Use of MSE Technology in Reconstruction and Retrofitting Highway Slopes and Embankments

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Submitted to:
Ginger McGovern, P.E.
Planning and Research Division Engineer
Oklahoma Department of Transportation
200 N.E. 21st Street
Oklahoma City, Oklahoma 73105

Submitted by:
Kianoosh Hatami, Gerald A. Miller & Lina Garcia
School of Civil Engineering and Environmental Science
University of Oklahoma
202 W. Boyd St., Room 334
Norman, OK 73019

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INTRODUCTION

Over many years, there have been problems with slope failures and landslides along the highways in Oklahoma. Many of these failures occur in eastern Oklahoma due to steeper topography, soil types or a combination of both. A recent example of these failures is the massive slope failure on Highway 82 in Latimer County in southeastern Oklahoma.

Mechanically Stabilized Earth (MSE) technology provides a viable approach to the construction or repair of these slopes and embankments. The design guidelines and specifications for MSE structures in North America (Elias et al. 2001, AASHTO 2002) recommend coarse-grained, free-draining soils in the construction of MSE retaining structures. However, these soils are not commonly available in Oklahoma. Commonly available soils in Oklahoma are marginal soils (e.g. soils with more than 15% of fine content). Consequently, the cost of transportation and select fill materials can be very significant which would render the cost of repair and reconstruction of the slopes and embankments prohibitive.

The objective of the present study is to explore the possibility of using locally available soils as construction materials for reinforced soil slopes and embankments. These soils would require significantly less material transportation, fuel consumption and generated pollution compared to using high-quality offsite soils. It has been estimated that fuel costs constitute about 20% of the total costs for transportation of high-quality soil. Past experience by other agencies such as the Forest Service has shown that using marginal soils in Mechanically Stabilized Earth structures can help reduce the cost of fill material by up to 60% (e.g. Keller 1995). However, in order to reinforce earthen structures with marginal soils, it is important to obtain a satisfactory soil-reinforcement performance.

An important consideration in the design of reinforced soil structures with significant fines content is the possibility of loss of suction and development of excess pore water pressure due to wetting. This can result in excessive deformations and even failure. As a result, the design procedures need to take into account the influence of soil moisture content on soil strength, the strength of soil-geosynthetic interface and the resulting factors of safety against failure. Such design provisions are currently not available for reinforced soil structures constructed with marginal soils.

Typically, construction materials for reinforced soil structures are tested at moisture content values near optimum (i.e. Optimum Moisture Content - OMC). However, in actual field conditions, several factors could make the fill moisture content deviate from the design value during the construction period or the structure service life. Examples include precipitation during construction, groundwater infiltration and development of excess pore water pressure due to compaction. These factors, in addition to seasonal variations of soil moisture content, can significantly reduce the strength of the soil-reinforcement interface and lead to excessive deformations or failure.

PURPOSE AND SCOPE

Reinforcing marginal soils with geosynthetics along with other slope stabilization techniques (e.g. berms, rip raps, etc.) can provide a cost-effective solution for the stabilization, construction or repair of slopes and embankments along the highways in Oklahoma and other parts of the U.S. However, one main concern in internal stability analysis of reinforced soil structures constructed with marginal soils is the reduction in reinforcement pullout resistance due to the increase in the soil moisture content. This can result in excessive deformations of even failure of the reinforced soil structure.

The main objective of this study is to develop a moisture reduction factor, $\mu(\omega)$, to account for the influence of soil moisture content on the reinforcement pullout resistance in the design of reinforced soil structures with marginal soils.

ACCOMPLISHMENTS DURING FY 2009

In this one-year study, $\mu(\omega)$ values were determined for a polypropylene (PP) woven geotextile reinforcement placed in a marginal soil called Minco silt (**Figure 1**). The study included an initial set of eleven (11) large-scale pullout tests in a uniformly graded fine sand with the same PP woven geotextile reinforcement (**Table 1**). The objective for this series of tests was to validate the pullout test setup and the measured data against the results reported in the published literature and the ASTM D6706 testing procedure. Through these tests, we determined that a minimum of 200 mm (8") of soil needed to be placed above and below the reinforcement specimen in order to minimize boundary effects in the pullout test box. This value is slightly greater than the minimum of 150 mm (6") recommended in the ASTM D6706 test protocol. We also obtained an interface friction angle of 24° for the soil and the geotextile reinforcement, which is within the range of values reported in the literature for comparable materials (Koerner 2005).

