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ABSTRACT

Expansive soils have long been recognized as problematic because they cause failure to civil structures constructed above them. The main problem of these soils can be attributed to poor understanding of the volume changes caused by moisture fluctuations. Current swell and shrinkage characterization models are limited by both the lack of standardized tests and tests that employ volume changes in uniaxial direction. In the present research, a comprehensive laboratory investigation was undertaken to study the volume change related swell-shrinkage behaviors of five different types of expansive clayey soils sampled from various regions in Texas, USA. Extensive experimental programs consisting of basic, chemical and mineralogical soil properties were first determined. Three-dimensional free swell and shrinkage tests were performed on all soils at various compaction moisture content conditions. Soil water characteristic curves (SWCCs) of all test soils were determined by studying the suction potentials of these soils over a wide range of moisture contents. Volume change measurements of soils showed a good correlation with soil properties, including plasticity and soil compaction properties. SWCC results also showed a clear variation in SWCC profiles of soils with respect to soil plasticity. Overall, a large database of soil properties was developed and is presented here. It includes physical and mineralogical properties, and engineering test results including swell, shrinkage and SWCCs.

INTRODUCTION AND BACKGROUND

Expansive soils are a worldwide problem, and they undergo considerable amounts of volume changes due to moisture content fluctuations (Nelson and Miller, 1992). Typically, these volume changes of expansive soils cause considerable distress to civil infrastructures built on them (Pedarla et al., 2011). Hence, it is important to appropriately estimate the total volume change potentials of these soils, from both swell and shrink related movements, thus enabling us to better characterize the y nature of the subsoils, and explore appropriate treatment or modification methods to reduce volume changes of soils.

Several direct and indirect methods have been developed for estimating shrink-swell potentials of expansive soils (Seed et al., 1962; Kormonik and David, 1969; Erguler and Ulusay, 2003; Sridharan, 1986; Puppala et al. 1995). Indirect methods developed so far involve the use of soil properties and classification schemes to estimate shrink-swell potential, while direct methods provide the actual physical measurements of swelling potentials in percent values (Chen, 1963; Puppala et al. 1995). A few of the limitations of these models is the variations in test procedures used for swell and shrink property measurements in the measured laboratory test database and the use of devices that can only provide vertical swells.

In addition, shrinkage strain characterization of expansive soils has been given no or limited attention, and this could lead to poor interpretation of total volume changes in soils, as moisture content conditions can change drastically from summer to winter conditions. Hence, there is an important research need to develop reliable swell and shrinkage strain models that could provide better volume change predictions in both swell and shrinkage environments. Tests that could capture the performance of subsoils in real field conditions need to be employed in order to produce reliable characterization models. In addition, these models should be correlated with a combination of physical, chemical and mineralogical soil properties that capture the variety of expansive soils encountered in the field.

A research investigation conducted at the University of Texas at Arlington (UTA) explored the development of new models for volume change predictions in expansive soils. A comprehensive physical and mineralogical test database was then developed for several different expansive soils sampled from various regions of Texas, USA. The same soils were subjected to volumetric swell and shrinkage strain testing as well as unsaturated soil test related SWCC testing. This paper presents a comprehensive summary of these test results on various soils sampled from the state of Texas.

LABORATORY TESTS AND ANALYSIS OF TEST RESULTS

The laboratory testing program was designed to determine properties relating to volume change behaviors of expansive soils sampled from five sites, namely Fort Worth, Paris, San Antonio, El Paso and Houston, Texas, USA. The experimental program was mainly comprised of tests to determine basic soil properties, such as plasticity and compaction properties; clay mineralogy data; and engineering characteristics, including volume change related swell and shrinkage strain properties. A brief summary of the laboratory procedures, equipments used and results obtained are presented in the following sections.

Basic Soil Property Tests

All representative soil samples were subjected to various physical property measurements, including grain size and hydrometer tests, Atterberg limits, and Proctor compaction tests. All test results are presented in Table 1. Based on the physical soil characteristics, four soils were characterized as high plasticity clays, and one soil was classified as lean or low plastic clay.

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Generally, soils that exhibit plastic behavior over a wide range of moisture contents and have high liquid limits tend to undergo larger swelling and shrinking. As per the expansive soil characterization, soils sampled from the Fort Worth, Houston, San Antonio and Paris sites were considered as high swelling potential, and soil from El Paso was considered as a low swell potential material. Four of the five soils are classified as A-7-6 as per the American Association of State Highway and Transportation Officials (ASSHTO) classification system and CH as per Unified Soil Classification System (USCS).

Also, an attempt is made to determine the clay mineralogy of these soils based on chemical measurements, including specific surface area, cation exchange capacity and total potassium.

Chemical Tests

Three chemical property related tests known as cation exchange capacity (CEC), specific surface area (SSA), and total potassium (TP) were studied here, and details of these test procedures are briefly discussed here.

Cation exchange capacity or CEC can be used to determine the mineral composition since a high CEC value indicates the presence of the clay mineral such as Montmorillonite and a low CEC indicates the presence of non-expansive clay mineral such as Kaolinite. CEC of a soil can be defined as the capacity or the ability of the soil to exchange free cations that are available in the exchange locations. It may also be understood simply as a measure of the quantity of readily exchangeable cations neutralizing negative charge in the clay mineral (Chapman, 1965).

The CEC test method involves the addition of a saturating solution to the soil sample, followed by removal of the adsorbed cations, using an extracting solution. In the method used here, ammonium acetate (NH_4OAc) is the saturating solution, which has the ability to replace all the exchangeable cation locations with the ammonium (NH_4^+) cation. This is possible because of the low valence ($^{1+}$) of this cation that makes it more stable and electro-negatively stronger than higher valence cations such as Ca^{2+}, Al^{3+} and others. While replacing the similar valence cations such as Na^+, the higher atomic weight of NH_4^+ helps in replacing them. Hence, the cation exchange process involving this saturating solution makes it appropriate for the reliable estimation of CEC of a soil.

The specific surface area or SSA of a soil sample is the total surface area of soil particles contained in a unit mass of soil. This property of the soil is primarily dependent on the particle size distribution of the soil mass. Typically, soils with a large number of smaller particle sizes have higher specific surface areas. It should be noted here that a clayey soil with a high specific surface area has a high water holding capacity and greater swell potential due to the large surface area that is negatively charged and attracts dipole- natured water.

This test method involves saturating the prepared soil sample, equilibrating them in a vacuum over a calcium chloride – EGME ($CaCl_2$-EGME) solvate, and then determining the weight when the equilibrium (constant weight) is reached. The specific surface is then determined from the mass of retained EGME in comparison to the amount retained by pure Montmorillonite, which is assumed to have a surface area of 810 m^2/g (Carter et al. 1986). This test method was fully evaluated for its potential application in the geotechnical field by Cerato and Lutenegger (2002), and they concluded that the method is applicable to a wide range of soils with different clay mineralogies and is capable of determining the specific surface area ranging from 15 to 800 m^2/g.

Potassium is the interlayer cation in the clay mineral, Illite, and this stable clay mineral is the only one that possesses potassium in its structure (Mitchell and Soga, 2003). Hence, measuring the amount of potassium ion in the soil gives a direct indication of the presence of the clay mineral, Illite. The test procedure formulated by Knudsen et al. (1984) was followed to determine the amount of total potassium present in the soil. The method involves a double acid digestion technique developed originally by Jackson (1958), which uses two acids, Hydrofluoric acid and Perchloric acid, to break the mineral structure of the soil and then extract the potassium ions from the structure. Once the potassium is extracted, its concentration in the solution can be obtained with the help of a spectrophotometer or any other appropriate device.

These chemical test results, along with interpreted clay mineralogy, are presented in Table 2. Interpretations were made based on the analysis of chemical measurements induced by the clay mineral fractions of a given soil. Details of this analysis can be found in Chittoori and Puppala (2011). The interpreted clay mineralogy data is presented in Table 3. Overall, it can be mentioned that both Fort Worth and Paris clays contain high amounts of Montmorillonite, whereas San Antonio clay contains moderate amounts of Montmorillonite. Houston clay contains a similar amount of Kaolinite and Montmorillonite, whereas El Paso clays contain low amounts of Montmorillonite and high amounts of Illite.

