CENTER FOR INFRASTRUCTURE ENGINEERING STUDIES

Evaluation and Utilization of the WP4 Dewpoint PotentiaMeter Phase I & II

By

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The University of Missouri-Rolla

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Technical Report Documentation Page

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16. Abstract

1. Select and sample subject clay soil(s) to use for evaluation. 2. Determine the basic physical properties of the subject soil(s). Suggest multiple tests for selected properties to be determined on representative samples. Index Properties: Atterberg Limits, Linear Shrinkage, Grain Size Distribution, Compaction Characteristics, Swell Potential at various water contents. 3. Using both the WP4 and the Filter Paper method, determine the water content–soil suction curves for the soil(s). 4. Determine a way(s) to differentiate, through testing, the matric and osmotic suction of the soil(s) at differing water contents, using the WP4 and Filter Paper method. 5. Using the subject soil(s), make up large, homogeneous samples to be distributed to test laboratories volunteering to conduct a specified test protocol using the WP4. 6. Synthesize the results of the Round-Robin Testing and provide a report to the participants. 7. Develop a testing protocol and testing standard for the use of the WP4 for measurement of clay soil suction.

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Final Project Report:Evaluation and Utilization of the WP4 Dewpoint Potentiameter

EXECUTIVE SUMMARY

The potential use of the WP4 dewpoint potentiamenter to determine total suction of expansive clay soils has been substantiated by initial testing by the Principal Investigator, as shown in the paper in the Appendix. This project provided further evaluation using a process of Round-Robin testing of prepared specimens of three expansive clay soils at three water content-dry unit weight configurations. One soil came from Texas, one was sampled in New Mexico and the third one came from Missouri. Seven geotechnical laboratories evaluated the suction characteristics of the nine specimens provided and returned their results to the UMR Geotechnical laboratory. There were involved three geotechnical companies from Texas, one geotechnical company from each of Colorado and New Mexico, the geotechnical engineering laboratory at BYU and the UMR Geotechnical laboratory. The results indicate that the relationships of total suction to soil moisture as defined by the WP4 device had significantly less variance and provided slightly more conservative values of suction, when compared to the filter paper method. Research to separate the osmotic and matric suction components of total suction using the WP4 is ongoing. The Round-Robin test results clearly support a revision of the most current ASTM testing standard for use of the WP4 device.

INTRODUCTION

Expansive clays exhibit high potential for volume change whe changes in soil moisture occur. It has been estimated that the annual const of damage to facilities built on expansive clay in the United States exceeda $9 billion. The use of expansive soil suction measurements to predict potential clay volume changes has shown significant promise, yet the currently utilized method to determine soil suction, the filter paper method, has serious drawbacks. The first is that the test takes approximately 8 days to complete, making it less than practical for broad use by practicing engineers. The second, and more troublesome fact is that the filter paper test is difficult to conduct successfully and the results are significantly affected by small differences in procedure, which are all in agreement with the ASTM standard still in use by engineers, even though it was rescinded by ASTM while the reported research was ongoing.. The WP4 dewpoint potentiometer has been shown to provide total soil suction measurements that are very consistent and repeatable within 24 hours. Successful demonstration of the effectiveness of the WP4 device has the potential of providing a method for all geotechnical engineers to use soil suction for all project situations, thereby, reducing the cost and increasing the reliability of predicting clay soil volume change. The current ASTM standard for measurement of soil suction allows its use, yet does not specify how it should be used.

PURPOSE

The purpose of this research was to fully evaluate the potential of the WP4 Dewpoint PotentiaMeter for use in predicting expansive clay behavior and to eventually submit a standard procedure for Its use to ASTM for possible revision of ASTM standard D 6836. This was to be done using a Round-Robin test sequence, involving as many as 10 university and practicing geotechnical engineering laboratories from five differing states where expansive clays are found. The results were to be published in the ASTM testing journal and a proposed revision of the standard was to be offered for ASTM consideration. A supplemental task was the determination of a method to use the WP4 and other simple methods to split out the components of total suction – osmotic and matric suctions.

