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STRENGTH PARAMETERS OF BACKFILLS FOR DESIGN AND CONSTRUCTION OF RETAINING WALLS

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University of Colorado at Denver

July 2001

DEPARTMENT OF TRANSPORTATION
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COLORADO DEPARTMENT OF TRANSPORTATION
RESEARCH BRANCH

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by

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Prepared by
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16. Abstract
A study was undertaken to examine the strength parameter ϕ of backfills of retaining walls. The objectives were to evaluate the current practice employed by the Colorado Department of Transportation for determination of design strength parameters and to propose improved criteria for determination of design strength parameters. Laboratory tests were performed to compile the strength parameters and index properties of 100 soils. The complied properties include gradation, liquid and plastic limits, maximum dry density and optimum water content, and internal friction angle. Analysis of the test results indicated that the current practice of assigning $c = 0$ and $\phi = 34^{o}$ for Class-1 soils was indeed a conservative measure. To provide improved criteria for determination of the internal friction angle of soils without performing any shear tests, two statistical decision trees were established based on the index properties of the 100 soils. One decision tree was for soils with LL$\leq$ 35 and PI$\leq$ 6, and the other was for Class-1 soils. More data may be needed to validate or refine the decision trees for routine applications of the decision trees.

Implementation The two decision trees can be used as a preliminary guide for determination of the friction angles of "good quality" backfill (say, $\phi \geq 38^{o}$). The friction angle of 34 degrees should continue to be used for Class-1 soils with tree branches yielding a friction angle less than 37 degrees.

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Executive Summary

A study was undertaken to examine the strength parameter ϕ of backfills for design of retaining walls. The objectives of the study were twofold. The first objective was to evaluate the current practice employed by the Colorado Department of Transportation for determination of design value of the strength parameters. The second objective was to propose improved criteria for determination of design value of the strength parameters.

To achieve the objectives, laboratory tests were performed on 100 soils to determine various soil properties, including particle sizes, gradation, liquid and plastic limits, maximum dry density and optimum water content, and internal friction angle. Some of these parameters are readily available in the data base of the Soil Lab in the Colorado Department of Transportation. Supplementary tests were performed to compile a complete set of data for 100 soils. The internal friction angles were determined by direct shear tests on soil specimens prepared at 2% wet of optimum moisture content and 95% of maximum dry density per T99 (or 90% of maximum dry density per T180).

The study indicated that the current practice of assigning c = 0 and $\phi = 34^{\circ}$ for Class-1 soils was indeed a conservative measure. Among the various parameters, the gradation was found to have the most significant effect on the internal friction. To explore the use of $\phi > 34^{\circ}$ for "good quality" backfill in the design of retaining walls, statistical analysis with a tree-based model was performed on all the soil parameters. Two decision trees, one for soils with LL $\leq$ 35 and PI $\leq$ 6 and the other for the Class-1 soils, were established for the internal friction angle. The coefficients of the tree branches were fairly small. These decision trees can be used as a preliminary guide for determination of

the friction angle of "good quality" backfill (say, $\phi \geq 38^{\circ}$). The friction angle of 34 degrees should continue to be used for tree branches yielding a friction angle less than 37 degrees. More data may be needed to validate or refine the decision trees for routine applications.

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1. Introduction

1.1 Problem Statement

The design of retaining structures requires an accurate assessment of the shear strength of the backfill. Shear strength of soil has been expressed by various failure criteria, among which Mohr-Coulomb failure criterion is most commonly used in the design of retaining walls. Mohr-Coulomb failure criterion involves two strength parameters: cohesion (c) and angle of internal friction (ϕ). For granular soils, the strength parameter c is generally ignored although nonzero values are typically obtained from tests. This is because the cohesion (termed "apparent cohesion") is not dependent on inter-particle cementation or bonding, rather, it is a result of capillary stresses and mechanical forces due to particle geometry and packing. Therefore, the shear strength of granular soil is defined by the angle of internal friction.

The common procedure employed by the Colorado Department of Transportation (CDOT) for determination of the internal friction angle of a soil for the design of a retaining wall is mostly empirical. The procedure involves determination of whether a soil satisfies the criteria of Class-1 structure backfill based on soil gradation and plasticity.

The Colorado Department of Transportation specifies that soils satisfying the following criteria are Class-1 structure backfill (or "Class-1 soil"):

Percent passing sieves 2-in., No. 4, No. 50, No. 200 must be 100%, 30-100%, 10-60%, and 5-20% respectively. The plasticity index (PI) and liquid limit (LL) are not over 6 and 35. An internal friction angle of 34 degrees is assumed for all Class-1 structure backfill.

Since a Class-1 structure backfill appears to encompass a very large variety of different soils, two important questions arise:

1. How valid is the assumption of internal friction angle is 34 degrees for Class-1 structure backfill?
2. Can an improved criterion be established to determine the internal friction angle of soils suited for construction of retaining walls?

1.2 Research Objectives

The objectives of this study were twofold. The first objective was to examine the internal friction angle of Class-1 structure backfill and to investigate the validity of the current criterion in use by the CDOT. The second objective was to propose an improved criterion for assigning safe values of internal friction angles for the design of retaining walls. The criterion is to be based on soil parameters obtained from routine soil tests.

1.3 Research Methodology

To achieve the research objectives outlined above, the following tasks were carried out:

Task 1: Perform laboratory tests and compile soil parameter data for 100 different soil samples. The soil parameters include gradation test results (percents of soil passing the U.S. standard sieves No. 4, No. 10, No. 40, No. 50, and No. 200), liquid limit, plasticity index, maximum dry unit weight, optimum water content, and internal friction angle.

Task 2: Synthesize the soil parameter data to evaluate the internal friction angles for the soils that pass and fail the CDOT Class-1 structure backfill criteria.

Task 3: Perform a statistical "decision tree" analysis to propose an improved method for assigning a safe value of internal friction angle for the design of retaining walls.

It should be noted that Class-1 structure backfill requires that the plasticity of the soil must be low (liquid limit ≤ 35, and plasticity index ≤ 6). This requirement is to ensure that there will not be significant time-dependent deformation when the backfill becomes "wet" and that the soil will be sufficiently "free-draining" under various conditions. It is believed that the requirement needs to be observed in selecting backfill for the construction of retaining walls. As a result, soils that do not satisfy the low plasticity requirement were excluded from the "decision tree".

It should also be noted that the internal friction angles in this study were determined by direct shear tests. The direct shear test is considered the most efficient method for determining the internal friction angle of a granular soil because it is fast, simple, and relatively inexpensive. The internal friction angles determined by direct shear tests may be higher or lower than those determined by triaixal tests on the same soil (Taylor, 1939). The internal friction angle determined by direct shear tests has also been found to be dependent on the sample size and test conditions. All of the direct shear tests in this study employed one test device and were performed under the same test conditions.

2. Laboratory Tests

This chapter presents the test material, the soil parameters and the tests for determination of various soil parameters.

2.1 Test Materials

The CDOT Soil Unit at the Charles E. Shumate Laboratory stores soil samples in drawers at room temperature. These samples were collected from construction sites around Colorado. These soils are different in many aspects such as gradation, grain shape, moisture, color, homogeneity, and mineralogical composition. From this inventory, a total of 100 different soils were selected for this study.

2.2 Soil Parameters

To achieve the objectives of this study as described in Chapter 1, soil parameters for 100 different soils had to be compiled. The soil parameters include:

- soil classification (per American Association of State Highway and Transportation Officials, AASHTO, Soil Classification System)
- liquid limit (per AASHTO T89)
- plastic limit (per AASHTO T90)
- maximum dry unit weight (per AASHTO T99 or T180)
- optimum moisture content (per AASHTO T99 or T180)

- gradation (percent of soil passing the U.S. Standard Sieves No. 4, No. 10, No. 40, No. 50, and No. 200)
- internal friction angle (as determined by direct shear tests)

2.3 Test Procedure

2.3.1 Gradation Test by Colorado Procedure CP-31A-98 (Sieve Analysis of Fine and Coarse Aggregate)

(A) Method A

For samples of aggregates having a nominal maximum size greater than 3/4 inch, the test procedure can be described as follows (CDOT and WAQTC, 1998):

1. Dry the test sample using air, a hot plate with continuing stirring, or an oven at $121 \pm 16^{\circ}C$. Do not use the hot plate to dry samples which will be tested for Atterberg limits.
2. Separate the sample over a 4.75 mm (No. 4) screen (see Figure 2.1).
3. Clean all the aggregate that is retained on the 4.75 mm screen using a wire brush or a mortar and rubber covered muller and add all of the material passing the 4.75 mm screen to the fine fraction.
4. If free moisture is visible as a shiny surface on the material retained on the 4.75 mm screen, dry the material using an oven or a hot plate with continuous stirring. If the aggregate is saturated surface dry or drier, additional drying is not necessary.
5. Separate the aggregate part over a stack of sieves, from large opening to

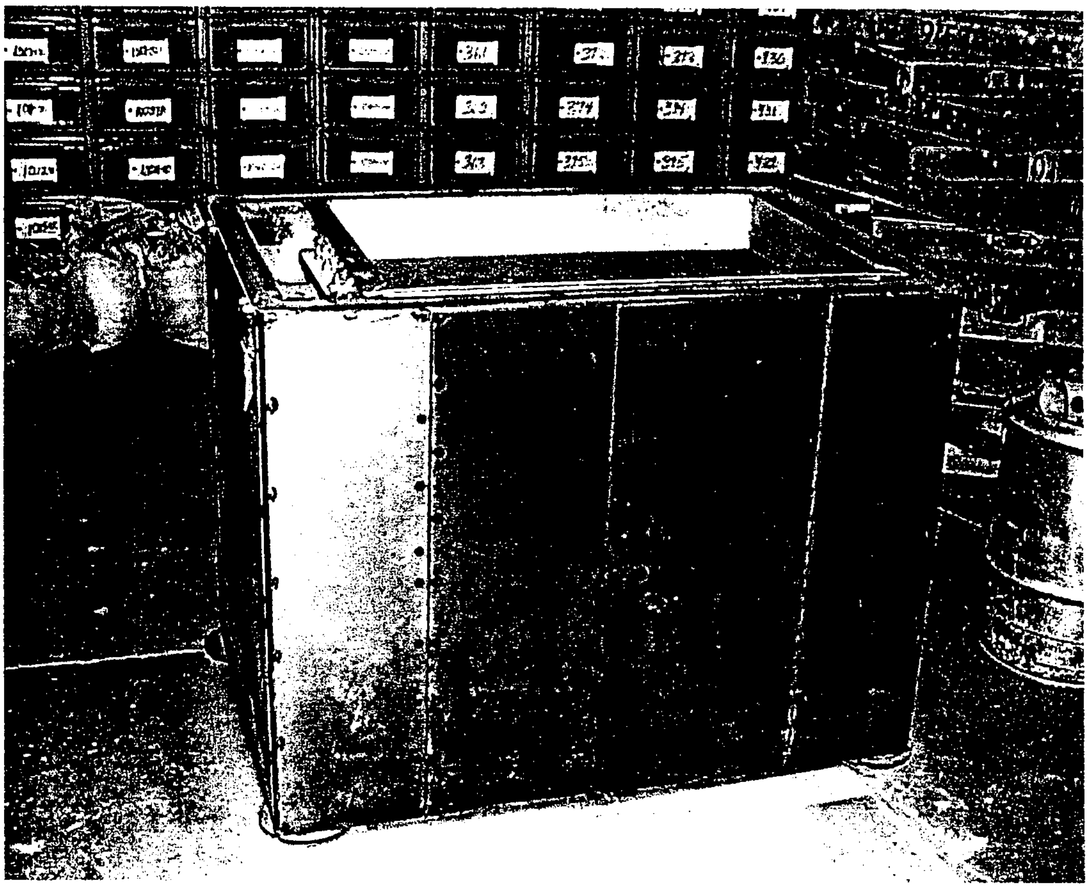


Figure 2.1 Screen table (with the U.S. Standard No. 4 sieve)

small opening. Sieves with 75 mm, 50 mm, 25 mm, 19 mm, and 9.5 mm openings were used in the test (see Figure 2.2).

6. Add all of the material passing the 4.75 mm screen from the pan to the fine fraction.

7. Determine the weight of each size increment by weighing on a scale, including the material passing the 4.75 mm screen. The total weight of the material after sieving should check closely with original weight of sample placed on the sieves.

8. Split the material passing the 4.75 mm screen to obtain two specimens of approximately 500 grams each. Immediately weigh the two specimens and record their weights. One for the fine sieve analysis; the other for checking moisture and Atterberg limits.

9. Dry one of the 250-gram specimens to constant weight using a hot plate or at 121±6°C oven.

10. For the other sample (500 grams), use Part (B) Test Method to determine the fraction of the material passing the 75μm (No. 200) sieve size. Test the washed and oven dried specimen.

(B) Method B

For samples of aggregates having a nominal maximum size smaller than or equal to 3/4 inch, the test procedure can be described as follows (CDOT and WAQTC, 1998):

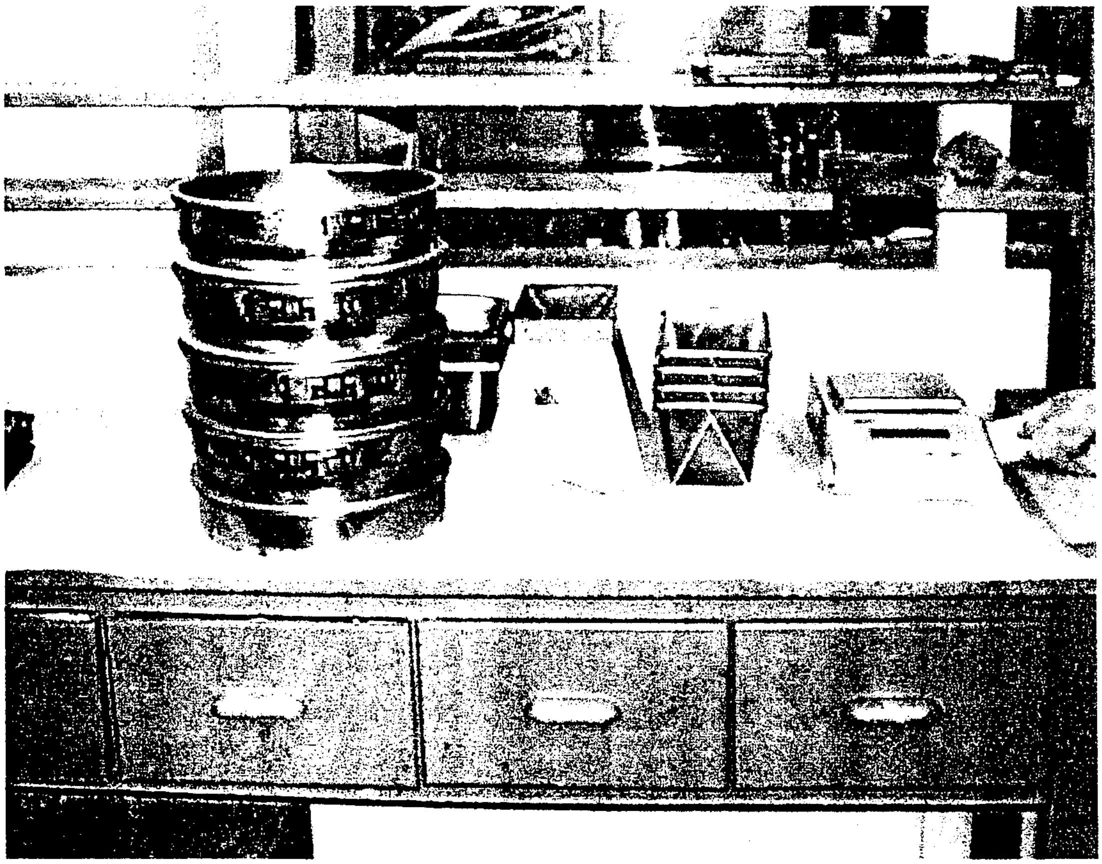


Figure 2.2 Sieves No. 4, No. 10, No. 40, and No. 200 for the dry process

1. Dry the specimens from step 7 of Part (A) to constant weight using a hot plate or at 121 ± 6^{o}C oven.
2. After drying and determining the mass, place the sample in the container. Add sufficient water to cover the sample. Then, soak the sample overnight.
3. The entire sample is placed into the upper sieve of nested sieves and washed until the water is clean. All the water used must pass through the 75 μm (No. 200) sieve (see Figure 2.3).
4. Return all material retained on the nested sieves by flushing the washed sample back into the container. Dry the washed aggregate to constant mass at a temperature of 121 ± 16^{o}C. Determine the mass to the nearest 0.1 percent of the original mass of the sample or proceed with CP-31A-98.
5. Weigh the sample to be tested.
6. Suitable sieves shall be selected to furnish the information required by the specifications covering the materials to be used. Agitate the sieves by hand or by mechanical shaker for a sufficient period (around 5 minutes).
7. Determine the weight of each size increment by weighing on a scale. The total weight of the material after sieving should check closely with original weight of sample placed on the sieves.

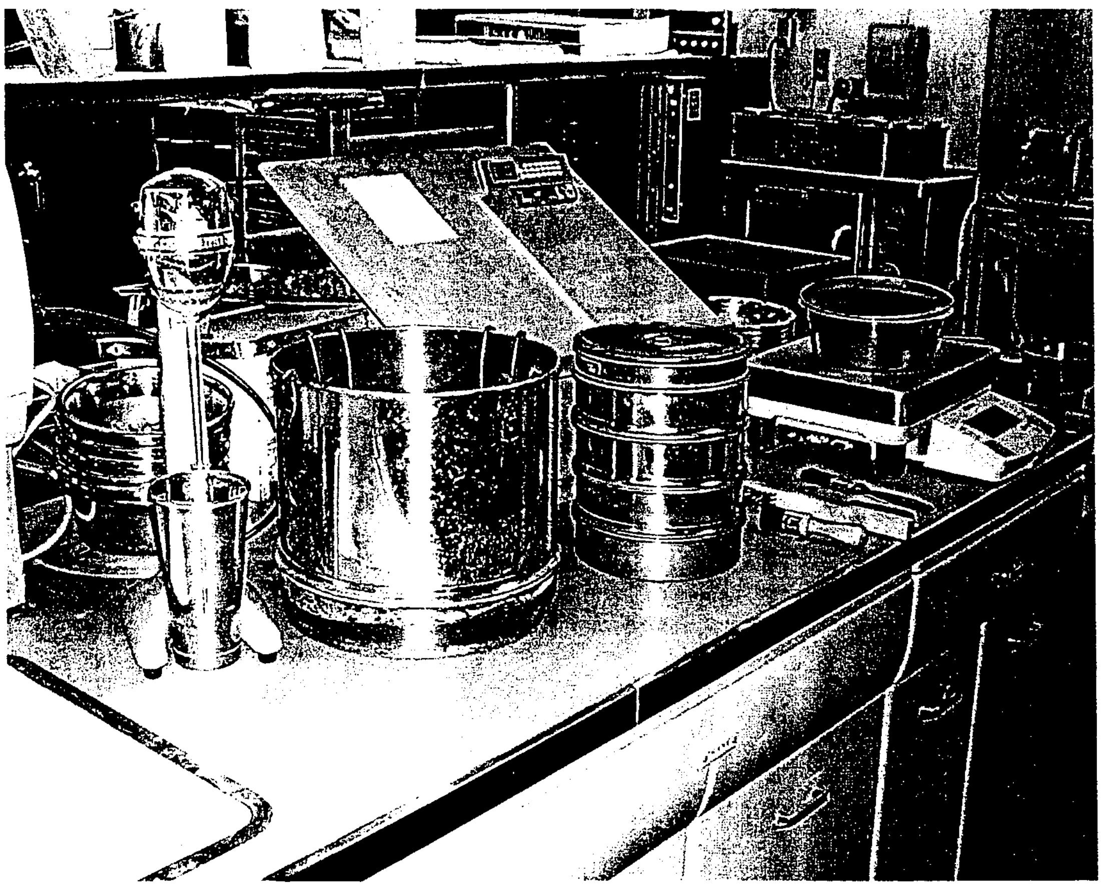


Figure 2.3 Washing screen for sieve analysis of small grains

2.3.2 Atterberg Limit Tests

The Atterberg limits include liquid limit and plastic limit. The liquid and plastic limits are used internationally for soil identification and classification and for strength correlation. The potential for volume change can often be detected from the value of liquid and plastic limits.

The liquid limit is defined as the water content at which a pat of soil, smaller than 0.3-mm diameter or passing sieve No. 40, placed in a brass cup, cut with the standard groove, and then dropped from a height of 10 mm will undergo a closure of 12.7 mm when the cup of soil is dropped 25 times at the rate of 120 drops/minute. The equipment used for the liquid limit test is shown in Figure 2.4.

The plastic limit is defined as the water content at which a soil thread, with particle sizes passing sieve No. 40, just crumbles when it is rolled down to a diameter of 3 mm. The original requirement was a thread diameter of 1/8 inch. Note that 1/8 in implies some rounding but an exact hard conversion to SI is 3.2 mm (as given in the ASTM D 4318). At best the diameter is "eyed" to size by the operator. This test is somewhat more operator-dependent than the liquid-limit test, since what constitutes crumbling and a visual detection of a 3-mm diameter are subject to some interpretation (thus 3 mm is adequate instead of the 3.2 given by ASTM). With some practice, the plastic-limit values can be produced within 1 to 3 percent water content by different laboratory technicians on the same soil.

Figure 2.4 Equipment for liquid limit test

The following steps describe the test procedure for determination of liquid limit, per AASHTO T 89 (AASHTO, 1998):

1. Obtain a sample with a mass about 100 g taken from the material passing 0.425-mm (No. 40) sieve.
2. Place the sample in the dish and thoroughly mix with 8 to 10 mL of distilled water by repeatedly stirring, kneading and chopping with a spatula.
3. Add sufficient water to form a uniform mass of a stiff consistency.
4. Place the enough material in the cup so that, when squeezed and spread with the spatula, the soil will rest in the cup above the spot where the cup rests on the point of maximum thickness. Use as few strokes of the spatula as possible, taking care to prevent the entrapment of air bubbles in the sample.
5. Divide the soil in the cup with a firm stroke of the grooving tool. Avoid tearing of the sides of the groove or slipping on the soil cake on the cup. Up to six strokes are permitted. The depth of the groove should be increased with each stroke, and only the last stroke should scrape the bottom of the cup.
6. Lift and drop the cup by turning the crank at a rate of approximately two revolutions per second until the two halves of the soil pat come together along a distance of about 13 mm (0.5 in.) within 22 to 28 shocks of the

cup. Do not hold the base while the crank is turned. Record the number of shocks required to close the groove.

7. Return the soil remaining in the cup to the mixing dish and, without adding any water, repeat Step 6. If the closure again occurs within the acceptable range, obtain a moisture content specimen.

8. Determine the moisture content of the moisture content sample.

Calculate the liquid limits as follows:

$$LL = (W_N)(N/25)^{0.121} \qquad \text{eq.2.1}$$

where, LL = liquid limit

W_N = moisture content of sample at N blows

N = number of blows

The following steps describe the procedure for determination of plastic limit, per AASHTO T90 (AASHTO, 1998):

1. Squeeze and form the test sample into an ellipsoidal-shape mass.
2. Roll this mass between the fingers or palm and the rolling surface with just sufficient pressure to roll the mass into a thread of uniform diameter along its length. Roll out between 80 to 90 strokes per minute, counting a stroke as one back and forth motion.
3. Break the thread into six or eight pieces when the diameter of the thread reaches 3 mm (1/8 inch).

4. Squeeze the pieces together between the thumbs and fingers of both hands into an ellipsoidal-shape mass and reroll.
5. Continue this process of alternately rolling to a thread 3 mm (1/8 in.) in diameter, cutting into pieces, gathering together, kneading and rerolling until the thread crumbles under the pressure required for rolling and the soil can no longer be rolled into thread.
6. Gather the portion of the crumbled soil together and place in a suitable, tarred container.
7. Determine the moisture content of the sample.

2.3.3 Compaction Test

The compaction test consisted of taking about 3 kg of soil, passing it through No. 4 sieve, adding water, and compacting it into a 944-cm^3 mold in layers.

For Standard Proctor Test (T99) the soil in the mold was compacted with a 24.5-Newton rammer dropping 0.305 m onto the soil in three layers. Each layer was subjected to 25 blows. This provides a nominal compactive effort of 592.7 kJ/m^3.

For Modified Proctor Test (T180), the soil in the mold was compacted with a 44.5-Newton rammer dropping 0.457 m onto the soil in five layers. This provides a nominal compactive effort to the soil of 2693.0 kJ/m^3.

The compacted sample is then broken down to the No. 4 size as determined visually, water content samples are taken, more water is added, the soil is thoroughly remixed, and the process of compacting a mold of soil is repeated. This sequence is repeated a sufficient number of times so that a curve of dry unit weight versus water content can be drawn which has a zero slope (a maximum value) with the sufficient points on either side of the maximum unit weight point to define its location. Dry unit weight is always the ordinate of this curve. The maximum ordinate value is termed maximum dry unit weight (γ_d), and the water content at which this dry unit weight occurs is termed the optimum moisture content (OMC). The test equipment for the compaction test is shown in Figures 2.5 and 2.6.

Samples of soil or soil-aggregate mixtures are prepared at several moisture contents and compacted into molds of specified size using manual or mechanical rammers or tampers delivering a specified quantity of compactive energy. The moist masses of the compacted samples are divided by the volume of the mold to determine moist density values.

Moisture contents of the compacted samples are determined and used to obtain the dry density values of the same samples. The maximum dry density and optimum moisture content for the soil or soil-aggregate mixture is determined by plotting the relationship between dry density and moisture content.

The procedure of a compaction test can be described as follows (AASHTO, 1998):

1. Determine the mass of the clean, dry mold. Include the base plate, but exclude the extension collar. Record the mass in kilograms to the closest 0.005 kg for the Proctor tests.

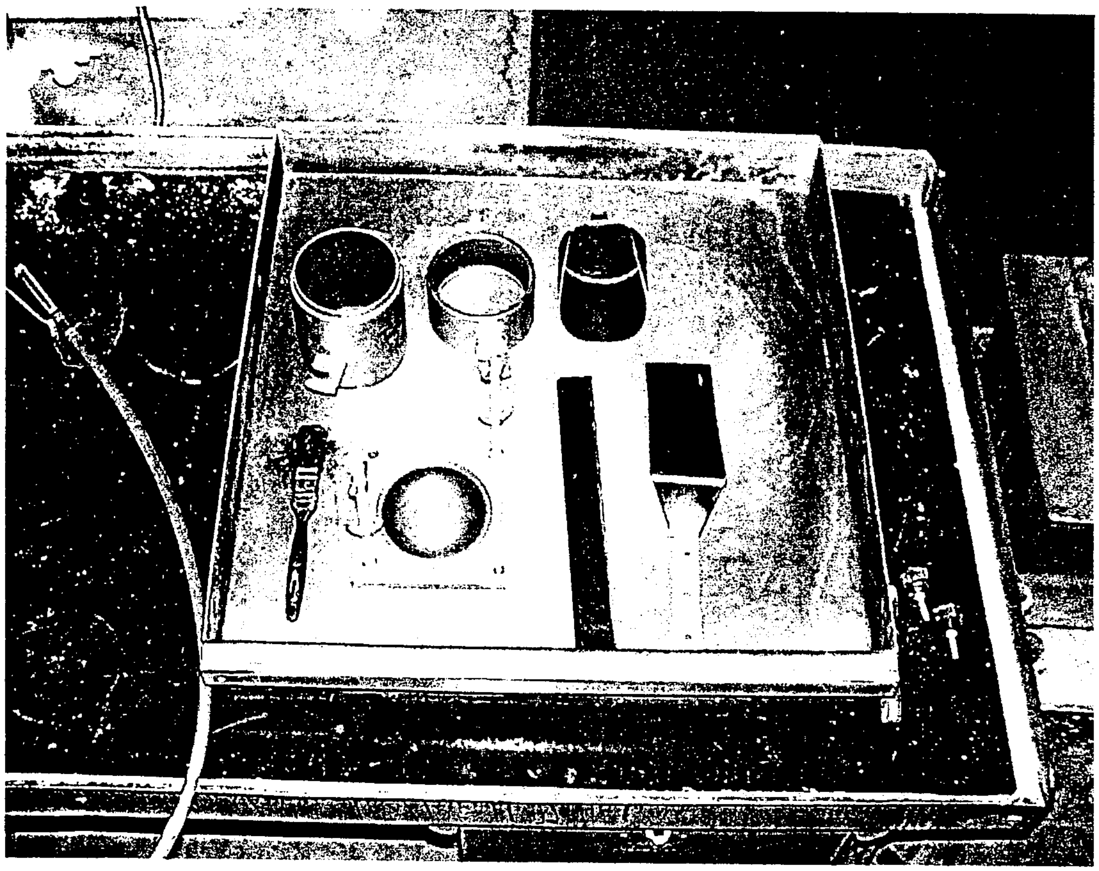


Figure 2.5 Equipment for compaction test

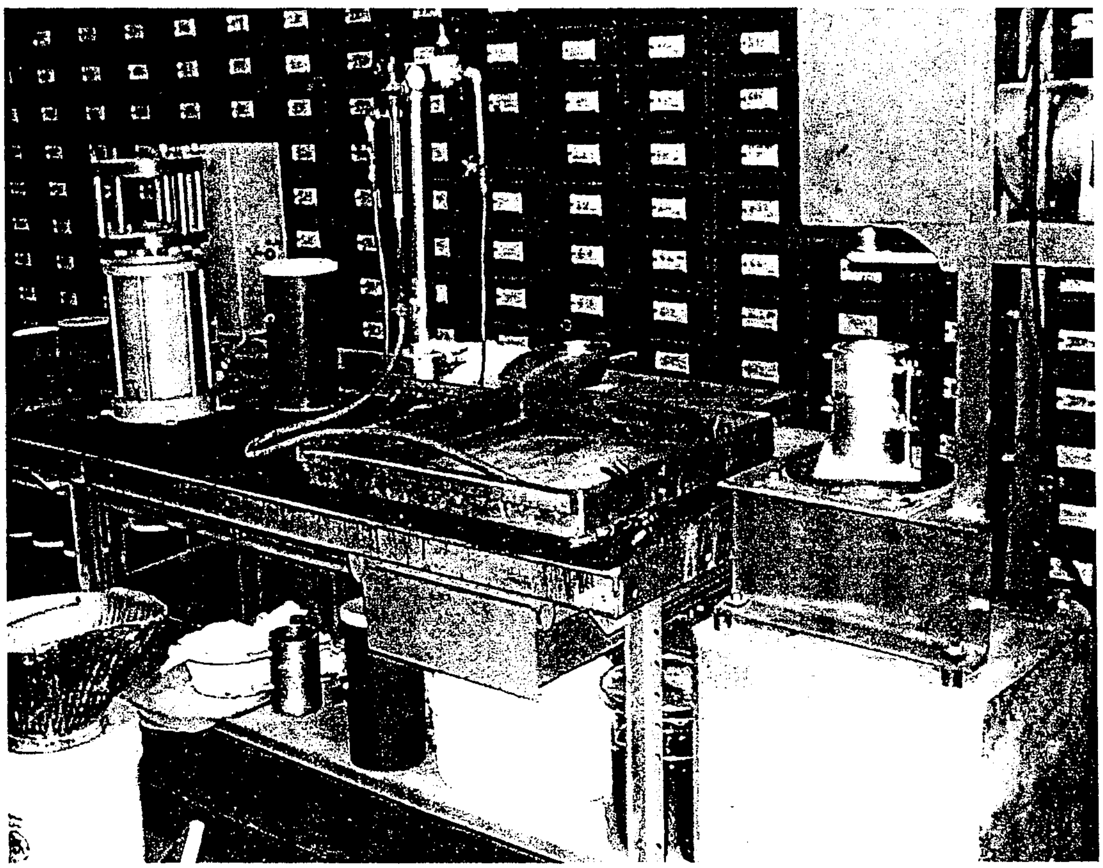


Figure 2.6 Mechanical rammer and hydraulic extruder for compaction test

2. Thoroughly mix the selected representative sample with sufficient water to dampen it to approximately 4 to 6 percentage points below optimum moisture content.
3. Form a specimen by compacting the prepared soil in the mold in approximately equal layers (3 layer for T99, and 5 layers for T180). Compact each layer with uniformly distributed blows from the rammer or tamper.
4. Remove the extension collar.
5. Trim the compacted soil even with the top of the mold with the straightedge.
6. Determine the mass of the mold and wet soil in kilograms to the nearest 0.005 kg for the Proctor tests.
7. Determine the wet mass of the sample by subtracting the mass in Step 1 from the mass in Step 6.
8. Calculate the wet density.
9. Extrude the material from the mold, slice vertically through the center and take a representative moisture content sample of at least 100 g from one of the cut faces.
10. Determine the moisture content of the sample.

