Cooper Morris

The Effect of Water Content on the Unconfined Compression Strength of Western Tennessee Loess

Faculty Sponsors

Dr. David Arellano

Abstract

The unconfined compression strength of loess can be affected by the water content. The results of an unconfined compression strength test are used to estimate the shear strength of the soil with the use of an empirical equation that assumes the soil is fully saturated. There is a lack of empirical relationships that provide estimates of shear strength as it relates to water content values that are less than the fully saturated condition. The literature suggests that as the water content increases, the unconfined compression strength decreases. A series of unconfined compression strength tests were conducted at various water contents on remolded loess specimens from soil collected in the Memphis area. Two primary conclusions about the soil behaviors of loess can be made based on the results from this study. First, loess exhibits brittle behavior at water contents less than 11.2% and dry unit weight of less than 18.1 kN/m^3 (115.3 lb/ft^3); a ductile behavior is exhibited at water contents higher than 15.2% and dry unit weights greater than 18.3 kN/m^3 (116.2 lb/ft^3). Second, specimens with brittle behavior exhibited higher unconfined compression strength values than specimens with ductile behavior. In the future, an empirical equation between water content and the unconfined compression or shear strength can possibly be incorporated into the design of foundations of various structures within the Memphis area.

Introduction

National Geographic Society (2012) defines loess as a loosely compacted, windblown sediment that can be found within the Mississippi River Valley as shown in Figure 1. Loess is made up of silt and sand particles which are coated in clay, and most of the strength in loess is attributed to the clay binder and negative pore water pressures. When the clay becomes wet, negative pore pressures are reduced and the clay binder softens, lowering the shear strength of loess (Beard 1983). This is also confirmed by Milovic (1988) who states, "Water content influences the unconfined compression strength of loess and the higher the water content the lower the strength."

Figure 1. Approximate Locations of Loess Deposits in the United States (Bandyopadhyay 1983).

There is no established empirical relationship on how water content affects the strength of loess, so the fully saturated condition is typically used in practice to determine the strength of soil. The unconfined compression strength is commonly used to estimate the undrained shear strength of soil because these tests are simpler to perform than shear strength testing procedures such as triaxial tests. The general empirical relationship between the unconfined compression strength, q_u, and undrained shear strength, S_u, is shown in Equation (1):

$$S_u = \frac{1}{2} q_u \qquad (1)$$

Location and Description of Tested Loess

The loess sample material was collected from an exposed bluff located at Fulton Wildlife Refuge (GPS coordinates 35.6344400N, -89.8219360E), north of the city of Memphis. The disturbed sample was scraped from the edge of the bluff with a shovel, collected in buckets, and transported to the laboratory. Emhatsion (2018) reports that the soil from this location is classified as a low plasticity silt, ML, based on the Unified Soil Classification System with 0% sand, 83% silt, and 17% clay. The soil is considered silty loess, and Atterberg limit tests indicate the soil has a liquid limit of 30 and plasticity index of 1.

Sample Preparation

The original target of this study was three water contents which were 7%, 11%, and 17% with a dry unit weight of 16.0 kN/m^3 (102 lb/ft^3). The water contents were chosen based upon previous results from Emhatsion (2018), as these target water contents appeared to be the best choice to achieve useful specimens. If the water content was not in this range, the risk of specimen degradation increased. The target dry unit weight of 16.0 kN/m^3 (102 lb/ft^3) was decided after a trial batch of specimens were created. This dry unit weight was the best option to achieve specimens with approximately the same dry unit weight even with a variation of water content (W_C). The first step in preparing specimens was to compute W_C of the sample material by using Equation (2):

$$W_C = M_W - M_D \times 100\% \tag{2}$$

where M_W is the wet sample mass and M_D is the dry sample mass. The air-dried sample material was obtained from a bulk soil sample which was air-dried for several months. The air-dried sample material contained a minimal amount of moisture because most soils, especially those that contain fine-grained particles, will retain a slight moisture content after air drying. Thus, it was acceptable to neglect the initial W_C.

The next step was to mix the sample to the targeted W_C which was done by adding a calculated amount of distilled water to the air-dried soil sample in a mixing vessel. The amount of water to be added was determined by using Equation (3):

$$W_A = M_S \times W_{CT} \quad (3)$$

where W_A is the weight of water added to the sample, W_S is the weight of the sample, and W_{CT} is the target W_C. In this research, a No. 40 sieve was used to eliminate large particles such as pebbles and sticks from the material. Once the sample was mixed with water, it was placed inside an airtight container that was then placed inside a plastic bag to minimize moisture loss due to evaporation. The sample was allowed to cure for at least 48 hours to allow the W_C to stabilize. Then the sample was molded into 32.1 mm (1.263 in) diameter by 71.5 mm (2.816 in) high cylindrical specimens by using the Harvard Miniature Compaction apparatus shown in Figure 2.

