Tube Suction Test for Evaluating Durability of Cementitiously Stabilized Soils

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By

Pranshoo Solanki
Musharraf M. Zaman
Roy Khalife

School of Civil Engineering and Environmental Science
University of Oklahoma
Norman, Oklahoma

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# Table of Contents

LIST OF FIGURES .................................................................................................................. 3
LIST OF TABLES ....................................................................................................................... 3
SUMMARY .................................................................................................................................. 4

1. ACCOMPLISHMENTS ........................................................................................................... 6
   1.1 LITERATURE REVIEW ..................................................................................................... 6
   1.2 COLLECTION OF SOILS AND ADDITIVES ...................................................................... 6
       1.2.1 Collection of Soils .................................................................................................. 6
       1.2.2 Collection of Additives ......................................................................................... 8

2. LABORATORY TESTING ......................................................................................................... 8
   2.1 SOIL CLASSIFICATION TESTS ........................................................................................ 8
   2.2 MOISTURE-DENSITY TESTS ............................................................................................ 9
   2.3 CONVENTIONAL FREEZE-THAW TEST: RESILIENT MODULUS .................................... 10
   2.4 CONVENTIONAL WET-DRY TEST: RESILIENT MODULUS .............................................. 11
   2.5 CONVENTIONAL FREEZE-THAW TEST: UNCONFINED COMPRESSIVE STRENGTH .... 13
   2.6 TUBE SUCTION TEST .................................................................................................... 14

3. WORK PLANNED FOR THE COMING YEAR ..................................................................... 17
REFERENCES CITED. ................................................................................................................. 17
List of Figures

Figure 1: Location of Latimer and Muskogee County on Oklahoma State Map ...................... 7
Figure 2: Collection of Carnasaw Series Soil from (a) Latimer County, and (b) Muskogee County .............................................................................................................................................. 7
Figure 3: Particle Size Distribution of Carnasaw Series Soil ......................................................... 9
Figure 4: Resilient Modulus Specimens under (a) Freezing and (b) Thawing ......................... 10
Figure 5: Resilient Modulus Specimens at the End of Freezing During 4 F-T cycles (a) 6% Lime, (b) 10% CFA, and (c) 10% CKD ................................................................................................................. 10
Figure 6: Resilient Modulus Values of Stabilized Specimens under F-T Testing (σd = 5.4 psi, σ3 = 4.0 psi) .............................................................................................................................................. 11
Figure 7: Wetting of Resilient Modulus Specimens (a) 0 hrs and (b) 5 hrs .............................. 12
Figure 8: Resilient Modulus Values of Stabilized Specimens under W-D Testing (σd = 5.4 psi, σ3 = 4.0 psi) .............................................................................................................................................. 12
Figure 9: Harvard Miniature Specimens under (a) Freezing and (b) Thawing ......................... 13
Figure 10: UCS of Raw and Stabilized Specimens at the End of 0, 1, 4, 8, and 12 F-T Cycles ........................................................................................................................................... 14
Figure 11: Photographic View of Specimens (a) Raw at the End of Cycle 10, (b) 6% Lime-stabilized at the End of Cycle 12, (c) 10% CFA-stabilized at the End of Cycle 12, (d) 10% CKD-stabilized at the End of Cycle 12 .......................................................................................................................... 14
Figure 12: Setup for Tube Suction Test ....................................................................................... 15
Figure 13: Final Dielectric Values of Raw and Stabilized Soil Specimens ......................... 16

List of Tables

Table 1: Summary of Literature Review of Tube Suction Test on Cementiously Stabilized Materials ........................................................................................................................................... 6
Table 2: Testing Designation and Soil Properties ........................................................................ 8
Table 3: Summary of OMC-MDD of Lime-, CFA- and CKD-C-Soil Mixtures ............................ 9
**Summary**

Strength and stability of subgrade soil, which supports the pavement structure, is a key factor in pavement performance. Although cementitious stabilization is widely used in Oklahoma to improve subgrade soil properties, effect of freeze-thaw (F-T) and wet-dry (W-D) conditions, referred to as “durability” in this project is not frequently addressed. This is partly because the current methods for assessment of durability of cementitiously stabilized subgrade soils are time-consuming and costly. A more time-efficient, inexpensive and non-abrasive method, called Tube Suction Test, is being used in the present study to evaluate durability of selected stabilized soils that are frequently encountered in Oklahoma. One of the objectives of this study is to develop a test protocol for the assessment of durability using the Tube Suction Test (TST) and to compare results with the current test methods, namely wet-dry (ASTM D 559), freeze-thaw (ASTMD560), vacuum saturation (ASTM C 593), and unconfined compressive strength (UCS). This study is co-funded by Oklahoma Department of Transportation (ODOT).