11. Thoroughly break up the remaining portion of the molded specimen until it will again pass through the sieve, as judged by eye, and add to the remaining portion of the sample being tested.
12. Add sufficient water to increase the moisture content of the soil by approximately 2 percentage points and repeat the above procedure.
13. Continue determinations until there is either a decrease or no change in the wet density. A minimum of five determinations is usually necessary.

2.3.4 Direct Shear Test

The procedure of the direct shear tests performed in this study basically follows ASTM D 3080-72. All the tests were conducted in the Charles E. Shumate Laboratory using a direct shear machine manufactured by Geotest, Inc. (see Figure 2.7).

For every soil tested in this study, normal stresses of 0.7, 1.4, 2.8 kg/cm^2 (10, 20, 40 psi) were employed. The soil specimen was 63.5-mm (2.5-in) in diameter with a cross sectional area of 31.7 cm^2 (4.91 inch^2). The thickness of the specimen was 3.15 cm (1.24 in) and was prepared in three equal layers. Each layer was about 1.04 cm (0.41 inch) thick. The volume of the test specimen was 99.8 cm^3 (0.003523 ft^3). The soil specimen was compacted to 95% of maximum dry unit weight (per T90) or 90% of maximum dry unit weight (per T180). Figure 2.8 shows the shear box. Figure 2.9 shows a test specimen being prepared.

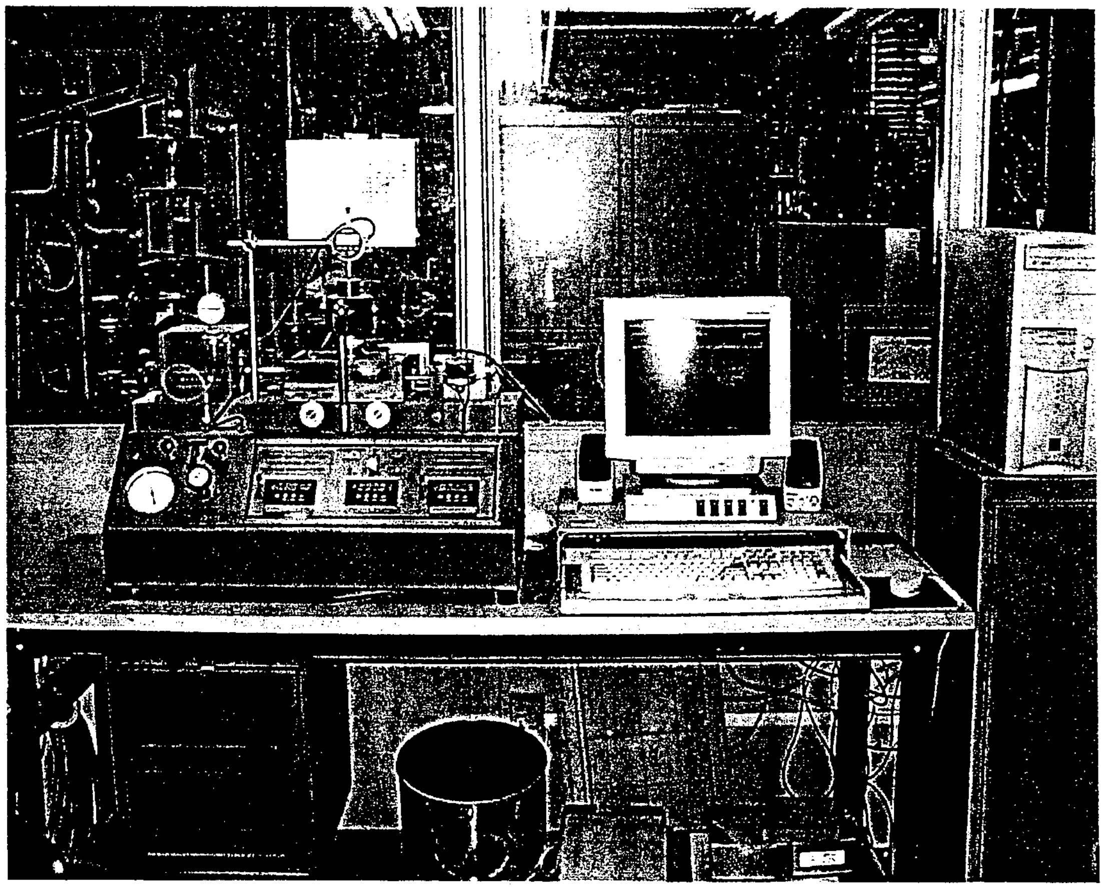


Figure 2.7 Geotest direct shear apparatus

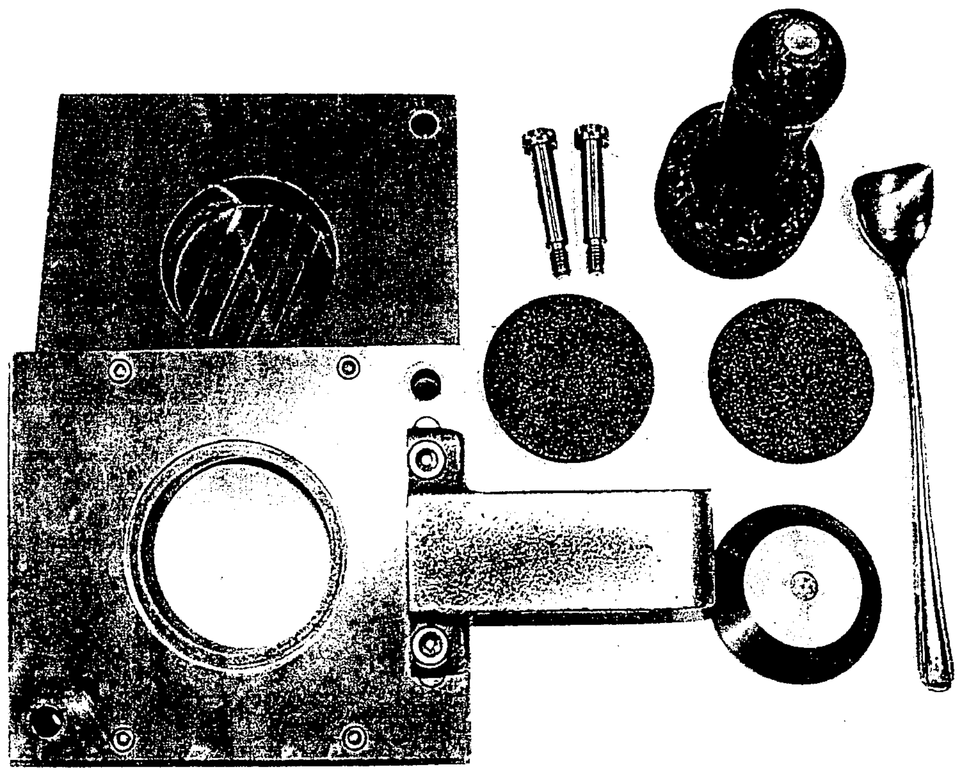


Figure 2.8 Shear box with swan-neck attachment

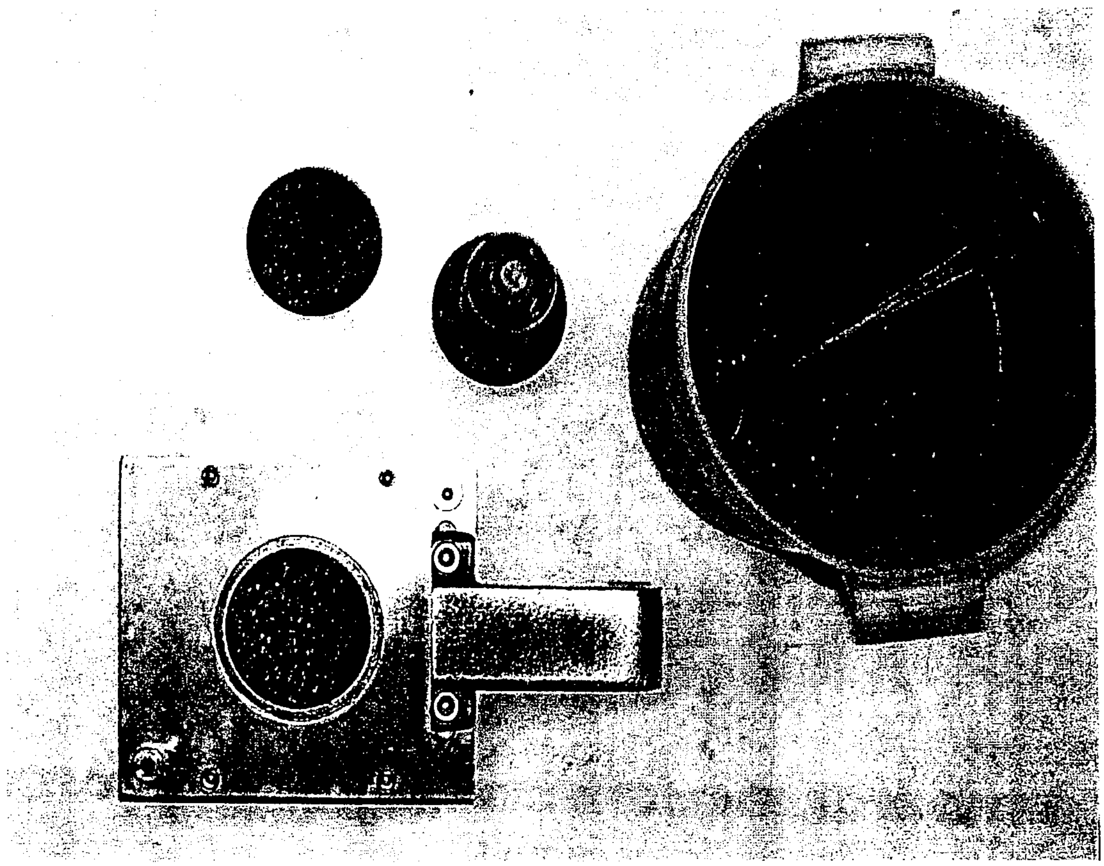


Figure 2.9 Preparation of test specimen

The soil specimen was prepared at 2% wet of optimum moisture content. The soils were cured overnight in an enclosed container before being tested. After a prescribed normal stress was applied, the soil specimen was allowed to consolidate for 15 minutes to acquire an equilibrium state. The specimen was then sheared at a constant rate of 0.5 mm/min. Figure 2.10 shows a direct shear test being conducted. The test data were collected by a data acquisition program with a computer. The data were then converted into Excel format for data analysis.

The procedure of the direct shear test is described as follows (ASTM, 1963):

1. Dry the specimens (passing sieve No. 4) to constant weight using a hot plate or in a 121±6°C oven.
2. After drying and determining the mass, place the sample in the container. Add sufficient water to obtain moisture content ±2 percent of the optimum moisture content. Then, cure the sample overnight in a covered container.
3. Calculate the mass of moist soil needed for the test.
4. Compose the upper part and lower part of the direct shear box with the alignment screws. Check that the Teflon pads are keeping a gap of about 0.005 inch between the two halves. Put the porous stone in the bottom of the box.
5. Place the soil in the shear box in three layers, tamp the specimen with a wooden tamper for each layer.

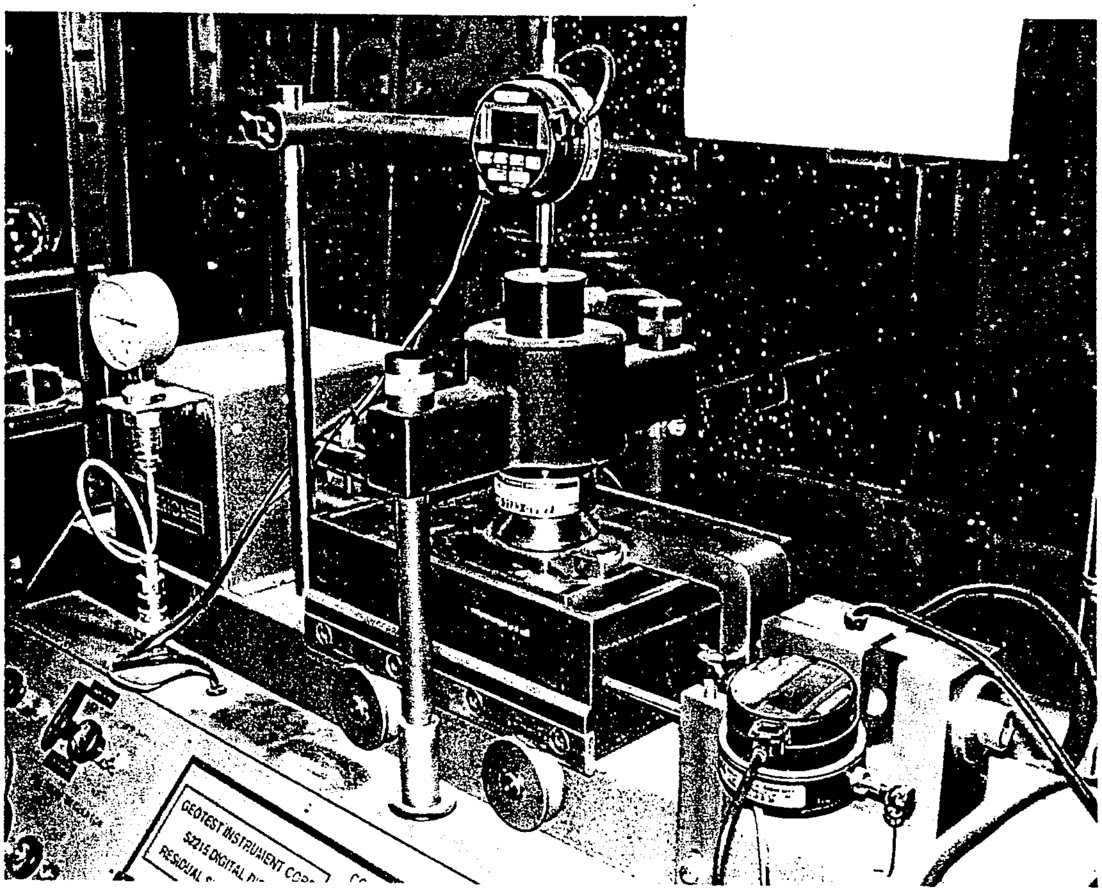


Figure 2.10 A direct shear test in progress

6. Scratch the surface of the first and second layer to avoid the arbitrary shear plane.
7. Cover the specimens with a porous stone.
8. Swing the indicator and load assembly out of the way. Place the shear box inside the machine. Check that the pin in shear yoke is properly installed.
9. Swing the upper cross bar into place and secure it with the front tie bar. Place the loading block on the top of the sample and check if it is properly lined up with the normal force load cell.
10. Reassemble cross bar and indicator. Turn on indicator.
11. Check that mode selector switch is in internal position; both control knobs are at counter clockwise stop. Check computer cable.
12. Turn on shear strain dial indicator, main power and computer switch and open supply pressure valve. Check that the valve is open and applies a slight seating pressure on vertical load by turning load control clockwise until about 5N appears on the normal stress display (see Figure 2.11). This initial load will overcome any resistance from springs on tie rods. Apply slight shear load by turning large knurled knob on the right of shear container. Record the applied vertical load and horizontal load and reading of shear strain indicator. Indicate data collection by the computer.

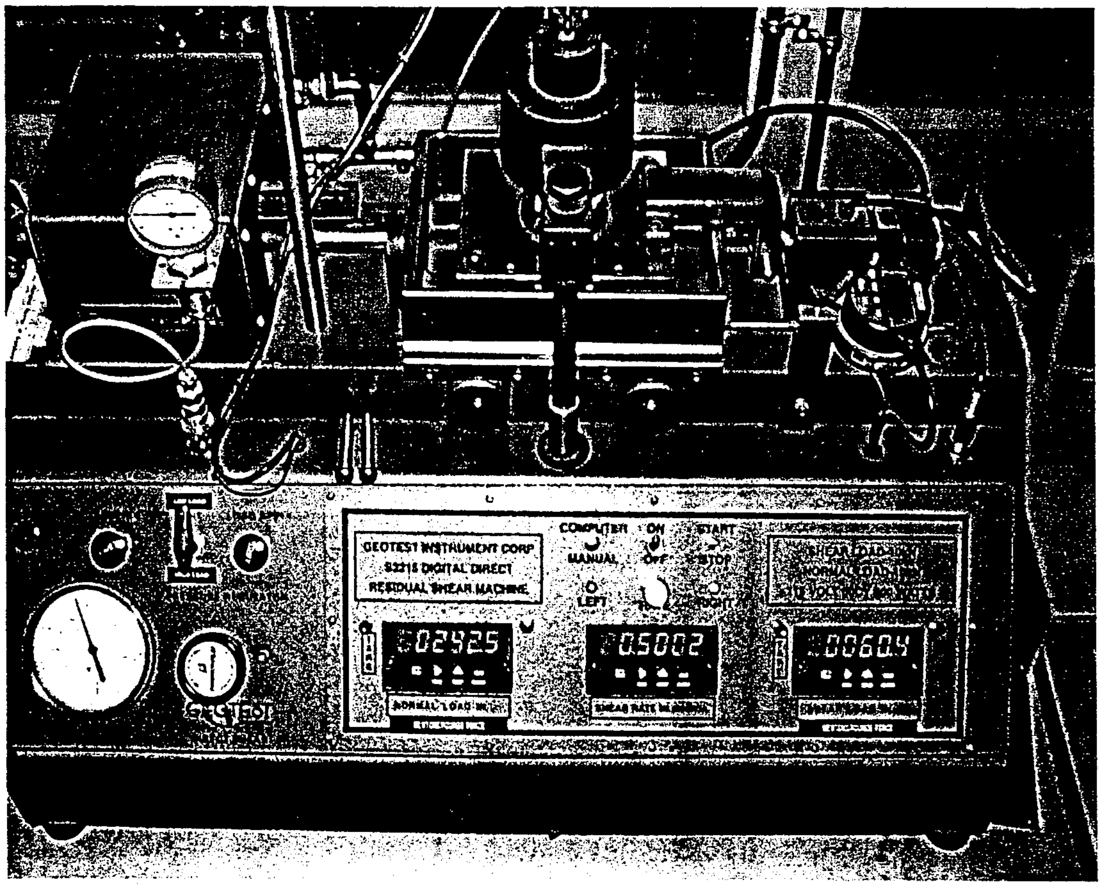


Figure 2.11 Control panel of the direct shear machine

13. Apply normal loads for incremental consolidation, closing the load applies valve, preset load pressure and open load apply valve at time "zero". Complete all required increments and proceed to shear the specimen.
14. After the consolidation stages are completed, check that the two alignment screws are removed from the shear box and the limit switches are set then push start switch and turn rate control shear clockwise slowly to obtain the desired rate reading on panel meter. Initial movement is to the right, compressing shear force load cell. Panel display is increasing positive load. Direction will be changed automatically by the limit switches until the operator terminates the test. Shear force reading will be negative in reverse moment.
15. Finish the test by driving the container back to the starting position, obtain the initial reading on the lateral strain indicator and turn off start the switch.
16. The two alignment screws are in place. Release the pin and take the shear box out of the container.
17. Remove the soil specimen from the shear box by releasing the screws.
18. Weigh the specimen and determine the moisture content of the specimen.

3. Test Results and Evaluation of Practice for Determining Design Strength Parameters

This chapter presents a study on the repeatability of the test method, the test results of 100 different soils, and evaluation of the current practice for determining design strength parameters of backfills.

The soil specimens in the direct shear tests performed in this study were prepared at 2% wet of optimum moisture and either 95% of T99 (standard Proctor) or 90% of T180 (modified Proctor) maximum dry density. It is to be noted that the test specimens used only the portion of the soil with grain size smaller than 4.75 mm, i.e., the portion passing the No. 4 U.S. standard sieve. This is necessary as the test box was only 63.5 mm (2.5 in.) in diameter. The effect of excluding larger particles is likely to lead to conservative values of internal friction angle. It is to be noted also that CDOT typically requires the placement density be at least 100% of T99 or 95% of T180. The strength parameters obtained from these tests, therefore, are likely to be on the conservative side.

Upon examining the CDOT's data base of soils, it was found that there were complete sets of data for 58 different soils, and that there were no direct shear test result for the other soils. It was decided to perform direct shear tests for soils that have sufficient quantity for the testing so that a total of 100 complete sets of data can be established.

3.1 Repeatability of the Direct Shear Test

Before starting the test program, it was deemed necessary to assure that the tests are performed correctly and in a manner consistent with these performed by CDOT personnel. Repeatability of the direct shear test, as performed by the investigator, was examined.

Nine different soils were randomly selected and tested to determine the internal friction angles. Two tests were performed on five different soils and four tests were performed on four different soils. The results were then compared with those obtained by CDOT. Table 3.1 shows the results of the test results. These test results demonstrated an acceptable margin of differences. The variance in the internal friction angle ranged from 0.1 to 2.0 degree.

Based on the repeatability test results, it was considered reasonable to assume that the friction angles determined from the direct shear tests have a $\pm$ 1 degree probable variation. This assumption was used for analyzing the test data in this study.

3.2 CDOT Class-1 Structure Backfill

The Colorado Department of Transportation specifies that soils satisfying the following criteria in Table 3.2 are Class-1 structure backfill (or "Class-1 soil").

LAB_ID	Angle of internal friction (peak),degrees						Remark			
	Test 1	Test 2	Test 3	Test 4	average value	maximum varience	Note	Method	Max. Dry Den. (pcf)	OMC (%)
146	40.6*	40.1	-	-	40.35	0.5	Class-1	T180	133.2	6.9
123	37.3	37.9	36.7	38.5	37.60	1.8	Class-1	T99	122.6	9.9
170	37.3*	37.8	-	-	37.55	0.5	Class-1	T180	126.9	8.5
208	36.4	35.7	36.1	37.7	36.48	2.0	Class-1	T99	123.0	10.6
238	39.5*	39.4	39.5	39.4	39.45	0.1	Class-1	T99	122.7	10.5
348	40.5*	39.6	-		40.05	0.9	-	T99	113.5	12.5
469	36.5*	37.4	-	-	36.95	0.9	-	T99	128.6	10.5
204	34.4	33.9	32.9	33.7	33.73	1.5	-	T99	112.2	10.5
202	34.3	33.7	-	-	34.00	0.6	-	T99	118.9	11.6

*Tests conducted by CDOT

Table 3.1 Repeatability of the direct shear tests

Sieve Size	Mass Percent Passing Square Mesh Sieves
50 mm (2”)	100%
4.75 mm (No. 4)	30%-100%
300 μm (No. 50)	10%-60%
75 μm (No. 200)	5%-20%

Plastic index, PI ≤ 6

Liquid limit, LL ≤ 35

Table 3.2 Class-1 soil criteria

The gradation limits of the Class-1 soil are shown graphically in Figure 3.1.

3.3 Test Results

Of the 100 soils, 47 soils are Class-1 soils and 53 soils are Non-Class-1 soils. Tables 3.2 and 3.3 show the results of gradation tests, Atterberg limit tests, compaction tests and direct shear tests for the Class-1 and Non-Class-1 soils, respectively. For the direct shear test results, the "peak" internal friction angles were reported.

It is to be noted that the cohesion, as obtained from direct shear tests, is generally ignored for granular soils. This is because the cohesion for these soils is not dependent on inter-particle cementation or bonding; rather, it is a result of capillary stresses and particle geometry and packing with no physical or chemical attractions between particles. This type of cohesion will vanish when the soil becomes dry (thus, termed "apparent cohesion"). The apparent cohesion measured in the direct shear tests of the Class-1 soils ranged from 0.15 kg/cm^2 to 0.4 kg/cm^2 (0.3 ksf to 0.8 ksf). Designs that do not include the apparent cohesion for granular soils have added safety margins.