Standard Proctor Compaction Tests and Results

In order to determine the compaction moisture content and dry unit weight relationships and establish compaction conditions for engineering tests, standard Proctor compaction tests were performed on all five soils. Compaction moisture or water contents corresponding to maximum dry unit weight, 95% of maximum dry unit weight conditions on both dry and wet sides of the standard Proctor compaction curve were then established. These three moisture content conditions were later used to perform engineering volume change related tests. All compaction test results can be seen in Figure 1, and compaction state conditions for each soil are included in Table 3. These three moisture content conditions are referred to as wet of Optimum Moisture Content or OMC, OMC and dry of OMC conditions in the paper.

Engineering Tests

Engineering tests performed included volumetric shrinkage tests, three-dimension free swell tests, and total soil suction measurement tests. Brief details of these tests are provided in the following.

Volumetric Shrinkage Strain Test

Due to limitations in the linear shrinkage bar test, researchers utilized a three- dimensional volumetric shrinkage strain test method, originally developed at UTA by Puppala et al. (2004). This method uses a cylindrical compacted soil specimen, which was subjected to the drying process, and then measures volumetric, axial and radial shrinkage strains of the soil specimen by using a digital imaging technology. This test offers several advantages over the conventional linear shrinkage bar test: reduced interference of boundary conditions, the ability to test a larger amount of soil, and simulation of compaction states of different moisture contents and dry density conditions.

Volumetric shrinkage tests were thus conducted on all test soils to measure the decrease in the total volume of soil specimens due to loss of moisture content, from predetermined initial moisture content to a completely dry state. Specimens were prepared by mixing the clayey soil with the appropriate amount of water to achieve the designed moisture contents. After thoroughly mixing, soil specimens were compacted into cylindrical soil specimens of 5.7 cm. diameter and 12.7 cm. height molds. Soil specimens were then cured at room temperature conditions for twelve (12) hours and then transferred to an oven preset at a temperature of 105^{o}C for 24 hours (Figure 2). The average height and diameter of the shrunk soil specimen are then manually measured. The same soil specimen was subjected to digital imaging, and the images captured were analyzed to determine the areas and perimeter of the images in pixels. These results are used in the following Equation 1 to determine the final volumetric shrinkage strains. Figure 3 shows the digital images of the shrunk soil specimen. Further details on the image analysis can be found in Puppala et al. (2004).

$$V.S. = \frac{V_i - V_f}{V_i} = 1 - \frac{V_f}{V_i} = 1 - \left[\frac{A_{sf}}{A_{si}} * \frac{A_{cf}}{A_{ci}} * \frac{P_{ci}}{P_{cf}} \right] = 1 - \left(R_s * R_c * R_p \right) \qquad (1)$$

Where

R_s	=	ratio of surface area of the soil specimen = A_{sf}/A_{si}
R_c	=	ratio of circular cross-section area of soil specimen = A_{cf}/A_{ci}
R_p	=	ratio of the circular perimeter of the soil specimen = P_{ci}/P_{cf}
V_f	=	final volume of the cylindrical specimen
V_i	=	initial volume of the cylindrical specimen
A_{sf}	=	area of the final surface area of specimen after shrinkage in pixels
A_{si}	=	area of initial surface area of specimen before shrinkage in pixels

A_{cf}	=	area of final circular area of specimen after shrinkage in pixels
A_{ci}	=	area of initial circular area of specimen before shrinkage in pixels
P_{cf}	=	perimeter of the final circular area after shrinkage in pixels
Pci	=	perimeter of circular area before shrinkage in pixels

Equation 1 was used to determine the volumetric shrinkage strain by capturing and analyzing digital images of surface and aerial pictures of cylindrical soil specimen before and after the shrinkage test. Image analysis software was used for the analysis. Figure 3 presents surficial cracking of a soil specimen after the shrinkage test. As noted earlier, three states of compaction moisture conditions were simulated and studied.

Test results are expressed in terms of original volumetric shrinkage strain in percent values. Shrinkage strains in radial and vertical directions were first recorded and then used to determine volumetric shrinkage strains. Triplicate soil specimens were tested for each soil and moisture condition. Table 4 and Figure 4 present average values of volumetric shrinkage strain test results of all tested soils.

As expected, the highest magnitudes of volumetric shrinkage strain values were obtained for all clays compacted at wet of optimum conditions, which represents close to 90% of saturation conditions. At dry of optimum, the shrinkage strains are small, indicating lower shrinkage strain potentials at this state. Among test soils, clays sampled from Paris, Fort Worth, San Antonio districts in Texas have experienced larger strains than the other two soils at similar compaction conditions. This may be directly attributed to high MM content in these clays.

Volumetric Free Swell Test

The volumetric swell test was conducted on soil specimens to determine their maximum vertical, radial and volumetric swell potentials. Three different moisture content conditions, with densities corresponding to optimum, dry of optimum and wet of optimum moisture content conditions, were studied. A soil specimen of 10.2 cm. diameter and 11.7 cm. height, wrapped in a rubber membrane, was placed between two porous stones and then subjected to moisture soaking by inundating it with water from both ends (Punthutaecha et al., 2003). No seating pressure was applied during testing.

Figure 5 shows a photograph of this test in progress. Both vertical and radial swell movements were measured at various time periods by using ‘dial gauge’ and ‘Pi tape’ (Figure 5), respectively. Tests were terminated when there was no swell movement as indicated by dial gage readings for a period of six hours. All tests were conducted at room temperature conditions after similar curing at room temperature. Three identical soil specimens were used for each variable condition. Both test procedures were verified for repeatability, and the swell and shrink strain values for several identical specimens varied by a standard deviation of only 0.5%.

Typical test results are shown in Figure 6, depicting vertical, radial and total swell strains versus time elapsed during the test. The majority of swell strains in soils was observed within the first eight hours, and subsequent swell strains were continuously recorded until no swell movement was observed. Table 5 and Figure 7 present the average values of swell strain test results of all five soils. All four high PI clayey soil types (Fort Worth, San Antonio, Paris and Houston soils), have experienced large volumetric swell strain (more than 10%) at OMC condition, and these magnitudes considered are characterized as a very high degree of expansion potential as per the free swell strain characterization methodology given by Chen (1965). As expected, El Paso clay exhibited the lowest swell strain results due to the low plasticity properties (low PI) as well as low amounts of montmorillonite mineral content.

Suction and SWCC Measurements

Expansive soils are often characterized by the soil suction characterization methods due to their common occurrence in unsaturated conditions (Snethen, 1979b, Hamberg, 1985, and Lytton, 2004). Therefore, soil suction was measured on present soils at different moisture contents, which were later used to establish Soil Water Characteristic Curves (SWCCs). The SWCC describes a unique relationship between the matric suctions and compaction moisture contents of a given soil type. In unsaturated soil mechanics, the SWCC, known to depend on the size and distribution of pore structures in the soils, is used in direct and indirect interpretations of soil strength, permeability and volume change related characteristics (Fredlund et al. 1994). A few tests utilizing matric and total suction tests performed on the test soils, using the filter paper method, showed that both suctions are similar, indicating that the osmotic suction is small and practically negligible. As a result, matric suction methods are followed in the rest of the experimental program.

Filter paper and pressure plate methods are commonly used to determine 'Soil Water Characteristic Curves (SWCCs)' of unsaturated soils, which provides a relationship between the matric suction and compaction moisture content conditions of the soils. Hence, SWCCs studies were planned and performed on all five test soils. The limitation of the present pressure plate device used here was that it can only measure matric suctions up to 1,000 kPa. Hence, for high suction ranges, the filter paper method was followed, as this method can provide suctions larger than 1,000 kPa (Bulut et al. 2001). Overall, both pressure plate and filter paper test methods were utilized in the development of complete SWCC profiles of the test soils.

