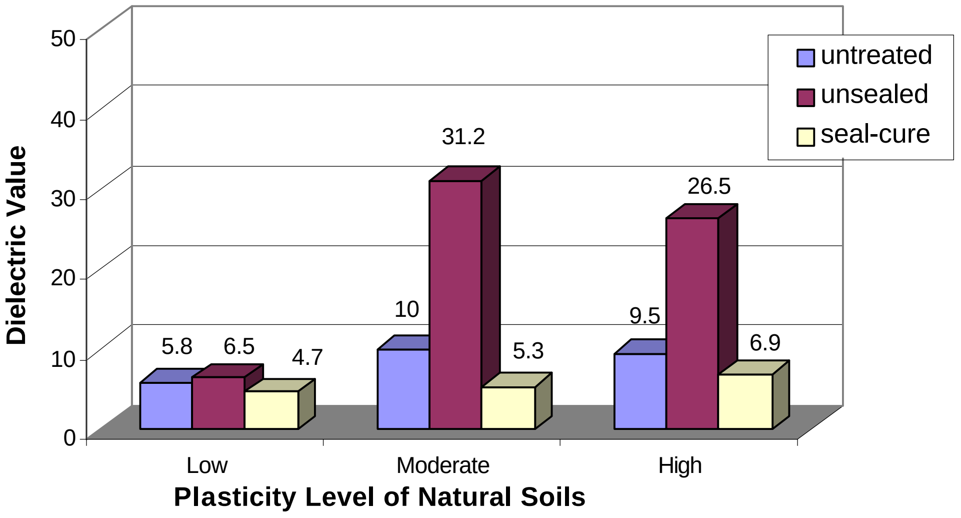

Figure 1. Comparison of Equilibrium DVs for Low, Moderate, and High Plasticity Soils

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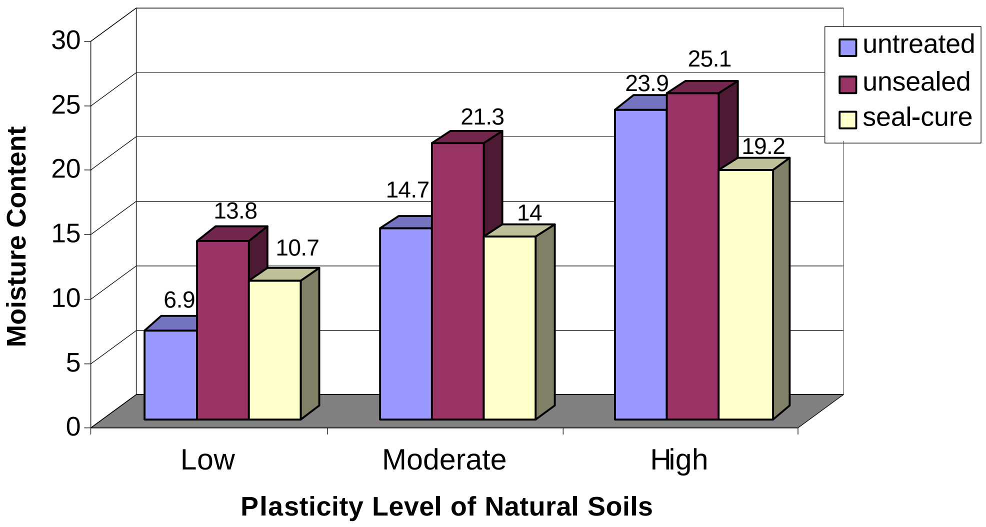

Figure 2. Comparison of Equilibrium Moisture Contents for Low, Moderate, and High Plasticity Soils.

V. SUMMARY OF FINDINGS AND RECOMMENDATIONS FOR IMPLEMENTING THE MIXTURE DESIGN AND TESTING PROTOCOL

Level 1 Testing

1. The Eades and Grim pH test followed by compressive strength testing provide an accurate assessment of optimum lime content.

2. Unconfined compressive strength testing using the recommended compaction, curing, and moisture conditioning protocol approximates the structural properties of lime stabilized pavement layers.

3. The design resilient modulus can be approximated from the unconfined compressive strength.

4. A lime stabilized layer can be assumed to have reasonable resistance to fatigue cracking damage and concomitant strength loss if its unconfined compressive strength is at least eight times the flexural tensile stress induced by traffic load in the lime stabilized layer.

5. A lime stabilized layer can be assumed to have reasonable resistance to permanent deformation if the load-induced compressive stresses do not exceed one-half the unconfined compressive strength.

6. The Tube Suction Test can supplement moisture sensitivity evaluations. Using this convenient test in conjunction with the MDTP in future field projects will generate data to correlate changes in DV to changes in moisture damage potential.

Level 2 Testing

Level 2 testing is identical to level 1 testing except that the resilient modulus is measured according to the RaTT protocol. The rapid test is faster, provides more accurate measurements, and conserves material. It is currently being considered by NCHRP 1-37A for evaluation of unbound aggregate bases and hot mix asphalt layers. The RaTT can be effectively used with lime stabilized soils. The improvement in resilient moduli through lime-stabilization (following simulated moisture damage) is substantial and structurally significant for the wide range of soils tested.

APPENDIX A

IMPLEMENTATION PLAN FOR THE MDTP IN A MISSISSIPPI DEPARTMENT OF TRANSPORTATION STUDY AND THE AASHTO 2002 DESIGN GUIDE

Ten subgrade soils that have been lime stabilized are under study in Mississippi by the Mississippi Department of Transportation. The laboratory and in situ data will together provide the next phase of validation of this mixture design protocol and will be developed into a design example for consideration by the AASHTO 2002 Pavement Design Team (NCHRP Team 1-37A). The study is being conducted at TTI.

Natural and stabilized soils have been collected from the roadways. The natural soils are being subjected to the design protocol discussed in this report. In addition, the natural and stabilized versions of these soils are being subjected to extensive mineralogical testing and microscopic evaluation. Six of the ten soils have produced stabilized layers that have performed extremely well. The other four were selected for this study because of their marginal or poor performance. The laboratory testing will determine if the original mixture designs were adequate, and/or mineralogical conditions could have interfered with the pozzolanic reaction, and/or inadequate lime was added during construction.

Field testing has been performed on pavements containing lime-stabilized subgrades studied and tested in the lab. This field testing consists of Falling Weight Deflectometer (FWD) testing, Ground Penetration Radar (GPR) testing, and Dynamic Cone Penetrometer (DCP) testing. The FWD data has provided in situ resilient moduli data of the lime stabilized layers. The GPR data has defined the in situ moisture sensitivity of the lime stabilized layers. The DCP testing has defined the in situ strength with depth of the lime stabilized layers.