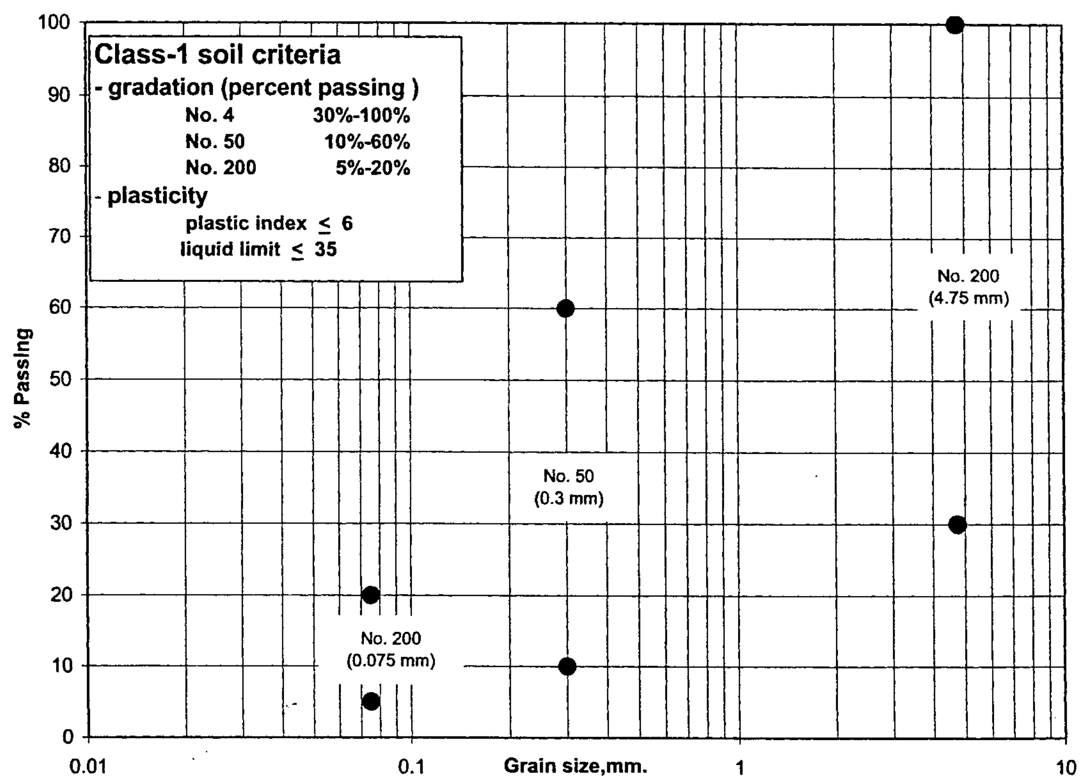


Figure 3.1 Gradation limit of Class-1 soil

No.	LAB ID	Group Classification	Atterberg Limits LL (%)	PI (%)	Compaction Result Method	Max. Unit weight (pcf)	water content (%)	Target dry unit wt. for DST Unit weight (pcf)	Dry density (Mg/m^3)
1	231	A-1-b(0)	NV	NP	T99	131.1	9.7	124.5	1.99
2	1064	A-1-a(0)	NV	NP	T99	128.4	9.8	122.0	1.95
3	108	A-1-a(0)	28	5	T99	121.3	11.2	115.2	1.84
4	1143	A-1-b(0)	23	6	T99	126.3	9.6	120.0	1.92
5	69	A-1-a(0)	NV	NP	T99	123.4	9.6	117.2	1.87
6	146	A-1-a(0)	22	4	T180	133.2	6.9	119.9	1.92
7	74	A-1-b(0)	NV	NP	T99	121.6	10.2	115.5	1.85
8	862	A-1-b(0)	NV	NP	T99	126.0	9.7	119.7	1.91
9	148	A-1-a(0)	24	3	T180	129.7	8.1	116.7	1.87
10	1114	A-1-a(0)	NV	NP	T99	122.6	10.5	116.5	1.86
11	65	A-1-b(0)	NV	NP	T99	124.5	9.1	118.3	1.89
12	238	A-1-b(0)	23	5	T99	122.7	10.5	116.6	1.86
13	962	A-1-b(0)	23	2	T99	129.8	8.6	123.3	1.97
14	67	A-1-a(0)	NV	NP	T99	122.2	10.0	116.1	1.86
15	796	A-1a(0)	20	5	T99	127.5	9.4	121.1	1.94
16	340	A-1-b(0)	NV	NP	T99	118.3	10.0	112.4	1.80
17	1146	A-1-b(0)	NV	NP	T99	128.7	8.4	122.3	1.96
18	572	A-1-a(0)	NV	NP	T99	121.0	10.9	115.0	1.84
19	1065	A-1-a(0)	NV	NP	T99	119.7	12.7	113.7	1.82
20	100	A-1-b(0)	NV	NP	T99	124.4	9.3	118.2	1.89
21	1063	A-1-a(0)	NV	NP	T99	125.3	11.5	119.0	1.90
22	345	A-1-b(0)	NV	NP	T180	132.0	8.6	118.8	1.90
23	123	A-1-b(0)	NV	NP	T99	122.6	9.9	116.5	1.86
24	147	A-1-a(0)	21	4	T180	134.1	7.2	120.7	1.93
25	90	A-1-b(0)	18	2	T99	128.0	9.0	121.6	1.94
26	103	A-1-b(0)	18	2	T180	135.2	6.5	121.7	1.95
27	530	A-1-a(0)	21	3	T99	123.3	10.0	117.1	1.87
28	209	A-1-a(0)	22	5	T180	136.2	6.4	122.6	1.96
29	1144	A-1-b(0)	21	3	T99	126.0	9.4	119.7	1.91
30	1066	A-1-a(0)	19	4	T99	126.9	9.4	120.6	1.93
31	170	A-1-b(0)	24	5	T180	126.9	8.5	114.2	1.83
32	21	A-1-a(0)	NV	NP	T99	114.0	11.3	108.3	1.73
33	68	A-1-a(0)	NV	NP	T99	125.8	10.1	119.5	1.91
34	122	A-1-a(0)	NV	NP	T99	125.0	9.7	118.8	1.90
35	203	A-1-b(0)	NV	NP	T180	136.8	6.9	123.1	1.97
36	172	A-1-a(0)	26	4	T99	114.7	12.7	109.0	1.74
37	208	A-1-b(0)	21	6	T99	123.0	10.6	116.9	1.87
38	101	A-1-a(0)	NV	NP	T99	122.9	9.4	116.8	1.87
39	289	A-1-a(0)	NV	NP	T99	121.7	10.6	115.6	1.85
40	1031	A-1-a(0)	NV	NP	T99	124.3	9.8	118.1	1.89
41	73	A-3(0)	NV	NP	T99	114.0	10.9	108.3	1.73
42	1129	A-1-b(0)	NV	NP	T99	117.8	13.0	111.9	1.79
43	205	A-1-b(0)	24	2	T99	122.1	11.4	116.0	1.86
44	99	A-1-a(0)	NV	NP	T99	122.0	8.9	115.9	1.85
45	197	A-1-a(0)	23	3	T180	131.8	6.9	118.6	1.90
46	1042	A-1-b(0)	NV	NP	T99	123.5	10.1	117.3	1.88
47	66	A-1-b(0)	NV	NP	T99	119.6	10.7	113.6	1.82

Table 3.2 Parameters of the 47 Class-1 soils

No.	Percent Passing			DST Result			
	No_4 4.75mm. (%)	No.50 0.3mm. (%)	No_200 0.075mm. (%)	Unit weight (pcf)	water content (%)	Dry density (Mg/m^3)	phi (peak) (degree)
1	77	27	12	127.0	8.1	2.03	**44.4**
2	67	22	11	122.0	9.9	1.95	**43.7**
3	56	12	6	117.1	10.0	1.87	**41.9**
4	79	29	16	119.2	10.2	1.91	**41.9**
5	57	18	9	116.9	9.8	1.87	**41.5**
6	60	20	12	121.0	5.8	1.94	**40.6**
7	85	19	7	117.0	9.2	1.87	**40.3**
8	69	28	16	119.8	9.7	1.92	**39.9**
9	49	10	6	118.2	6.7	1.89	**39.8**
10	41	10	5	117.1	10.0	1.87	**39.7**
11	59	26	14	117.9	9.5	1.89	**39.5**
12	53	30	20	117.6	9.6	1.88	**39.5**
13	79	34	17	123.6	8.4	1.98	**39.4**
14	55	19	9	115.9	10.0	1.85	**39.2**
15	46	24	14	121.1	9.3	1.94	**39.2**
16	88	38	11	112.9	9.5	1.81	**39.1**
17	73	30	14	122.3	8.5	1.96	**39.1**
18	56	15	5	122.1	9.8	1.95	**39.1**
19	40	11	7	113.7	12.6	1.82	**39.1**
20	59	25	9	119.1	9.0	1.90	**38.5**
21	47	19	8	118.8	11.7	1.90	**38.4**
22	86	36	14	118.9	8.4	1.90	**38.3**
23	83	26	10	117.8	9.3	1.88	**38.0**
24	55	21	12	122.0	6.1	1.95	**38.0**
25	68	30	16	122.7	8.1	1.96	**38.0**
26	71	30	13	121.7	6.4	1.95	**37.7**
27	44	19	12	114.2	13.0	1.83	**37.6**
28	59	20	12	122.6	6.2	1.96	**37.5**
29	76	35	19	118.7	10.3	1.90	**37.4**
30	46	23	14	120.7	9.4	1.93	**37.3**
31	71	34	20	115.5	7.2	1.85	**37.3**
32	42	23	6	109.5	10.6	1.75	**37.2**
33	42	14	7	119.0	10.5	1.90	**37.2**
34	51	22	9	119.9	9.1	1.92	**37.0**
35	75	36	14	123.1	6.8	1.97	**36.8**
36	40	23	15	109.7	11.7	1.75	**36.6**
37	78	36	16	118.2	9.9	1.89	**36.4**
38	57	22	8	118.0	8.8	1.89	**36.4**
39	35	16	7	116.1	9.9	1.86	**36.2**
40	35	16	6	118.7	9.2	1.90	**35.9**
41	95	56	6	105.8	10.2	1.69	**35.8**
42	87	32	11	110.6	14.3	1.77	**35.6**
43	60	27	13	118.7	9.2	1.90	**35.6**
44	50	21	7	117.0	8.3	1.87	**35.5**
45	58	24	12	119.0	6.7	1.90	**35.4**
46	89	24	11	119.1	8.9	1.90	**35.4**
47	85	35	14	113.8	10.5	1.82	**35.1**

Table 3.2 (continued) Parameters of the 47 Class-1 soils

No.	LAB ID	Group Classification	Atterberg Limits LL (%)	PI (%)	Compaction Result Method	Max. Unit weight (pcf)	water content (%)	Target dry unit wt. for DST Unit weight (pcf)	Dry density (Mg/m^3)
1	1035	A-2-4(0)	26	8	T99	126.0	10.8	119.7	1.91
2	1149	A-2-4(0)	26	10	T99	126.5	9.9	120.2	1.92
3	348	A-2-4(0)	NV	NP	T99	113.5	12.5	107.8	1.72
4	304	A-1-b(0)	NV	NP	T99	127.4	8.8	121.0	1.94
5	1147	A-2-4(0)	19	5	T99	132.0	7.4	125.4	2.01
6	1148	A-2-6(0)	28	11	T99	124.0	9.8	117.8	1.88
7	202	A-2-4(0)	24	5	T99	118.9	11.6	113.0	1.81
8	290	A-1-b(0)	24	5	T99	117.0	11.9	111.2	1.78
9	120	A-2-4(0)	26	8	T99	119.4	11.7	113.4	1.81
10	338	A-2-4(0)	30	9	T99	116.2	11.3	110.4	1.77
11	863	A-2-4(0)	29	9	T180	127.0	9.8	114.3	1.83
12	469	A-2-4(0)	NV	NP	T99	128.6	10.5	122.2	1.95
13	936	A-2-4(0)	29	9	T99	120.4	11.2	114.4	1.83
14	481	A-2-4(0)	24	7	T99	122.4	10.3	116.3	1.86
15	339	A-2-4(0)	NV	NP	T99	123.4	9.8	117.2	1.87
16	346	A-2-4(0)	27	10	T99	115.9	14.1	110.1	1.76
17	127	A-2-4(0)	23	9	T180	136.9	6.6	123.2	1.97
18	22	A-1-b(0)	NV	NP	T99	107.9	16.0	102.5	1.64
19	866	A-2-4(0)	27	8	T99	119.7	11.1	113.7	1.82
20	930	A-2-4(0)	26	7	T99	117.6	12.4	111.7	1.79
21	158	A-2-4(0)	23	5	T99	126.1	8.9	119.8	1.92
22	159	A-2-4(0)	26	9	T99	116.7	12.5	110.9	1.77
23	186	A-2-4(0)	24	7	T180	136.5	6.3	122.9	1.96
24	1041	A-2-4(0)	NV	NP	T180	126.4	8.3	113.8	1.82
25	1145	A-2-4(0)	22	6	T99	122.7	10.0	116.6	1.86
26	907	A-2-6(0)	27	13	T99	120.5	10.7	114.5	1.83
27	88	A-2-6(0)	27	11	T99	122.3	9.9	116.2	1.86
28	204	A-2-4(0)	NV	NP	T99	112.2	10.5	106.6	1.70
29	42	A-2-4(0)	NV	NP	T99	117.6	10.8	111.7	1.79
30	126	A-3(0)	NV	NP	T99	103.0	17.0	97.9	1.56
31	52	A-3(1)	NV	NP	T99	106.6	13.9	101.3	1.62
32	115	A-2-4(0)	NV	NP	T99	115.9	10.0	110.1	1.76
33	183	A-3(0)	NV	NP	T99	104	14.3	98.8	1.58
34	1082	A-4(1)	29	6	T99	112.8	14.3	107.2	1.71
35	394	A-2-4(0)	25	10	T99	118.7	12.1	112.8	1.80
36	349	A-2-4(0)	NV	NP	T99	107.8	12.8	102.4	1.64
37	1089	A-4(3)	24	8	T99	121.5	12.5	115.4	1.85
38	259	A-1-b(0)	24	6	T99	121.6	10.9	115.5	1.85
39	563	A-2-4(0)	NV	NP	T99	114.3	10.7	108.6	1.74
40	288	A-3(0)	NV	NP	T99	106.7	12.3	101.4	1.62
41	175	A-2-4(0)	NV	NP	T99	112.1	11.2	106.5	1.70
42	960	A-3(1)	NV	NP	T99	106.4	13.5	101.1	1.62
43	51	A-3(1)	NV	NP	T99	106.7	13.7	101.4	1.62
44	114	A-3(0)	NV	NP	T99	104.8	13.4	99.6	1.59
45	952	A-2-4(0)	NV	NP	T99	99.3	19.6	94.3	1.51
46	102	A-6(4)	32	12	T99	105.2	17.4	99.9	1.60
47	118	A-2-7(3)	49	29	T99	110.6	15.4	105.1	1.68
48	119	A-7-6(7)	49	32	T99	110.8	15.3	105.3	1.68
49	987	A-4(4)	27	9	T99	114.8	13.6	109.1	1.74
50	988	A-6(9)	36	19	T99	107.5	16.7	102.1	1.63
51	814	A-2-4(0)	NV	NP	T99	113.8	12.8	108.1	1.73
52	470	A-6(19)	40	25	T99	107.4	14.7	102.0	1.63
53	347	A-6(4)	35	12	T99	108.0	18.5	102.6	1.64

*numbers in shaded cells fail the Class-1 criteria

Table 3.3 Parameters of the 53 non-Class-1 soils

No.	Percent Passing			DST Result			
	No_4 4.75mm. (%)	No.50 0.3mm. (%)	No_200 0.075mm. (%)	Unit weight (pcf)	water content (%)	Dry density (Mg/m^3)	phi (peak) (degree)
1	73	24	14	122.1	9.0	1.95	**41.8**
2	73	29	17	124.7	11.0	1.99	**41.7**
3	99	48	21	109.3	11.1	1.75	**40.5**
4	78	44	23	120.2	9.6	1.92	**40.0**
5	79	45	27	124.7	8.0	1.99	**39.3**
6	81	42	27	116.3	11.2	1.86	**38.3**
7	87	54	21	114.4	10.8	1.83	**38.0**
8	57	35	24	111.7	11.4	1.79	**37.6**
9	41	24	17	114.8	10.2	1.84	**37.4**
10	79	42	27	111.6	10.0	1.78	**37.1**
11	88	48	26	115.9	8.8	1.85	**37.1**
12	89	74	20	123.4	8.8	1.97	**36.5**
13	91	26	14	115.8	10.4	1.85	**36.2**
14	87	48	26	117.6	9.6	1.88	**36.1**
15	86	49	25	117.7	9.6	1.88	**36.0**
16	76	50	33	110.4	13.9	1.77	**36.0**
17	76	38	22	123.0	6.8	1.97	**35.5**
18	63	8	21	105.0	13.7	1.68	**35.4**
19	79	40	23	115.4	10.0	1.85	**35.2**
20	85	50	28	111.6	12.7	1.78	**34.8**
21	93	46	25	120.3	8.1	1.92	**34.5**
22	92	58	32	113.2	10.7	1.81	**34.3**
23	73	37	22	122.9	6.4	1.97	**34.3**
24	93	61	20	115.3	7.4	1.84	**34.0**
25	77	44	28	115.9	10.7	1.85	**33.9**
26	96	38	22	116.5	9.3	1.86	**33.9**
27	84	47	28	117.7	9.1	1.88	**33.9**
28	100	61	19	108.0	9.7	1.73	**33.7**
29	97	65	24	112.7	10.4	1.80	**33.7**
30	100	60	3	99.0	16.2	1.58	**33.1**
31	100	70	5	102.5	13.1	1.64	**32.9**
32	100	68	16	110.7	10.2	1.77	**32.6**
33	100	72	7	100.2	13.2	1.60	**32.5**
34	79	62	49	108.8	13.1	1.74	**32.5**
35	83	57	28	114.0	10.9	1.82	**32.4**
36	100	88	19	103.3	12.0	1.65	**32.2**
37	100	73	69	117.9	12.8	1.89	**32.1**
38	76	41	21	117.3	9.7	1.88	**31.9**
39	100	61	13	109.7	10.1	1.75	**31.6**
40	100	78	4	102.7	11.5	1.64	**31.0**
41	98	70	13	108.0	10.2	1.73	**31.0**
42	100	69	5	102.4	12.3	1.64	**30.7**
43	100	65	7	102.3	13.2	1.64	**29.9**
44	100	74	10	100.7	12.6	1.61	**29.4**
45	100	79	20	95.1	19.2	1.52	**28.2**
46	94	80	57	99.6	18.0	1.59	**27.3**
47	78	37	30	105.3	15.2	1.68	**25.2**
48	88	52	40	106.4	14.1	1.70	**24.8**
49	91	84	71	110.4	12.7	1.77	**23.9**
50	97	80	63	103.7	15.5	1.66	**23.2**
51	83	47	28	108.5	12.6	1.74	**22.8**
52	98	90	82	102.9	14.4	1.65	**20.8**
53	99	82	51	101.0	20.1	1.62	**16.0**

* numbers in shaded cells fail the Class-1 criteria

Table 3.3 (continued) Parameters of the 53 non-Class-1 soils

3.4 Internal Friction Angles of the 47 Class-1 Soils

Upon examining the internal friction angles of the 47 Class-1 soils, three groups of soils were identified:

Group 1: 28 soils with $39^{\circ} > \phi \geq 35^{\circ}$ (with the gradation curves shown in Figure 3.2)

Group 2: 17 soils with $43^{\circ} > \phi \geq 39^{\circ}$ (with the gradation curves shown in Figure 3.3)

Group 3: 2 soils with $\phi \geq 43^{\circ}$ (with the gradation curves shown in Figure 3.4)

It is noted that all 47 Class-1 soils have an internal friction angle greater than 35°. Considering the $\pm 1^{\circ}$ probable variance, the current practice of assigning $\phi = 34^{\circ}$ is an excellent conservative measure for selecting the friction angle value without performing any laboratory tests. It is interesting to note that, while the lower limit line of Figures 3.2 and 3.3 are nearly the same, the upper limit line of Figures 3.2 through 3.4 appears to become closer to the lower limit line as the internal friction angle becomes larger. Since there were only two soils with $\phi \geq 43^{\circ}$, a definitive guide cannot be established with the present data. However, Figure 3.5, deduced from Figures 3.2 to 3.4, can be used as a preliminary guide.

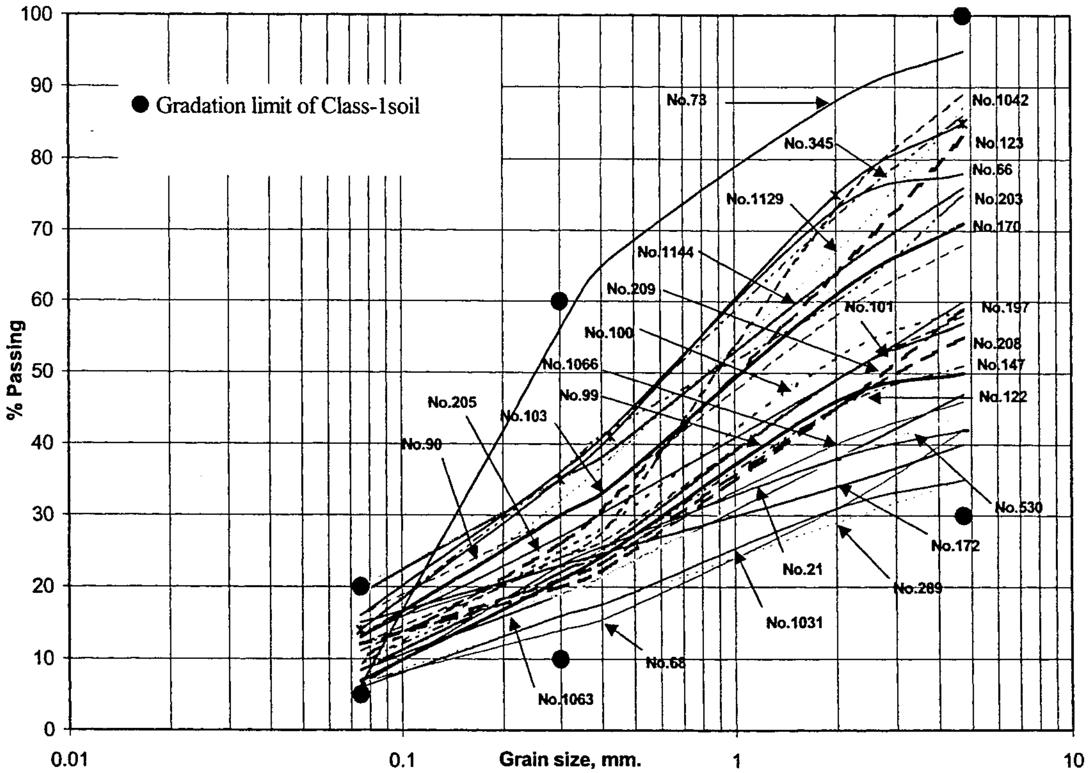


Figure 3.2 Gradation of the 28 Class-1 soils with $39^{o} > \phi \geq 35^{o}$

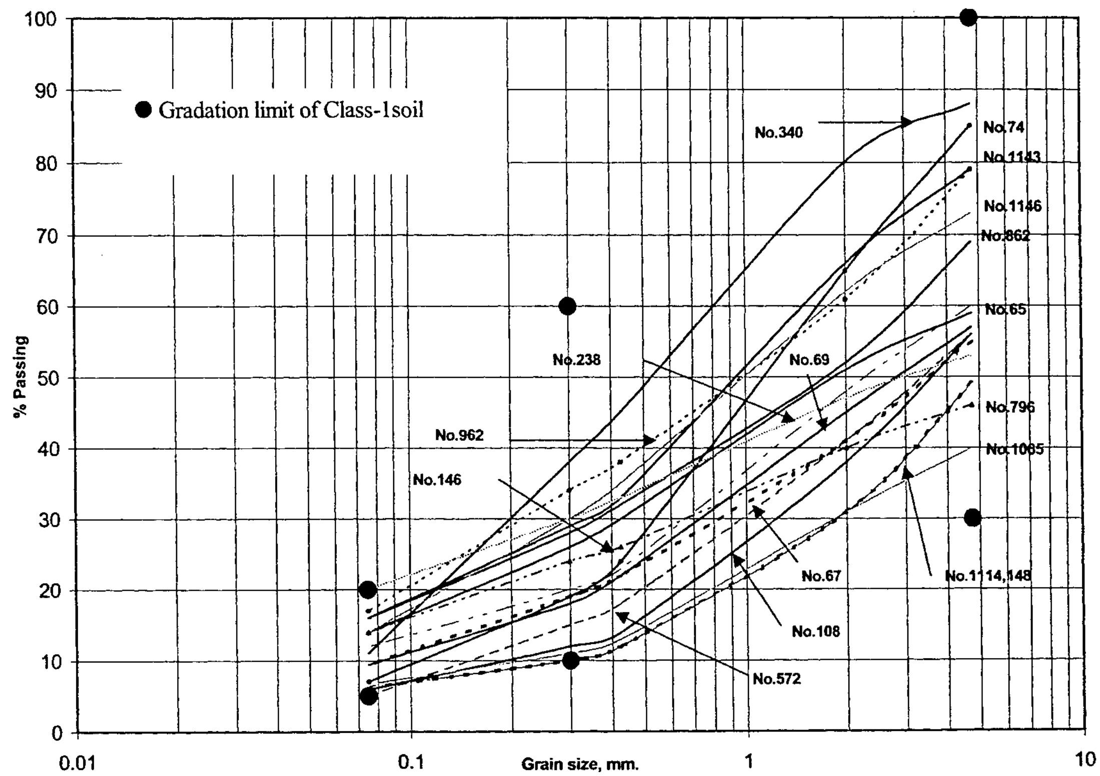


Figure 3.3 Gradation of the 17 Class-1 soils with $43^{\circ} > \phi \geq 39^{\circ}$

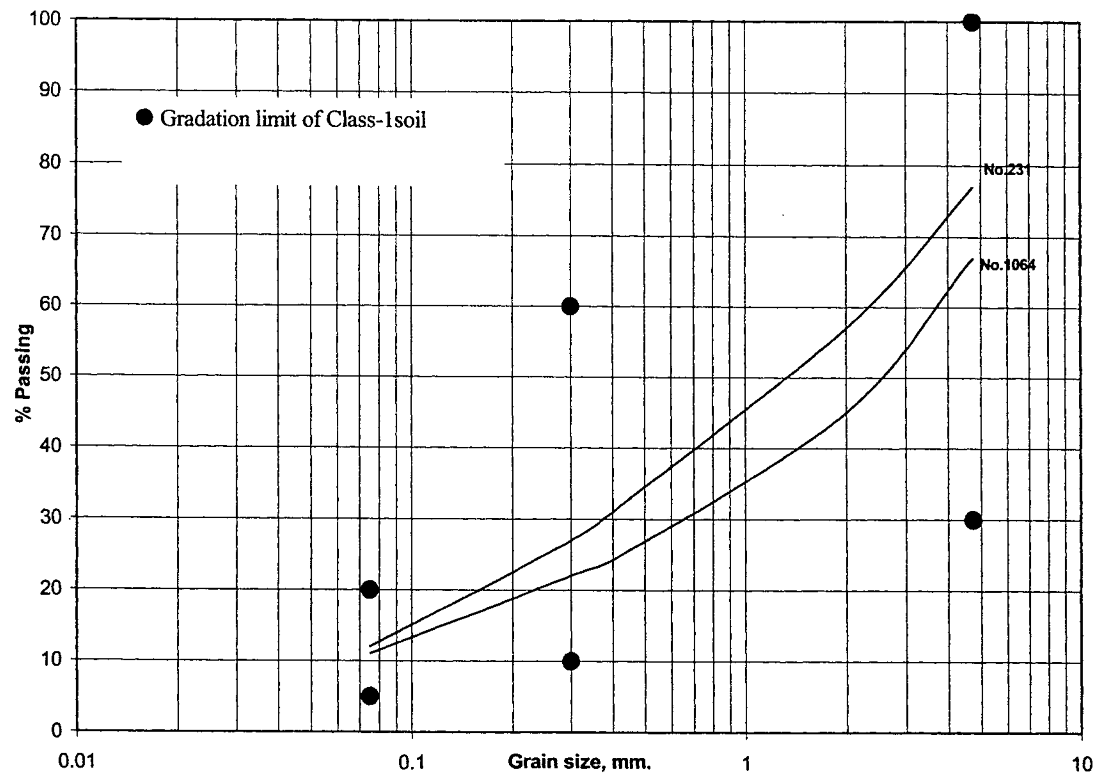


Figure 3.4 Gradation of the 2 Class-1 soils with $\phi \geq 43^{\circ}$

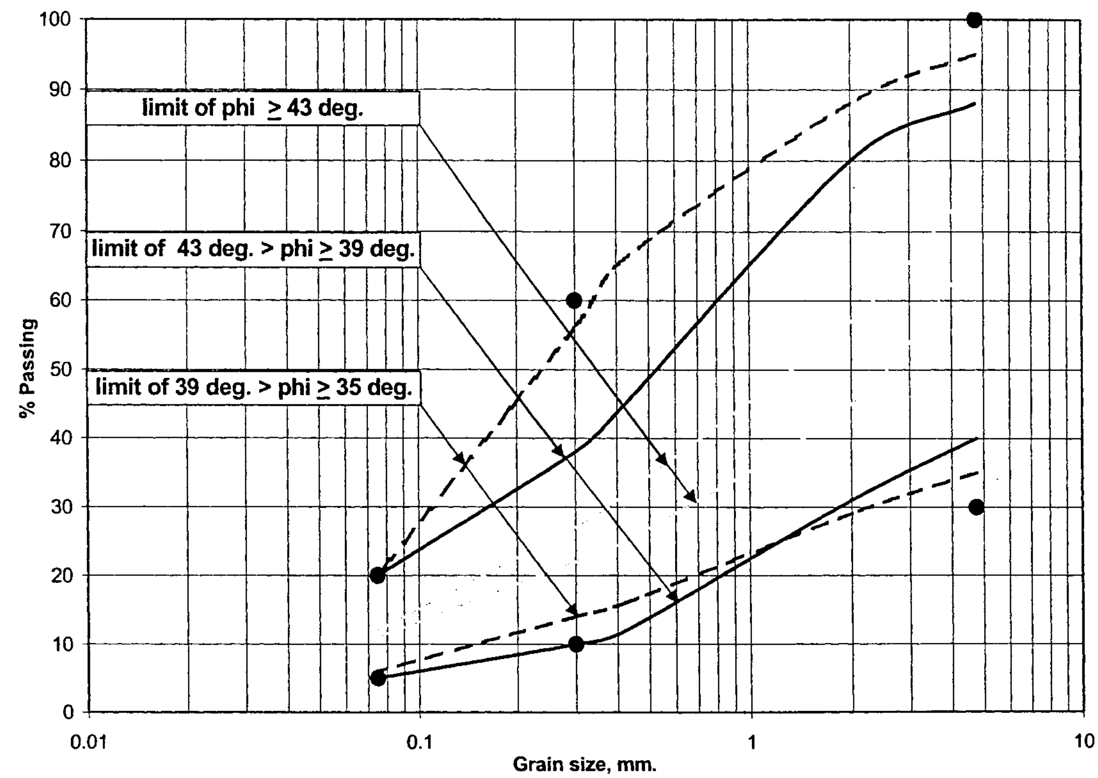


Figure 3.5 Gradation limit lines for the Class-1 soils

3.5 Internal Friction Angles of the 53 Non-Class-1 Soils

Upon examining the internal friction angles of the 47 Class-1 soils, the following observations were made:

- 14 soils with $\phi < 31^{\circ}$ (with the gradation curves shown in Figure 3.6)
- 20 soils with $35^{\circ} > \phi \geq 31^{\circ}$ (with the gradation curves shown in Figure 3. 7)
- 14 soils with $39^{\circ} > \phi \geq 35^{\circ}$ (with the gradation curves shown in Figure 3.8)
- 5 soils with $43^{\circ} > \phi \geq 39^{\circ}$ (with the gradation curves shown in Figure 3.9)
- 0 soil with $\phi \geq 43^{\circ}$

From the gradation curves, it is seen that, with only a few exceptions, the non-Class-1 soils with $\phi < 35^{\circ}$ typically have a large fraction of small particles, notably a large percentage of fines (passing No. 200 sieve). For the non-Class-1 soils with $\phi \geq 35^{\circ}$, the gradation curves generally fall within the limits of Class-1 soil, In other words, these soils tend to have LL > 35 and/or PI > 6. A general implication is that gradation of a soil may have a much stronger effect on the internal friction angle than LL and PI. It is believed by CDOT's Bridge Department, however, that soils with LL > 35 or PI > 6 are not suitable for construction of "permanent" retaining walls (CDOT, 1999).