Figure 8 shows the photographs of a typical pore water extraction testing setup using a pressure plate apparatus. The primary components of the system are a steel plate pressure vessel and a saturated High Air Entry (HAE) ceramic plate. As shown, a small water reservoir is formed beneath the plate using an internal screen and a neoprene diaphragm. The water reservoir is vented to the atmosphere through an outflow tube located on top of the plate, thus allowing the air pressure in the vessel and the water pressure in the reservoir to be separated across the air-water interfaces bridging the saturated pores of the HAE material (Lu and Likos, 2004).

Soil specimens were initially saturated, typically by applying a partial vacuum to the air chamber and then allowing the specimens to imbibe water from the underlying reservoir through the ceramic disk. Air pressure in the vessel was then increased to some desired level while pore water was allowed to drain from the specimens in pursuit of moisture equilibrium. The outflow of water was monitored until it ceased, the pressure vessel was then opened, and the water contents of the soil specimens were measured, thus generating a one point on the soil-water characteristic curve. Subsequent increments in air pressure were applied to generate addition points on the curve using the other specimen.

For the filter paper method, a filter paper, Schleicher and Schuell No. 589-WH type, was suspended in the headspace above the soil specimen so that the moisture transfer from soil occurred in the vapor phase. The equilibrium amount of water absorbed by the filter paper is presented as a function of the pore-air relative humidity and the corresponding total soil suction. The water content of the filter paper was later measured after the test reached equilibrium condition after undergoing the vapor transmittal for a period of ten days. The suction was estimated from the moisture content of the filter paper using a calibration curve established by Bulut et al. (2001). By measuring the soil suctions at various compaction moisture content conditions, the soil-water characteristic curves were then drawn from low to high suction conditions. The combined SWCC test results of all soils from pressure plate and filter paper methods are presented in Figure 9 and 10.

SWCCs of all four high plastic soils exhibited similar characteristics. The only noticeable difference is that the saturated moisture content (at zero suction) of Houston clay is much lower than the other soils. This lower value indicates less ability to hold up water or moisture content, which implies that they do not undergo large swelling when hydrated. Overall, trends noted in the engineering swell, shrinkage and SWCC studies show a direct relationship with the chemical analyses results in particular specific surface area results and related clay mineralogy interpretations.

As seen by the above described experimental program, a large database of soil properties comprised of physical, mineralogical and engineering volume change properties and SWCC profiles was prepared. These test results were analyzed and studied for both evaluating the existing swell and shrinkage strain predictions and developing new models for predicting swell and shrinkage related volume changes in soils. These analyses and results will be included in the future paper.

SUMMARY AND CONCLUSIONS

The following lists a few of the major conclusions obtained from the present experimental program:

1. Among tested soils, three soils from Fort Worth, Paris and San Antonio contained moderate to large amounts of Montmorillonite, and these soils exhibited high plasticity index property. The soil from Houston contained a moderate amount of Montmorillonite, but still exhibited high plasticity index. The only exception was the soil from El Paso, which had low plasticity index property and contained low amounts of Montmorillonite.

2. Both volume change related swell and shrinkage studies have yielded test results that are not only repeatable due to low standard deviations, but also reliable, as they show the trends that are expected for different types of expansive soils. These tests, the shrinkage tests in particular, provide shrinkage strain potentials as a function of moisture content and dry unit weight conditions.

3. Soils with high plasticity properties experienced large volume changes during swell and shrinkage strain characterizations studies. This reconfirms the well established notion that high plastic soils are indeed mostly highly expansive.

4. Largest magnitudes of shrinkage volumetric strains were measured at wet of optimum moisture content conditions, and largest magnitudes of volumetric swell strains were recorded at dry of optimum moisture content conditions. These trends are expected as soils compacted at these moisture conditions are either close to dry conditions or full saturation conditions, and swell or shrinkage tests are expected to provide large and small magnitudes.

5. SWCCs of all four high PI soils exhibited similar suction characteristics. The only noticeable difference is that the saturated moisture content (at zero suction) of Houston clay is much lower than the other three soils. This lower value indicates less ability to hold up water or moisture content, which implies that they do not undergo large swelling when hydrated.

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Table 1 Basic Soil Properties

Property	**Soil Types**				
	Fort Worth	**San Antonio**	**Paris**	**Houston**	**El Paso**
Passing #40 (%)	100	100	100	100	100
Passing #200 (%)	85	83	81	87	88
Specific Gravity	2.7	2.7	2.7	2.7	2.7
Liquid Limit (LL, %)	61	58	60	54	30
Plastic Limit (PL, %)	24	22	23	21	14
Plasticity Index (PI, %)	37	36	37	33	16
AASHTO Classification	A-7-6	A-7-6	A-7-6	A-7-6	A-6
USCS Classification	CH	CH	CH	CH	CL

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Table 2 Chemical Measurements and Clay Mineralogy of Test Soils

Item	**Soil Types**				
	Fort Worth	**San Antonio**	**Paris**	**Houston**	**El Paso**
Specific Surface Area (m^2/g)	314	269	431	236	167
Cationic Exchange Capacity (meq/100 g)	117	96	133	76	57
Total Potassium (%)	0.96	1.08	0.78	1.56	3.78
% Illite	16	18	13	26	63
% Kaolinite	34	40	17	38	29
% Montmorillonite	50	42	70	36	8

Table 2 Standard Proctor Compaction Test Results of Test Soils

		Fort Worth	**San Antonio**	**Paris**	**Houston**	**El Paso**
Moisture Content (%)	**Wet of OMC**	33.0	31.8	33.0	27.3	20.0
	OMC	24.0	21.7	23.0	20.1	16.5
	Dry of OMC	15.1	10.5	13.0	12.9	13.0
Dry Density (kg/m^3)	**Wet of OMC**	1,392	1,392	1,402	1,507	1,704
	OMC	1,466	1,466	1,475	1,587	1,794
	Dry of OMC	1,392	1,392	1,402	1,507	1,704

Table 4: Volumetric Shrinkage Strain Test Results of Five Expansive Soils

Moisture Condition	**Parameter**	**Shrinkage Strain (%)**				
		Fort Worth	**San Antonio**	**Paris**	**Houston**	**El Paso**
Wet of OMC	**Vertical**	8.43	9.91	8.78	5.11	4.28
	Radial	8.87	9.66	9.45	7.37	3.55
	Volumetric	23.59	26.68	24.66	18.58	10.97
OMC	**Vertical**	5.29	6.98	4.92	2.25	1.86
	Radial	2.47	5.33	4.91	4.57	1.77
	Volumetric	12.51	18.08	14.04	10.97	5.30
Dry of OMC	**Vertical**	2.17	2.81	2.41	1.44	0.36
	Radial	0.97	2.13	1.46	1.75	1.50
	Volumetric	5.22	7.55	6.15	4.85	3.33