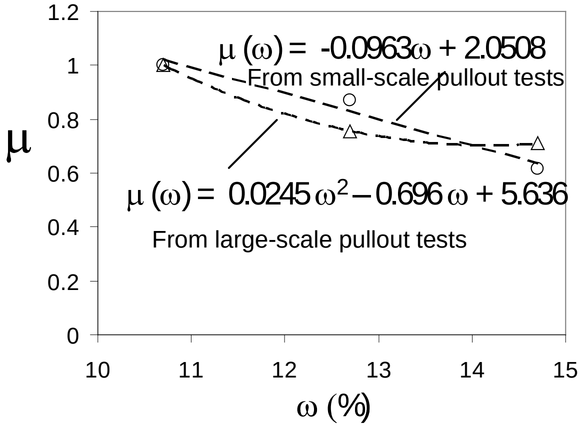

Figure 1. Moisture reduction factor, $\mu(\omega)$, developed for Minco silt-woven geotextile in our recent study using large-scale and small-scale pullout tests

Table 1. Large-scale pullout test cases and material properties

Test information	*Uniformly graded fine sand*	*Minco silt (CL-ML)*
Geosynthetic reinforcement	TenCate HP370, woven PP 600 mm x 300 mm (2'X1')	TenCate HP370, woven PP 600 mm x 300 mm (2'X1')
Overburden pressures, kPa (psi)	3 (0.4), 8 (1.2), 10 (1.5), 20 (2.9), 50 (7.3), 68 (9.7)	10 (1.5), 20 (2.9), 50 (7.3)
Moisture Content, ω (%)	NMC(*)	OMC-2%; OMC; OMC+2%
% of Maximum dry unit weight	90	86, 90
Number of tests	Eleven (11) large-scale pullout tests at six (6) overburden pressure values	Thirteen (13) large-scale pullout tests at (3) moisture contents, three (3) overburden pressure and two (2) dry unit weight values

(*) NMC: Natural Moisture Content (ω = 0.6%); OMC (Optimum Mositure Content) = 12.7%.

In our second (and main) series of tests, we carried out thirteen (13) large-scale pullout tests in Minco silt, twelve of which are shown in **Table 2**. The tests were carried out using the same geotextile at three different moisture content values (10.7%, 12.7% and 14.7%) in order to determine the influence of soil moisture content on the reinforcement maximum pullout resistance. Four tests were carried out at OMC-2% (ω = 10.7%) at 86% of the soil maximum dry unit weight and four different overburden pressure magnitudes (10 kPa, 20 kPa, 35kPa and 50 kPa). Three pullout tests were carried out at OMC (ω = 12.7%) at 86% of the soil maximum dry unit weight and overburden pressure magnitudes 10 kPa, 20 kPa and 50 kPa. Three pullout tests were carried out at OMC (ω = 12.7%) at 90% of the soil maximum dry unit weight and overburden pressure magnitudes 10 kPa, 20 kPa and 50 kPa. Finally, three tests were carried out at OMC+2% (ω = 14.7%) at 86% of the soil maximum dry unit weight and overburden pressure magnitudes 10 kPa, 20 kPa and 50 kPa.

Table 2. Details of large-scale pullout tests

Test details(1-3)	*Test 1* *OMC -2%*	*Test 2* *OMC -2%*	*Test 3* *OMC -2%*	*Test 4(1)* *OMC*	*Test 5(1)* *OMC*	*Test 6(1)* *OMC*	*Test 7* *OMC*	*Test 8* *OMC*	*Test 9* *OMC*	*Test 10* *OMC + 2%*	*Test 11* *OMC + 2%*	*Test 12* *OMC + 2%*
Target σ_n on the interface, kPa (psi)	10 (1.5)	20 (2.9)	50 (7.3)	10 (1.45)	20 (2.91)	50 (7.25)	10 (1.5)	20 (2.9)	50 (7.3)	10 (1.5)	20 (2.9)	50 (7.3)
Target ω (%)(2)	10.7	10.7	10.7	12.7	12.7	12.7	12.7	12.7	12.7	14.7	14.7	14.7
Meas. ω (%)	10.8	10.4	10.8	12.4	12.4	12.5	12.5	12.6	12.5	14.8	14.6	14.7
Meas. suction kPa (psi)	10.7 (1.5)	18.6 (2.7)	18.4 (2.7)	17.25 (2.5)	17.7 (2.6)	17.6 (2.5)	17.2 (2.5)	17.7 (2.6)	17.6 (2.5)	13.4 (1.9)	11.8 (1.7)	13.1 (1.9)