LABORATORY TEST PROGRAM

Soil Specimen Manufacture

The soils chosen for the research were from Texas, New Mexico and Missouri. The soils were provided to the geotechnical engineering laboratory at the University of Missouri-Rolla. Upon arrival each soil was air dried and processed thru a Number 4 U.S, Series sieve. These soils will be referred to throughout this report by #1 for the Missouri soil, #2 for the Texas soil, and #3 for the New Mexico soil.. The Missouri soil came from a building site at the Rolla, Missouri industrial park, east of the city, off Interstate Highway 44. The Texas soil was sampled from an area of Grand Prairie, Texas and contained materials weathered from the Eagle Ford geologic formation. The New Mexico soil was provided by Gordon Mckeen.

Testing Procedure

Eight different laboratory tests were conducted on the three subject soils. The laboratory tests were:

- Atterberg Limits (ASTM D 4318) (Linear Shrinkage determined by the TXDOT method)
- Standard compaction (ASTM D698)
- Soil Suction Testing (ASTM D 5298) (Standard Rescinded but still in use by Geotechnical Engineers)
- WP4 Dewpoint Potentiameter testing (ASTM D 6836, using developed protocol)
- Determination of Soluble and Exchangeable Salts (Standard Soil Chemistry Methods)
- X-Ray Diffraction of the Clay Portions (Standard Crystallography Methods)

Atterberg limits – The standard ASTM procedure was followed for Atterberg limits testing. A four point liquid limit test procedure was used to develop the liquid limit curve. Linear Shrinkage potential was determined as well.

Standard compaction – Generation of the optimum moisture content vs. dry unit weight curve for these soils was constructed using five moisture content/unit weight data points.

.*Soil Suction testing* - The former ASTM procedure as adapted through experience was utilized. This procedure is further explained in the paper in the appendix. The procedure used for WP4 device testing was as described in the paper in the appendix.

Soil chemical testing and X-ray diffraction testing were delayed by equipment availability. The procedures used were standard for extraction of soil chemical constituents and an Atomic Absorption Flame Spectrophotometer was used to assess the ion concentrations. X-ray diffraction was done in the laboratory of the Department of Geology and Geophysics at UMR, using their standard procedures.

Separation of osmotic and matric suction as components of total suction is on going as a research subject. Currently, it is thought that the use of electrical conductivity or evaluation of saturation extracts may provide suitable results.

GENERAL SOILS RESULTS

The general soils properties results will be presented in three parts. The first part will cover the measured physical properties of the soils, the second will include the soil chemical properties found, and the third will illustrate the x-ray results determined.

Physical Properties

The physical properties measured for the three research soils are shown in Table 1, below. The Missouri soil and Texas soil were found to have Atterberg Limits classifying them as CH, using the USCS system. The New Mexico soil was classified as CL, or moderately plastic clay. The linear shrinkage determined for each of these soils as they dried from about their liquid limit, show them to have moderate potential shrinkage activity. The standard effort compaction results show the New Mexico soil to be the most easily compacted and the other two having similar compaction characteristics.

Swelling potential tests were conducted for each soil at differing moisture levels, and similar dry unit weights to see how they would expand under 150 psf pressures. Table 2 through 4 show the final results of these tests. The Texas soils exhibited the larges swell potential, while the New Mexico soil showed the least. It is important to note that all of these active soils can express damaging heave when they take on moisture when relatively dry.