Note: OMC – Optimum Moisture Content

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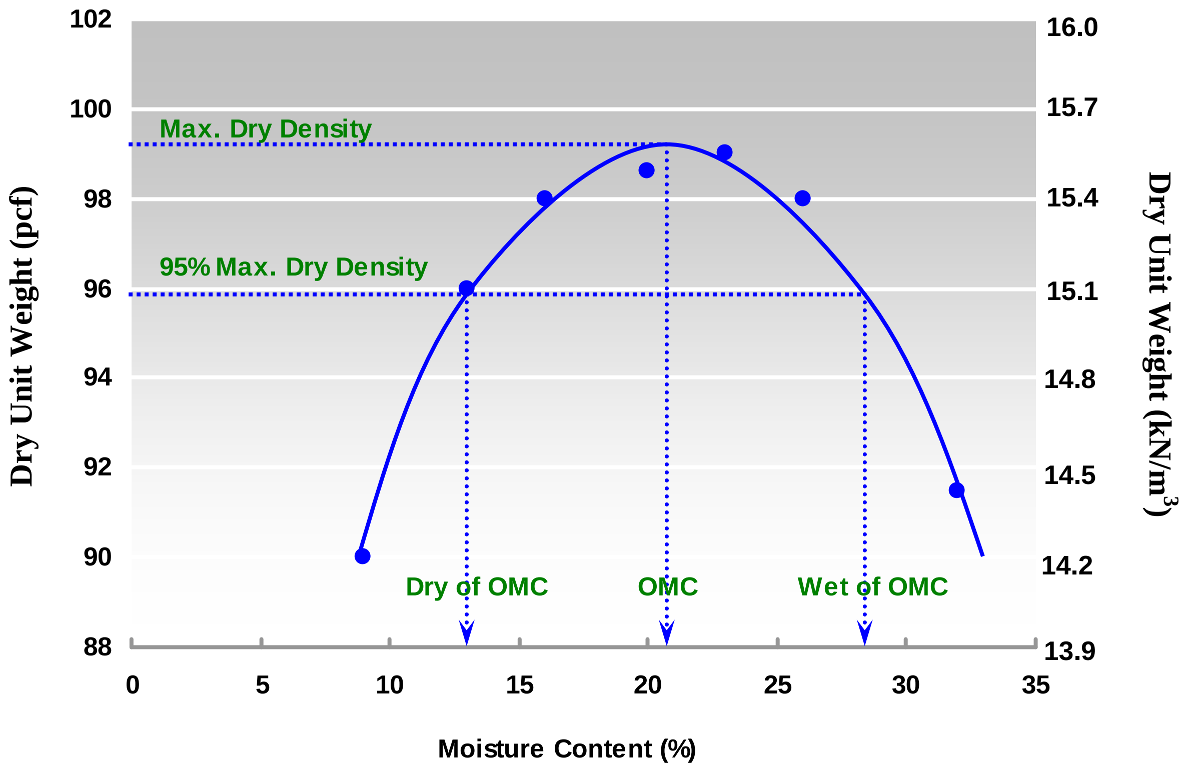
Table 5: Volumetric Swell Strain Test Results

Moisture Content Condition	Parameter	Volumetric Swell Strain (%)				
		Fort Worth	San Antonio	Paris	Houston	El Paso
Wet of OMC	Vertical	3.63	2.99	1.43	4.14	1.47
	Radial	1.95	1.95	1.51	1.63	0.81
	Volumetric	7.71	7.04	4.50	7.56	3.11
OMC	Vertical	9.28	6.98	7.37	6.71	2.43
	Radial	3.46	3.80	3.60	3.81	1.27
	Volumetric	16.97	15.27	15.25	14.99	5.04
Dry of OMC	Vertical	14.13	14.92	14.35	11.44	4.51
	Radial	4.26	5.93	5.36	4.49	1.76
	Volumetric	24.07	28.95	26.93	21.69	8.23

Note: OMC – Optimum Moisture Content



Remark *OMC = Optimum Moisture Content
Figure 1: Compaction Moisture Content Conditions

(a) (b)

Figure 2: Volumetric Shrinkage Test Specimen (a) Before Oven Drying and (b) After Oven Drying

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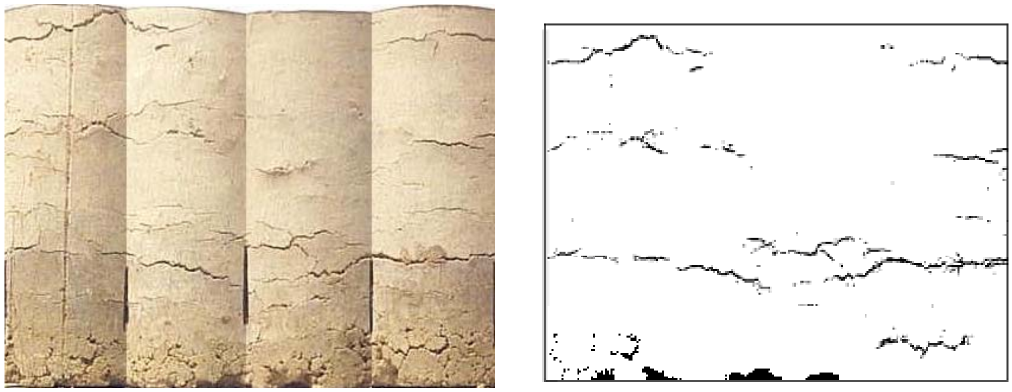

(a) (b)

Figure 3 (a) Typical Photograph of a Soil Specimen Surface Area with Cracks after Test, (B) Threshold Image of the Surface Area Showing only Cracks