Figure 2. Harvard Miniature Compaction apparatus.

In order to achieve a consistent density throughout the specimen, at least three layers of approximately the same thickness were used as shown in Figure 3.

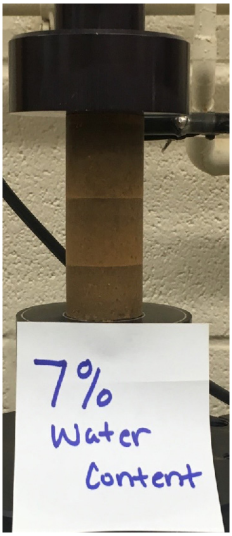

Figure 3. Individual Layers of Specimen.

The specimens were prepared using the procedure utilized by Tohidi (2017). The first step in making the specimen was to apply a light coat of oil, WD-40, on the inside of the mold to allow for easier extraction of the specimen. Before placing each subsequent layer, a soil knife was used to scratch the top of each molded layer to allow for better bonding. The next step was to try to apply the same amount of energy throughout the compaction of the specimen. After the sample molding process was completed, any excess soil was carefully trimmed from the top of the specimen to obtain a specimen that was the same size as the mold. Finally, the specimen was extracted from the mold and double-bagged to minimize the loss of W_C.

Constraints and Issues of Specimen Preparation

As with some specimen preparation methods, constraints were encountered and the specimen preparation procedure had to be modified. Initially, the goal was to target one dry unit weight that would be independent of W_C, but it became apparent that this goal could not be achieved with the Harvard Miniature Compaction apparatus. Since this device is manually operated, inconsistencies in the force applied by the user can result in a variation of the density in the specimen's soil layers. Thus, meeting a single targeted dry unit weight was difficult to achieve. Due to these reasons, the specimen preparation objectives were revised from achieving a target dry unit weight and W_C to only a target W_C.

Another issue was due to using at least three layers in each specimen to achieve as uniform a density throughout the specimen as possible. The first problem arose in compaction because it was very difficult to achieve three layers with equal thickness, and a thin fourth layer was often present in order to achieve the proper sample height of 71.5 mm (2.816 in). Second, the manual compaction associated with the Harvard Miniature Compaction apparatus could possibly yield specimens where the unit weight might vary within each layer. This variation was evident in the completed specimen when the color of each layer varied from the top to the bottom. Thus, to ensure this constraint did not affect the overall results, the unit weight was based on the total weight of the specimen. Similar constraints were observed by Felice (1986) who conducted a small study to determine the effects of this constraint. In this study, it was noted that specimens had a varied density throughout the sample from the use of the Harvard Miniature Compaction apparatus.

Specimen Testing

The unconfined compression strength testing machine shown in Figure 4 was used for this research.

Figure 4. Unconfined Testing Machine.

This machine applies a load at a constant axial strain rate of 1.27 mm/minute (0.05 in/minute) while recording the change in load and resulting vertical displacement of the soil specimen. Once the unconfined compression strength test concluded, the W_C of the specimen was determined to compare with the W_C measured during sample preparation to check for potential moisture loss that may have occurred during the time between specimen preparation and testing. The W_C that was taken after testing was used to calculate the dry unit weight of the specimen, while the W_C taken during the sample preparation was only used as an intermediate check.

Calculations of Stress and Strain

The strain values can be calculated by use of Equation (4):

$$\varepsilon_V = \frac{\Delta L}{L_0} \tag{4}$$

where ε_V is the strain, mm/mm, ΔL is the displacement, mm, and L_0 is the initial length of 71.5 mm (2.816 in). The initial cross-sectional area of the specimen was calculated by use of Equation (5):

$$A_0 = \frac{\pi D_0^2}{4} \tag{5}$$

where A_0 is the initial cross-sectional area, mm^2, and D_0 is the initial diameter of 32.1 mm (1.263 in). As the specimen deforms, its cross-sectional area increases and the corrected area is obtained by use of Equation (6):

$$A_C = \frac{A_0}{1-\varepsilon_V} \tag{6}$$

where A_C is the corrected area, mm2. The A_C was then converted to m2 for the next calculation. Finally, the vertical stress was calculated by use of Equation (7):

$$\sigma = \frac{Load}{A_C} \tag{7}$$

where σ is the stress in kPa (lb/in^2) (Das 2013). The results of the unconfined compression strength test were evaluated on a plot of stress versus strain. Based on ASTM 2166, the unconfined compression strength is defined as the peak stress on the stress versus strain plot as long as the peak is reached at a strain level of less than 15%. If the peak stress is not reached before 15% strain, the unconfined compression strength is the stress at 15% strain.