In the first year of this study, two soils (fat clays) and three additives (lime, class C fly ash, cement kiln dust) were collected in cooperation with ODOT personnel. A fairly comprehensive laboratory study was undertaken to determine the durability of these soils when cementitiously stabilized with the selected additives. The laboratory tests conducted so far include soil classification, moisture-density, resilient modulus (Mr) at the end of freeze-thaw (F-T) or wet-dry (W-D) cycles, unconfined compressive strength (UCS) at the end of F-T cycles, and tube suction test (TST) of both raw and stabilized soil specimens. Both the selected soils, Carnasaw Series (Latimer County) and Dennis Series (Muskogee County), are frequently encountered in pavement construction in Oklahoma. These soils were stabilized with three locally produced and economically viable stabilizers used in Oklahoma, namely, hydrated lime (or lime), class C fly ash (CFA), and cement kiln dust (CKD).

Cylindrical specimens (diameter = 4.0 in., height = 8.0 in.) of stabilized soil were compacted with a target dry density between 95-100% of maximum dry density (MDD), and cured for 7 days in a moist room having a constant temperature (23.0±1.7°C) and controlled relative humidity (about 96%). After curing, specimens were tested for resilient modulus (Mr). These specimens were then placed in a freeze-thaw (F-T) chamber and tested in accordance with ASTM D 560 test method. The procedure requires freezing specimens for 24 hours at a temperature not warmer than -23.3°C (-10°F) and thawing for 23 hours at 21.1°C (70°F) and 100 percent relative humidity. Following the specified thawing periods, namely 1, 4, 8 and 12 F-T cycle, the specimens were tested for Mr. Similarly, specimens were also prepared for conducting Mr tests on specimens subjected to W-D cycles in accordance with ASTM D 559 test method. Each W-D cycle consisted of placing a 7-day cured specimen in a water bath at room temperature for five hours and then placing it in an oven at a temperature of 71°C (160°F) for 42 hours. Following the specified drying period concluding 1, 4, 8 and 12 W-D cycles, the specimens were tested for Mr. Cylindrical specimens of smaller size (1.315 in. x 2.819 in.) were also prepared by using Harvard miniature device. After 7-day curing, specimens were subjected to F-T cycles followed by UCS after 1, 4, 8, and 12 F-T cycles. Results showed that lime-stabilized specimens exhibit the highest resistance toward F-T and W-D cycles, followed by specimens stabilized with CKD and CFA.

A total of four different methods were used for conducting tube suction tests (TST) by taking into account different specimen sizes (4.0 in. x 4.0 in., 6.0 in. x 6.0 in., 4.0 in. x 8.0 in.)
and compaction methods (standard Proctor and Superpave gyratory compactor). It was observed that dielectric values determined by each method are different. Hence, the selection of method influences the dielectric value of stabilized specimens. Additional testing is in progress for selecting and rationalizing the TST method that will be more representative of the F-T and W-D durability of cementitiously stabilized soils. Based on these results, a test protocol will be selected/established in Year 2. Also, additional soils will be tested in Year 2 for their dielectric values, determined from different TST methods.