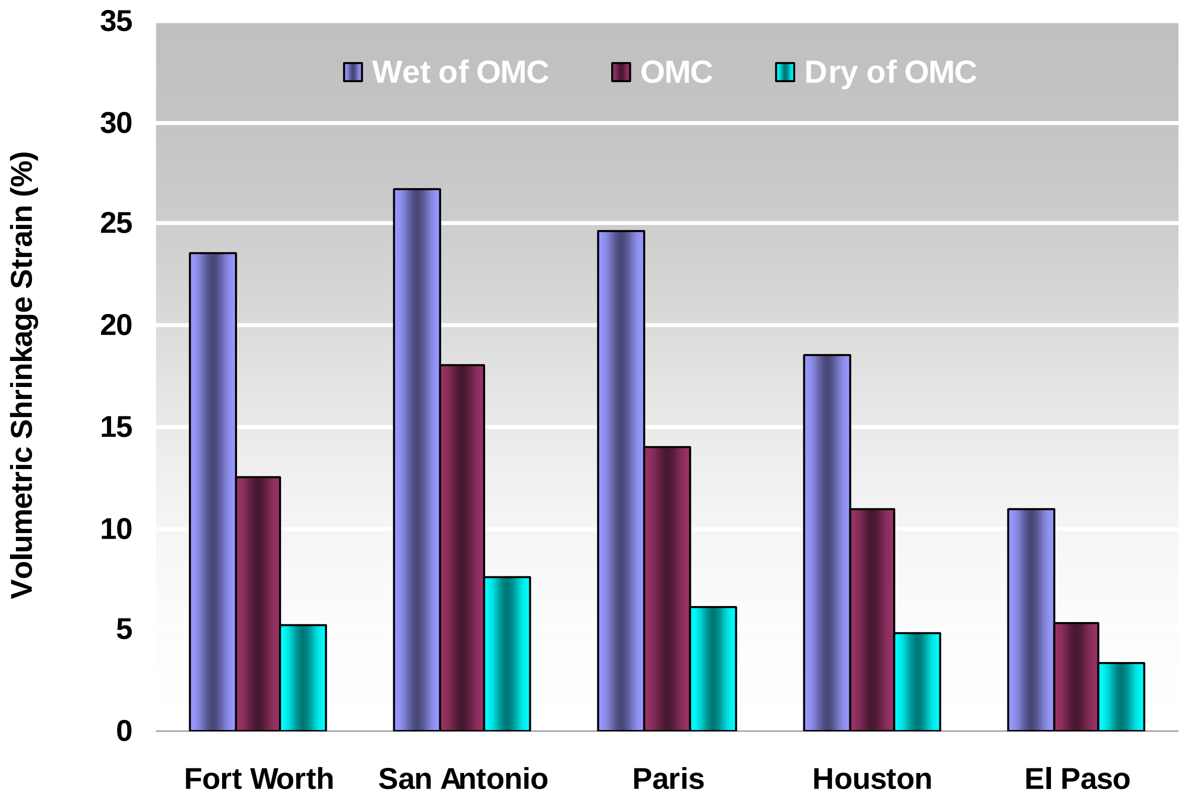

Figure 4: Volumetric Shrinkage Strain Test Results of Five Soils

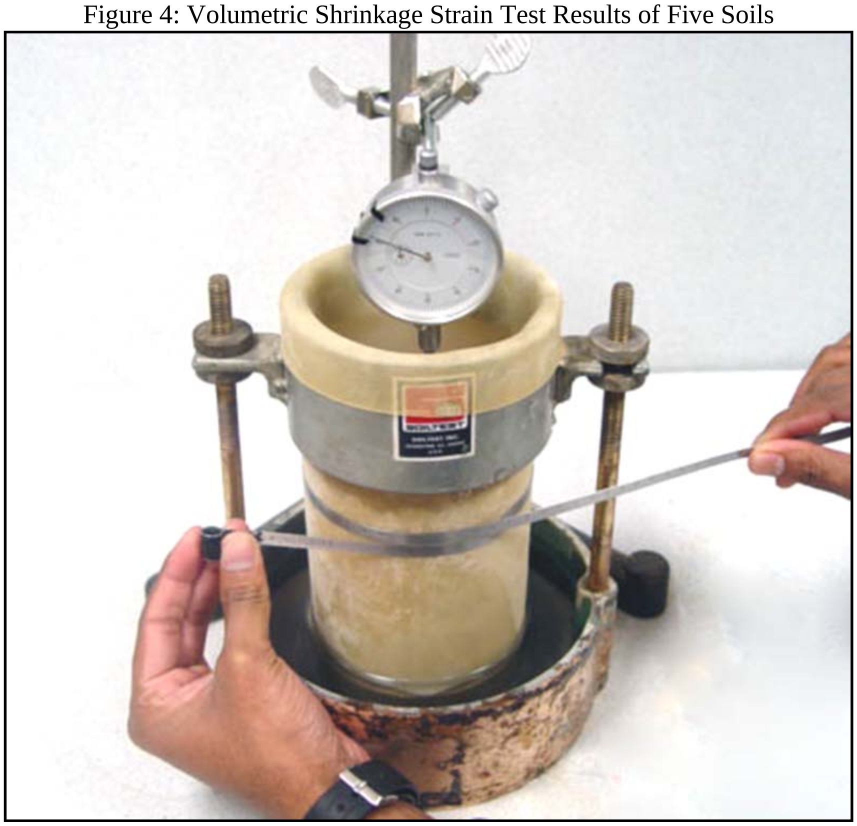

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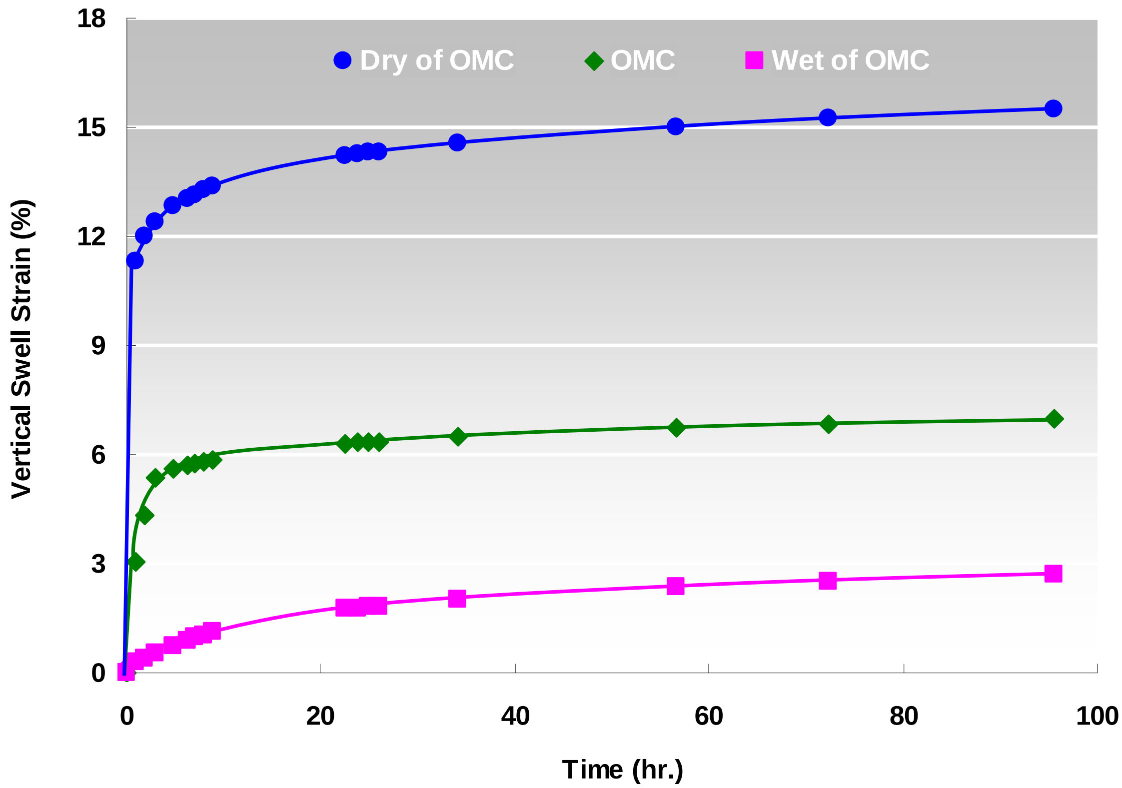
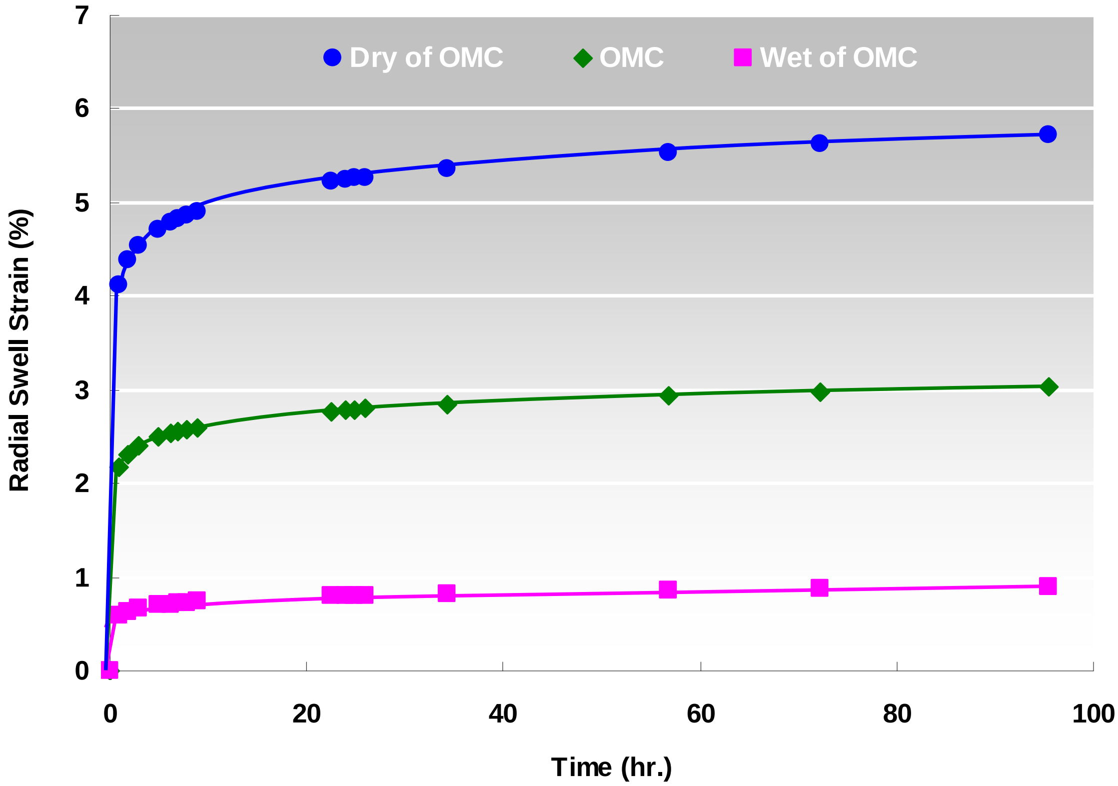
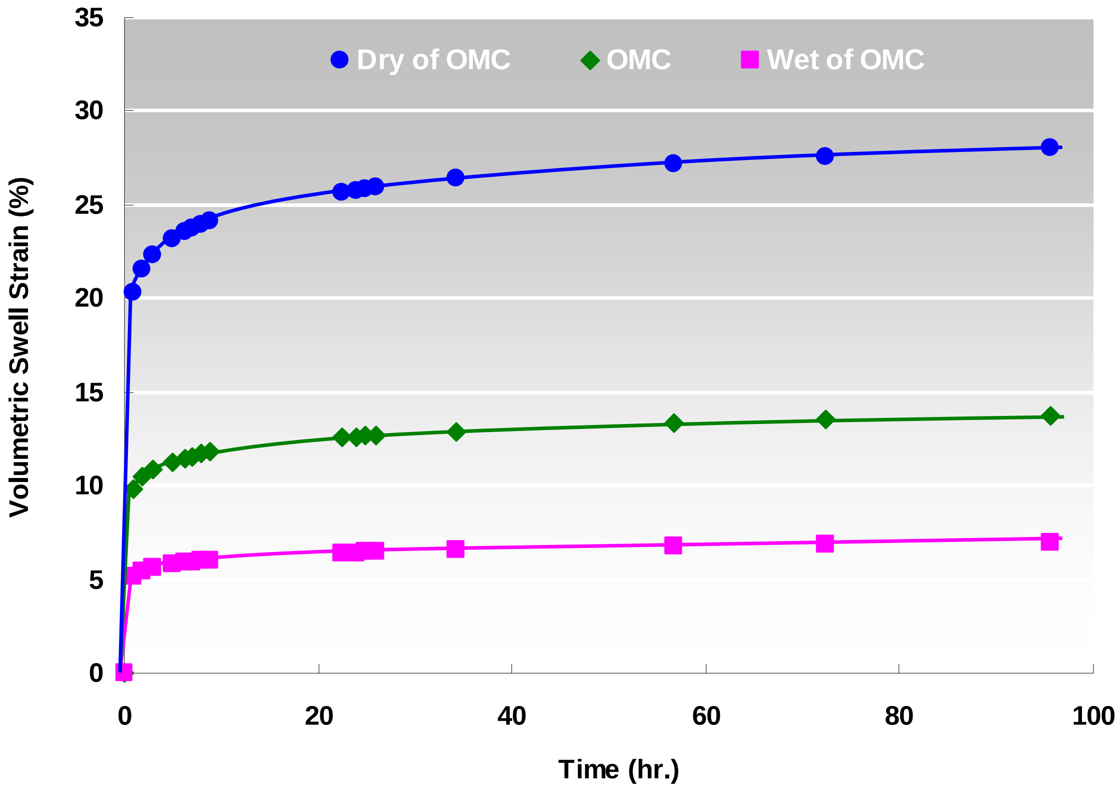
Figure 5: Three-Dimensional Volumetric Free Swell Test Setup