Test Results and Analysis

Figure 5 shows the stress versus strain plots obtained from the unconfined compression strength tests. The legend in Figure 5 shows the W_C in percent and dry unit weight in kN/m^3 of each sample respectively. Tables 1 and 2 provide a summary of the specimen W_C and dry unit weights values as well as the unconfined compression strengths.

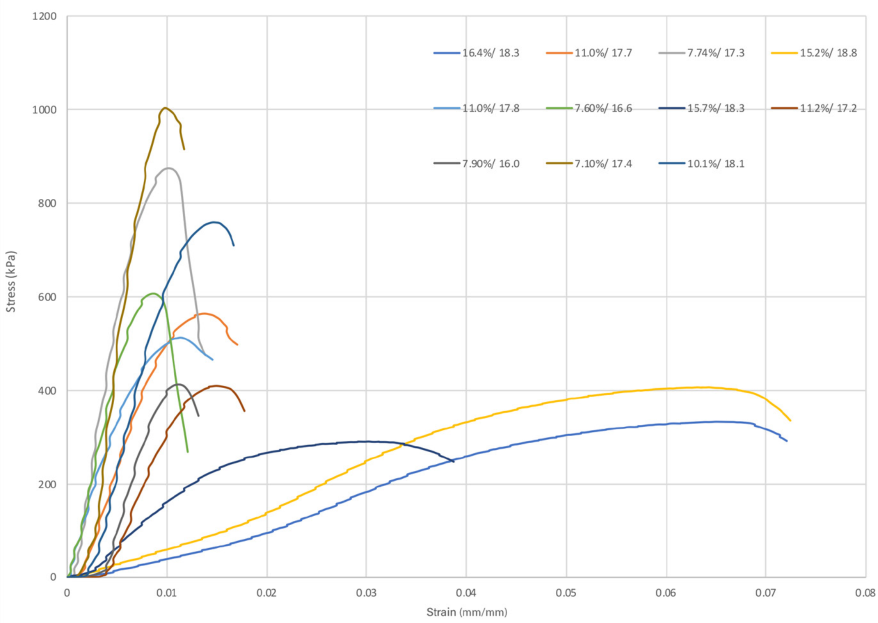

Figure 5. Stress vs. Strain Graph.

W_C	Peak Force (kN)	Strain (mm/mm)	A_C (m^2) ($x10^{-4}$)	Unconfined Compression Strength q_u (kPa)	S_u (kPa)	Dry Unit Weight γ_d (kN/m^3)
7.10%	0.818	0.00994	8.13	1000	500	17.4
10.1%	0.622	0.01460	8.19	759	380	18.1
7.90%	0.337	0.01100	8.19	412	206	16.0
11.2%	0.336	0.01490	8.19	410	205	17.2
15.7%	0.242	0.03130	8.32	290	145	18.3
7.60%	0.494	0.00852	8.13	607	304	16.6
11.0%	0.419	0.01140	8.19	513	257	17.8
15.2%	0.351	0.06430	8.65	407	204	18.8
7.74%	0.713	0.01300	8.13	874	437	17.3
11.0%	0.462	0.01390	8.19	564	282	17.7
16.4%	0.288	0.06500	8.65	333	167	18.3

Table 1. Data from Testing in SI units.

W_C	Peak Force (lb)	Strain (in/in)	A_C (in^2)	Unconfined Compression Strength q_u (lb/in^2)	S_u (lb/in^2)	Dry Unit Weight γ_d (lb/ft^3)
7.10%	184	0.00994	1.26	145	72.7	111
10.1%	140	0.01460	1.27	110	55.0	115
7.90%	75.7	0.01100	1.27	59.8	29.9	102
11.2%	75.5	0.01490	1.27	59.4	29.7	109
15.7%	54.4	0.03130	1.29	42.1	21.1	116
7.60%	111	0.00852	1.26	88.0	44.0	105
11.0%	94.2	0.01140	1.27	74.4	37.2	113
15.2%	78.9	0.06430	1.34	59.0	29.5	119
7.74%	160	0.01300	1.26	127	63.4	110
11.0%	104	0.01390	1.27	81.8	40.9	113
16.4%	64.7	0.06500	1.34	48.3	24.2	117

Table 2. Data from Testing in USCS units.