Table 1. Index Properties of Test Soils

Test Soils	USCS Classification	Linear Shrinkage (%)	Atterberg Limits[b]			Standard Proctor Compaction[c]	
			PL (%)	LL (%)	PI (%)	OMC (%)	γ_{dmax} (pcf)
Soil#1 Missouri Clay	CH	11.6	21.7	50.3	28.6	21	99.6
Soil#2 Texas Clay	CH	13.4	24.1	67.7	43.6	23	99.0
Soil#3 New Mexico Clay	CL	10.5	19.7	39.2	19.5	20	103.0

[a]Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) (ASTM D 2487, 2000).
[b]Plastic Limit, Liquid Limit, and Plasticity Index (ASTM D 4318, 2000).
[c]Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (ASTM D 698, 2000a).

Table 2. Missouri Soil Vertical Swell

Initial W.C. (%)	Initial γ_d (pcf)	Vertical Swell (%)	Final W.C. (%)	Final γ_d (pcf)
13.8	94.6	4.9	30.6	90.1
18.3	98.9	3.8	29.6	92.6
21.4	100.8	0.9	26.0	98.1
22.9	99.5	0.3	25.6	98.81
25.0	94.4	0.3	31.4	100.9

Seating Pressure : 150psf

Table 3. Texas Soil Vertical Swell

Initial W.C. (%)	%	Vertical Swell (%)	Final W.C. (%)	Final γ_d (pcf)
13.8	95.3	10.5	36.3	85.9
18.0	100.0	9.8	34.7	90.4
22.4	104.2	7.0	N/A	N/A
24.8	97.0	5.0	31.3	91.7
30.2	90.2	2.4	34.3	88.0

Seating Pressure : 150psf

Table 4. New Mexico Soil Vertical Swell

Initial W.C. (%)	Initial γ_d (pcf)	Vertical Swell (%)	Final W.C. (%)	Final γ_d (pcf)
12.8	104.8	2.6	24.1	101.2
16.4	103.2	0.6	21.9	102.1
21.6	101.2	0	24.3	100.5

Seating Pressure : 150psf

Chemical Properties

Two types of chemical properties were determined for the research soils. An extraction of pore water cations was made using a 1:1, dry soil to DI water, suspension. An extraction of the cations in the exchange complex was done by using Ammonium Acetate and several washings. The quantities of extracted fluids were measured during the process. The concentrations of cations of the four major types, Calcium, Sodium, Potassium and Magnesium, in each fluid specimen were determined using Atomic Absorption Flame Spectrophotometry. The milliequivalents of pore water cations per liter of extract and milliequivalents of exchangeable cations per 100 g of dry soil were calculated from the fluid concentrations found. Table 5 and 6 contain the results of this testing. The results shown are the mean values of 8 tests.

Table 5

Pore water cations (meq/l)

Soil Type / Cations	Ca2+	Na+	K+	Mg2+
Soil#1-Missouri Soil	0.02	1.10	0.05	0.05
Soil#2-Texas Soil	4.15	2.23	0.60	1.91
Soil#3-New Mexico Soil	0.96	1.94	0.03	0.10

Table 6

Exchange Complex Cations (meq/100gm)

Soil Type / Cations	Ca2+	Na+	K+	Mg2+
Soil#1-Missouri Soil	18.70	0.59	0.36	4.86
Soil#2-Texas Soil	88.10	0.83	0.96	4.76
Soil#3-New Mexico Soil	74.79	0.66	0.43	2.81

X-Ray Diffraction Results

The X-ray diffraction testing was done in the Clay Mineralogy laboratory of the Department of Geology and Geophysics at UMR. The procedures used were standard for this type of analysis and according to the laboratory's protocols. Figures 1 through 3 are the diffractograms for the research soils with indications of the minerals found.

The Missouri soil contains a mixture of clay minerals, including Illite, Chlorite and Kaolinite. It is likely that the active nature of this soil comes from its Illite and Chlorite constituents. The Texas soil contains mostly Montmorrilonite (Smectite) and Kaolinite. This is in agreement with several past analyses of this soil. Its activity is likely a result of the Smectite present and from the fact that it is heavily overconsolidated. The New Mexico soil contains clay constituents of both sodium and calcium Montmorrilonite, which account for its activity.