a) Vertical Swell Strain Results



b) Radial Swell Strain Results



c) Volumetric Swell Strain Results

Figure 6: Typical Laboratory Volumetric Swell Strain Test Results of San Antonio Soil

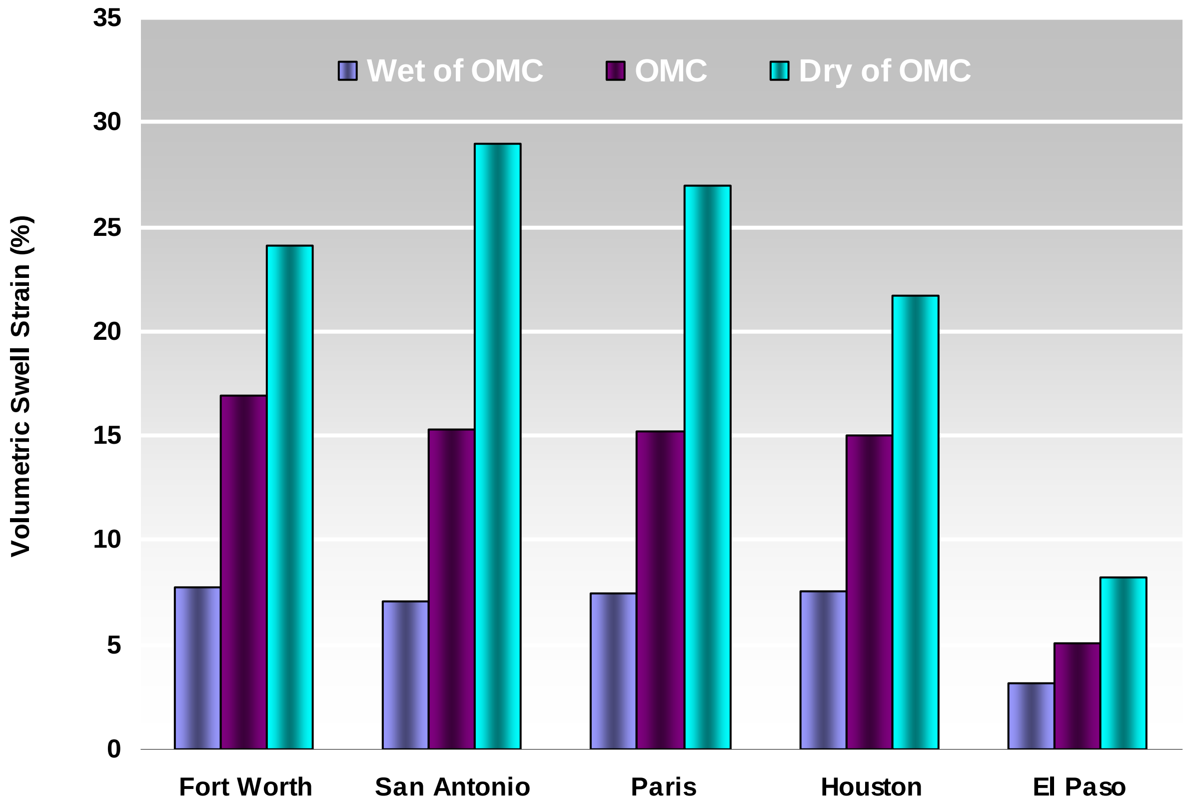
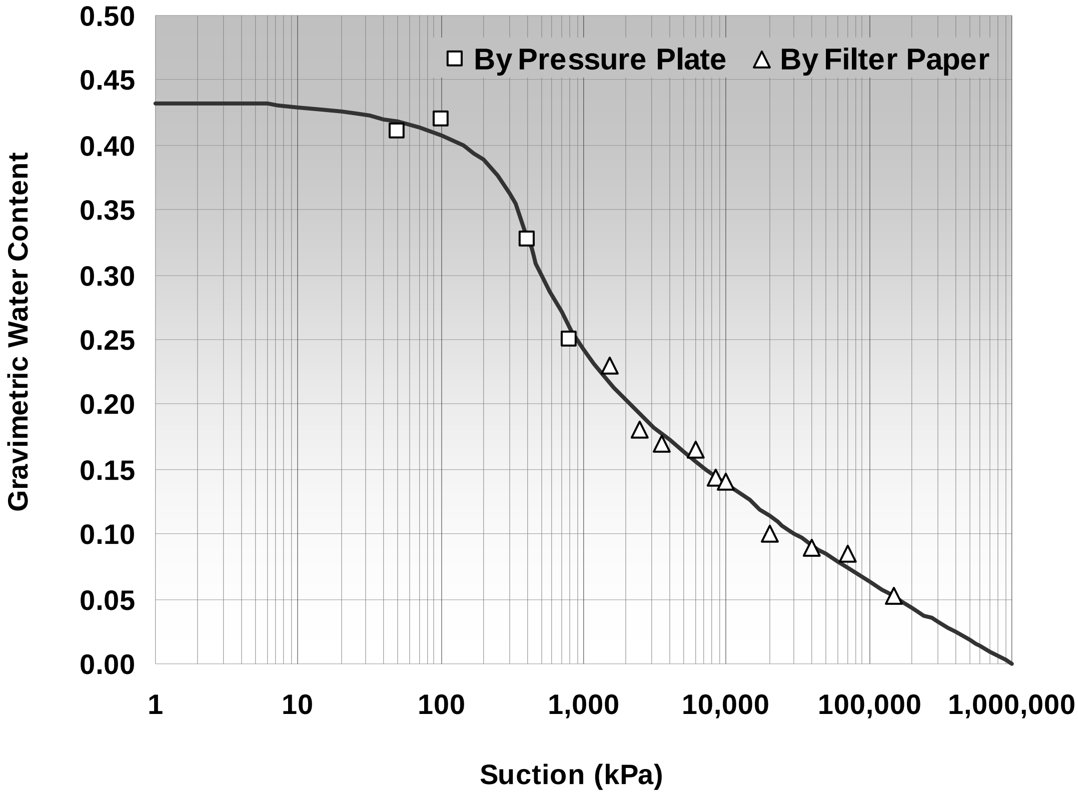