Notes: (1) *tests carried out at 90% maximum dry density,* (2) *OMC for Minco Silt is 12.7%*

In addition to the original scope of the project, we leveraged our NSF-REU funding to recruit an undergraduate student to help carry out a series of custom-made, small-scale pullout tests and interface shear tests to generate a multi-scale database of $\mu(\omega)$ values for Minco silt and the geotextile used in the study (**Figure 1**). The small-scale pullout and interface shear tests were carried out using a direct shear test machine at the same soil moisture content, unit weight and overburden pressure magnitudes as in the large-scale pullout tests.

Other tasks in the project included calibration of instruments (i.e. tensiometers, wireline extensometers, earth pressure cell, load cell), collecting 1250 lb of Minco silt from a site in Geary, Oklahoma and determining its properties, and comparing them with the values reported by Tan (2005), in addition to direct shear tests on sand and Minco silt. Testing of soils included determining their maximum dry density, gradation, and consistency (i.e. Atterberg) limits.

Results of Large-Scale Pullout Tests

Table 3 summarizes results of the large-scale pullout tests in sand. The sand-geotextile interface friction angle of 24° is consistent with the values reported in the literature for similar materials (Koerner 2005).

Table 3. Large-scale pullout test results in sand (200 mm soil embedment cases)

ω (%)	*σ_n kPa (psi)*	*P_r kN (lb)*	*τ_{max} kPa (psi)*	*δ' (^{o}) (1)*	*C_a kPa (psi) (1)*
0.6 (NMC)	3 (0.4)	1.9 (429.6)	5.1 (0.8)	24	4.9 (0.8)
	8 (1.2)	2.9 (661.0)	7.9 (1.2)		
	10 (1.4)	3.5 (791.1)	9.5 (1.4)		
	20 (2.9)	6.1 (1376.2)	16.5 (2.4)		
	50 (7.3)	9.9 (2223.2)	26.6 (3.9)		

Notes: (1) *calculated from maximum pullout resistance (P_r).*

Table 4. Interface strength properties from large-scale pullout tests in Minco silt

Target ω (1)	*σ_n kPa (psi)*	*ω (%)(2)*	*ψ kPa (psi)(3)*	*P_r kN (lb)*	*τ_{max} kPa (psi)*	*δ' (^{o})(4)*	*C_a kPa (psi) (5)*
10.7 (OMC-2%)	10 (1.4)	10.8	10.7 (1.55)(6)	3.1(690.5)	8.3 (1.2)	21.7	5.5 (0.8)
	20 (2.9)	10.4	18.6 (2.7)	5.6 (1260.1)	15.1(2.2)		
	50 (7.3)	10.8	18.4 (2.67)	9.3 (2086.7)	25.0 (3.6)		
12.7 (OMC)	10 (1.4)	12.5	17.2 (2.49)	3.7 (842.9)	10.1 (1.5)	17.2	6.8 (0.99)
	20 (2.9)	12.6	17.7 (2.57)	4.7 (1058.7)	12.7 (1.8)		
	50 (7.3)	12.5	17.6 (2.55)	8.3 (1864.3)	22.3 (3.2)		
14.7 (OMC+ 2%)	10 (1.4)	14.8	13.4 (1.94)	3.4 (761.3)	9.1 (1.3)	16.3	6.2 (0.9)
	20 (2.9)	14.6	11.8 (1.71)	4.5 (1011.8)	12.1 (1.8)		
	50 (7.3)	14.7	13.1 (1.9)	7.7(1741.0)	20.8 (3.0)		

Notes: (1) *target moisture content with variations of ± 2% OMC,* (2) *mean value of moisture content is calculated over the soil-geotextile interface,* (3) *The mean value of suction (ψ) obtained from the tensiometers,* (4,5) *calculated from maximum pullout resistance (P_r),* (6) *suction taken with tensiometer readout cylinder at different elevation compared to other tests.*