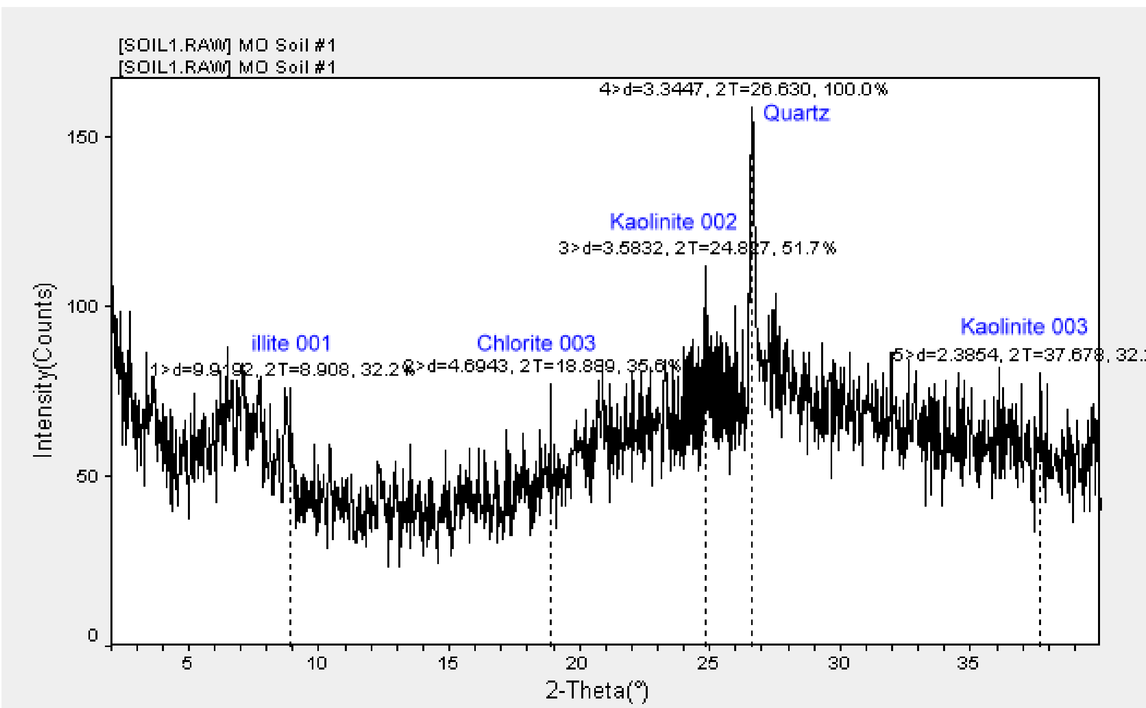


Figure 1. X-Ray results for the Missouri Soil

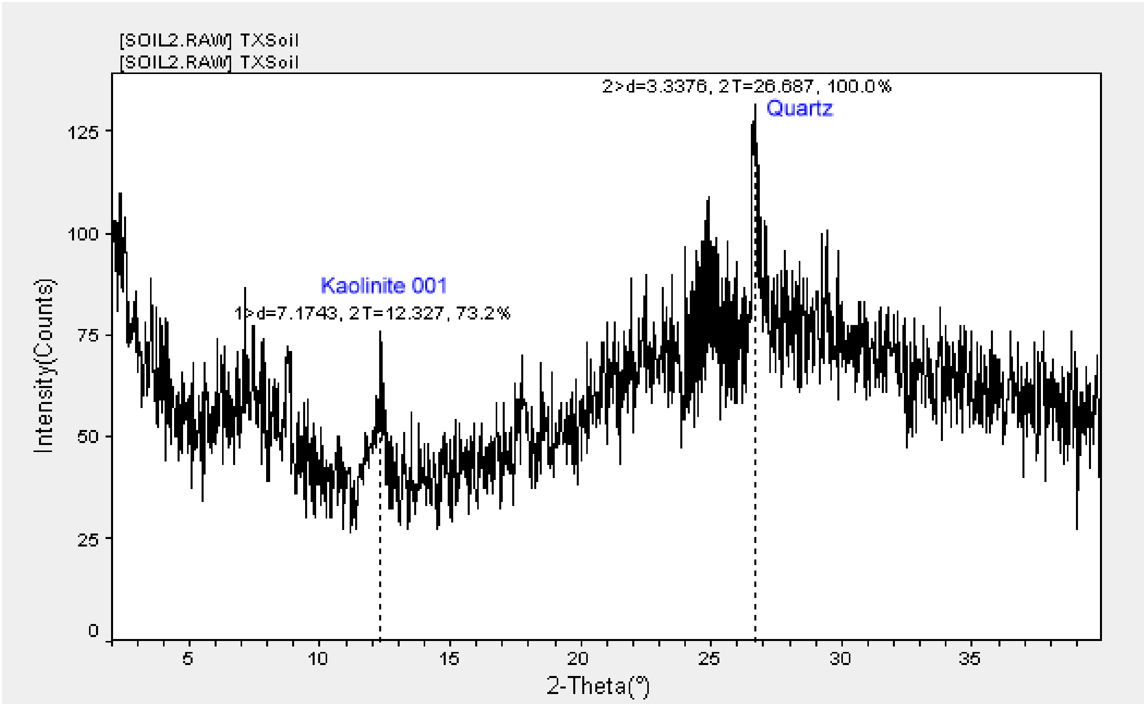


Figure 2. X-Ray Results for the Texas Soil

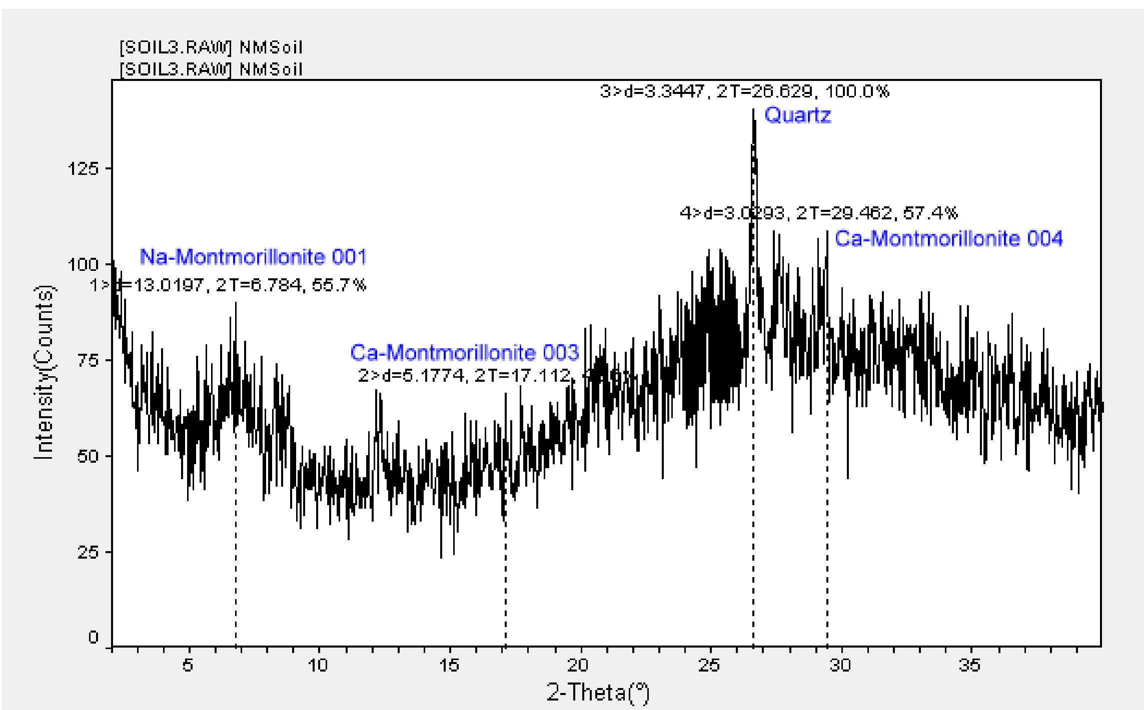


Figure 3. X-Ray Results for the New Mexico Soil

ROUND-ROBIN SPECIMENS

Information was developed about how the dry unit weight of the soils from Texas and from Missouri varied as compacted near their optimum water content then allowed to vary water content both up and down. The New Mexico soil was compacted at about its plastic limit, which would be nearly the same as its optimum water content for Standard Proctor compaction and its dry unit weight was determined. An approximation of the change in dry unit weight of the New Mexico soil with changes in water content up and down from this optimum was developed, using the average changes for the other two soils.

Water contents were chosen at nearly the plastic limit, significantly above the plastic limit and significantly below the plastic limit for each soil. Then a prediction was made for the resulting dry unit weights using the relationships as described immediately above. Specimens