Figure 5 appears to show two different stress-strain behaviors because some of the specimens reach their peak stress at strains of less than 0.02 mm/mm and display a dramatic shear failure surface as shown in Figure 6. This type of stress-strain behavior is typical of brittle materials. Other stress-strain plots have a more gradual curve that peaks at strain values greater than 0.02 mm/mm, resulting in a bulging failure as shown in Figure 7. This type of behavior is typical of ductile materials. The specimens that failed in a brittle manner had a W_C range of 7.1% to 11.2% and a dry unit weight range of 16.0 to 18.1 kN/m^3 (101.7 to 115.3 lb/ft^3). The specimens that failed in a ductile manner had a W_C range of 15.2% to 16.4% and a dry unit weight range of 18.3 to 18.8 kN/m^3 (116.2 to 119.5 lb/ft^3).

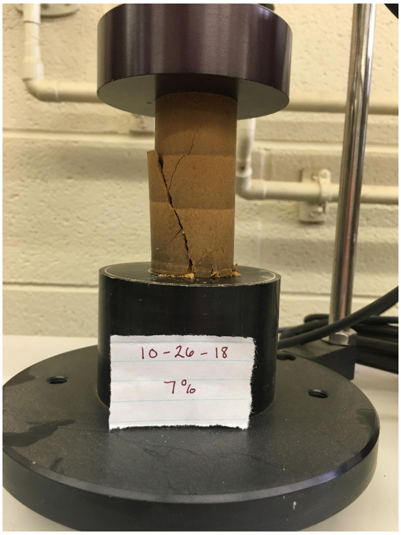

Figure 6. Typical Shear Failure.

Figure 7. Typical Bulging Failure.

Thus, from this study, a W_C range between 11.2% to 15.2% was established where the two types of failures appear to change from brittle to ductile. In this W_C range, the dry unit weight is between 18.1 to 18.3 kN/m^3 (115.3 to 116.2 lb/ft^3). Another conclusion is that as the W_C increases the unconfined compression strength decreases, which is consistent with the observations of Molvic (1988).

Conclusions and Future Research

Two primary conclusions about loess soil behavior can be made based on the results of this study: (1) Loess exhibits brittle behavior at W_C less than 11.2% and dry unit weights less than 18.1 kN/m^3 (115.3 lb/ft^3). Ductile behavior was exhibited at W_C greater than 15.2% and dry unit weights greater than 18.3 kN/m^3 (116.2 lb/ft^3). (2) Specimens with brittle behavior exhibited higher unconfined compression strength values than specimens with ductile behavior. Therefore, specimens with lower W_C (less than 11.2%), yielded higher unconfined compression strengths than specimens of higher W_C (greater than 15.2%).

More testing will need to be conducted to add to the collection of data in order to develop an empirical equation that provides an estimate of unconfined compression strength with changes in water content and dry unit weight. From this research, different constraints have been identified, and different types of specimens, such as undisturbed specimens, will need to be tested in order to include in-situ natural conditions. These tests can be used to verify that the constraints encountered in this study do not affect the unconfined compression strength results. Undisturbed samples from the same field location where the loess were originally collected will need to be tested. Furthermore, these additional test results can confirm the accuracy of the Harvard Miniature Compaction apparatus, and if the results do not agree, then a correction for soil disturbance can possibly be introduced into the empirical equation. Once the undisturbed specimens have been tested, a critical W_C and/or dry unit weight value, where the transition from brittle to ductile behavior is located, can possibly be determined.

References

Bandyopadhyay, S. S. (1983). "Geotechnical Evaluation of Loessial Soils in Kansas." *Transportation Research Record* 945, 29-36.

Beard, L., Higgins, J., Fragaszy, R., Kilian, A., Peters, A. (1986). "Physical Properties of Southeastern Washington Loess Related to Cut Slope Design." *Transportation Research Record* 1089, 29.

Das, B. M. (2013). "Unconfined Compression Test." *Soil Mechanics Laboratory Manual*, Oxford University Press, 159–167.

Emhatsion, E. (2018). "Dynamic Properties of Local Memphis Area Loess." M.S. Thesis, Civil Engineering, University of Memphis, Memphis.

Felice, C. (1986). "The Response of Soil to Impulse Loads Using the Split Hopkinson Pressure Bar Technique." Final Report AFWL-TR-85-92, Air Force Weapons Laboratory, Kirtland Air Force Base, NM 87117.

Milovic, D. (1988). "Stress Deformation Properties of Macroporous Loess Soils." *Engineering Geology* 25, 283-302.

National Geographic Society. (2012). "Loess." *National Geographic Society*, <https://www.nationalgeographic.org/encyclopedia/loess/>.

Tohidi, H. (2017). "Effect of Sand and Water Content on Squeezing Behavior." M.S. Thesis, Civil Engineering, Idaho State University, Pocatello.