Further, unconfined compressive strength tests will be conducted in Year 2 on stabilized specimens subjected to selected F-T or W-D cycles, as an indicator of durability. Statistical models or correlations among 7-day UCS without any F-T or W-D cycles, 7-day UCS after F-T cycles, 7-day UCS after W-D cycles, and final dielectric values obtained from TST tests will be developed. Further, acceptance criteria by discriminating between good and poor cementitiously stabilized soils on the basis of the dielectric values will be recommended.
1. Accomplishments

1.1 Literature Review

This study involves using Tube Suction Test (TST) method to evaluate F-T and W-D durability of cementitiously stabilized soils. Therefore, a review of current knowledge of TST test method was conducted. A summary of literature review of TST on cementitiously stabilized materials is provided in Table 1. It is clear from Table 1 that only few studies have attempted to evaluate durability (moisture susceptibility) of stabilized soil specimens without using any standard procedures. To the authors’ knowledge there are no data comparing the moisture susceptibility of lime, CFA and CKD as stabilizing agents for subgrade soils. The present study is being pursued to fill this void.

Table 1: Summary of Literature Review of Tube Suction Test on Cementiously Stabilized Materials

<table>
<thead>
<tr>
<th>Reference</th>
<th>Type of material</th>
<th>Specimen size</th>
<th>Drying period</th>
<th>Experimental details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little (2000)</td>
<td>Silty soil with lime</td>
<td>6.0 in. x 6.0 in.</td>
<td>4 days (40°C)</td>
<td>Specimen was placed in a tray with a porous plate at the bottom of the specimen</td>
</tr>
<tr>
<td>Syed et al. (2000)</td>
<td>Aggregates with liquid stabilizer</td>
<td>6.0 in. x 8.0 in.</td>
<td>---</td>
<td>Specimen was compacted in cylindrical plastic molds with holes at the bottom of mold</td>
</tr>
<tr>
<td>Guthrie et al. (2003)</td>
<td>Hanson aggregates</td>
<td>6.0 in. x 8.0 in.</td>
<td>2 days (60±5°C)</td>
<td>Specimen was compacted in cylindrical plastic molds with holes at the bottom of mold</td>
</tr>
<tr>
<td>Saeed et al. (2003)</td>
<td>NA</td>
<td>6.0 in. x 8.0 in.</td>
<td>3 days (38°C)</td>
<td>Specimen was compacted in cylindrical plastic molds with holes at the bottom of mold</td>
</tr>
<tr>
<td>Syed et al. (2003)</td>
<td>Aggregates with cement</td>
<td>4.0 in. x 4.6 in.</td>
<td>3 – 4 days (40°C)</td>
<td>Specimen was placed in a tray with a porous plate at the bottom of the specimen</td>
</tr>
<tr>
<td>Barbu et al. (2004)</td>
<td>Silty sand with cement</td>
<td>6.0 in. x 12.0 in.; 4.0 in. x 7.0 in.</td>
<td>2 days (50°C)</td>
<td>The bottom of tube was cut and replaced with aluminum foil with holes</td>
</tr>
<tr>
<td>Zhang and Tao (2006)</td>
<td>Clayey silt with cement</td>
<td>4.0 in. x 7.0 in.</td>
<td>7 days (40°C)</td>
<td>Specimen was compacted in cylindrical plastic molds with holes at the bottom of mold</td>
</tr>
<tr>
<td>Parker (2008)</td>
<td>Silty sand and lean clay with CFA/lime-fly ash, lime, cement</td>
<td>4.0 in. x 5.0 in.</td>
<td>3 days (40°C)</td>
<td>Specimen was compacted in cylindrical plastic molds with holes at the bottom of mold</td>
</tr>
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1.2 Collection of Soils and Additives

1.2.1 Collection of Soils

In this study, two soils were collected from two different counties namely, Latimer County and Muskogee County in Oklahoma (Figure 1). The first soil with high plasticity index (PI) was sampled from on-ramp junction of SH 52 and NE 1130th Avenue in Latimer County. This soil belongs to Carnasaw series (called C-soil in this report) and classified as fat clay according to the Unified Soil Classification System (USCS). Hence, this soil is suitable for cementitious stabilization. Latimer County is located in ODOT Division II. Figure 2 (a) shows photographs taken during collection of bulk soil samples from Latimer County.
On May 27, 2009, the second soil series was sampled from the NW corner intersection of Gibson street and US 165, in collaboration with ODOT. This soil belongs to Dennis series (called D-soil in this report) and classified as fat clay according to USCS. The site is located in Muskogee County (ODOT Division I) near Muskogee, as shown in Figure 2 (b). Before soil sampling, a bore hole was drilled using rotary drilling method with compressed air and Standard Penetration Test (SPT) was conducted at an interval of 1.5 ft. A total number of eight bore holes were drilled for soil sampling from B-horizon (1.0 - 5.5 ft.). A special auger used by U.S. Army Corps of Engineers was used for sampling a large volume of soil. Approximately 1,000 lbs of soil was sampled using this method, filled in plastic bags, and transported to Broce Laboratory for processing and testing.