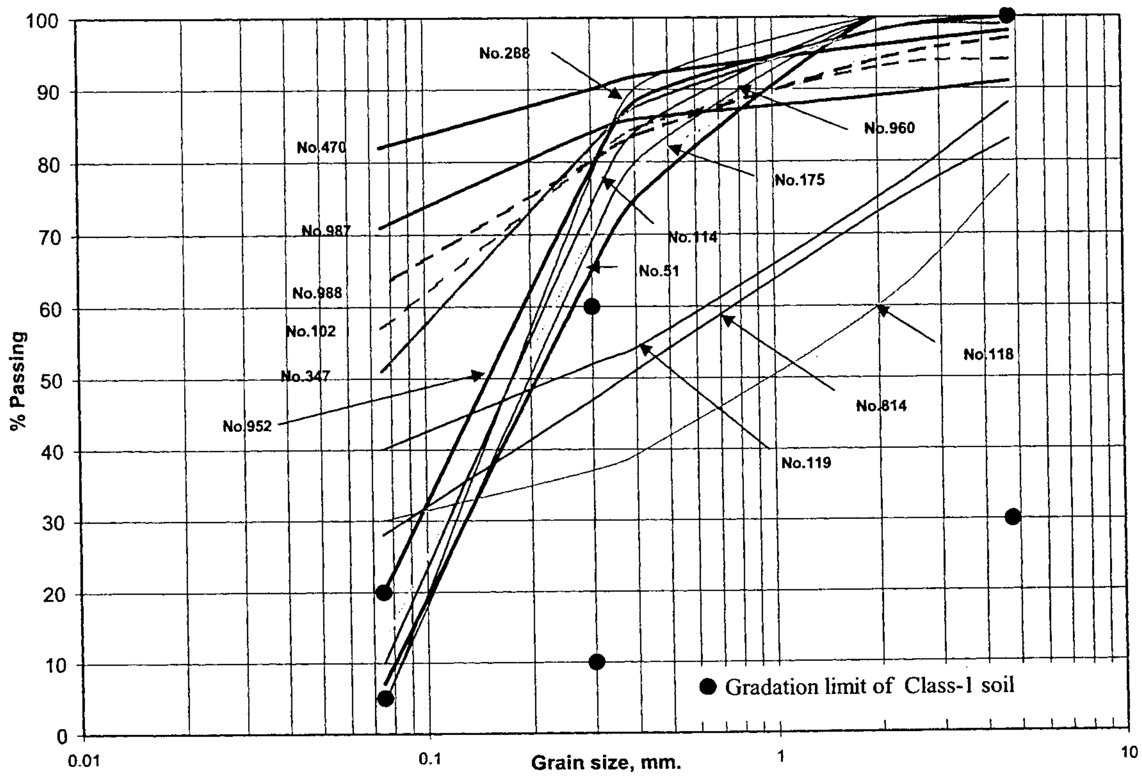


Figure 3.6 Gradation curves of the14 non-Class-1 soils with $\phi < 31^{\circ}$

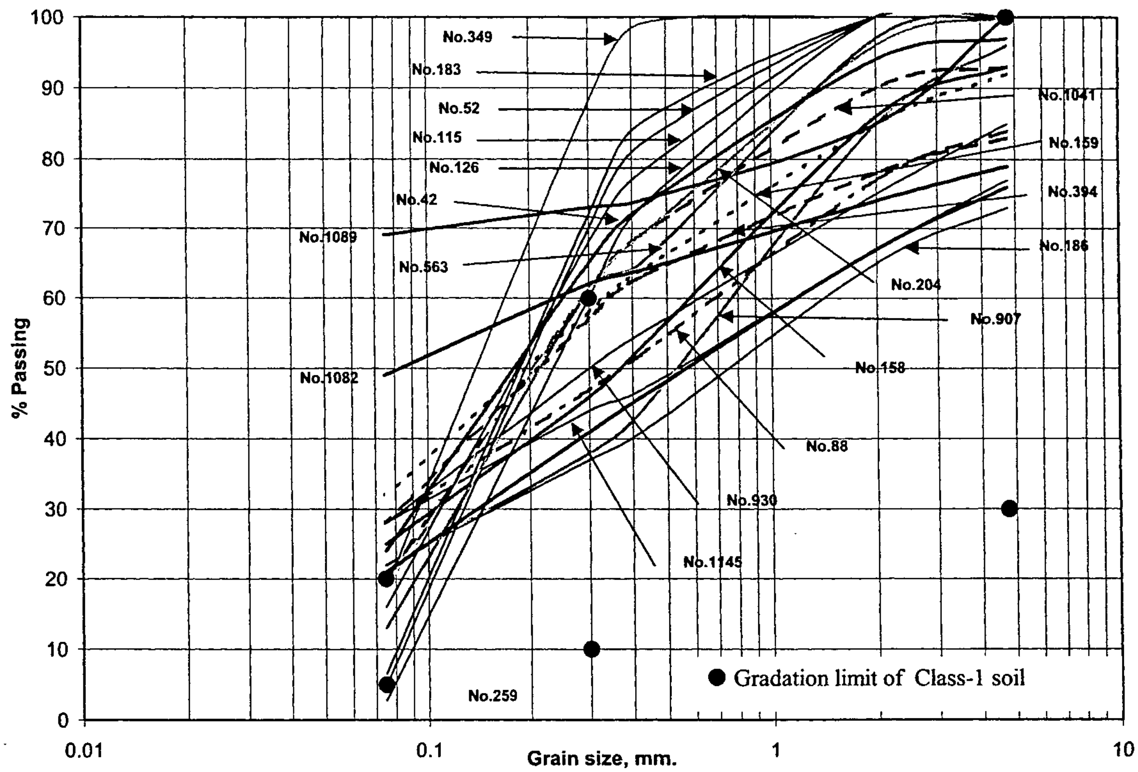


Figure 3.7 Gradation curves of the 20 non-Class-1 soils with $35^{\circ} > \phi \geq 31^{\circ}$

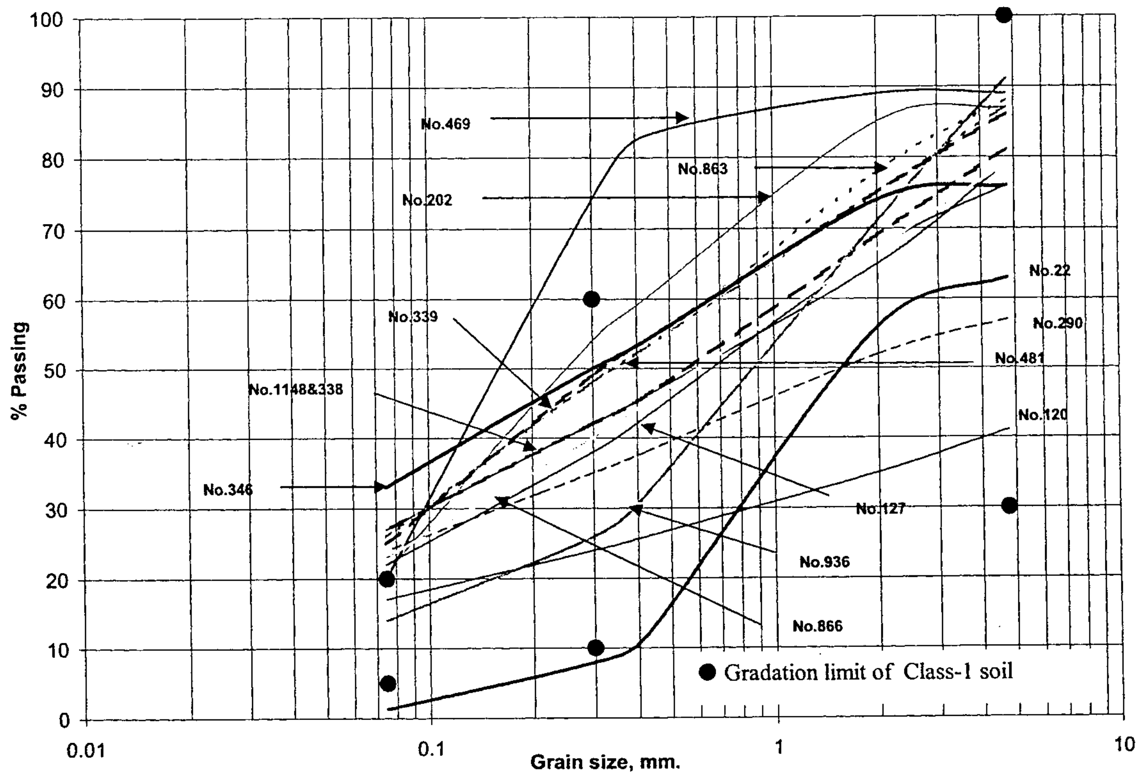


Figure 3.8 Gradation curves of the 14 non-Class-1 soils with $39^{\circ} > \phi \geq 35^{\circ}$

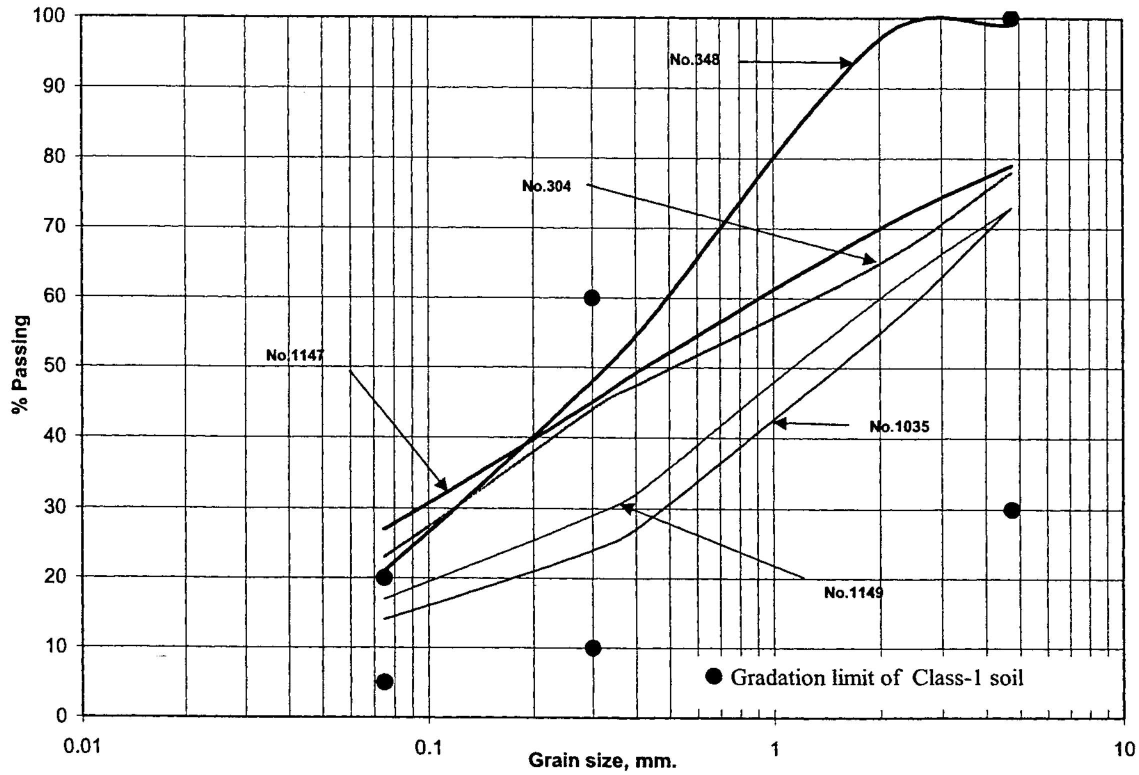


Figure 3.9 Gradation curves of the 5 non-Class-1 soils with $43^{\circ} > \phi \geq 39^{\circ}$

4. Correlation between Internal Friction Angle and Some Soil Index Parameters

In Chapter 3, it was concluded that all the Class-1 soils indeed have an internal friction angle greater than 34°, with some soils having an internal friction angle as high as 43°. The next question, then, is "Can improved criteria be established to determine the internal friction angle of soils suited for construction of retaining walls? ". To address this question, a study was undertaken to examine the correlations between the internal friction angles of soils with a number of soil parameters, including percent passing sieves No. 4, No. 10, No. 40, No. 50, No. 200, liquid limit, plastic index, maximum dry density and optimum moisture content. The study began with an examination of correlations with each soil parameter alone, and followed with correlations with multiple soil parameters. The latter correlations were examined by statistical analysis.

4.1 Correlations between Internal Friction Angle and Single Soil Parameter of Class-1 Soils

4.1.1 Direct Correlation with Gradation

The internal friction angle was plotted against the percentage of soil passing the U.S. Standard Sieve No. 10, No. 40, No. 50, and No. 200, as shown in Figures 4.1 through 4.4. It is seen that no correlation can be established between the internal

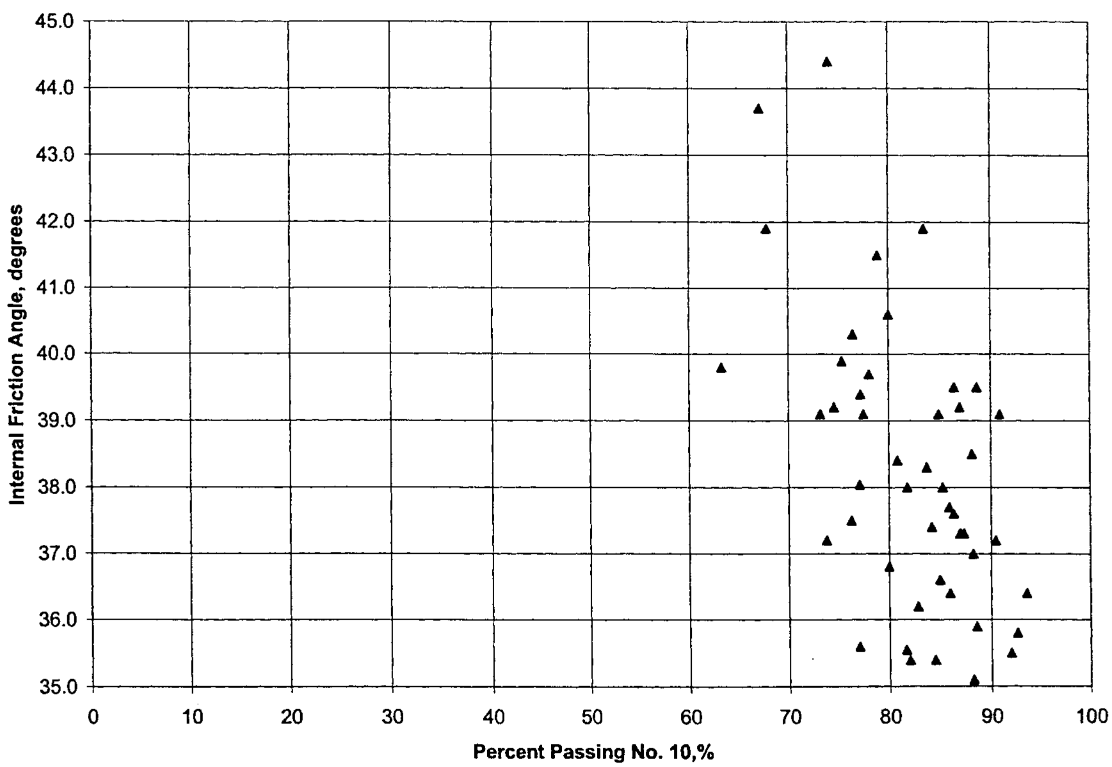


Figure 4.1 Relationship between internal friction angle and percent passing sieve No. 10

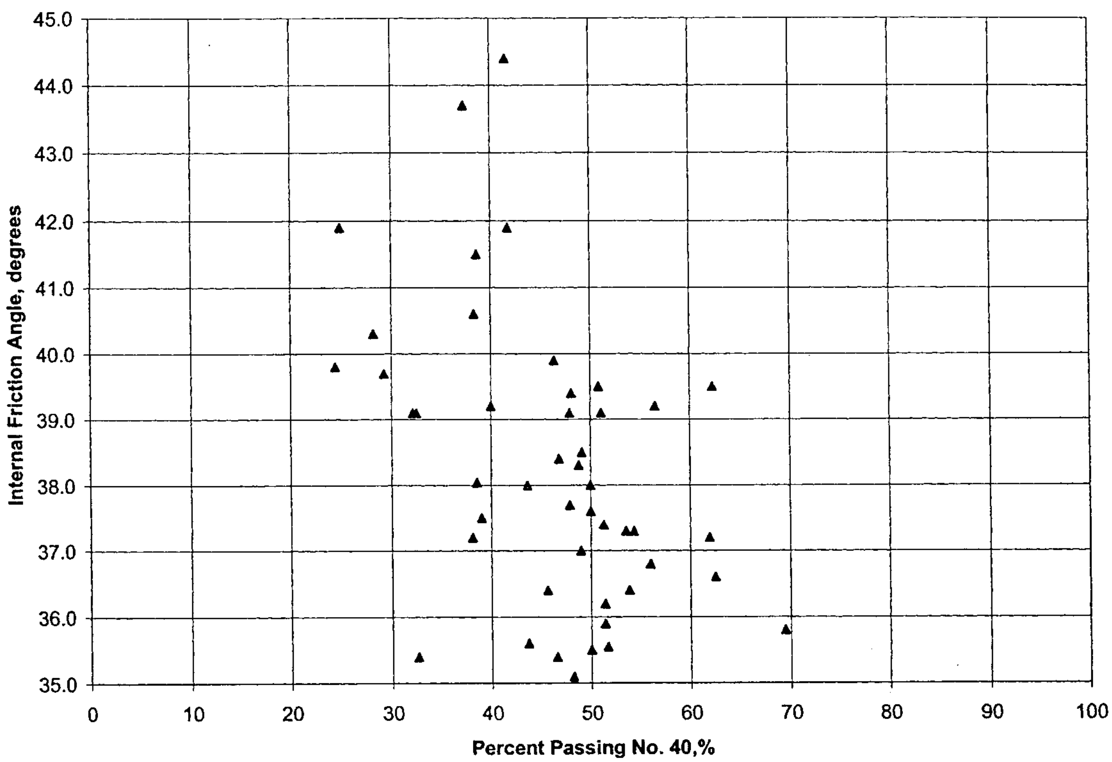


Figure 4.2 Relationship between internal friction angle and percent passing sieve No. 40

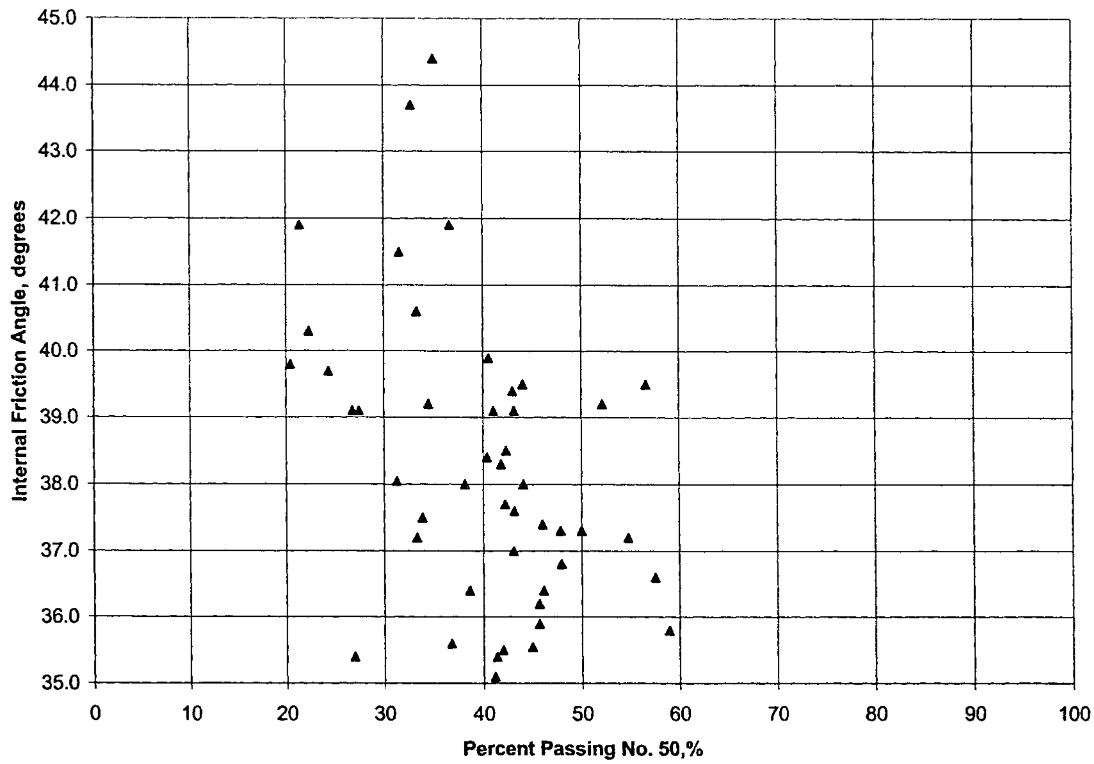


Figure 4.3 Relationship between internal friction angle and percent passing sieve No. 50

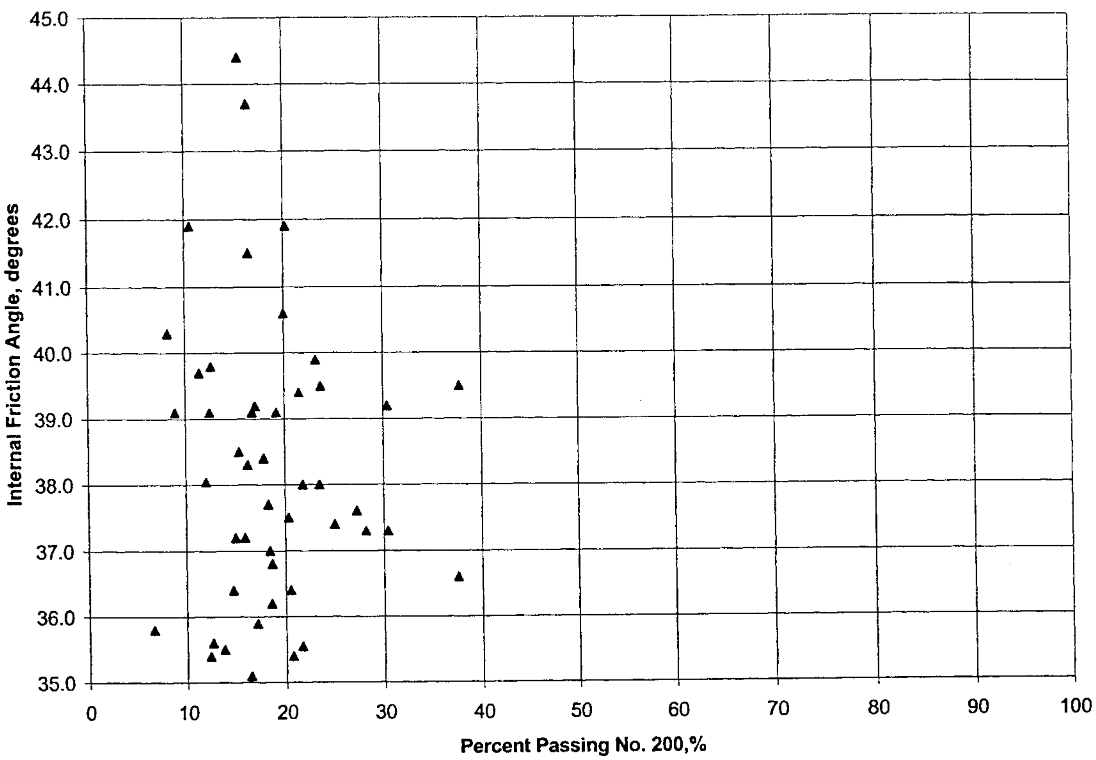


Figure 4.4 Relationship between internal friction angle and percent passing sieve No. 200

friction angle and any single percent passing numbers. Note that the percent passing presented herein are referred to the portion of soil passing No. 4 sieve.

4.1.2 Direct Correlation with Plasticity-related Parameters

Figure 4.5 shows the relationships between internal friction angle of the soils and their respective liquid limits and plasticity indices. As may be expected, no correlation can be established.

4.1.3 Direct Correlation with Compaction-related Parameters

Figure 4.6 shows the correlation between the internal friction angle and the maximum dry unit weight. The term, "maximum dry unit weight" was referred to 95% of T99 maximum dry unit weight or 90% of T180 maximum dry unit weight, whichever is applicable. It is seen that there is no correlation between them. Figure 4.7 shows the correlation between the internal friction angle and the optimum moisture content. Again, no correlation can be established with the optimum moisture content.

4.2 Correlation between Internal Friction Angle and Multiple Soil Parameters of Class-1 Soils----Regression Analysis

A statistical analysis was performed to examine the correlations between internal friction angle and multiple soil parameters.

4.2.1 Regression Analysis

(a) Central Tendency and Dispersion

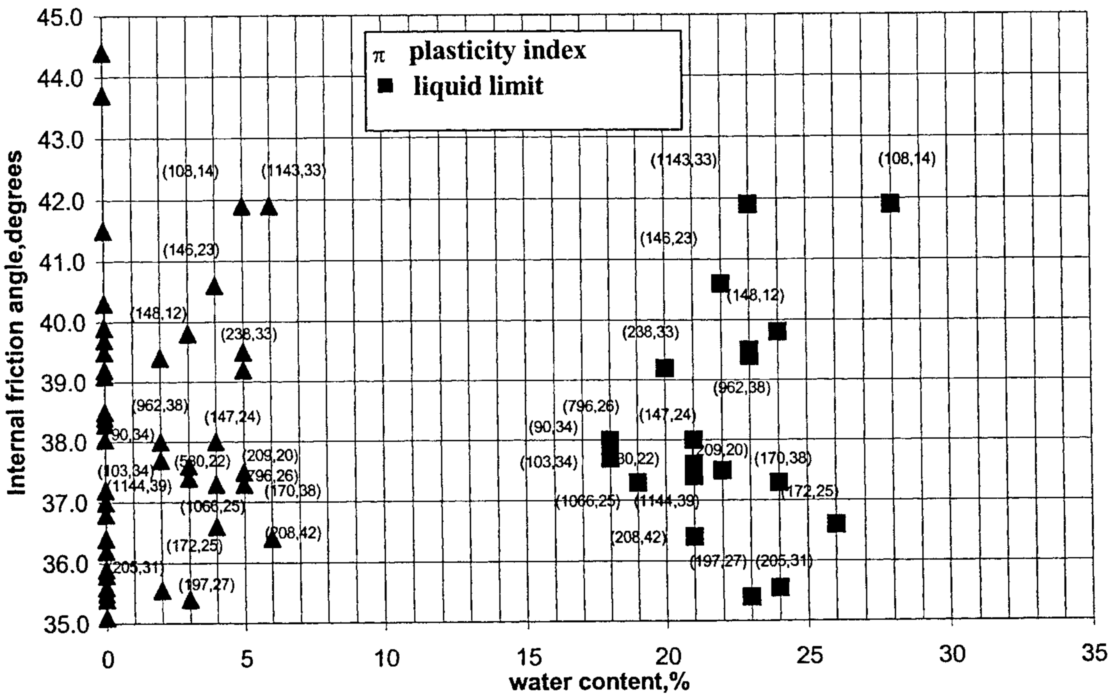


Figure 4.5 Relationship between internal friction angle and liquid limit and plasticity index

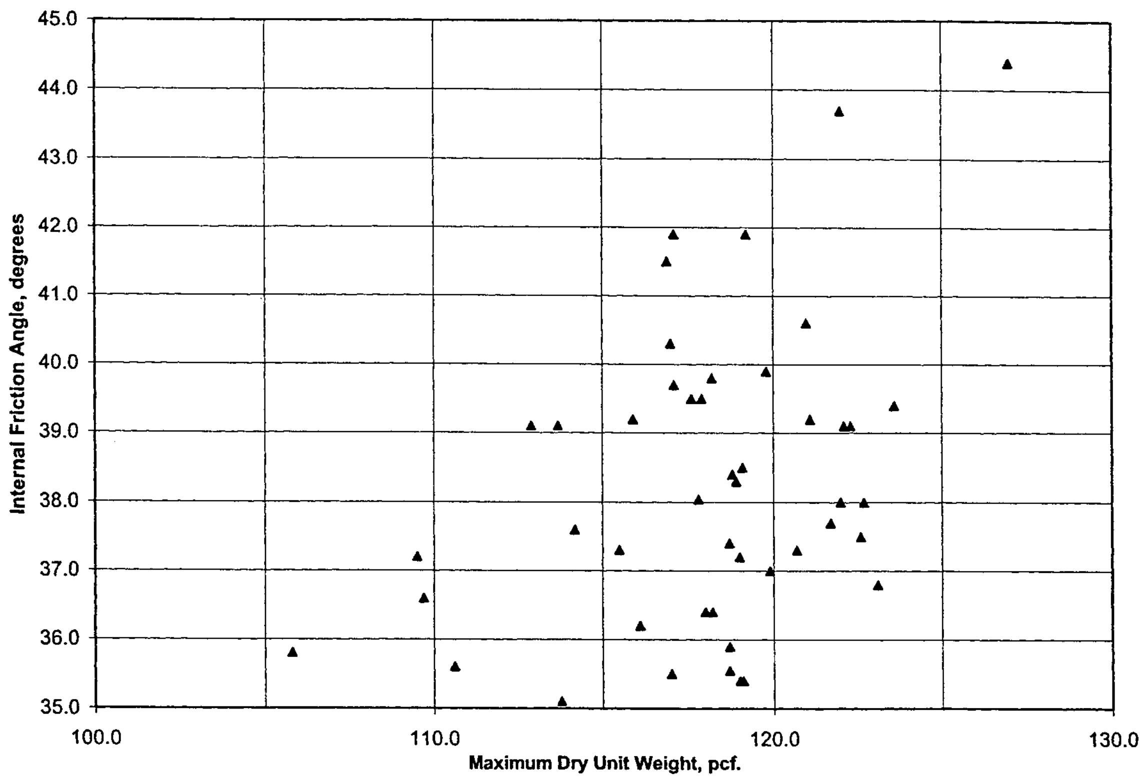


Figure 4.6 Relationship between internal friction angle and maximum dry unit weight

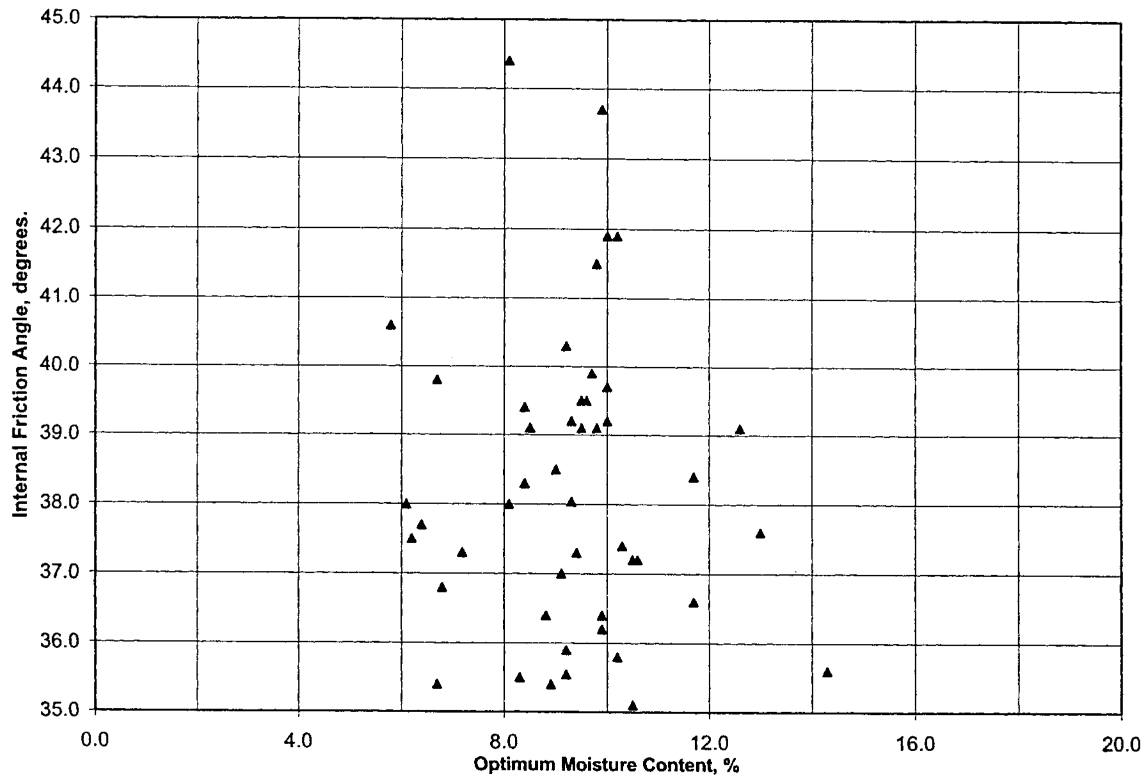


Figure 4.7 Relationship between internal friction angle and optimum moisture content

There are three parameters commonly used to denote the central tendency of data: arithmetic mean, standard deviation, and coefficient of variation. The arithmetic mean is the most commonly used measure of central tendency. Summing all the values in the sample and then dividing the total by the number of observations in the sample yields the arithmetic mean. Thus, for a set of n values $x_1, x_2 \ldots x_n$, the sample mean is calculated by the following equations (Spiegel, 1961):

$$\bar{x} = \frac{x_1 + x_2 + \ldots\ldots x_n}{N} \qquad \text{eq. 4.1}$$

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{N} \qquad \text{eq. 4.2}$$

where, $\bar{x}$ = sample arithmetic mean

$x_1, x_2, \ldots, x_n$ = sample values

N = sample size

The standard deviation, S, is calculated by the following equation:

$$S = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{N}} \qquad \text{eq. 4.3}$$

The coefficient of variation, V, is a useful parameter to express the degree of variation of the data:

$$C_v = (s / \overline{X}) * 100 \ \% \qquad \text{eq. 4.4}$$

(b) Correlation and Regression

Regression analysis was generally used for the purpose of prediction. There are many equations that can be used to predict values of a single variable, y, from given values of another variable, x. The simplest and most widely used equation is the linear equation:

$$y = a_o + a_1x_1 + a_2x_2 + a_3x_3 + \ldots.. \qquad \text{eq. 4.5}$$

where 'a_o' is the y-intercept (the value of 'y' for x = 0) and '$a_1 \ldots a_n$' are the coefficients. When the sample data are plotted on a x-y plot, a 'best fit' line is drawn through all the data points. The criterion used most commonly for defining a 'best fit' is the method of least squares. This method requires that a line fitted to the data be such that the sum of the squares of the vertical deviations of the points from the line is a minimum.