Table 5. Values of α and F* in the FHWA (Elias et al. 2001) design equation calculated from large-scale pullout test results in Minco silt (see Quarter 4 below)

Target ω (%) (2)	*σ_n kPa (psi)*	*P_r kN (lb)*	*τ_{peak} kPa (psi)*	*α*	*$F^* = \tau_{peak}/\sigma_n$*
10.7 (OMC-2%)	10 (1.4)	3.1 (690.5)	8.3 (1.2)	0.52	0.83
	20 (2.9)	5.6 (1260.1)	15.1 (2.2)	0.46	0.75
	50 (7.3)	9.3 (2086.7)	25.0 (3.6)	0.63	0.5
12.7 (OMC)	10 (1.4)	3.7 (842.9)	10.1 (1.5)	0.55	1.01
	20 (2.9)	4.7 (1058.7)	12.7 (1.8)	0.59	0.63
	50 (7.3)	8.3 (1864.3)	22.3 (3.2)	0.6	0.45
14.7 (OMC+ 2%)	10 (1.4)	3.4 (761.3)	9.1 (1.3)	0.51	0.91
	20 (2.9)	4.5 (1011.8)	12.1 (1.8)	0.56	0.61
	50 (7.3)	7.7 (1741.0)	20.8 (3.0)	0.59	0.42

Results of Small-Scale Tests

A summary of the test conditions, material properties and test results for the small-scale tests is presented in **Tables 6 through 8** below:

Table 6. Small-scale tests and material properties

Test information	*Uniformly graded fine sand*	*Minco silt (CL-ML)*
Type of test	Interface Shear	Interface shear, Pullout
Geosynthetic reinforcement	TenCate HP370, woven PP 50.8 mm x 24.5 mm (2”X1.6”)	TenCate HP370, woven PP 50.8 mm x 24.5 mm (2”X1.6”)
Overburden pressure, kPa (psi)	10 (1.5), 20 (2.9), 50 (7.3)	10 (1.5), 20 (2.9), 50 (7.3)
Moisture Content	NMC	OMC-2%; OMC; OMC+2%

Table 7. Minco silt strength properties from direct shear tests

Target ω (%) (1)	*σ_n kPa (psi)*	*ω (%)(2)*	*ψ kPa (psi)(3)*	*τ_{max} kPa (psi)*	*φ' (^{o})(4)*	*C kPa(psi)(5)*
10.7 (OMC-2%)	10 (1.4)	11.0	19 (2.75)	17.02 (2.5)	43.2	7.4 (1.07)
	20 (2.9)	10.7	18 (2.61)	25.89 (3.8)		
	50 (7.3)	10.7	18 (2.61)	54.43 (7.9)		
12.7 (OMC)	10 (1.4)	13.2	12 (1.74)	16.49 (2.4)	41.2	8.8 (1.28)
	20 (2.9)	12.9	12 (1.74)	27.68 (4.0)		
	50 (7.3)	12.8	12 (1.74)	52.22 (7.6)		
14.7 (OMC+ 2%)	10 (1.4)	15.0	10 (1.45)	16.17 (2.4)	40.9	8.6 (1.25)
	20 (2.9)	14.6	10 (1.45)	27.41 (4.0)		
	50 (7.3)	14.4	10 (1.45)	51.52 (7.5)		

Notes: (1) *Target moisture content,* (2) *determined after direct shear tests,* (3) *suction (ψ) obtained from SWCC (Tan 2005),* (4,5) *calculated from maximum pullout resistance (P_r).*

Table 8. Interface strength properties obtained from small-scale pullout tests

Target ω (%) (1)	*σ_n kPa (psi)*	*ω (%)(2)*	*ψ kPa(psi)(3)*	*τ_{max} kPa (psi)*	*δ(4) (^{o})*	*C_a (kPa)(5)*
10.7 (OMC-2%)	10 (1.4)	11.0	19 (2.75)	3.86 (0.6)	16	1.0
	20 (2.9)	11.1	19 (2.75)	7.03 (1.0)		
	50 (7.3)	10.6	19 (2.75)	15.66 (2.3)		
12.7 (OMC)	10 (1.4)	12.7	13 (1.89)	1.28 (0.2)	14	0.1
	20 (2.9)	12.9	12 (1.74)	6.67 (1.0)		
	50 (7.3)	13.0	12 (1.74)	11.86 (1.7)		
14.7 (OMC+ 2%)	10 (1.4)	15.0	9 (1.31)	7.69 (1.1)	10	1.2
	20 (2.9)	15.0	9 (1.31)	7.22 (1.0)		
	50 (7.3)	14.8	9 (1.31)	9.89 (1.4)		