Bulk soils collected from field were air dried for approximately one week. After air drying, dried soils were broken in a crusher and sieved through US Standard Sieve No.4 to remove organic materials present in the soil.
1.2.2 Collection of Additives

As mentioned in the proposal, three cementitious additives namely, hydrated lime, class C fly ash (CFA), and cement kiln dust (CKD) are used in this study. Class C fly ash and cement kiln dust were obtained from Lafarge North America located in Tulsa. On the other hand, hydrated lime was obtained in the granular form from Texas Lime Company located in Cleburne, Texas.

2. Laboratory Testing
2.1 Soil Classification Tests

Soil was classified in accordance with AASHTO and Unified Soil Classification Systems (USCS). This included grain size distribution tests by using both sieve analysis and hydrometer tests in accordance with the ASTM C 136-84 and ASTM D 422-63 test methods, respectively. Also, the liquid limit and plastic limit tests were performed in accordance with the ASTM D 4318-95 test method. A summary of the soil properties determined in the laboratory and the corresponding standard testing identification are presented in Table 1. C-soil with a high plasticity index (PI) value of 29 is classified as fat clay (CH) according to USCS. Dennis series soil (called D-soil) is also classified as fat clay with a PI of 32 in accordance with the USCS classification system. Figure 3 shows particle size distribution curve of the C-soil.

<table>
<thead>
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<th>Methods</th>
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<td>ASTM D 2487</td>
<td>USCS Name</td>
<td>Fat clay</td>
<td>Fat clay</td>
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<tr>
<td>ASTM D 2487</td>
<td>% finer than 0.075 mm</td>
<td>94</td>
<td>97</td>
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<tr>
<td>ASTM D 422</td>
<td>% finer than 0.002 mm</td>
<td>48</td>
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<tr>
<td>ASTM D 4318</td>
<td>Liquid limit</td>
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<td>51</td>
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<tr>
<td>ASTM D 4318</td>
<td>Plastic limit</td>
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<td>19</td>
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<tr>
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<td>Plasticity index</td>
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<td>32</td>
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<tr>
<td>ASTM D 854</td>
<td>Specific gravity</td>
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<tr>
<td>ASTM D 698</td>
<td>Optimum moisture content (%)</td>
<td>20.3</td>
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<tr>
<td>ASTM D 698</td>
<td>Max. dry unit weight (pcf)</td>
<td>103.7</td>
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<tr>
<td>ASTM D 6276</td>
<td>pH</td>
<td>4.17</td>
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2.2 Moisture-Density Tests

The ASTM D698-91 test method was used to determine moisture-density relationship for C-soil mixed with different amounts of additives (3%, 6%, or 9% for lime and 5%, 10%, or 15% for CFA and CKD). The optimum moisture content (OMC) was found to be 20.3% for the raw C-soil. For lime- and CKD-stabilized soil samples, the OMC increased and maximum dry density (MDD) decreased with increasing percentage of lime, as illustrated in Table 3. For CFA stabilization, Proctor results show that MDD decreases for 5 percent of CFA, increases for 10 percent and then again decreases for 15 percent CFA, as shown in Table 3. On the other hand, OMC decreases with the increase in the percentage of CFA.