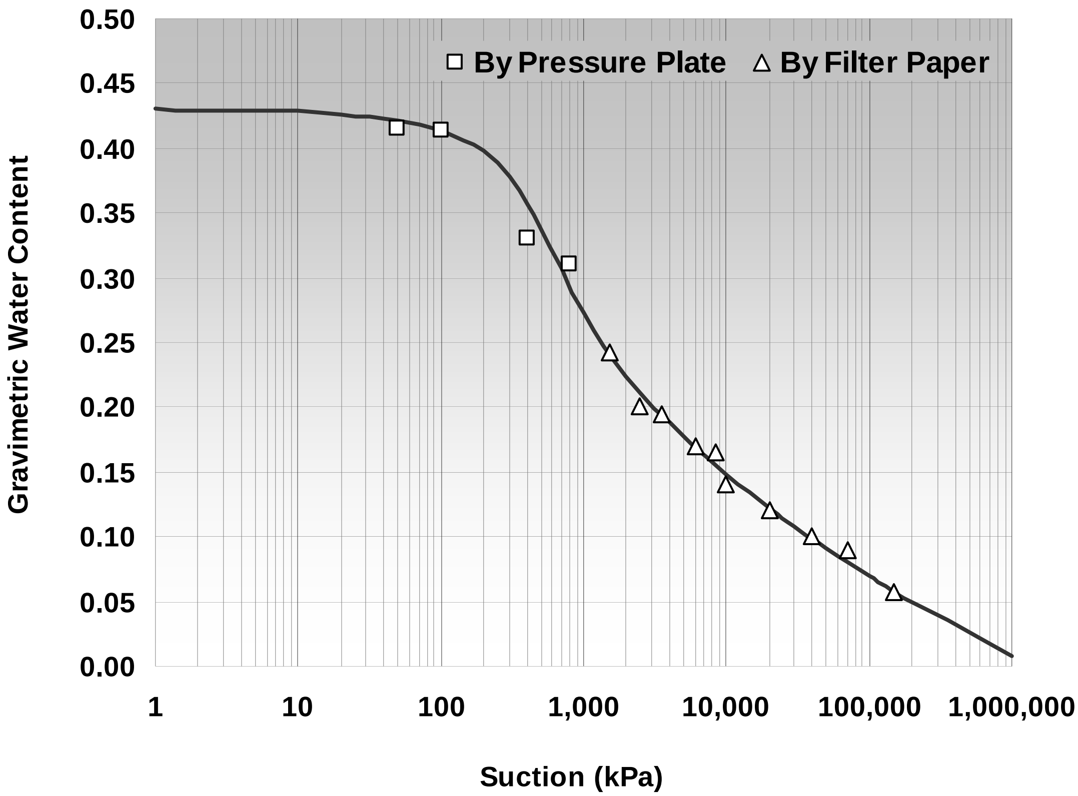
Figure 7: Volumetric Swell Strain Test Results of Five Soils

(a) (b)

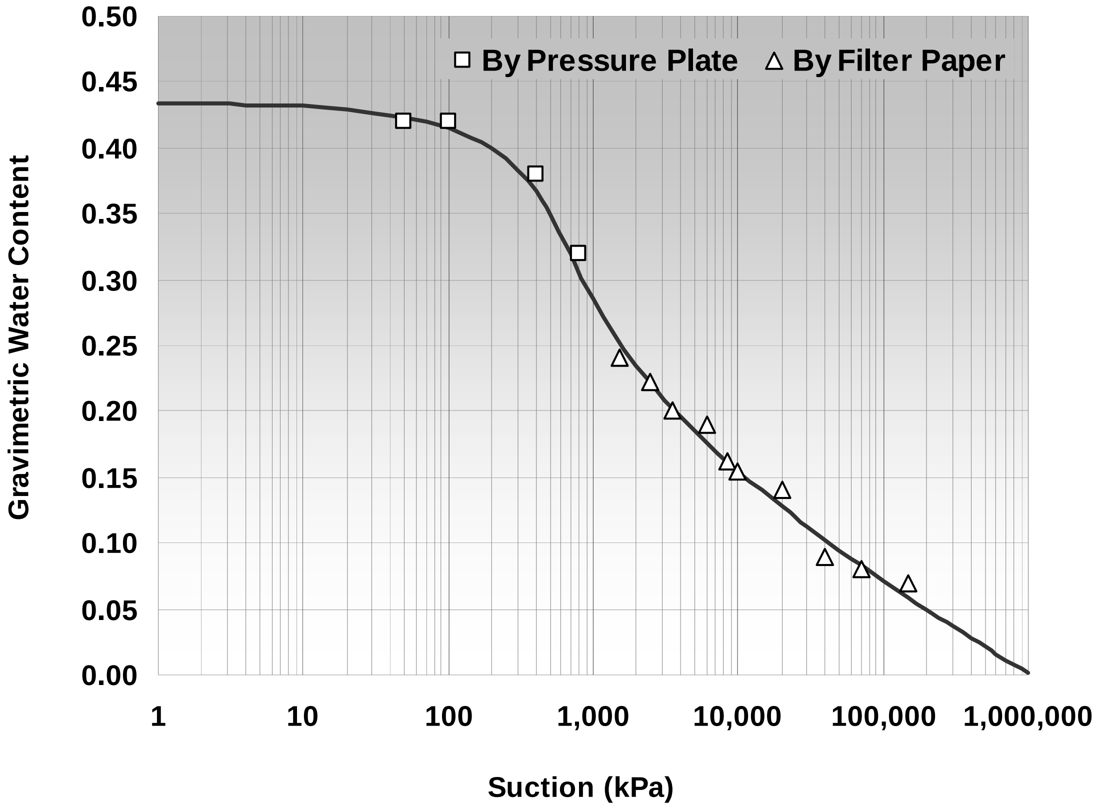
Figure 8: Pressure Plate Testing (a) Initial Setup of Testing Specimens and (b) Closed Pressure Vessel with Air Pressure Applied