Linear regression analysis between internal friction angle and multiple parameters was performed on the data obtained from the tests. The best fit equations for the Class-1 soils and soils with PI $\leq$ 6 and LL $\leq$ 35 are:

Class-1 soils:

$$\phi \text{ (in degrees)} = -12.3 - 0.12*LL + 0.65*PI + 0.19*\gamma_d \text{(in pcf)} + 0.12*OMC \text{ (in \%)} + 0.36*No.\,4 \text{ (in \%)} - 0.20*No.10 \text{ (in \%)} + 0.19*No.40 \text{ (in \%)} - 0.17*No.50 \text{ (in \%)} + 0.12*No.200 \text{ (in \%)} + 0.91*D_{23} + 0.25*D_{2075}$$

Soils with PI $\leq$ 6 and LL $\leq$ 35:

$$\phi \text{ (in degrees)} = -3.34 - 0.02*LL + 0.23*PI + 0.29*\gamma_d \text{(in pcf)} + 0.15*OMC \text{ (in \%)} + 0.14*No.4 \text{ (in \%)} - 0.08*No.10 \text{ (in \%)} + 0.23*No.40 \text{ (in \%)} - 0.31*No.50 \text{(in \%)} - 0.19*D_{23} + 0.01*D_{2075}$$

The R^2 values are on the order of 0.45 and 0.60 for 47 Class-1 soils and the 75 soils with PI $\leq$ 6 and LL $\leq$ 35, respectively. The R^2 values indicate that linear regression between ϕ and the soil parameters was unacceptable.

Even though non-linear regression could be used to fit the data, the results could not be accepted with any reliability due to insufficient data.

4.3 Correlation between Internal Friction Angle and Multiple Soil Parameter of Class-1 Soil----Tree-based Model

A tree-based model was used to correlate the internal friction angle of the Class-1 soils with multiple soil parameters. A tree-based model provides an alternative to linear and additive models for regression problems and to linear and additive logistic models for classification problems. Tree models are developed by successively splitting the data to form homogeneous subsets. The result is a hierarchical tree of decision rules useful for prediction or classification.

A statistical computer program "S-PLUS 4.5" (Release 2, by Brook/Cole Publishing) was used to perform a tree-model analysis. The model determines "Splits" that group similar values of internal friction angle through branches of a decision tree.

While it is desirable to characterize the shape of a soil gradation curve, it is not feasible to use the parameters commonly used in geotechnical engineering, such as the coefficient of uniformity and coefficient of curvature. This is because the information on the effective grain size, D_{10}, is missing from the data bank (as evidenced by Figures 4.2 and 4.3). Consequently, two new parameters were defined to better characterize the shape of a soil gradation curve. One parameter is referred is as D_{23}, which is the ratio between the percent of soil smaller than 2.0 mm to that smaller than 0.3 mm. The other parameter is referred to as D_{2075}, which is the ratio between the percent of soil smaller than 2.0 mm to that smaller than 0.075 mm.

The soil parameters included in the tree-based model analysis were liquid limit, plastic index, dry unit weight, optimum water content, percent passing sieves No. 4, No. 10, No. 40, No. 50, and No. 200, D_{23} and D_{2075}. Again, the term "dry unit weight" corresponds to 95% of T99 maximum dry unit weight or 90% of T180 maximum dry unit weight, whichever is applicable. Note that the percent passing for each sieve was determined with percent passing sieve No. 4 as the reference. Since the objective was to evaluate strength parameters of soils for retaining walls, only the data with LL $\leq$ 35 or PI $\leq$ 6 were analyzed. As a result, 25 out of the 100 soils were excluded. Soils with LL > 35 or PI > 6 are likely to experience significant time dependent movement when wet and will not be "free-drainage".

The decision tree of the analysis is shown in Figure 4.8. There are a total of 11 tree branches. The decision parameters involved include maximum dry unit weight, percent passing sieves No. 10, No. 40, No. 50 and No. 200, D_{23} and D_{2075}. The coefficient of variation of each branch is shown at the end of each branch. The coefficients of variation are typically less than 6%. The branch with the mean internal friction angle of 30 degrees was an unusually high variation (coefficient of variation = 11.4%).

A tree-based model analysis was also performed on the 47 Class-1 soils. The resulting decision tree is shown in Figure 4.9. There are eight tree branches for the Class-1 soils. The parameters involved include maximum dry unit weight, percent passing sieves No. 10, No. 40 and No. 200, D_{23} and D_{2075}. The coefficient of variation is somewhat smaller than those soils with LL $\leq$ 35 and PI $\leq$ 6. The largest coefficient of variation is 5.9% and is associated with a branch with mean internal friction angle of 38.8 degrees.

It should be noted that these decision trees should only be considered preliminary as more data are needed to established reliable rules for determination of the internal friction angle of backfills suited for construction of retaining walls.

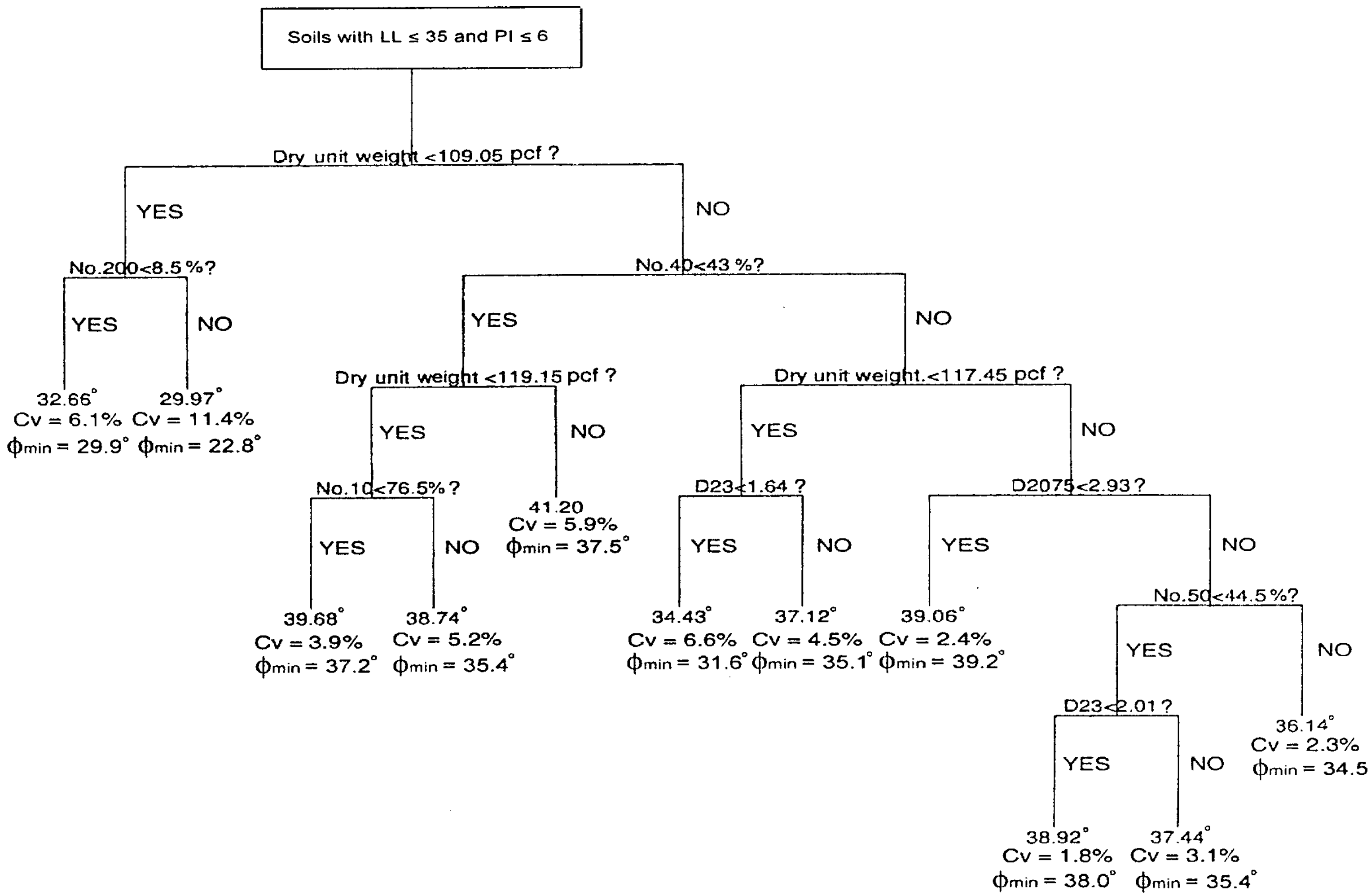


Figure 4.8 Decision Tree for Soils with LL $\leq$ 35 and PI $\leq$ 6

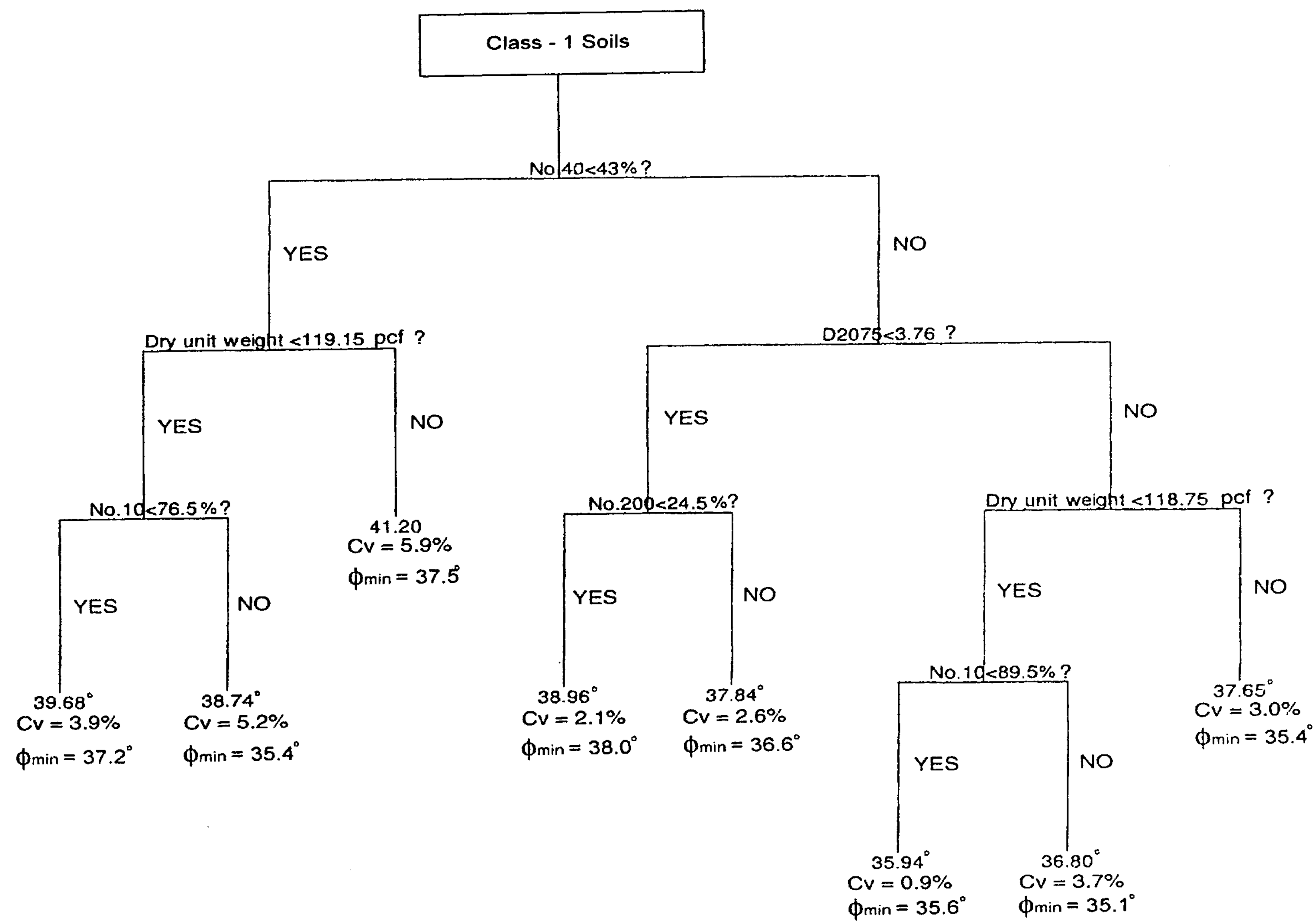


Figure 4.9 Decision Tree for Class-1 Soils

5. Findings and Conclusions

The findings and conclusions of this study can be summarized as follows:

1. Soil parameters for 100 different soils were compiled in this study. The soil parameters include gradation test results (percent of soil weight passing the U.S. standard sieves No. 4, No. 10, No. 40, No. 50 and No. 200), liquid limit, plasticity index, compaction test results (maximum dry unit weight and optimum water content), and internal friction angle. The maximum dry unit weights and optimum water contents were obtained from standard Proctor tests (AASHTO T99) or modified Proctor tests (AASHTO T180). The internal friction angles were obtained from direct shear tests performed on soil passing U.S. standard sieve No. 4. The test specimens for the direct shear tests were prepared at 2% wet of optimum water content and 95% of the maximum dry unit weight per T99 or 90% of the maximum dry unit weight per AASHTO T180.

2. To verify repeatability of the direct shear test, as conducted by the investigator, two repeated tests were performed on five soils, and four repeated tests were performed on four soils. The maximum difference

of the internal friction angle for the tests was 2 degrees. A "probable variance" of ± 1 degree of the internal friction angle was thus assumed in the data analysis.

3. Forty-seven of the 100 soils were Class-1 structure backfill. The internal friction angles of all 47 soils were larger than 35 degrees. Based on the value of internal friction angle, three groups of Class-1 soil were identified: 28 soils were in Group 1 (with $39^o > \phi \geq 35^o$), 17 soils were in Group 2 (with $43^o > \phi \geq 39^o$), and 2 soils were in Group 3 (with $\phi \geq 43^o$). Considering the $\pm$ 1^o probable variance, the current practice of assigning $\phi = 34^o$ is an excellent conservative measure for selecting the internal friction angle without performing any shear tests.

4. The gradation curves of the three groups of Class-1 soils had similar lower limits. The upper limit line of Group 1 soils was very close to the upper limit line for Class-1 soils. The upper limit line for Group 2 soils was closer to the lower limit line (thus with a narrower range of gradation than Group 1 soils). The upper limit line for Group 3 soils was even closer to the lower limit line. The gradation limit lines for all three groups of Class-1 soils are shown in Figure 3.5.

5. Of the 100 soils, 53 were non-Class-1 soils. The non-Class-1 soils with $\phi < 35^o$ typically had a large percentage of fines (percent passing the

No. 200 sieve). Nineteen (19) of the 53 non-Class-1 soils had $\phi \geq 35^{\circ}$. Many of these soils had fines contents between 20% and 30%. The soils with fines content less than 20% typically had PI > 6.

6. Correlation between the internal friction angles and each of the soil parameters listed in 1. (above) were examined by way of plotting the friction angle versus the soil parameter and by linear regression. No correlation was found between the internal friction angle and any single soil parameter.

7. Correlation between the internal friction angles and all the soil parameters was analyzed by linear regression for both the Class-1 soils and the soils with LL $\leq$ 35 and PI $\leq$ 6; the correlation was unacceptable for both groups of soils.

8. Correlation between the internal friction angle and multiple soil parameters was also examined by analyzing the data with statistical decision trees. Both the Class-1 soils and the soils with LL $\leq$ 35 and PI $\leq$ 6 were analyzed. The analysis of the Class-1 soils (47 soils) resulted in 6 tree branches. The coefficients of variation for the 6 branches ranged from 0.9% to 5.2%. The analysis of the soils with LL $\leq$ 35 and PI $\leq$ 6 (75 soils) resulted in 11 tree branches, with the coefficients of variation ranging from 1.8% to 11.4%. The decision tree for the Class-1 soils has generally smaller coefficients of

variation. Using the proper decision tree and soil parameters such as dry unit weight, gradation, D_{23} and D_{2075}, the friction angle of a soil may be determined with reasonable accuracy. The decision trees, however, should only be regarded as preliminary in nature because the data base was fairly small.

APPENDIX A

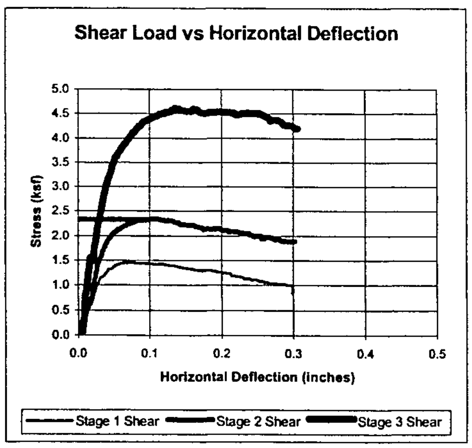
DIRECT SHEAR TEST RESULTS

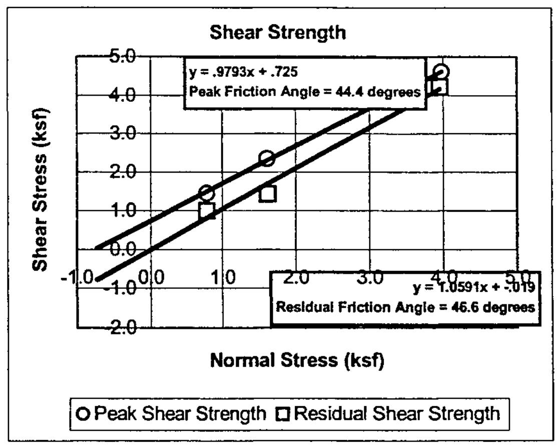
(14 specimens as shown in Table 3.2)

Observation No.	1			:		
Lab Test No. :	**2000-231**		Compaction Method	:	T-99	
Classification :	A-1-b(0)		Max. Dry Dens.	:	131.1	pcf.
Liquid Limit :	NV		Optimum Moisture	:	9.7%	
Plastic Limit :	NP		Peak friction angle	:	44.4	degrees
Plastic Index :	NP		Residual friction angle	:	46.6	degrees
Rate :	*****			:		

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.78	1.61	3.96
Compacted Dry Density (pcf)	127.1	126.8	127.1
Moisture Content	8.0%	8.3%	8.0%
Percent of Maximum Dry Density	96.9%	96.7%	96.9%



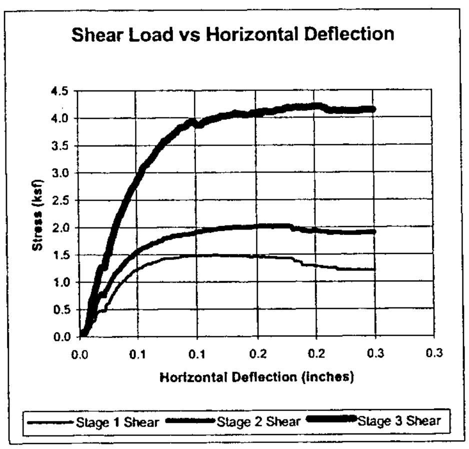


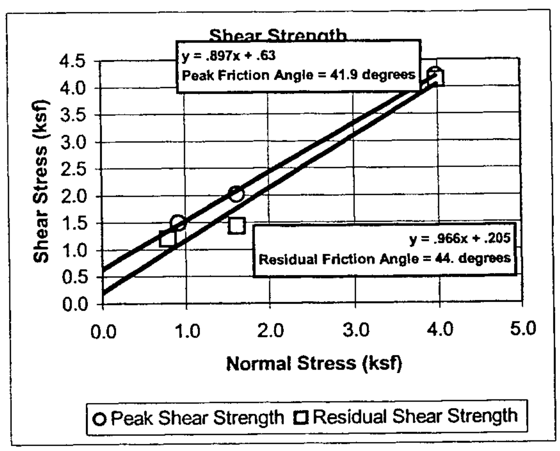
Observation No. **3**

Lab Test No. :	**2000-108**	Compaction Method	:	T-99	
Classification :	A-1-a(0)	Max. Dry Dens. (pcf)	:	121.3	
Liquid Limit :	28	Optimum Moisture	:	11.2%	
Plastic Limit :	23	Peak friction angle	:	41.9	degree
Plastic Index :	5	Residual friction angle	:	44	degree
Rate :	*****				

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.85	1.61	3.98
Compacted Dry Density (pcf)	117.2	117.0	117.0
Moisture Content	9.8%	10.0%	10.1%
Percent of Maximum Dry Density	96.6%	96.5%	96.4%



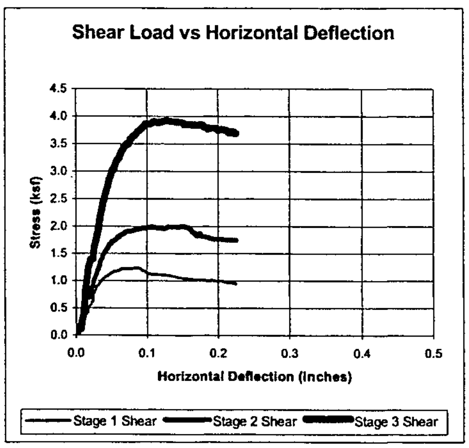


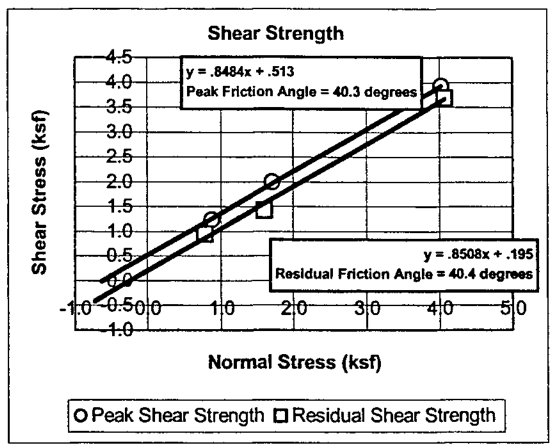
Observation No. **7**

Lab Test No. :	**2000-74**	Compaction Method	:	T-99		
Classification :	A-1-b(0)	Max. Dry Dens. (pcf)	:	121.6		
Liquid Limit :	NV	Optimum Moisture	:	10.2%		
Plastic Limit :	NP	Peak friction angle	:	40.3	degree	
Plastic Index :	NP	Residual friction angle	:	40.4	degree	
Rate :	*****					

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.83	1.66	4.05
Compacted Dry Density (pcf)	116.9	117.0	117.1
Moisture Content	9.4%	9.3%	9.2%
Percent of Maximum Dry Density	96.2%	96.2%	96.3%



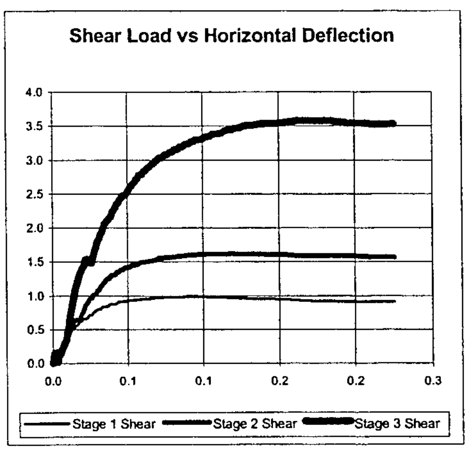


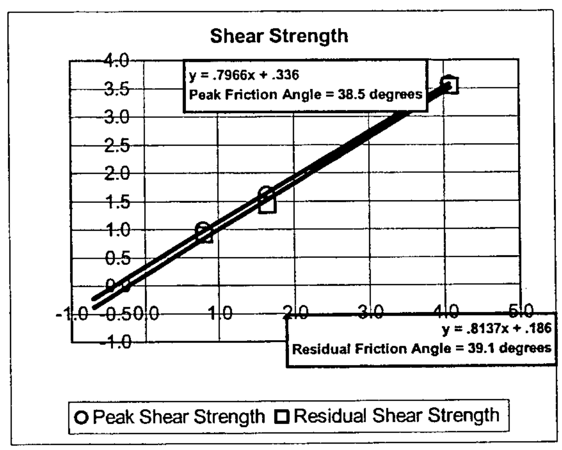
Observation No. **20**

Lab Test No. :	**2000-100**	Compaction Method	:	T-99	
Classification :	A-1-b(0)	Max. Dry Dens. (pcf)	:	124.4	
Liquid Limit :	NV	Optimum Moisture	:	9.3%	
Plastic Limit :	NP	Peak friction angle	:	38.5	degree
Plastic Index :	NP	Residual friction angle	:	39.1	degree
Rate :	*****				

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.80	1.64	4.08
Compacted Dry Density (pcf)	119.0	119.1	119.2
Moisture Content	9.0%	9.0%	8.9%
Percent of Maximum Dry Density	95.7%	95.7%	95.8%



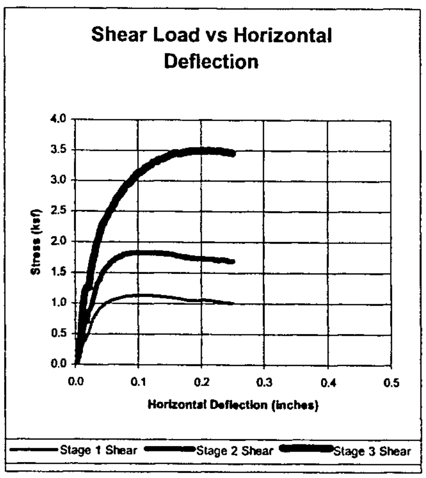


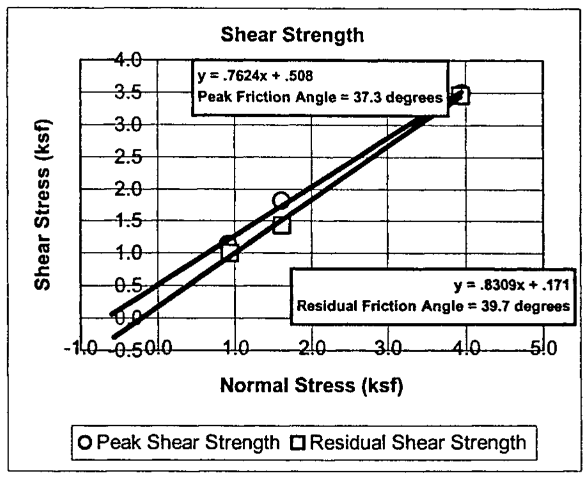
Observation No. **23**

Lab Test No. :	**2000-123**	Compaction Method	:	T-99	
Classification :	A-2-4(0)	Max. Dry Dens. (pcf)	:	122.6	
Liquid Limit :	NV	Optimum Moisture	:	9.9%	
Plastic Limit :	NP	Peak friction angle	:	37.3	degree
Plastic Index :	NP	Residual friction angle	:	39.7	degree
Rate :	*****				