Notes: (1) *Target moisture content,* (2) *determined after direct shear tests,* (3) *suction (ψ) obtained from SWCC (Tan 2005),* (4,5) *calculated from maximum pullout resistance (P_r).*

Quarter 1: Oct 2008 – Dec 2008

Major activities during this period included:

- Setup of the pullout test apparatus and calibration of instruments including an earth pressure cell, extensometers, tensiometers and Fredlund thermal sensors to determine soil suction and moisture content.
- Testing of soils and a geosynthetic material (i.e. a polypropylene (PP) woven geotextile) to determine their physical and mechanical properties.
- Carrying out three (3) preliminary tests for two distinct purposes before we conducted our final pullout tests in sand: One (1) preliminary (dummy) pullout test was carried out to test the performance and accuracy of the instruments and iron out any problems related to their calibration and data acquisition. The test was carried out using our candidate PP woven geotextile and fine sand. Two (2) additional tests were carried out to determine the optimal volume of soil that should be used in the future pullout tests.

Problems Encountered: Problems encountered were mainly related to ensuring that the tensiometer tubes were water tight and Fredlund thermal sensors were calibrated and operating properly. These efforts were time-consuming.

Figure 2. (a) A side view of the pullout test box filled with soil, (b) A PP woven geotextile instrumented with wire-line extensometers and placed at the middle of the pullout box.

Quarter 2: January 2009 – March 2009

Activities during this period included:

- Four (4) large-scale pullout tests in Minco silt at OMC-2% (10.7%) at 86% of its maximum dry unit weight.
- Six (6) large-scale pullout tests in sand at its natural moisture content, including the final tests. We determined the pullout response, pullout capacity and interface friction angle of the selected geotextile in sand as our control case.

Problems Encountered We had to spend a significant amount of time to ensure that all the instruments were reliable and accurate. The main problems we encountered included:

- Our existing tensiometers were not giving stable and consistent readings. We made a lot of effort to try and fix the problem. However, at the end we concluded that we needed brand new tensiometers to replace our old ones.
- The airbag system was not completely air tight and showed occasional signs of leaking, which would result in loss of overburden pressure on the soil. We fixed the air valve and the system now holds air properly.

- Two tests were lost due to computer problems. In one of them, the actuator force was not recorded in the main computer. In the other test, the data acquisition computer that measures extensometer readings stopped recording the data. These tests are not included in our report.

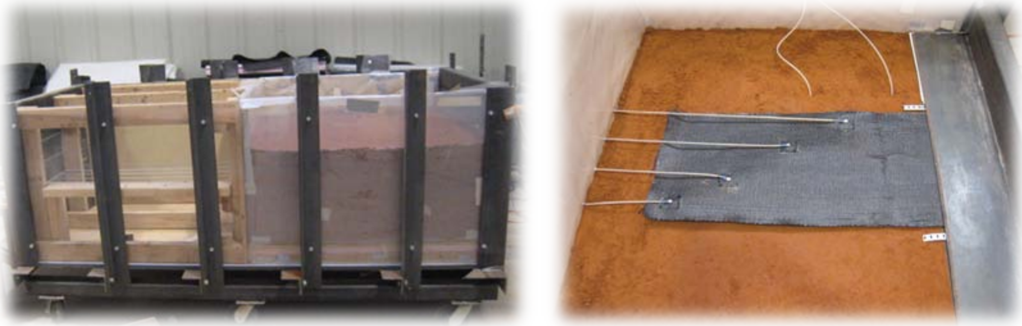

Figure 3. (a) A side view of the pullout test box filled with Minco silt (b) A PP woven geotextile placed instrumented with wire-line extensometers and placed at the middle of the pullout box. Tensiometer probes are embedded in the soil.