of approximately 2 to 3 inches high and 2 ½ inches in diameter were then molded using static compaction force. Large quantities of each soil were brought to the required water contents and placed in double sealed plastic bags. The water contents of the soils were allowed to equilibrate for several days. Then representative samples of soil, in each of the nine cases, were taken out and weighed, being careful to prevent moisture loss. Each sample was then compacted to the desired unit weight in the mold using static force, while the height of the specimen was controlled. A required weight of equivalent dry soil was placed in the known volume of the mold to provide, for each set, nine cylinders at the prescribed unit weights and water contents.

The specimens were sealed and allowed to equilibrate in moisture until packaging and mailing. In each case, nine specimens, three for each soil at differing prescribed unit weights and water contents, were sent to each laboratory in the Round-Robin group.

The Round-Robin Group consisted of three geotechnical engineering company laboratories located in the Dallas-Fort Worth, Texas area, one geotechnical engineering company laboratory from the Denver, Colorado area, and three geotechnical laboratories associated with universities, in New Mexico, Utah and Missouri. Each laboratory in the study has a designation used on all the graphs below. Bryant Consultants, Inc. of Carrollton, Texas is designated by “BC”. CTL Thompson, Inc. of Denver, Colorado is designated as “CTL”. The designation for Reed Engineering Group of Dallas, Texas is “REG”. The University of Missouri-Rolla geotechnical laboratory or the Department of Civil, Architectural and Environmental Engineering is designated by “UMR”. The results provided by Glenn C. Goss, Ph.D.,P.E. of Arlington, Texas are designated as “Goss”. McKeen Consulting Engineers and the University of New Mexico, Civil Engineering Department provided results that are designated by “McKeen”. Those results provided by the geotechnical laboratory of the Civil and Environmental Engineering Department of Brigham Young University or Utah are designated “BYU”. The efforts of all the individuals who have contributed to this study are essential to its success and the authors wish to thank them wholeheartedly for their contributions.