Table 3: Summary of OMC-MDD of Lime-, CFA- and CKD-C-Soil Mixtures

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<tr>
<th>Type of additive</th>
<th>Percentage of additive</th>
<th>OMC (%)</th>
<th>Maximum dry density kN/m³</th>
<th>Pcf</th>
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<td>0</td>
<td>20.3</td>
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<td>103.7</td>
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<tr>
<td>Lime</td>
<td>3</td>
<td>22.0</td>
<td>16.0</td>
<td>101.5</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>22.7</td>
<td>15.6</td>
<td>99.0</td>
</tr>
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<td></td>
<td>9</td>
<td>23.8</td>
<td>15.3</td>
<td>97.3</td>
</tr>
<tr>
<td>CFA</td>
<td>5</td>
<td>20.0</td>
<td>16.3</td>
<td>103.5</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>18.6</td>
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<td>105.3</td>
</tr>
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<td></td>
<td>15</td>
<td>16.6</td>
<td>16.4</td>
<td>104.1</td>
</tr>
<tr>
<td>CKD</td>
<td>5</td>
<td>21.6</td>
<td>16.1</td>
<td>102.3</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>21.7</td>
<td>16.0</td>
<td>101.8</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>21.9</td>
<td>15.9</td>
<td>101.4</td>
</tr>
</tbody>
</table>

1 pcf = 0.1572 kN/m³; OMC: optimum moisture content; MDD: maximum dry density; CFA: class C fly ash; CKD: cement kiln dust
2.3 Conventional Freeze-Thaw Test: Resilient Modulus

Raw and stabilized specimens were prepared using C-soil for freeze-thaw (F-T) testing. The procedure consists of adding a specific amount of additive to the raw soil. The amount of additive (6% for lime and 10% for CFA and CKD) was added based on the dry weight of the soil. The additive and soil were mixed manually for uniformity. After the blending process, a desired amount of water was added based on the OMC. Then, the mixture was compacted in a mold having a diameter of 101.6 mm (4.0 in) and a height of 203.2 mm (8.0 in) to reach a dry density of between 95% and 100% of the maximum dry density (MDD). After compaction, specimens were cured at a temperature of 23.0 ± 1.7° C and a relative humidity of approximately 96% for 7 days.

![Figure 4: Resilient Modulus Specimens under (a) Freezing and (b) Thawing](image)

![Figure 5: Resilient Modulus Specimens at the End of Freezing During 4 F-T cycles (a) 6% Lime, (b) 10% CFA, and (c) 10% CKD](image)

After 7-day curing, specimens were tested for resilient modulus ($M_r$). Then, these specimens were placed in freeze-thaw (F-T) chamber for testing specimens in accordance with ASTM D 560 test method. The procedure requires freezing for 24 hours at a temperature
not warmer than -23.3°C (-10°F) and thawing for 23 hours at 21.1°C (70°F) and 100 percent relative humidity. Following the specified thawing period concluding 1, 4, 8 and 12 F-T cycle, the specimens were tested for $M_r$. Figures 4 (a) and (b) show specimens under freezing and thawing, respectively.

![Figure 6: Resilient Modulus Values of Stabilized Specimens under F-T Testing ($\sigma_d = 5.4$ psi, $\sigma_3 = 4.0$ psi)](image)

Raw soil specimens failed during resilient modulus ($M_r$) testing at the end of first F-T cycle. Comparatively, specimens stabilized with 6% lime, 10% CFA, and 10% CKD showed substantial wide opened cracks at the end of freezing during fourth F-T cycle (Figure 5). A summary of mean $M_r$ results at a deviatoric stress ($\sigma_d$) of 5.4 psi and a confining pressure ($\sigma_3$) of 4.0 psi is presented in Figure 6. It is clear from Figure 6 that lime-stabilized specimens showed highest resistance toward F-T cycle, followed by specimens stabilized with CKD and CFA.

2.4 Conventional Wet-Dry Test: Resilient Modulus

By using similar to the aforementioned procedure, raw soil, 6% lime-, 10% CFA-, and 10% CKD-stabilized specimens were prepared. After 7 days of curing, specimens were subjected to 12 wet-dry (W-D) cycles, each W-D cycle consisting of placing a 7-day cured specimen in a water bath at room temperature for five hours, then placing it in an oven at a temperature of $71^\circ$C (160°F) for 42 hours. Following the specified drying period concluding 1, 4, 8 and 12 W-D cycles, the specimens were tested for $M_r$. 
Figure 7: Wetting of Resilient Modulus Specimens (a) 0 hrs and (b) 5 hrs