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.92	1.62	3.95
Compacted Dry Density (pcf	117.8	117.7	117.9
Moisture Content	9.2%	9.3%	9.1%
Percent of Maximum Dry De	96.1%	96.0%	96.2%





Observation No. **32**

Lab Test No. : **2000-21**

Classification : A-1-a(0)

Liquid Limit : NV

Plastic Limit : NP

Plastic Index : NP

Rate : *****

Compaction Method : T-99

Max. Dry Dens. (pcf) : 114

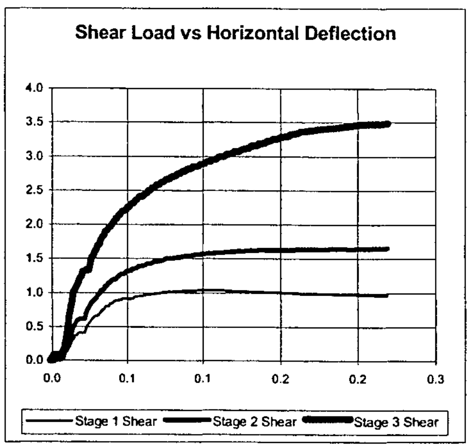
Optimum Moisture : 11.3%

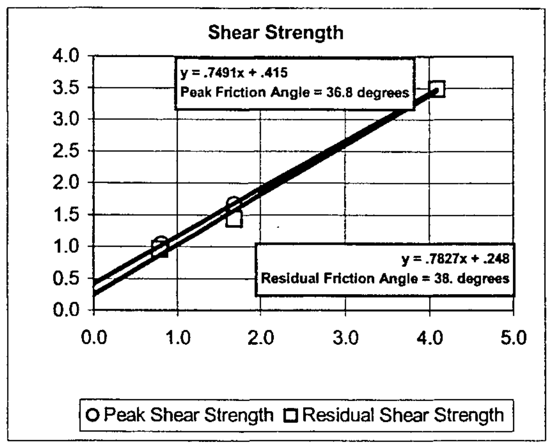
Peak friction angle : 36.8 degree

Residual friction angle : 38.0 degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.80	1.69	4.09
Compacted Dry Density (pcf)	109.2	109.3	110.0
Moisture Content	10.9%	10.8%	10.1%
Percent of Maximum Dry Density	95.8%	95.9%	96.5%





Observation No. **34**

Lab Test No. : **2000-122**

Classification : A-1-a(0)

Liquid Limit : NV

Plastic Limit : NP

Plastic Index : NP

Rate :

Compaction Method : T-99

Max. Dry Dens. (pcf) : 125

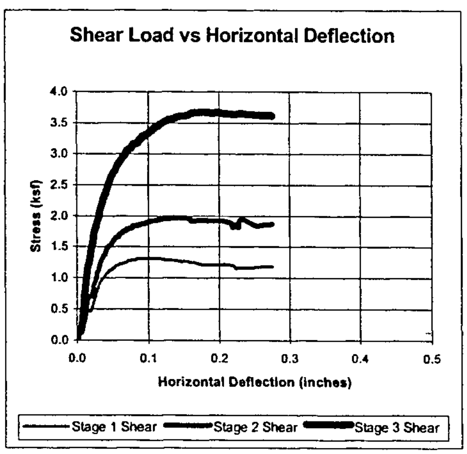
Optimum Moisture : 9.7%

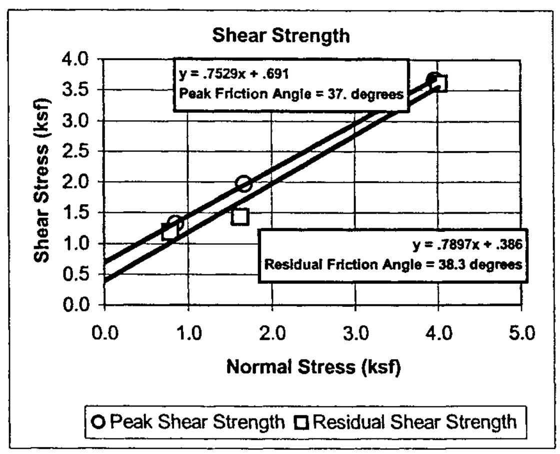
Peak friction angle : 37.0 degree

Residual friction angle : 38.3 degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.82	1.65	3.99
Compacted Dry Density (pcf)	120.0	119.7	120.0
Moisture Content	9.0%	9.3%	9.1%
Percent of Maximum Dry Density	96.0%	95.8%	96.0%



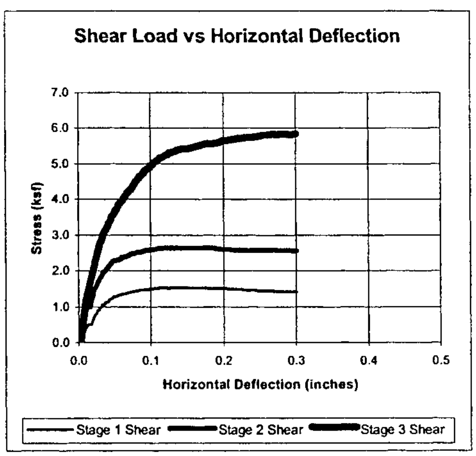


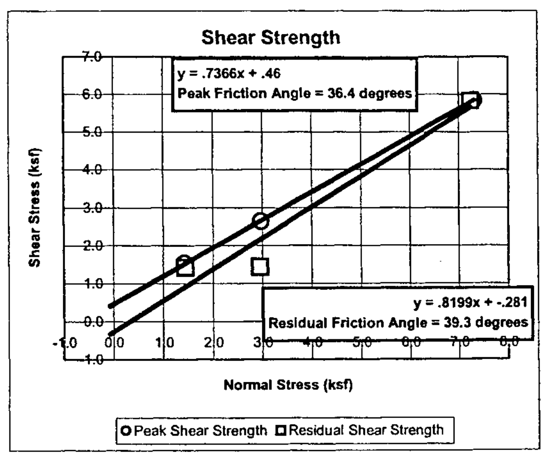
Observation No. **37**
Lab Test No. : **2000-208**
Classification A-1-b(0)
Liquid Limit : 21
Plastic Limit : 15
Plastic Index : 6
Rate : *****

Compaction Method : T-99
Max. Dry Dens. (pcf) : 123
Optimum Moisture : 10.6%
Peak friction angle : 36.4 degree
Residual friction angle : 39.3 degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	1.43	2.96	7.27
Compacted Dry Density (pcf)	107.4	107.4	107.7
Moisture Content	9.1%	9.1%	8.8%
Percent of Maximum Dry Density	87.3%	87.3%	87.6%



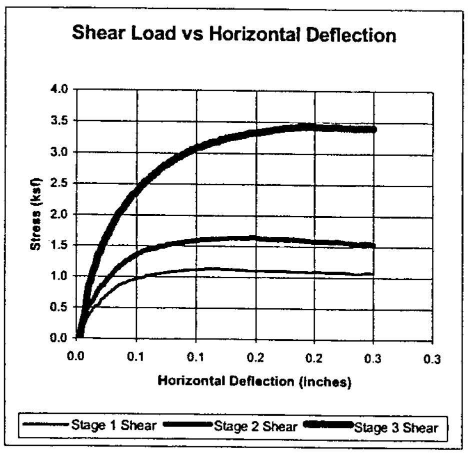


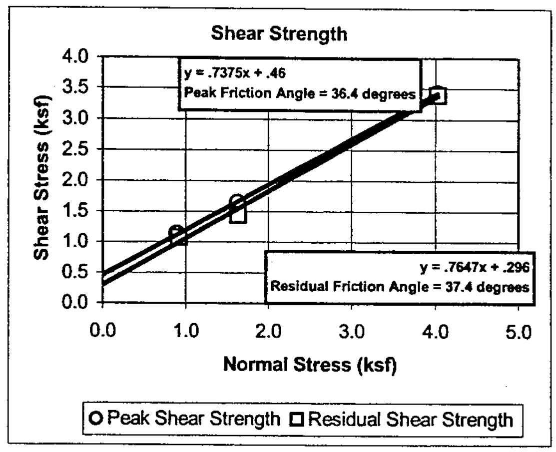
Observation No. **38**

Lab Test No. :	**2000-101**	Compaction Method	:	T-99	
Classification :	A-1-a(0)	Max. Dry Dens. (pcf)	:	122.9	
Liquid Limit :	NV	Optimum Moisture	:	9.4%	
Plastic Limit :	NP	Peak friction angle	:	36.4	degree
Plastic Index :	NP	Residual friction angle :		37.4	degree
Rate :	*****				

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.91	1.63	4.03
Compacted Dry Density (pcf)	118.1	117.8	118.0
Moisture Content	8.7%	9.0%	8.7%
Percent of Maximum Dry Density	96.1%	95.8%	96.0%

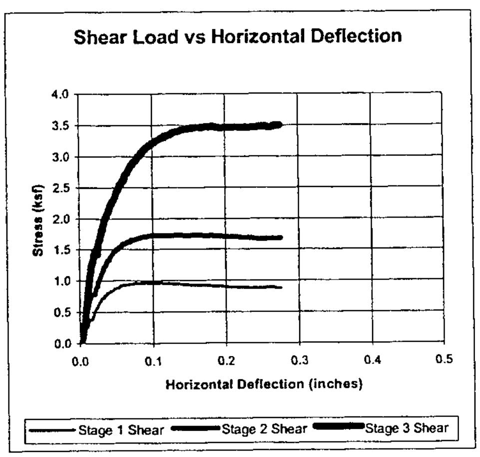


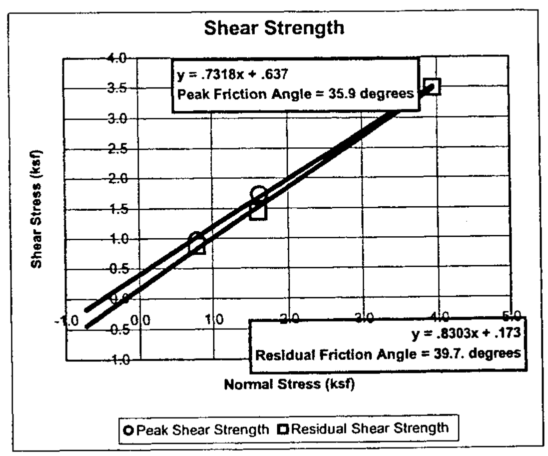


Observation No.	**40**		
Lab Test No.	: **1999-1031**	Compaction Method	: T-99
Classification	A-1-b(0)	Max. Dry Dens. (pcf)	: 124.3
Liquid Limit	: NV	Optimum Moisture	: 9.8%
Plastic Limit	: NP	Peak friction angle	: 35.9 degree
Plastic Index	: NP	Residual friction angle	: 39.7 degree
Rate	: ****		

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.78	1.62	3.95
Compacted Dry Density (pcf)	118.6	118.5	118.8
Moisture Content	9.1%	9.0%	8.8%
Percent of Maximum Dry Density	95.4%	95.3%	95.6%



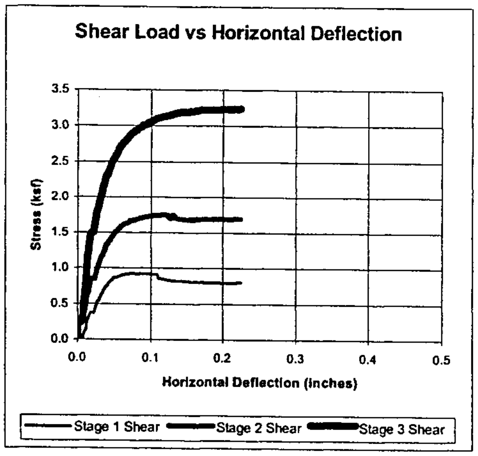


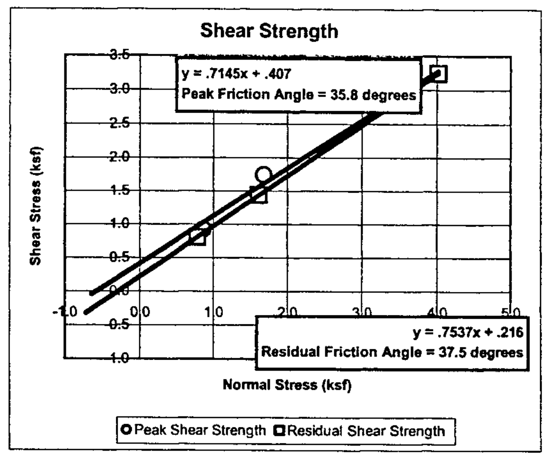
Observation No. **41**

Lab Test No.	: **2000-73**	Compaction Method	: T-99
Classification	A-3(0)	Max. Dry Dens. (pcf)	: 114
Liquid Limit	: NV	Optimum Moisture	: 10.9%
Plastic Limit	: NP	Peak friction angle	: 35.8 degree
Plastic Index	: NP	Residual friction angle	: 37.5 degree
Rate	: ***		

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.83	1.65	4.02
Compacted Dry Density (pcf)	106.0	105.6	105.8
Moisture Content	10.5%	9.9%	10.1%
Percent of Maximum Dry Density	93.0%	92.6%	92.8%



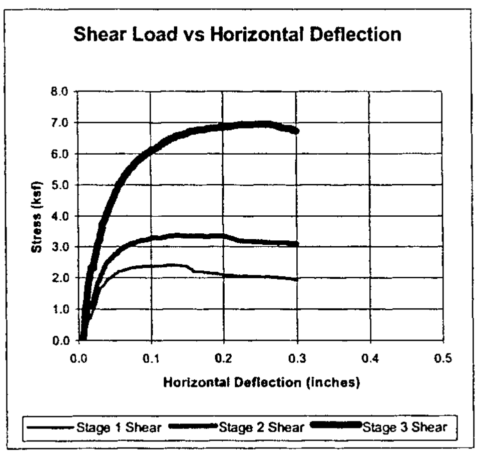


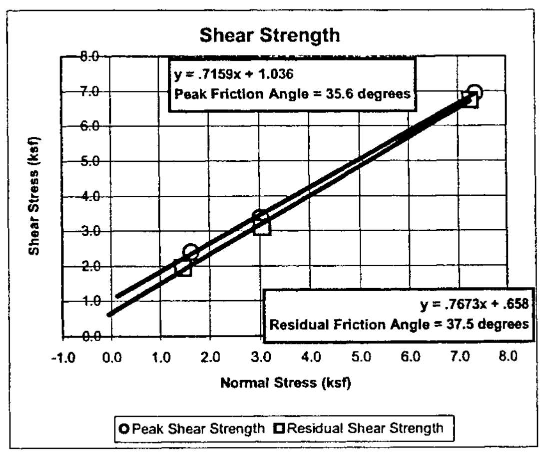
Observation No. **43**

Lab Test No.	: **2000-205**	Compaction Method	: T-99
Classification	: A-1-b(0)	Max. Dry Dens. (pcf)	: 122.1
Liquid Limit	: 24	Optimum Moisture	: 11.4%
Plastic Limit	: 22	Peak friction angle	: 35.6 degree
Plastic Index	: 2	Residual friction angle	: 37.5 degree
Rate	: ****		

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	1.55	3.04	7.30
Compacted Dry Density (pcf)	118.7	118.8	118.9
Moisture Content	8.9%	9.1%	9.0%
Percent of Maximum Dry Density	97.2%	97.3%	97.4%



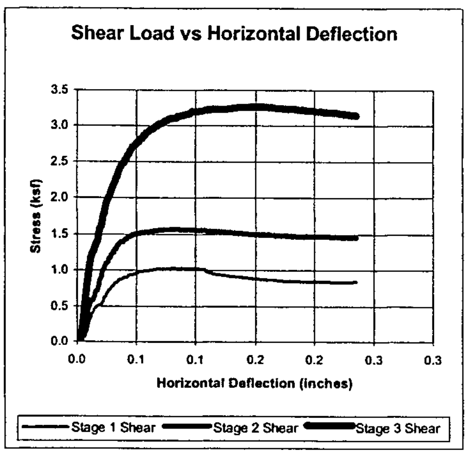


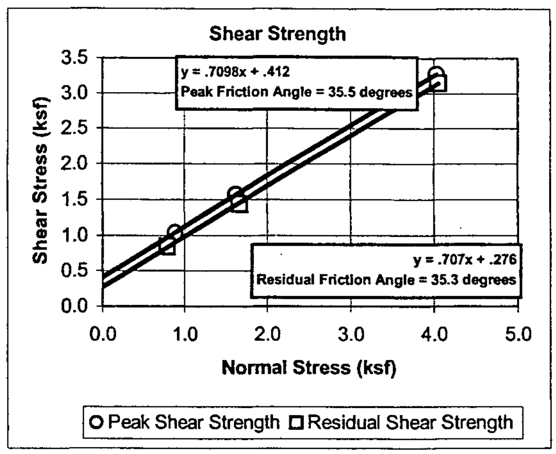
Observation No. **44**

Lab Test No. :	**2000-99**	Compaction Method	:	T-99	
Classification :	A-1-a(0)	Max. Dry Dens. (pcf)	:	122	
Liquid Limit :	NV	Optimum Moisture	:	8.9%	
Plastic Limit :	NP	Peak friction angle	:	35.5	degree
Plastic Index :	NP	Residual friction angle	:	35.3	degree
Rate :	*****				

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.83	1.65	4.04
Compacted Dry Density (pcf)	117.2	116.9	117.0
Moisture Content	8.2%	8.4%	8.4%
Percent of Maximum Dry Density	96.1%	95.9%	95.9%



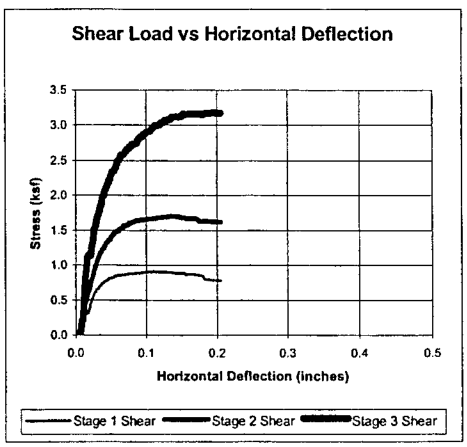


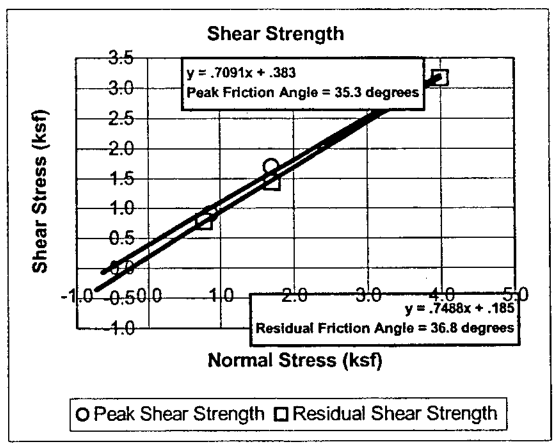
Observation No. **46**

Lab Test No. :	**1999-1042**	Compaction Method	:	T-99	
Classification :	A-1-b(0)	Max. Dry Dens. (pcf)	:	123.5	
Liquid Limit :	NV	Optimum Moisture	:	10.1%	
Plastic Limit :	NP	Peak friction angle	:	35.3	degree
Plastic Index :	NP	Residual friction angle	:	36.8	degree
Rate :	****				

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.82	1.70	3.99
Compacted Dry Density (pcf)	118.9	119.1	119.2
Moisture Content	9.1%	8.9%	8.9%
Percent of Maximum Dry Density	96.3%	96.5%	96.5%





DIRECT SHEAR TEST RESULTS

(28 specimens as shown in Table 3.3)

Observation No. **1**

Lab Test No. : **1999-1035**

Classification A-2-4(0)

Liquid Limit : 26

Plastic Limit : 18

Plastic Index : 8

Rate : ****

Compaction Method : T-99

Max. Dry Dens. (pcf) : 126

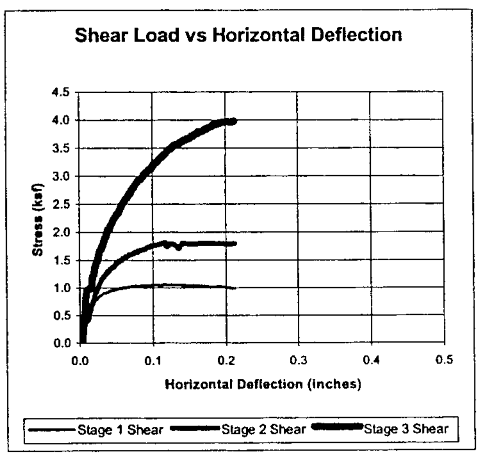
Optimum Moisture : 10.8%

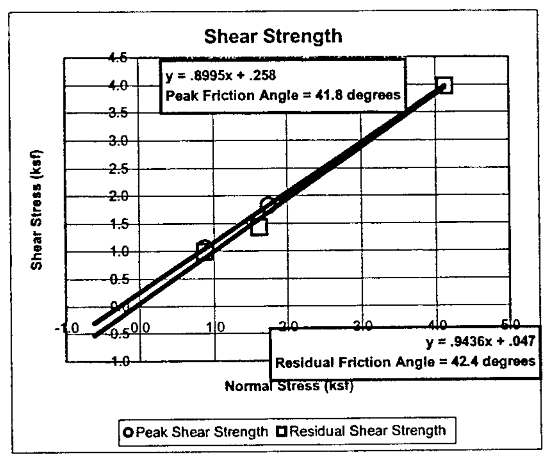
Peak friction angle : 41.8 degree

Residual friction angle : 42.4 degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.88	1.68	4.13
Compacted Dry Density (pcf)	122.1	122.2	122.1
Moisture Content	9.1%	9.0%	9.0%
Percent of Maximum Dry Density	96.9%	97.0%	96.9%



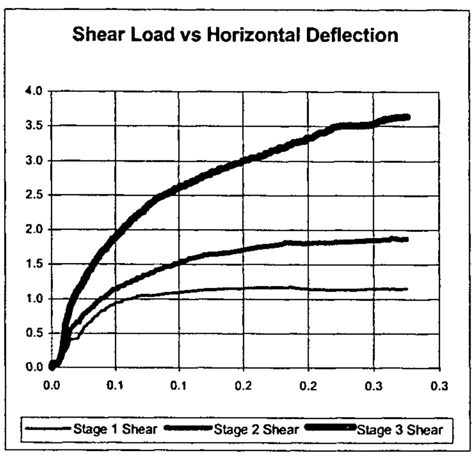


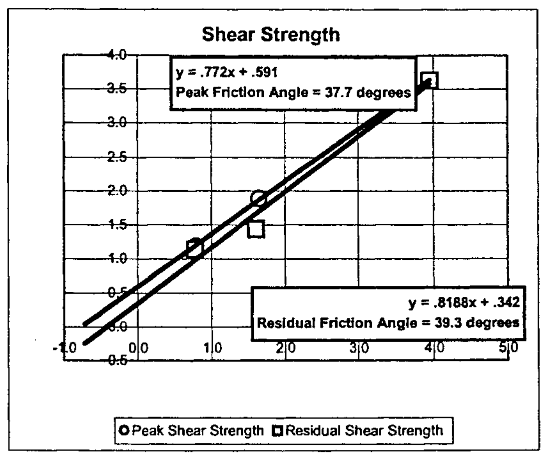
Observation No. **7**

Lab Test No.	: **2000-202**	Compaction Method	: T-99	
Classification	A-2-4(0)	Max. Dry Dens. (pcf)	: 118.9	
Liquid Limit	: 24	Optimum Moisture	: 11.6%	
Plastic Limit	: 19	Peak friction angle	: 37.7	degree
Plastic Index	: 5	Residual friction angle	: 39.3	degree
Rate	: *****			

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.79	1.63	3.95
Compacted Dry Density (pcf)	114.1	114.6	114.5
Moisture Content	11.0%	10.5%	10.6%
Percent of Maximum Dry Density	95.9%	96.4%	96.3%



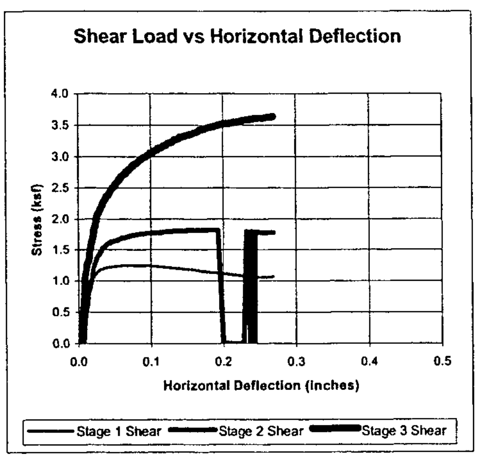


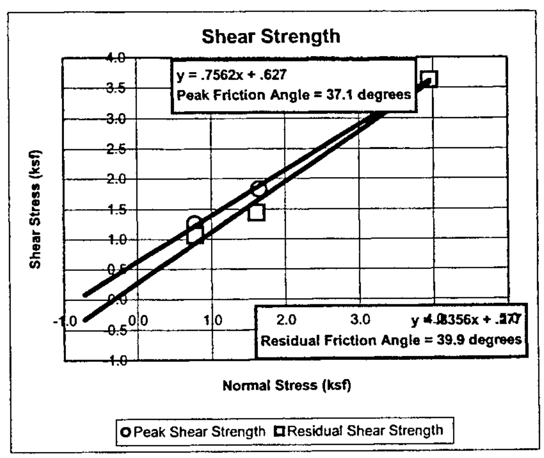
Observation No. **11**

Lab Test No.	: **1999-863**	Compaction Method	: T-99	
Classification	A-2-4(0)	Max. Dry Dens. (pcf)	: 127	
Liquid Limit	: 29	Optimum Moisture	: 9.8%	
Plastic Limit	: 20	Peak friction angle	: 37.1	degree
Plastic Index	: 9	Residual friction angle	: 39.9	degree
Rate	: ****			

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.78	1.63	3.95
Compacted Dry Density (pcf)	115.8	116.0	115.9
Moisture Content	8.9%	8.7%	8.8%
Percent of Maximum Dry Density	91.2%	91.4%	91.2%



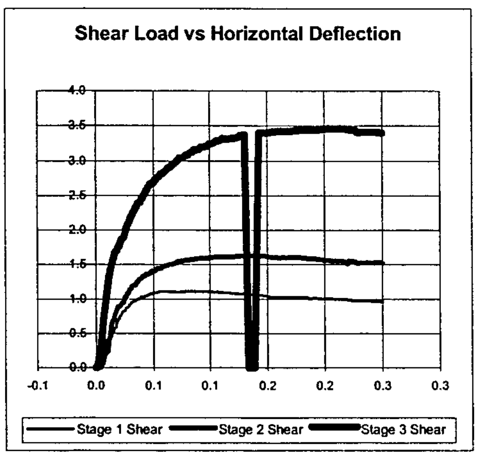


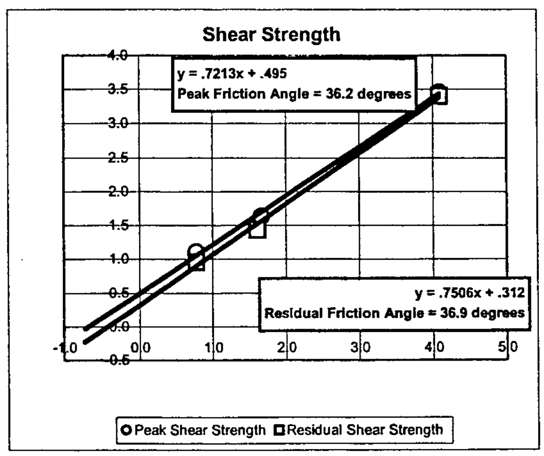
Observation No. **13**
Lab Test No. : **1999-936**
Classification A-2-4(0)
Liquid Limit : 29
Plastic Limit : 20
Plastic Index : 9

Compaction Method : T-99
Max. Dry Dens. (pcf) : 120.4
Optimum Moisture : 11.2%
Peak friction angle : 36.2 degree
Residual friction angle : 36.9 degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.78	1.64	4.09
Compacted Dry Density (pcf)	115.8	115.7	115.8
Moisture Content	10.3%	10.4%	10.4%
Percent of Maximum Dry Density	96.2%	96.1%	96.2%



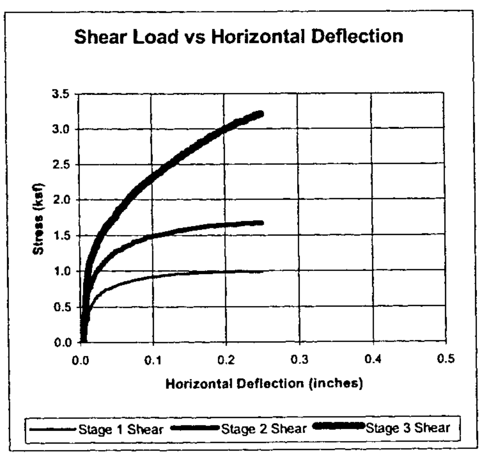


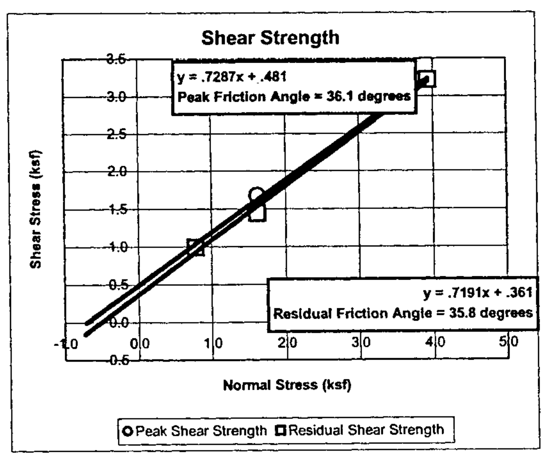
Observation No. **14**

Lab Test No.	: **1999-481**	Compaction Method	: T-99	
Classification	A-2-4(0)	Max. Dry Dens. (pcf)	: 122.4	
Liquid Limit	: 24	Optimum Moisture	: 10.3%	
Plastic Limit	: 17	Peak friction angle	: 36.1	degree
Plastic Index	: 7	Residual friction angle	: 35.8	degree
Rate	: ***			