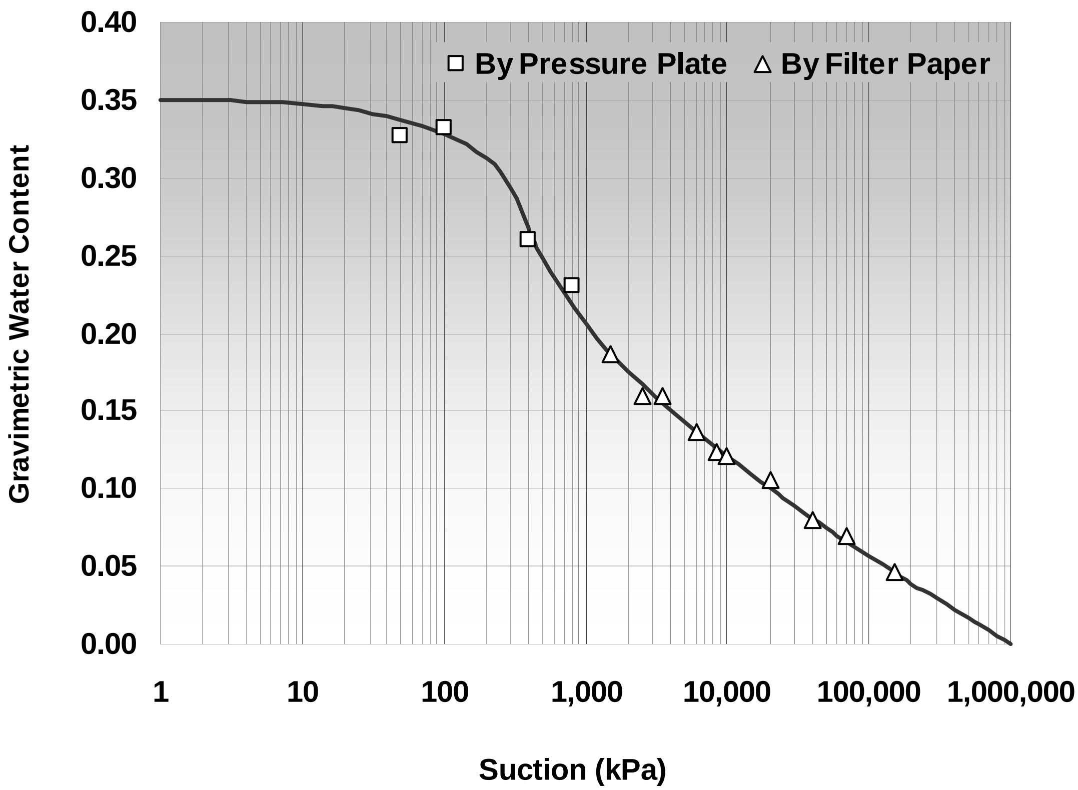
a) Fort Worth Soil



b) San Antonio Soil



c) Paris Soil



d) Houston Soil

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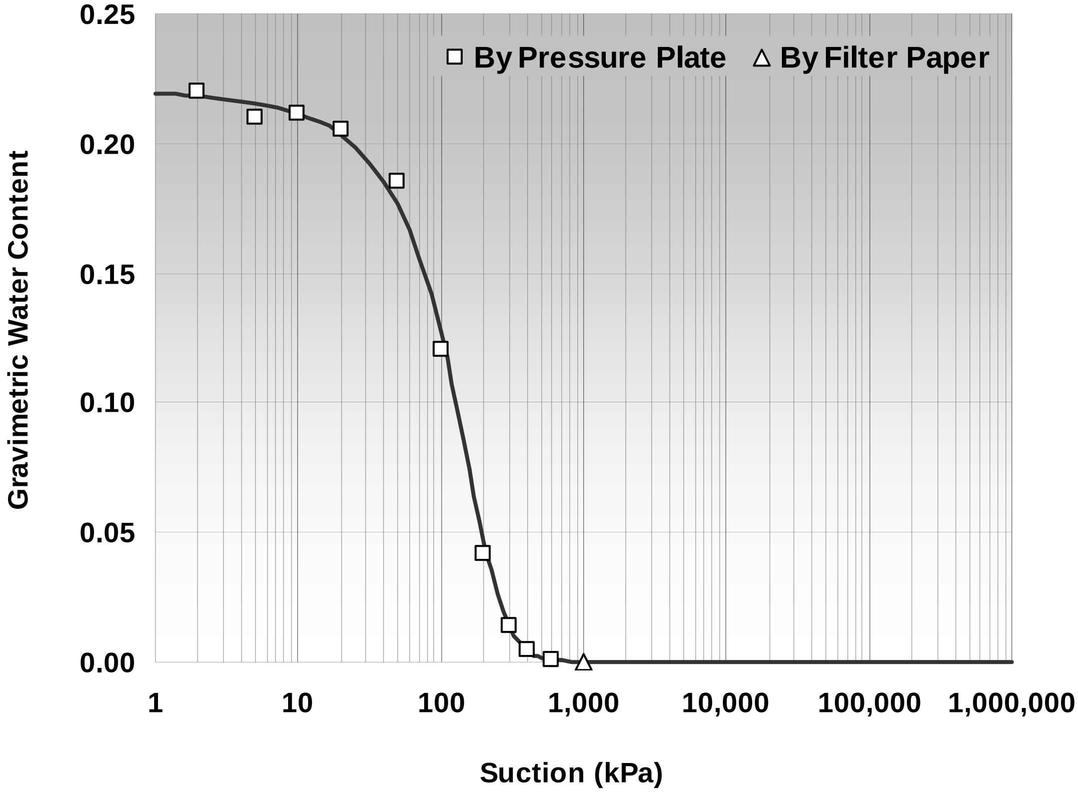

e) El Paso Soil

Figure 9: Soil Water Characteristic Curves of Expansive Soils

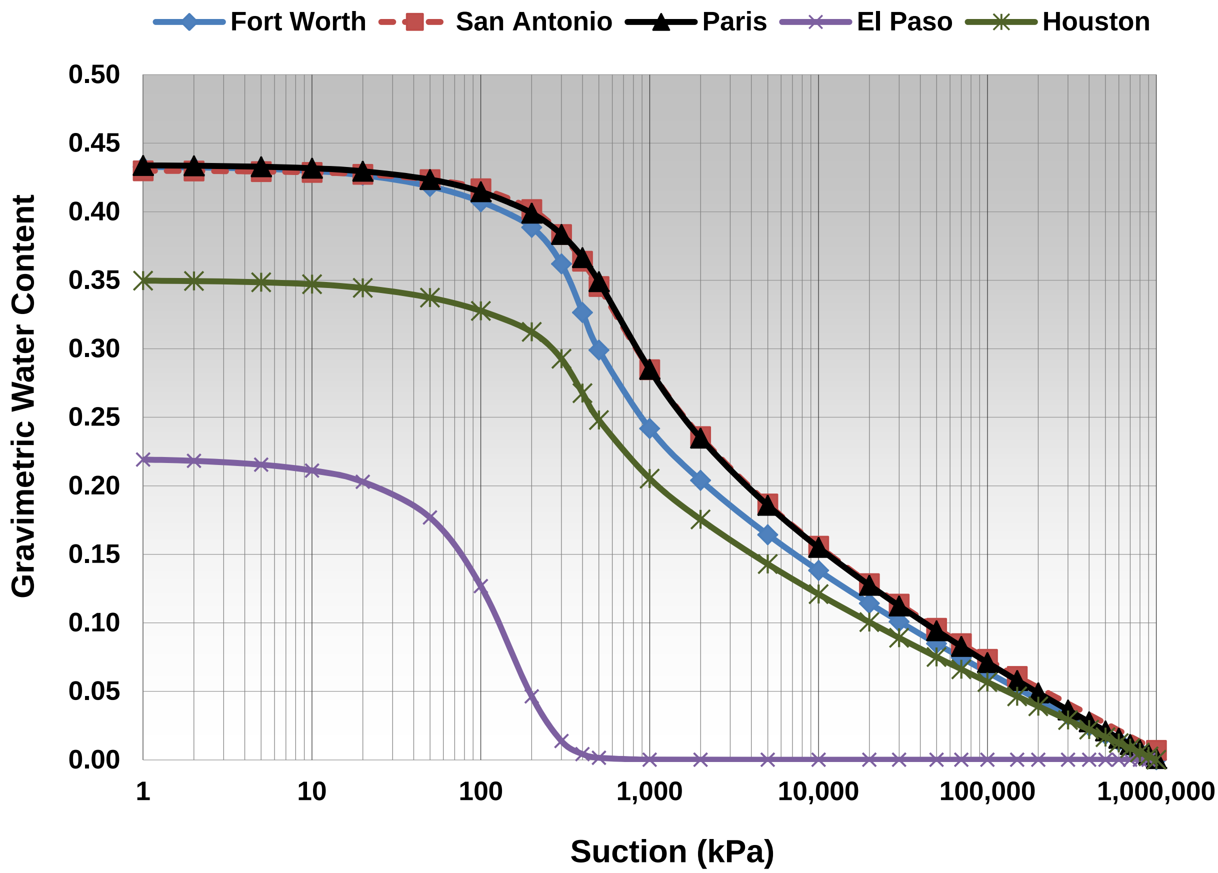

Figure 10: Combined Plots of Soil Water Characteristic Curves of Five Soils