Figure 8: Resilient Modulus Values of Stabilized Specimens under W-D Testing ($\sigma_d = 5.4$ psi, $\sigma_3 = 4.0$ psi)

Figures 7 (a) and (b) show photographic views of specimens under first W-D cycle at the end of 0 and 5 hours wetting, respectively. The raw and CFA-stabilized specimens slaked, expanded and collapsed at the end of 5 hours (Figure 7b). The specimens stabilized with lime and CKD showed some expansion and cracks at the end of 5 hours. Since CFA- and CKD-stabilized specimens were intact at the end of first W-D cycle, $M_r$ tests were conducted. A summary of mean $M_r$ results at a deviatoric stress ($\sigma_d$) of 5.4 psi and a confining pressure ($\sigma_3$) of 4.0 psi is presented in Figure 8. It is evident from Figure 9 that lime-stabilized specimens showed the highest resistance toward W-D cycle followed by specimens stabilized with CKD and CFA.
2.5 Conventional Freeze-Thaw Test: Unconfined Compressive Strength

A total of 40 specimens namely, raw soil (10 specimens), 6% lime (10 specimens), 10% CFA (10 specimens) and 10% CKD (10 specimens), were prepared. The procedure consists of adding a specific amount of additive to the raw soil and compacting Harvard miniature specimens (1.315 in. x 2.819 in.) at OMC and MDD of the soil-additive mixture, as listed in Table 2. After compaction, specimens were cured for 7 days at a temperature of 23.0 ± 1.7°C and a relative humidity of approximately 96%. Then, these specimens were placed in a freeze-thaw (F-T) chamber for testing specimens in accordance with the ASTM D 560 test method. Following the specified thawing period concluding 1, 4, 8 and 12 F-T cycles, the specimens were tested for UCS. A total of two replicates were prepared for each combination and then tested for UCS by loading specimens in a displacement control mode at a strain rate of 1% per min. Figures 9 (a) and 9 (b) show specimens under freezing and thawing states, respectively.

Figure 10 shows the overall results of all the specimens tested in this study so far. As evident from Figure 10, raw soil specimens showed maximum deterioration and failed at the end of cycle 10. On the other hand, specimens stabilized with 6% lime showed better performance as compared to specimens stabilized with 10% CFA and 10% CKD. For example, application of one F-T cycle reduced the strength of samples by approximately 95%, 62%, 97%, and 88% for raw, 6% lime-, 10% CFA-, and 10% CKD-stabilized specimens, respectively. Figure 11 shows the photographic view of specimens at the end of corresponding F-T cycles.
Figure 10: UCS of Raw and Stabilized Specimens at the End of 0, 1, 4, 8, and 12 F-T Cycles

Figure 11: Photographic View of Specimens (a) Raw at the End of Cycle 10, (b) 6% Lime-stabilized at the End of Cycle 12, (c) 10% CFA-stabilized at the End of Cycle 12, (d) 10% CKD-stabilized at the End of Cycle 12

2.6 Tube Suction Test
Since there is no standard protocol for conducting tube suction tests, specimens were compacted and tested by using the following four different methods:
1. **Case 1**

   Compaction: Standard Proctor compaction (five layers)
   Cylindrical specimen size: diameter = 4.0 in. and height = 8.0 in.
   Drying temperature = 104°F (40°C) for two days.
   Procedure: After 7-day curing followed by 2-day drying, specimens were covered with membrane and placed on a porous plate in a closed ice chest (RH ≈ 97%) containing approximately 0.4 in (10 mm) of de-ionized (DI) water.

2. **Case 2**

   Compaction: Standard Proctor compaction (five layers)
   Cylindrical specimen size: diameter = 4.0 in. height = 8.0 in.
   Drying temperature = 104°F (40°C) for two days.
   Procedure: After 7-day curing followed by 2-day drying, specimens were applied with a thin layer of grease around the lateral surface and placed on a porous plate in an open dish (RH ≈ 62%) containing approximately 0.4 in (10 mm) of DI water.

3. **Case 3**

   Compaction: Superpave Gyratory compactor (single layer)
   Cylindrical specimen size: diameter = 4.0 in. height = 4.0 in.
   Drying temperature = 104°F (40°C) for two days.