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.79	1.62	3.94
Compacted Dry Density (pcf)	114.7	117.8	120.3
Moisture Content	12.3%	9.4%	7.1%
Percent of Maximum Dry Density	93.7%	96.2%	98.3%



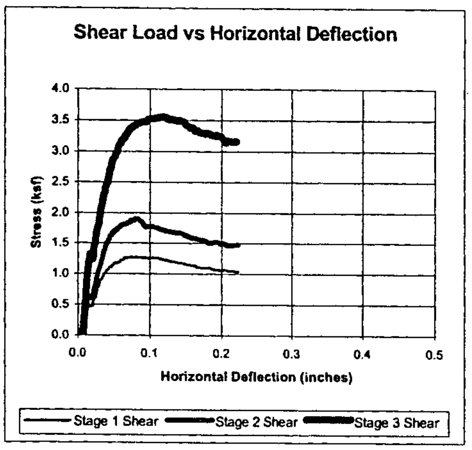


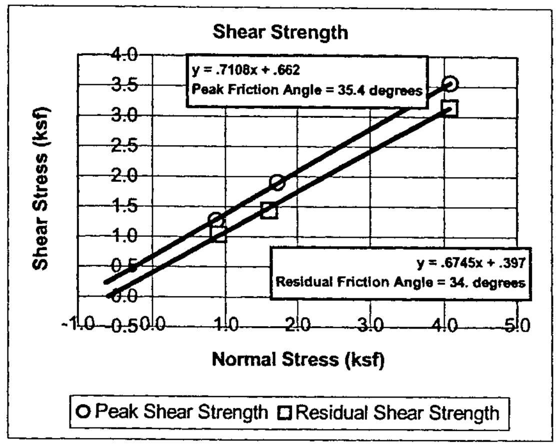
Observation No. **18**

Lab Test No. :	**2000-22**	Compaction Method	:	T-99	
Classification :	A-1-b(0)	Max. Dry Dens. (pcf)	:	107.9	
Liquid Limit :	NV	Optimum Moisture	:	16.0%	
Plastic Limit :	NP	Peak friction angle	:	35.4	degree
Plastic Index :	NP	Residual friction angle	:	34.0	degree
Rate :	***				

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.89	1.67	4.08
Compacted Dry Density (pcf)	105.8	104.9	104.4
Moisture Content	12.9%	13.9%	14.4%
Percent of Maximum Dry Density	98.1%	97.2%	96.7%



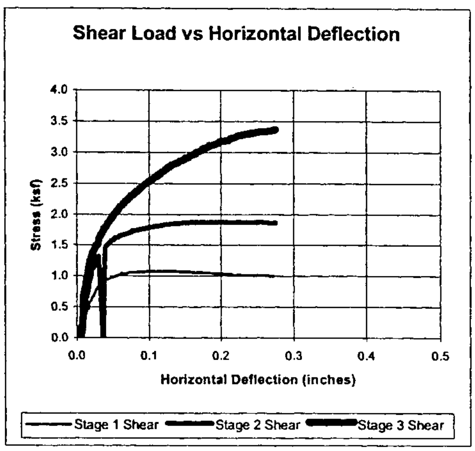


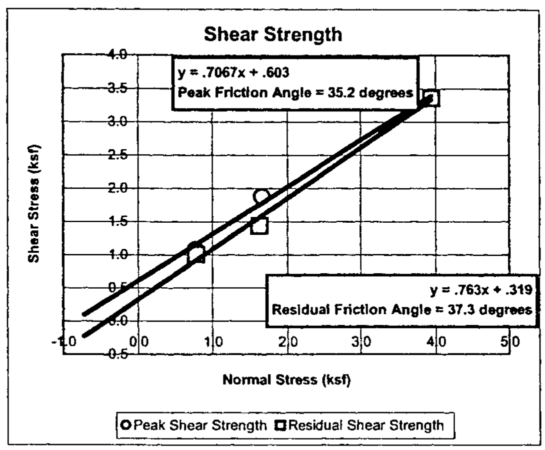
Observation No. **19**
Lab Test No. : **1999-866**
Classification A-2-4(0)
Liquid Limit : 27
Plastic Limit : 19
Plastic Index : 8

Compaction Method : T-99
Max. Dry Dens. (pcf) : 119.7
Optimum Moisture : 11.1%
Peak friction angle : 35.2 degree
Residual friction angle : 37.3 degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.78	1.64	3.95
Compacted Dry Density (pcf)	115.5	115.3	115.5
Moisture Content	9.9%	10.1%	9.9%
Percent of Maximum Dry Density	96.5%	96.3%	96.5%



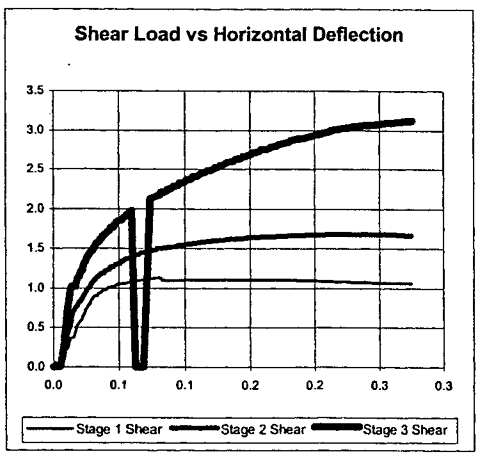


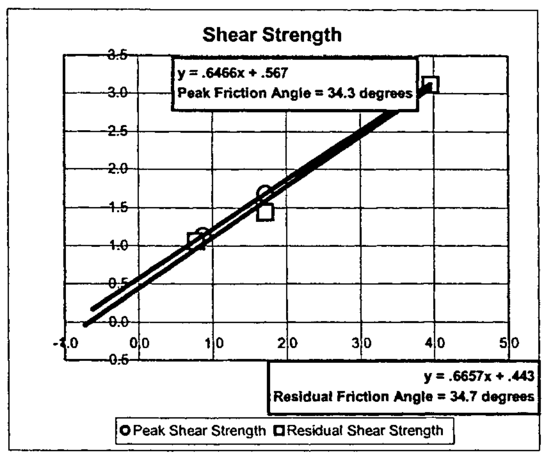
Observation No. **22**
Lab Test No. : **2000-159**
Classification A-2-4(0)
Liquid Limit : 26
Plastic Limit : 17
Plastic Index : 9
Rate : *****

Compaction Method : T-99
Max. Dry Dens. (pcf) : 116.7
Optimum Moisture : 12.5%
Peak friction angle : 34.3 degree
Residual friction angle : 34.7 degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.83	1.71	3.96
Compacted Dry Density (pcf)	112.9	113.2	113.4
Moisture Content	10.9%	10.7%	10.5%
Percent of Maximum Dry Density	96.8%	97.0%	97.2%



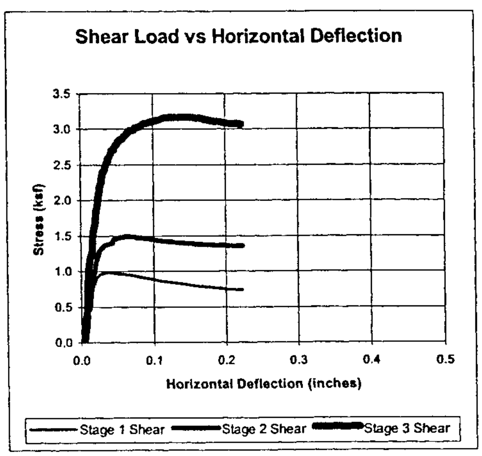


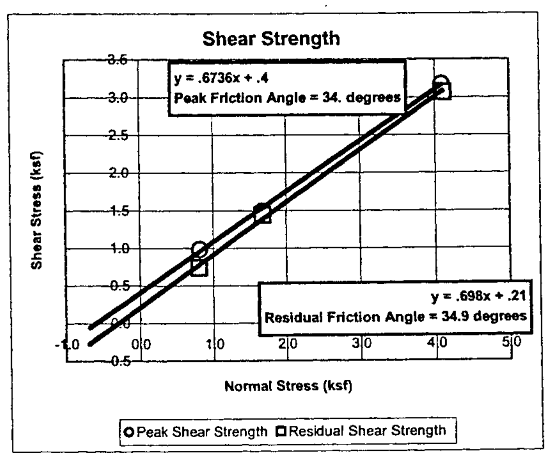
Observation No. **24**

Lab Test No.	: **1999-1041**	Compaction Method	: T-99	
Classification	A-2-4(0)	Max. Dry Dens. (pcf)	: 126.4	
Liquid Limit	: NV	Optimum Moisture	: 8.3%	
Plastic Limit	: NP	Peak friction angle	: 34	degree
Plastic Index	: NP	Residual friction angle	: 34.9	degree
Rate	: *****			

Specimens were compacted to 90% of AASHTO T-180 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.81	1.68	4.11
Compacted Dry Density (pcf)	115.2	115.3	115.3
Moisture Content	7.5%	7.4%	7.4%
Percent of Maximum Dry Density	91.1%	91.2%	91.2%



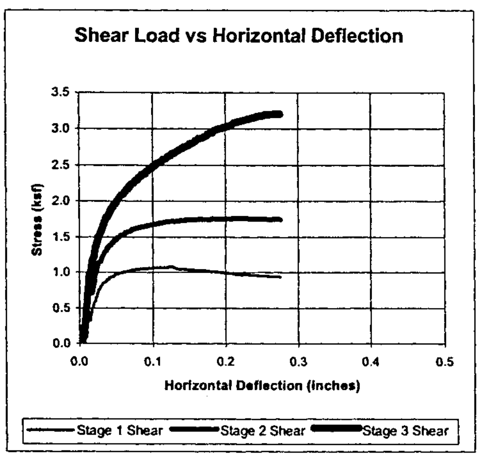


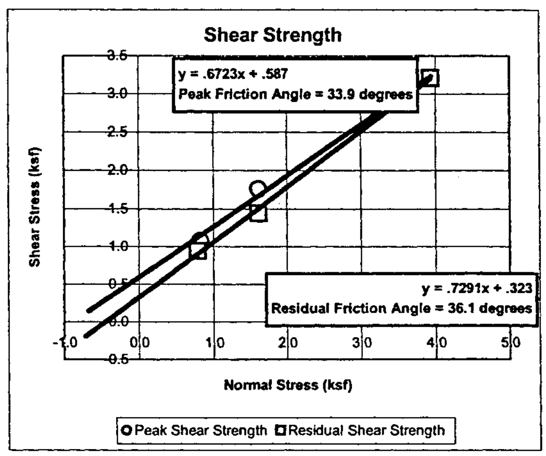
Observation No. **26**
Lab Test No. : **1999-907**
Classification A-2-6(0)
Liquid Limit : 27
Plastic Limit : 14
Plastic Index : 13
Rate : ****

Compaction Method : T-99
Max. Dry Dens. (pcf) : 120.5
Optimum Moisture : 10.7%
Peak friction angle : 33.9 degree
Residual friction angle : 36.1 degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.81	1.61	3.94
Compacted Dry Density (pcf)	116.2	116.4	116.7
Moisture Content	9.5%	9.4%	9.1%
Percent of Maximum Dry Density	96.5%	96.6%	96.8%



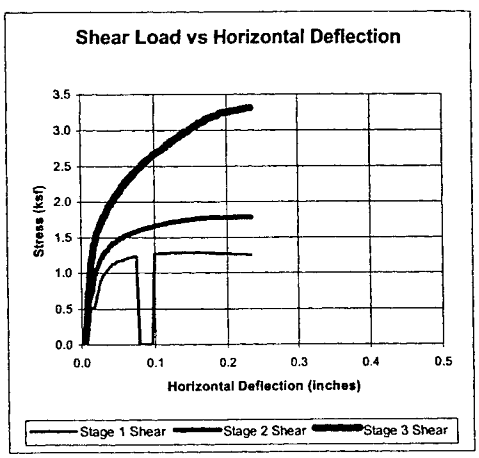


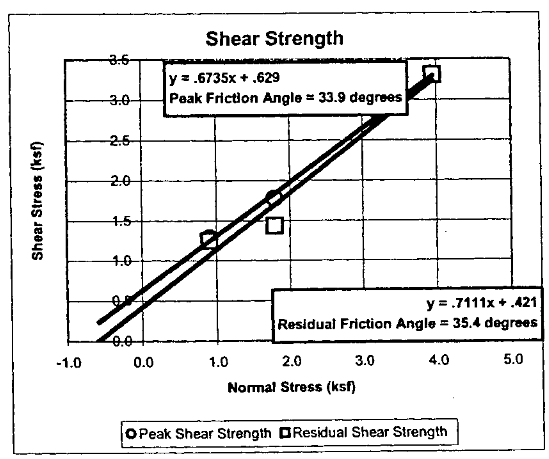
Observation No. **27**
Lab Test No. : **2000-88**
Classification A-2-6(0)
Liquid Limit : 27
Plastic Limit : 16
Plastic Index : 11
Rate : ****

Compaction Method : T-99
Max. Dry Dens. (pcf) : 122.3
Optimum Moisture : 9.9%
Peak friction angle : 33.9 degree
Residual friction angle : 35.4 degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.91	1.80	3.96
Compacted Dry Density (pcf)	117.4	117.6	117.9
Moisture Content	9.3%	9.1%	8.8%
Percent of Maximum Dry Density	96.0%	96.1%	96.4%

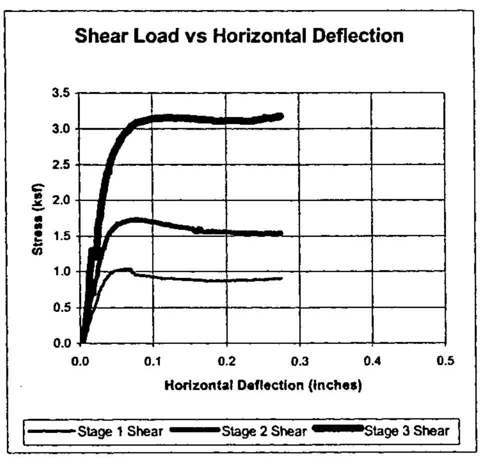


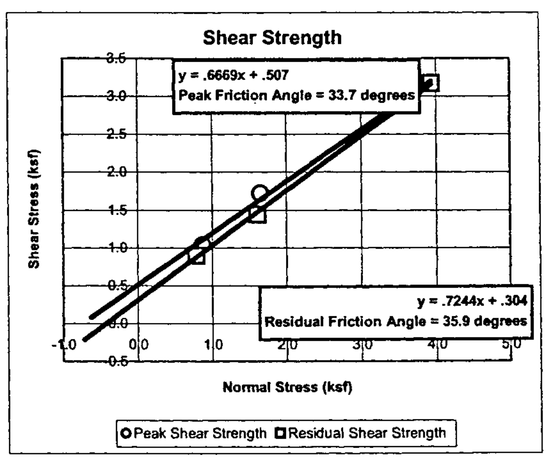


Observation No.	**28**		
Lab Test No.	: **2000-204**	Compaction Method	: T-99
Classification	A-2-4(0)	Max. Dry Dens. (pcf)	: 112.2
Liquid Limit	: NV	Optimum Moisture	: 10.5%
Plastic Limit	: NP	Peak friction angle	: 33.7 degree
Plastic Index	: NP	Residual friction angle	: 35.9 degree
Rate	: ****		

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.83	1.63	3.94
Compacted Dry Density (pcf)	107.9	108.1	108.0
Moisture Content	9.7%	9.7%	9.7%
Percent of Maximum Dry Density	96.1%	96.4%	96.3%

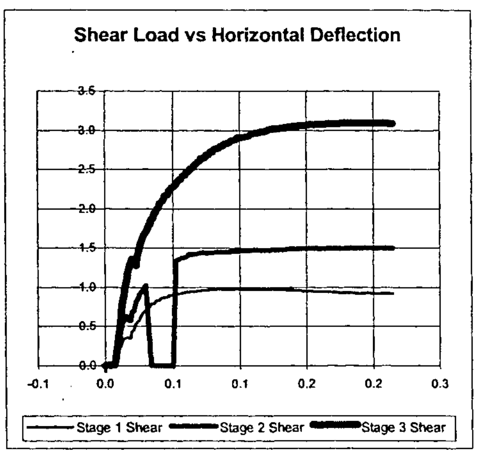


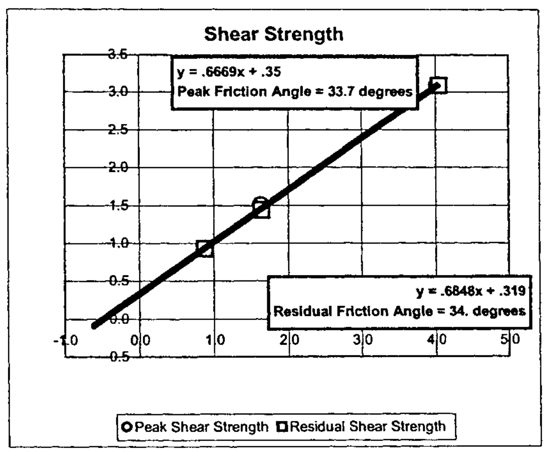


Observation No.	29			
Lab Test No.	: **2000-42**	Compaction Method	: T-99	
Classification	A-2-4(0)	Max. Dry Dens. (pcf)	: 117.6	
Liquid Limit	: NV	Optimum Moisture	: 10.8%	
Plastic Limit	: NP	Peak friction angle	: 33.7	degree
Plastic Index	: NP	Residual friction angle	: 34.0	degree
Rate	: *****			

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.88	1.64	4.04
Compacted Dry Density (pcf)	112.3	112.9	112.8
Moisture Content	10.7%	10.2%	10.2%
Percent of Maximum Dry Density	95.5%	96.0%	95.9%



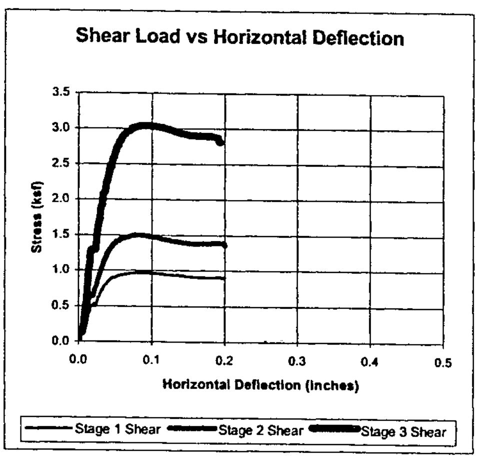


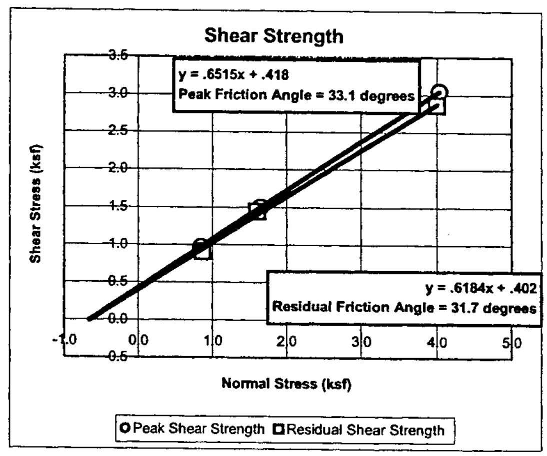
Observation No. **30**
Lab Test No. : **2000-126**
Classification A-3(0)
Liquid Limit : NV
Plastic Limit : NP
Plastic Index : NP
Rate : *****

Compaction Method : T-99
Max. Dry Dens. (pcf) : 103
Optimum Moisture : 17.0%
Peak friction angle : 33.1 degree
Residual friction angle : 31.7 degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.85	1.63	4.02
Compacted Dry Density (pcf)	98.4	99.4	99.2
Moisture Content	16.9%	15.7%	15.9%
Percent of Maximum Dry Density	95.5%	96.5%	96.3%



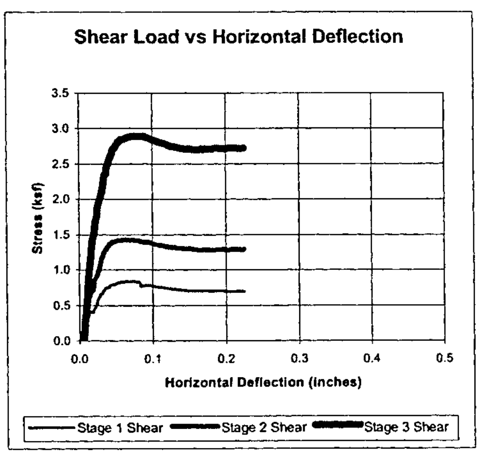


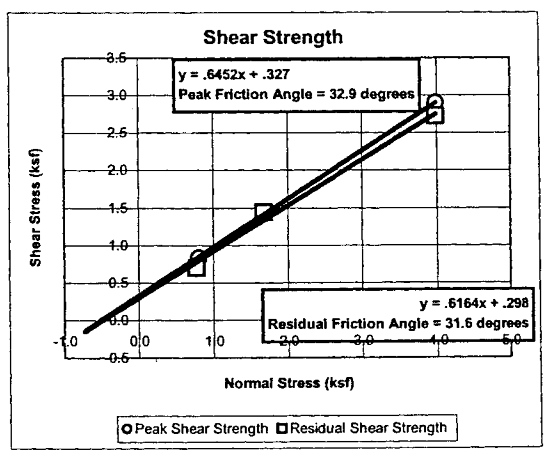
Observation No. **31**

Lab Test No.	: **2000-52**	Compaction Method	: T-99	
Classification	A-3(1)	Max. Dry Dens. (pcf)	: 106.6	
Liquid Limit	: NV	Optimum Moisture	: 13.9%	
Plastic Limit	: NP	Peak friction angle	: 32.9	degree
Plastic Index	: NP	Residual friction angle	: 31.6	degree
Rate	: *****			

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.79	1.68	3.99
Compacted Dry Density (pcf)	102.4	102.5	102.5
Moisture Content	13.2%	13.0%	13.1%
Percent of Maximum Dry Density	96.1%	96.2%	96.1%



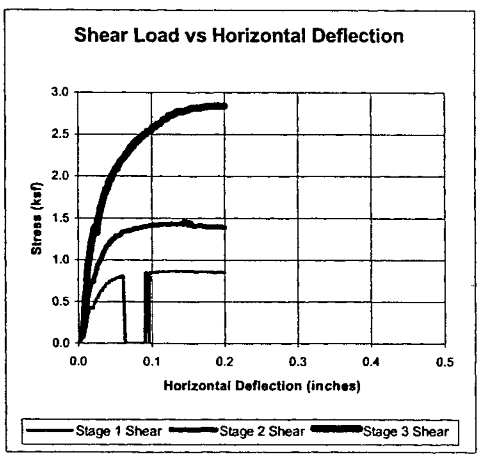


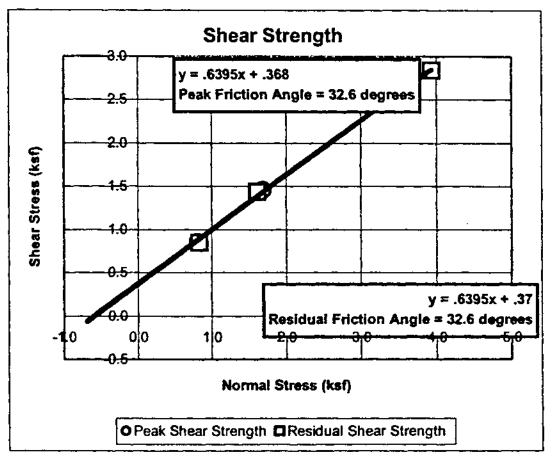
Observation No. **32**

Lab Test No.	: **2000-115**	Compaction Method	: T-99	
Classification	A-2-4(0)	Max. Dry Dens. (pcf)	: 115.9	
Liquid Limit	: NV	Optimum Moisture	: 10.0%	
Plastic Limit	: NP	Peak friction angle	: 32.6	degree
Plastic Index	: NP	Residual friction angle	: 32.6	degree
Rate	: ****			

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.82	1.65	3.94
Compacted Dry Density (pcf)	109.7	111.2	111.2
Moisture Content	10.9%	9.5%	9.4%
Percent of Maximum Dry Density	94.7%	95.9%	96.0%

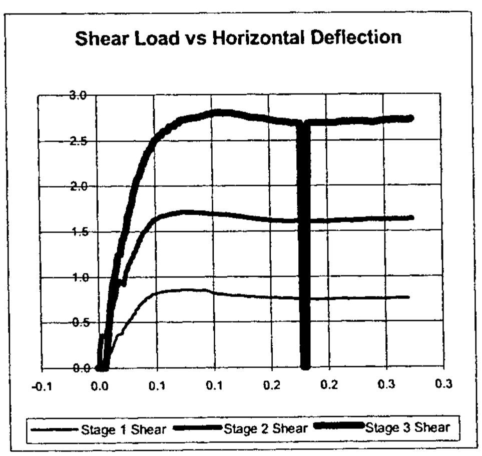


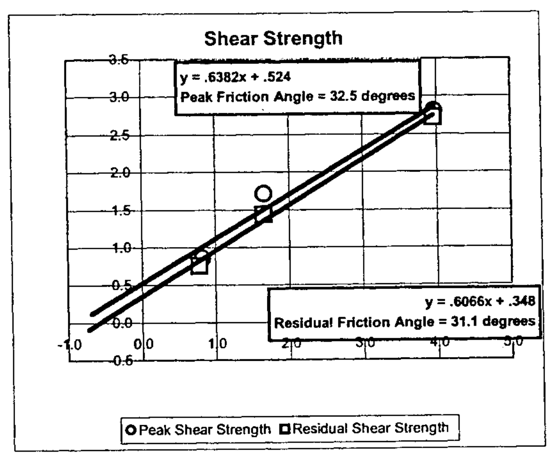


Observation No.	33			
Lab Test No.	: **2000-183**	Compaction Method	: T-99	
Classification	A-3(0)	Max. Dry Dens. (pcf)	: 104	
Liquid Limit	: NV	Optimum Moisture	: 14.3%	
Plastic Limit	: NP	Peak friction angle	: 32.5	degree
Plastic Index	: NP	Residual friction angle	: 31.1	degree
rate	: ****			

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.80	1.66	3.96
Compacted Dry Density (pcf)	100.2	100.4	100.1
Moisture Content	13.3%	13.0%	13.3%
Percent of Maximum Dry Density	96.3%	96.5%	96.3%



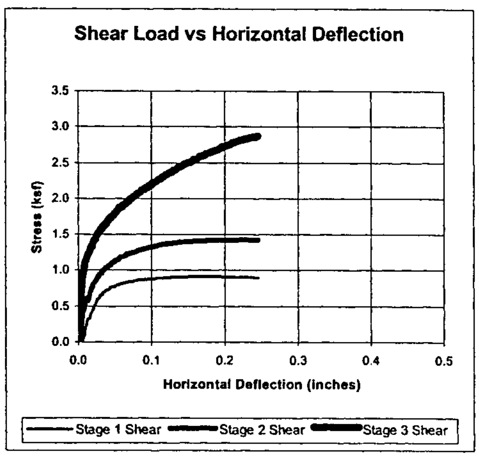


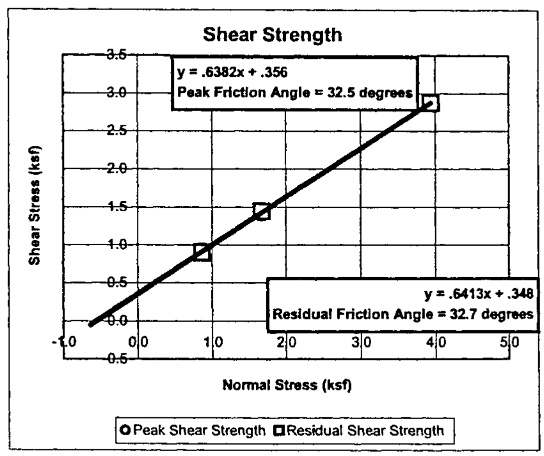
Observation No. **34**

Lab Test No.	: **1999-1082**	Compaction Method	: T-99
Classification	A-4(1)	Max. Dry Dens. (pcf)	: 112.8
Liquid Limit	: 29	Optimum Moisture	: 14.3%
Plastic Limit	: 23	Peak friction angle	: 32.5 degree
Plastic Index	: 6	Residual friction angle	: 32.7 degree
Rate	: *****		

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.87	1.68	3.95
Compacted Dry Density (pcf)	108.7	108.8	108.8
Moisture Content	13.2%	13.1%	13.1%
Percent of Maximum Dry Density	96.4%	96.4%	96.5%

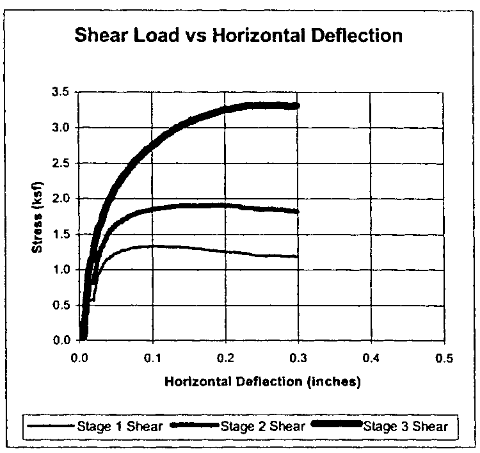


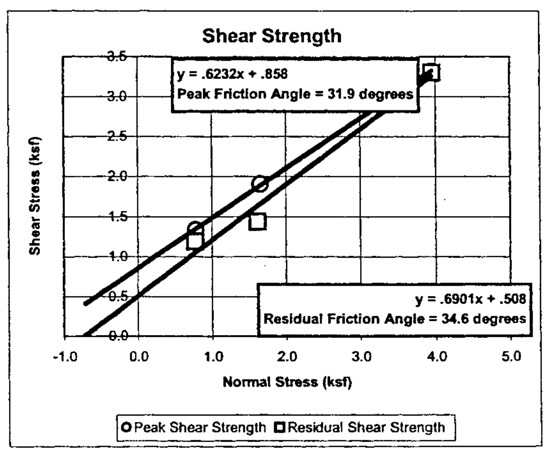


Observation No.	**38**		
Lab Test No.	: **2000-259**	Compaction Method	: T-99
Classification	A-1-b(0)	Max. Dry Dens. (pcf)	: 121.6
Liquid Limit	: 24	Optimum Moisture	: 10.9%
Plastic Limit	: 48	Peak friction angle	: 31.9 degree
Plastic Index	: 6	Residual friction angle	: 34.6 degree
Rate	: ****		