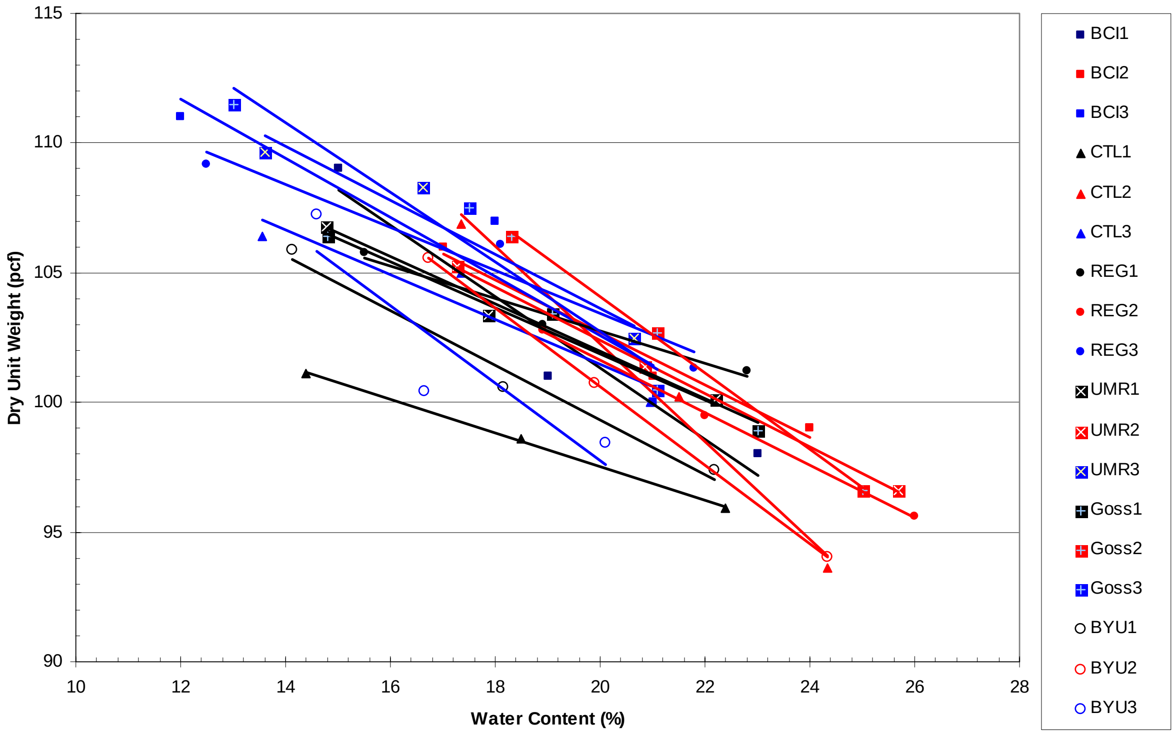
Each laboratory was asked to provide information on their calibration techniques for the filter paper method. All but one of the laboratories calibrated their filter paper, using salt solutions, using the types of filter paper suggested in the previous ASTM standard. Some used VWR filter paper and calibrated it themselves. Only one, commercial laboratory used the calibration as shown in the previous ASTM standard. Many of these individuals, with whom the authors have had personal contact, have indicated the kind of problems with the filter paper method which eventually have lead to its standard being rescinded by ASTM.

ROUND-ROBIN RESULTS

The Round-Robin results of soil suction testing will be presented in differing ways. However, the results of any one laboratory will not be presented by themselves. Indications of the variance to be expected for soil suction testing are what has been sought by this study. Figures 4 through 11 indicate the nature of these variances and the relative results using the filter paper method and the WP 4 Dewpoint Potentiameter.

Figure 4 indicates the scatter of the dry unit weight and water contents for all three soils when determined during suction testing. This data appears to have acceptable variance, especially considering the delays of mailing and testing. The plan was to provide as nearly identical specimens to each laboratory and this figure shows that this part of the project was reasonably acceptable.

Figure 4. DUW vs. Water Content For Three Soils



Figures 5 and 6 are the plots of soil suction as determined by each method versus the water content of the specimens for all three soils together. The groupings of data for each soil show the variance between laboratories and the variance for each laboratory. It is clearly evident that the results provided by using the WP 4 device are slightly more conservative and have significantly less variance than those provided using the filter paper method.

Figures 7 through 9 are plots of soil suction versus water content for each soil separately, yet with both the WP4 data and filter paper method data together. These plots have with them the correlation coefficients, R^2, and equations of the lines for each laboratory's data. The R^2 results are excellent, although consisting of only three points. What is more important is the relative agreement of the data from almost all the laboratories. In these graphs the WP 4 derived results are very consistent, supporting the use of this device, especially since its use is relatively quick and error free.