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**Figure 12: Setup for Tube Suction Test**

1. **Case 1**

   Compaction: Standard Proctor compaction (five layers)
   Cylindrical specimen size: diameter = 4.0 in. and height = 8.0 in.
   Drying temperature = 104°F (40°C) for two days.
   Procedure: After 7-day curing followed by 2-day drying, specimens were covered with membrane and placed on a porous plate in a closed ice chest (RH ≈ 97%) containing approximately 0.4 in (10 mm) of de-ionized (DI) water.

2. **Case 2**

   Compaction: Standard Proctor compaction (five layers)
   Cylindrical specimen size: diameter = 4.0 in. height = 8.0 in.
   Drying temperature = 104°F (40°C) for two days.
   Procedure: After 7-day curing followed by 2-day drying, specimens were applied with a thin layer of grease around the lateral surface and placed on a porous plate in an open dish (RH ≈ 62%) containing approximately 0.4 in (10 mm) of DI water.

3. **Case 3**

   Compaction: Superpave Gyratory compactor (single layer)
   Cylindrical specimen size: diameter = 4.0 in. height = 4.0 in.
   Drying temperature = 104°F (40°C) for two days.
Procedure: After 7-day curing followed by 2-day drying, specimens were applied with a thin layer of grease around the lateral surface and placed on a porous plate in an open dish (RH ≈ 62%) containing approximately 0.4 in (10 mm) of DI water.

4. Case 4

Compaction: Superpave Gyratory compactor (single layer)
Cylindrical specimen size: diameter = 6.0 in. height = 6.0 in.
Drying temperature = 104°F (40°C) for two days.
Procedure: After 7-day curing followed by 2-day drying, specimens were applied with a thin layer of grease around the lateral surface and placed on a porous plate in an open dish (RH ≈ 62%) containing approximately 0.4 in (10 mm) of DI water.

In all the above mentioned cases, the dielectric value (DV) increased with time due to capillary rise of water in the specimens. In this study, four measurements were taken along the circumference of the specimen in separate quadrants and the fifth reading was taken at the center of the specimen and an average of all five readings was calculated. Measurements were taken daily for 10 days using a dielectric probe (or Percometer™), and the highest average reading was calculated. A photographic view of the TST setup is shown in Figure 12. To ensure adequate contact of probe on the top of surface of the specimen, a surcharge of 4.86 lbs was applied (Figure 12).

A summary of the TST test results is presented in Figure 13. It is clear from this figure that selection of method influences the final DV value. For example, Cases 1, 2, 3 and 4 provided a final DV value of 28.1, 25.0, 38.5, and 39.0 for lime-stabilized specimens, respectively. Additional tests are in progress for selecting and rationalizing the TST method which will be more representative of the durability of cementitiously stabilized soils.

**Figure 13: Final Dielectric Values of Raw and Stabilized Soil Specimens**
3. Work Planned for the Coming Year

It is evident from the aforementioned results and discussions that this project is on schedule. The proposal provides details of the study tasks and the time schedule. These tasks will be followed in Year 2, so as to accomplish the project goals and realize its impacts. Laboratory tests, similar to those conducted on the C-soil, will be conducted on the second soil (D-soil). A bullet list of other tests is given below:

- To collect additional soils (at least one).
- To compare the different Tube Suction Test methods (see Section 4.4.3.5) for additional soils and propose a method suitable for evaluating durability of cementitiously stabilized soils.
- To evaluate the durability (F-T and W-D) of additional soil specimens stabilized with lime, class C fly ash, and cement kiln dust.
- To determine the unconfined compressive strength (UCS) of stabilized specimens after applying vacuum saturation on the 7-day cured specimens, in accordance with ASTM C 593.
- To develop statistical models (correlation among 7-day UCS without any F-T or W-D cycles, 7-day UCS after F-T cycles, 7-day UCS after W-D cycles, final dielectric value after TST) based on the laboratory data.
- To recommend acceptance criterion by discriminating between good and poor cementitiously stabilized material on the basis of the dielectric values (DV) achieved in TST.

References Cited

Transportation Research Record, 1709, Transportation Research Board, National Research Council, Washington D. C., 78-90