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.78	1.64	3.96
Compacted Dry Density (pcf)	117.3	117.3	117.4
Moisture Content	9.7%	9.8%	9.7%
Percent of Maximum Dry Density	96.5%	96.4%	96.5%



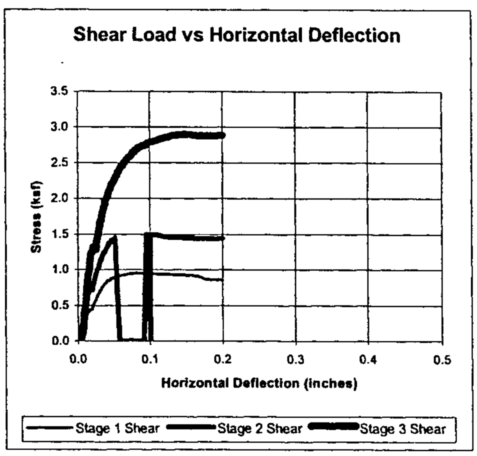


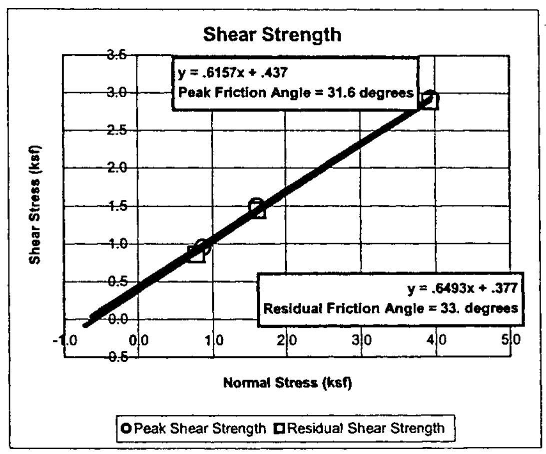
Observation No. **39**

Lab Test No.	: **1999-563**	Compaction Method	: T-99	
Classification	A-2-4(0)	Max. Dry Dens. (pcf)	: 114.3	
Liquid Limit	: NV	Optimum Moisture	: 10.7%	
Plastic Limit	: NP	Peak friction angle	: 31.6	degree
Plastic Index	: NP	Residual friction angle	: 33.0	degree
Rate	: ****			

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.82	1.61	3.95
Compacted Dry Density (pcf)	109.6	109.7	109.7
Moisture Content	10.2%	10.1%	10.1%
Percent of Maximum Dry Density	95.8%	96.0%	96.0%

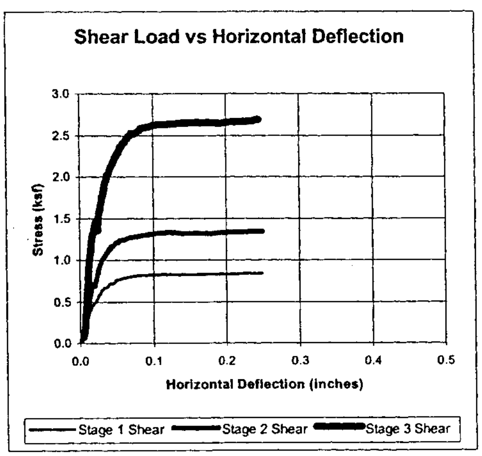


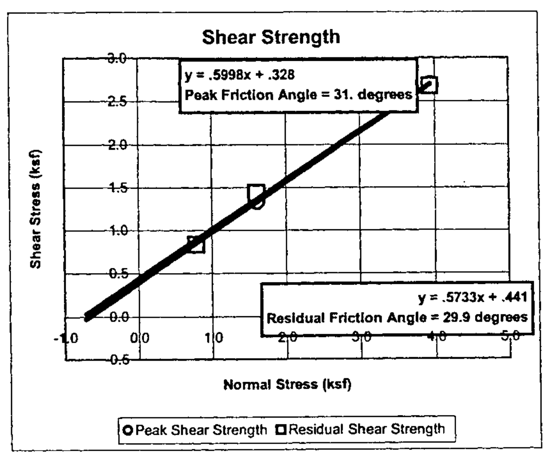


Observation No.	**40**			
Lab Test No.	: **2000-288**	Compaction Method	: T-99	
Classification	A-3(0)	Max. Dry Dens. (pcf)	: 106.7	
Liquid Limit	: NV	Optimum Moisture	: 12.3%	
Plastic Limit	: NP	Peak friction angle	: 31	degree
Plastic Index	: NP	Residual friction angle	: 29.9	degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.79	1.61	3.95
Compacted Dry Density (pcf)	102.7	102.7	102.5
Moisture Content	11.4%	11.4%	11.6%
Percent of Maximum Dry Density	96.2%	96.3%	96.1%

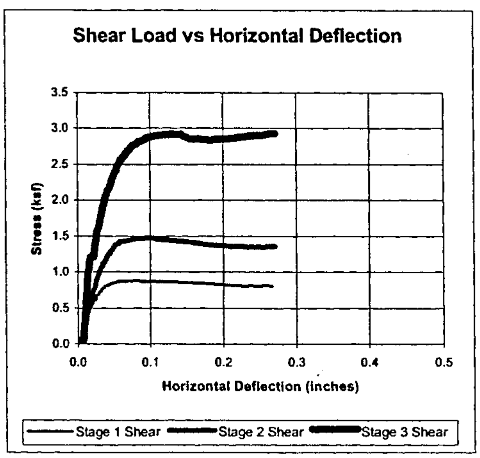


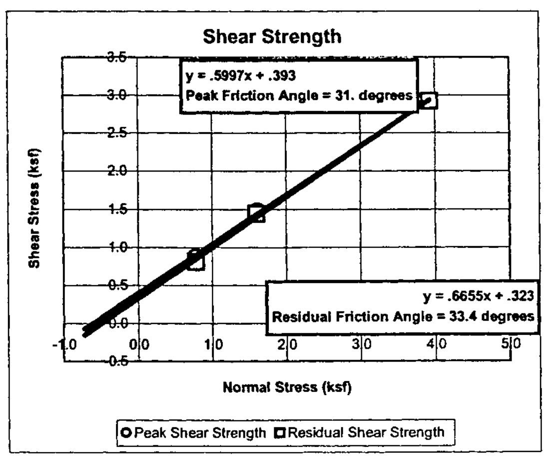


Observation No.	**41**				
Lab Test No.	: **2000-175**	Compaction Method	: T-99		
Classification	A-2-4(0)	Max. Dry Dens. (pcf)	: 112.1		
Liquid Limit	: NV	Optimum Moisture	: 11.2%		
Plastic Limit	: NP	Peak friction angle	: 31	degree	
Plastic Index	: NP	Residual friction angle	: 33.4	degree	

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.78	1.61	3.93
Compacted Dry Density (pcf)	108.1	107.7	108.0
Moisture Content	10.1%	10.5%	10.1%
Percent of Maximum Dry Density	96.4%	96.1%	96.4%



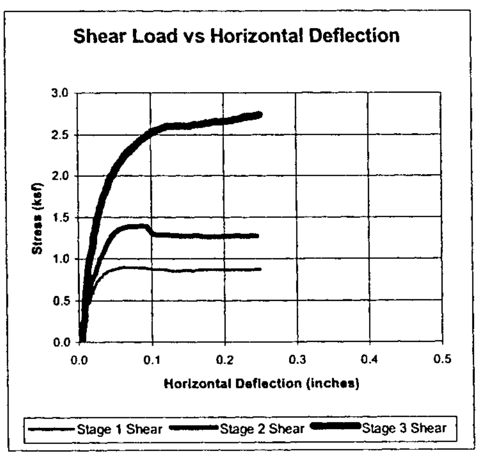


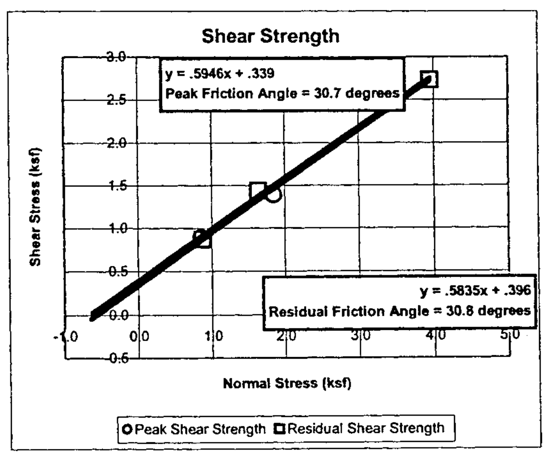
Observation No. **42**

Lab Test No.	: **1999-960**	Compaction Method	: T-99	
Classification	A-3(1)	Max. Dry Dens. (pcf)	: 106.4	
Liquid Limit	: NV	Optimum Moisture	: 13.5%	
Plastic Limit	: NP	Peak friction angle	: 30.7	degree
Plastic Index	: NP	Residual friction angle	: 30.8	degree
Rate	: ****			

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.87	1.74	3.96
Compacted Dry Density (pcf)	102.2	102.4	102.4
Moisture Content	12.8%	12.6%	12.6%
Percent of Maximum Dry Density	96.0%	96.2%	96.2%

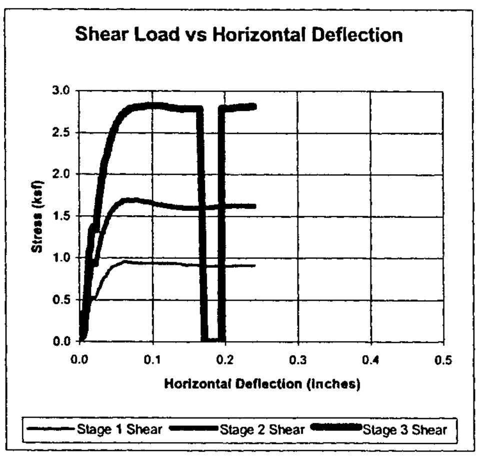


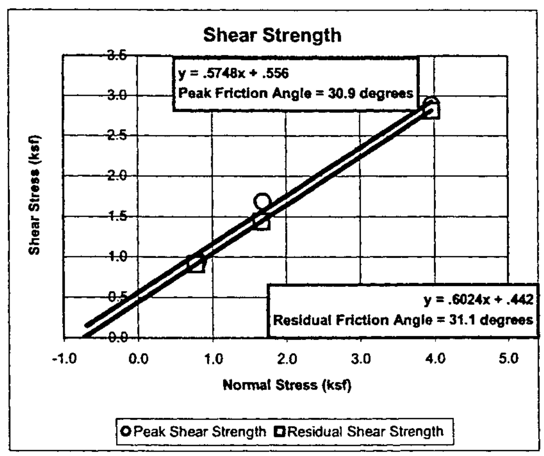


Observation No.	**43**		
Lab Test No.	: **2000-51**	Compaction Method	: T-99
Classification	A-3(0)	Max. Dry Dens. (pcf)	: 111.2
Liquid Limit	: NV	Optimum Moisture	: 10.4%
Plastic Limit	: NP	Peak friction angle	: 29.9 degree
Plastic Index	: NP	Residual friction angle	: 31.1 degree
Rate	: ***		

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.80	1.67	3.96
Compacted Dry Density (pcf)	102.2	102.3	102.4
Moisture Content	13.3%	13.2%	13.0%
Percent of Maximum Dry Density	91.9%	92.0%	92.1%



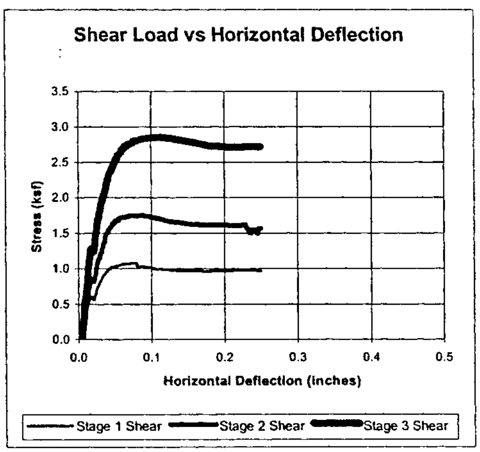


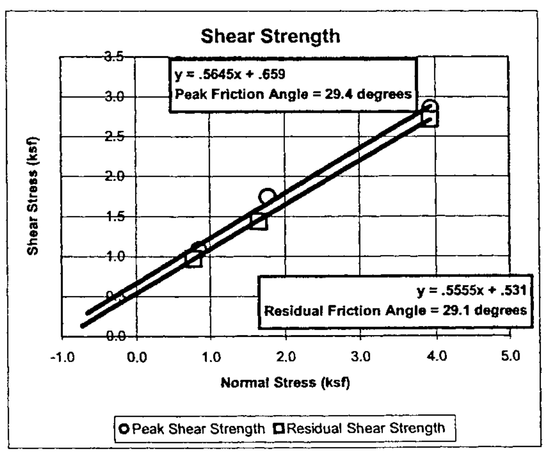
Observation No. **44**

Lab Test No.	: **2000-114**	Compaction Method	: T-99
Classification	A-3(0)	Max. Dry Dens. (pcf)	: 104.8
Liquid Limit	: NV	Optimum Moisture	: 13.4%
Plastic Limit	: NP	Peak friction angle	: 29.4 degree
Plastic Index	: NP	Residual friction angle	: 29.1 degree
Rtae	: ****		

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.82	1.71	3.94
Compacted Dry Density (pcf)	100.7	100.8	100.7
Moisture Content	12.6%	12.5%	12.6%
Percent of Maximum Dry Density	96.1%	96.2%	96.1%



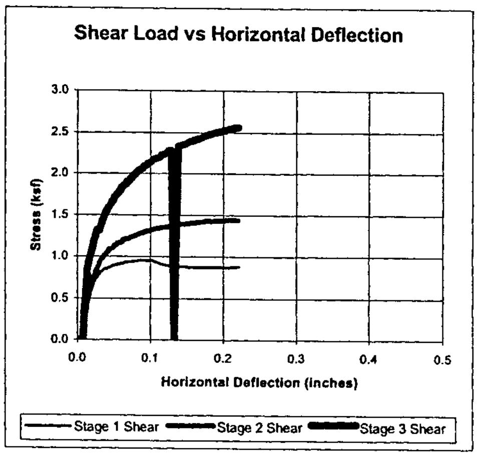


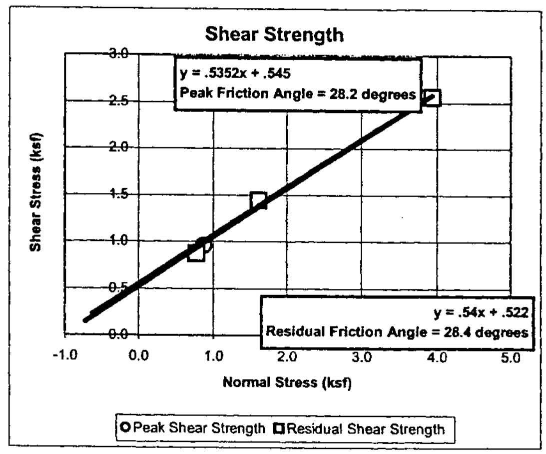
Observation No. **45**
Lab Test No. : **1999-952**
Classification A-2-4(0)
Liquid Limit : NV
Plastic Limit : NP
Plastic Index : NP
Rate : ****

Compaction Method : T-99
Max. Dry Dens. (pcf) : 99.3
Optimum Moisture : 19.6%
Peak friction angle : 28.2 degree
Residual friction angle : 28.4 degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.83	1.62	3.94
Compacted Dry Density (pcf)	95.1	95.0	95.1
Moisture Content	19.2%	19.3%	19.2%
Percent of Maximum Dry Density	95.7%	95.7%	95.8%



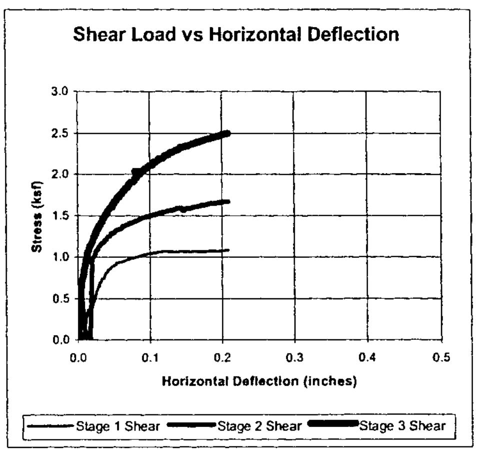


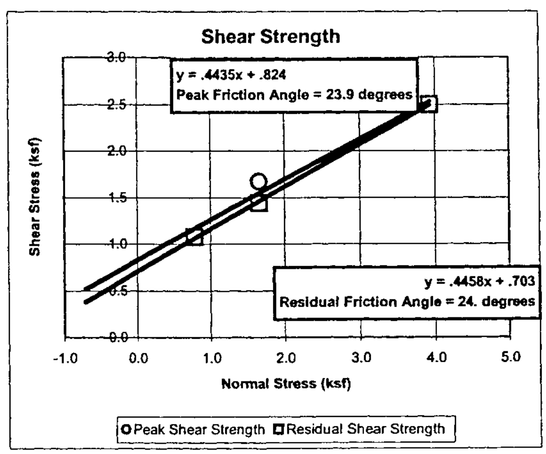
Observation No. **49**
Lab Test No. : **1999-987**
Classification A-4(4)
Liquid Limit : 27
Plastic Limit : 18
Plastic Index : 9
Rate : ****

Compaction Method : T-99
Max. Dry Dens. (pcf) : 114.8
Optimum Moisture : 13.6%
Peak friction angle : 23.9 degree
Residual friction angle : 24.0 degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.79	1.66	3.93
Compacted Dry Density (pcf)	110.6	110.3	110.4
Moisture Content	12.6%	12.8%	12.7%
Percent of Maximum Dry Density	96.3%	96.1%	96.2%



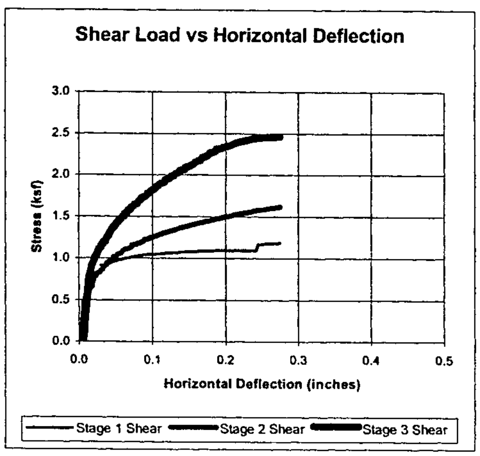


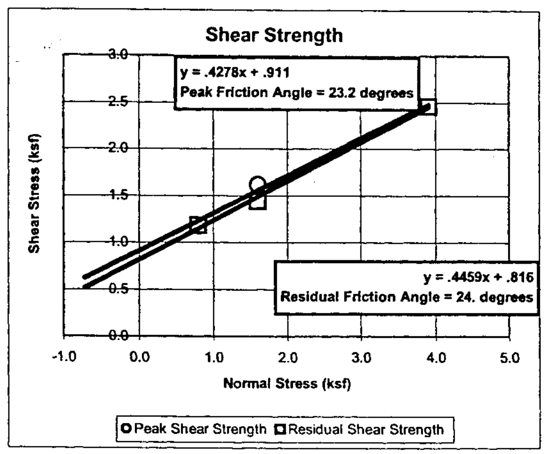
Observation No. **50**
Lab Test No. : **1999-988**
Classification A-6(9)
Liquid Limit : 36
Plastic Limit : 17
Plastic Index : 19
Rate : ****

Compaction Method : T-99
Max. Dry Dens. (pcf) : 107.5
Optimum Moisture : 16.7%
Peak friction angle : 23.2 degree
Residual friction angle : 24.0 degree

Specimens were compacted to 95% of AASHTO T-99 Method A at optimum moisture content

Specimen Preparation	Stage 1	Stage 2	Stage 3
Surcharge Pressure (ksf)	0.79	1.61	3.91
Compacted Dry Density (pcf)	103.7	103.7	103.6
Moisture Content	15.5%	15.5%	15.6%
Percent of Maximum Dry Density	96.4%	96.5%	96.3%





Appendix B

Questionnaire and Summary of Survey Result

A survey was conducted to examine the state of practice on selection of backfill, determination of design strength parameters, and field specifications for construction of retaining walls. The survey was conducted by distributing a questionnaire to the officials of each state agency in charge of transportation/highways of all 50 states in the US. The questionnaire and a summary of the survey results are presented below.

B.1 The Questionnaire

Respondent's Information:

Name: ______________________________

Title: ______________________________

Address: ______________________________

____

____

____

____

Telephone: ______________________________

Fax: ______________________________

E-mail: ______________________________

Would you like to receive a copy of the final report of this survey?

Yes ______ No ______

Backfill for construction of conventional earth retaining walls

(i.e., cantilever, gravity, and crib walls)

1. In selecting the backfill, do you determine whether a soil is suitable as a fill material based on
   Experience ______ Results of laboratory tests ______

   Type of tests:
   Gradation test ________
   Liquid limit and plastic limit tests ________
   Compaction (Proctor) test ________
   Permeability test ________
   Direct shear test ________
   Triaxial test ________
   Other (describe) ________________________
   ____

2. In obtaining strength parameters (c,ϕ) for design, do you:
   (a) Perform laboratory tests to determine the strength parameters
   Yes ______ No ______

   Type of tests:
   Direct shear test ________
   Triaxial test ________
   Other (describe) ________________
   ____

   (b) Use cohesion "c" of the fill in design
   Yes ______ No ______

   (c) Use an empirical correlation to determine the strength parameters
   Yes ______ No ______

   (If answer is Yes, please describe in the space provided under 4.)

   (d) Use an assumed value of c and ϕ for the fill
   Yes______ No ______

   Usually assume: c = ______ lb/ft^2 ; ϕ = ______ degrees

(If the strength parameters are assumed based on fill properties, please describe in the space provided under 4.)

3. In verifying that fill placement condition in wall construction meet the design requirements, do you perform any tests

   Yes ______ No ______

   Type of tests: ______________________________

   ____

   Required fill placement condition (typical):

   Dry density: ________% Std. Proctor (T99)

   Moisture: ________ % Optimum

   Other (describe) ______________________

   ____

4. Please explain here the answers to any questions for which the spaces provided above are inadequate, and give any pertinent comments

B.2 Summary of Responses

The questionnaire was sent to the state agencies in charge of transportation/highways of all 50 states in the US, of which 23 states responded. The respondents are as follows:

State	Name of Respondent
Alabama	Jeffery W. Brown
Connecticut	Leo Fontaine
Georgia	Thomas Scruggs
Idaho	Tri Buu
Illinois	Riyad Wahab
Louisiana	Mark Morvant
Massachusetts	Nahil Hourani
Maine	Laura Krusinki
Minnesota	Blake Nelson
Mississippi	James A. Williams, III
North Carolina	Nan Aba
Nebraska	Kenneth Cheney & Buddy C. Caples

New Hampshire	Charles Dusseault
Nevada	Parviz Noori
New York	Don Dwyer
Oregon	James B. Nevels, Jr.
Oklahoma	John M. Gent
Pennsylvania	Kerry Petrasie
Utah	Jon Bischoff
Virginia	J. Michael Hall
Wisconsin	Robert Amdorfer
Wyoming	James Dahill
(unknown)	Sek Wee

The results of the survey are summarized in Table B.1, and the comments made by the respondents are summarized in Table B.2.

Table B-1 Summary of responses on backfill of conventional retaining walls

Question No.	Brief description of the Question	Answer, %			
		Experiences	Tests	Both	No answer
1	Backfill was chosen based on	4	61	35	0
	Type of tests:				
	Gradation test	91 %			
	Liquid and plastic limit tests	61 %			
	Compaction test	61 %			
	Permeability test	9 %			
	Direct shear test	18 %			
	Triaxial test	18 %			
	Other	9 %			
		Answer, %			
		No	Yes	Sometimes	No answer
2a	Perform tests for c and phi?	57	30	13	0
	Type of tests;				
	Direct shear test	60 %			
	Triaxial test	70 %			
	Other	20 %			
2b	Use " cohesion" in design?	83	13	4	0
2c	Use empirical correlation?	52	43	4	0
2d	Use assumed values of c and phi?	9	74	4	13
	assume: c = 0	65 %			
	no answer	35 %			
	assume: phi = 30 degrees	24 %			
	phi = 32 degrees	6 %			
	phi = 33 degrees	6 %			
	phi = 34 degrees	29 %			
	phi = 35 degrees	6 %			
	no answer	29 %			
3	Field test for backfill?	13	83	4	0

Table B.2 Comments by the respondents

A. Question No.1: other tests

1. Resistance to Abrasion & Soundness (Connecticut).
2. Will sometimes use experience if in similar areas where tests have previously been done (Georgia).
3. pH and Resistivity (Nevada).
4. Magnesium sulfate soundness, plasticity index (New York).
5. Occasionally plan noted require special soil conditions which require laboratory testing (Oklahoma).
6. Durability Tests (Pennsylvania).
7. As long as the material does not contain organics, trash, or other undesires, it is OK (Virginia).

B. Comments Applicable to Question No.2

1. The material specified for backfill of retaining walls is high quality, granular backfill. We choose to use the maximum phi angle permitted by AASHTO where there is enough backfill material being placed (Connecticut).

2. Will sometimes use assumed strength parameters if previous tests have been done in the same areas (Georgia).

3. Assume an equivalent fluid pressure that depends on the anticipated condition to assume value of c and ϕ for the fill (Illinois).

4. Lab tests were sometimes performed to determine soil strength, not always (Idaho).

5. The backfill for the conventional retaining wall is required to be non-plastic sand material with at least 75% passing No.4 sieve and containing not more than 15 percent passing No. 200 sieve. Conventional retaining walls are generally used from a standard set of design plans with a limiting height of 1.8 meters. Larger walls are generally design for MSE structures and do not have a conventional wall alternate (Louisiana).

6. The use of either empirical correlation or assumed value is based on AASHTO Specification, and conventional soil mechanics (Massachusetts).

7. Use empirical correlations of type of fill with ϕ. An assumed value of c and ϕ is a function of fill, gradation and compaction (Maine).

8. Use empirical correlations made by correlation between SPT and friction angle (North Carolina).

9. Backfill soil is always specified to be granular, meeting the gradation requirement. This minimizes problems associated with frost and drainage behind the wall. Strength parameters are correlated to typical values (lowest one) for compacted fill from publication such as NAVFAC DM 7.2 (New Hampshire).

B. Comments Applicable to Question No.2 (*cont.*)

10. NYSDOT uses empirical relationships between friction angle and sampler blow counts to determine strength parameters (New York).

11. Cohesion using of the fill in design is based on CIU ASTM D4767 and AASHTO T226 and ASTM D3080. An empirical correlation to determine the strength parameters based on Atterberg limits. An assumed value for c and ϕ for the fill used only preliminary estimate (Oklahoma).

12. UDOT has standard drawing and spec for retaining walls and backfills, therefore no design for backfill is needed since the design for the backfill was done in conjunction with development of the standard drawing and specs (Utah).

13. Conventional retaining walls are basically " standard' designs that are based on assumed soil parameters. For example, our cantilever R.W. standards were developed based on an assumed equivalent fluid weight of 30 pcf. This information is stated on the standard. If the designer feels that, based on knowledge of the site or typical borrow source, that the equivalent pressure will be higher; the standard may have to be modified (Virginia).

14. Correlation is used for cohesionless soils to estimate phi angle based on soil description and in-situ density during drilling. Parameters are based on the assumed borrow sites and the in-situ sites on the project (Wisconsin).

15. Determine soil parameters for backfill as well as "fill" to be retained using similar laboratory tests. Use empirical correlation for "fill" to be retained based on SPT testing and soil classification. If assumed values for "fill" to be retained are used based on SPT testing and soil classification (Wyoming).

C. Question No.3: type of tests

1. 12" lifts uniformly compacted (Louisiana).
2. Nuclear Method (T238), Sand-Cone Method (T191), Rubber Method (T205) (Massachusetts).
3. Compaction, Moisture, Gradation (Maine).
4. Triaxial/direct shear. Nuclear Density Gauge (Mississippi).
4. Moisture and density tests (Nebraska).
5. AASHTO T191 Sand Cone, AASHTO T238 and T239 Nuclear In-situ Control Strip (New Hampshire).
6. Nuclear Density Gauge and Sand Cone Density (Nevada).
7. Compaction (New York).
8. Nuclear (Oklahoma).
9. Nuclear Gauge Density (Oregon).
10. Moisture/Density, Chlorides, Sulfates, pH, direct shear (Pennsylvania).
11. Density, AASHTO Classification (Utah).
12. Nuclear Density, Direct Transmission (Virginia).

D. Comments Applicable to Question No. 3

1. Moisture is not generally specified, but if % moisture is usually over 4 to 5% in the field, 100% is difficult (Georgia).

2. Maximum density determined per AASHTO T180, Method C or D. Field density is measured per AASHTO T191. Moisture is as needed to obtain required compaction (Maine).

3. Other fill placement condition: 200 mm (8inch) lift thickness (New Hampshire)

4. Other fill placement condition: 95% Harvard Miniature Test (Nevada)

5. Other fill placement condition: 150 mm loose lifts, 100 mm compacted lifts (Virginia).

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