Quarter 3: April 2009 – June 2009

Activities during this period included:

- Calibration and installation of six (6) new tensiometers in the vicinity of the soil-geotextile interface.
- Three (3) large-scale pullout tests in Minco silt at OMC (12.7%) at 90% of its maximum dry unit weight.
- Two (2) large-scale pullout tests in sand at its natural moisture content.
- Nine (9) small-scale pullout tests in Minco Silt at OMC-2% (10.7%), OMC (12.7%) and OMC+2% (14.7%) at 86**%** of its maximum dry unit weight.
- Twelve (12) direct shear tests in sand at its natural moisture content and Minco silt at OMC-2% (10.7%), OMC (12.7%) and OMC+2% (14.7%) at 90**%** of its maximum dry unit weight.

Problems Encountered: There were occasional inaccuracies or malfunctioning of one or two tensiometers. However, since we placed several tensiometers along the soil-geotextile interface, we could easily identify and dismiss the invalid data points.

Figure 4. (a) Direct shear test cell before test, (b) direct shear test cell after test.

Quarter 4: July 2009 – September 2009

Activities during this period included:

- Interpretation of data and analysis of the influence of soil moisture content on the reinforcement pullout resistance.
- Obtaining pullout parameters for each test as F* = pullout resistance factor, and, α = a scale effect correction factor to account for a nonlinear stress reduction over the embedded length of highly extensible reinforcements (**Table 5**).
- Three (3) large-scale pullout tests in Minco silt at OMC+2% (14.7%) at 86% of its maximum dry unit weight to determine soil-geosynthetic interface friction angle at different moisture content values.
- Three (3) large-scale pullout tests in Minco silt at OMC (12.7%) at 86% of its maximum dry unit weight
- Nine (9) small-scale pullout tests at OMC-2% (10.7%), OMC (12.7%) and OMC+2% (14.7%) in Minco Silt at 86% of its maximum dry unit weight with geotextile dimensions 50.8 mm x 24.5 mm (2”X 1”)
- Fifteen (15) small-scale interface direct shear tests at OMC-2% (10.7%), OMC (12.7%) and OMC+2% (14.7%) in Minco silt at 86% of its maximum dry unit weight with geotextile dimensions 57.5 mm x 57.5 mm (2.35”X2.35”).

Problems Encountered: There were occasional inaccuracies or malfunctioning of one or two tensiometers. However, since we placed several tensiometers along the soil-geotextile interface, we could easily identify and dismiss the invalid data points. Some inconsistencies were observed in small-scale interface shear test results. Additional work is in progress to repeat selected interface shear tests.

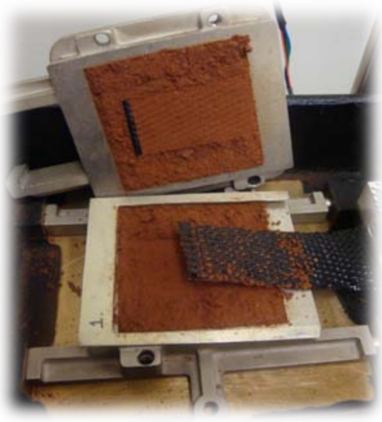

Figure 5. Small-scale pullout tests

PROPOSED ACTIVITIES FOR FY 2010

We are in the process of obtaining a new type of marginal soil from a candidate site with the assistance of ODOT engineers in the Materials Division. Additional multi-scale pullout tests will be carried out in the new type of soil at different moisture contents. These additional tests will include at least nine (9) large-scale and (9) small-scale pullout tests in a carefully monitored and controlled indoor laboratory environment. New results will be used to verify or adjust the $\mu(\omega)$ equations we developed in our recent study using another marginal soil in Oklahoma. We also intend to carry out some tests at an additional moisture content value, especially on the wet side of optimum (e.g. OMC+4%). The new series of tests will help increase our confidence in the developed $\mu(\omega)$ values for the pullout equation in the FHWA design guidelines.

Table 9. Description of pullout test cases planned in the proposed study

Test information	***Description***
Soil	A soil from a candidate site (in coordination with ODOT engineers) to complement current findings on Minco silt
Overburden pressure (kPa), psi	10 (1.4), 30 (2.9), 50 (7.3)
Moisture content (%)	OMC, OMC+2%, OMC+4% (3 tests each; i.e. 3 overburden pressure values for each moisture content case)
Number of tests (18 tests: 9 Large-scale, 9 small-scale)	Three (3) moisture content and three (3) overburden pressure values

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