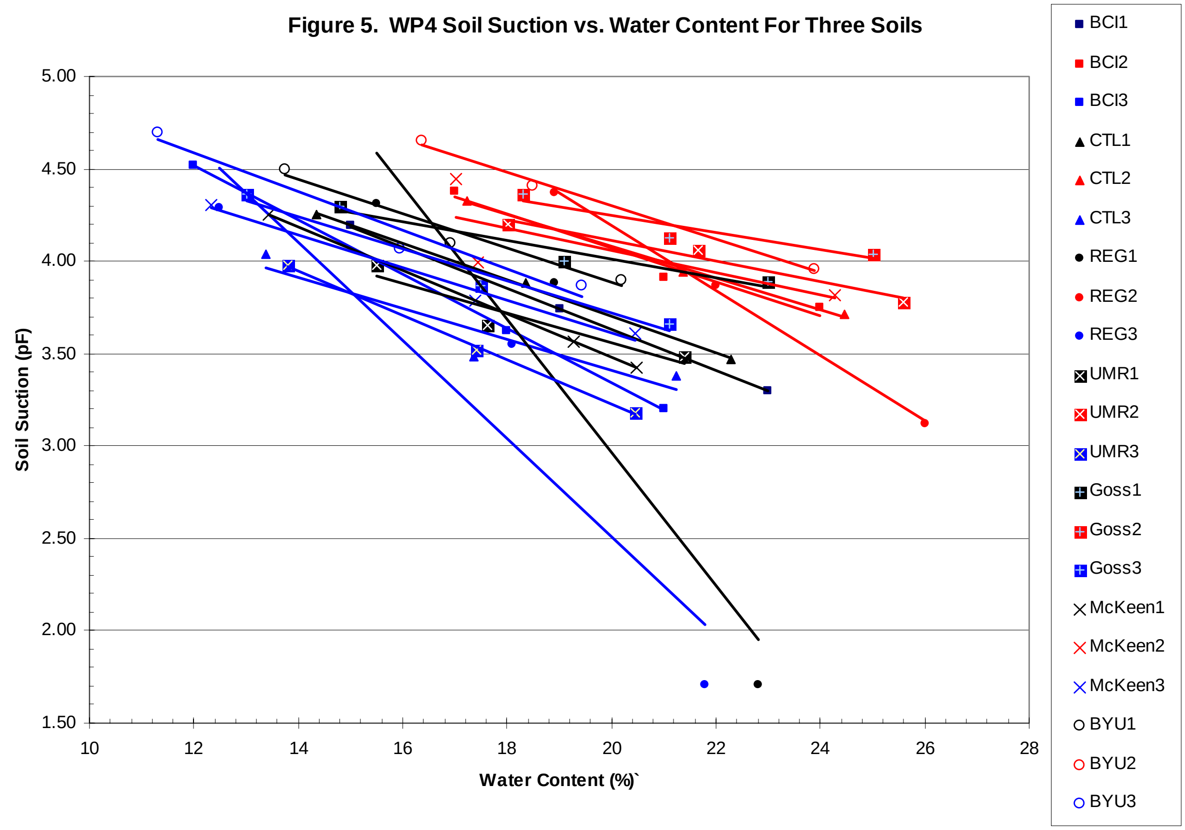


Figure 5. WP4 Soil Suction vs. Water Content For Three Soils
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
Soil Suction (pF)
10
12
14
16
18
20
22
24
26
28
Water Content (%)`
BCI1
BCI2
BCI3
CTL1
CTL2
CTL3
REG1
REG2
REG3
UMR1
UMR2
UMR3
Goss1
Goss2
Goss3
McKeen1
McKeen2
McKeen3
BYU1
BYU2
BYU3

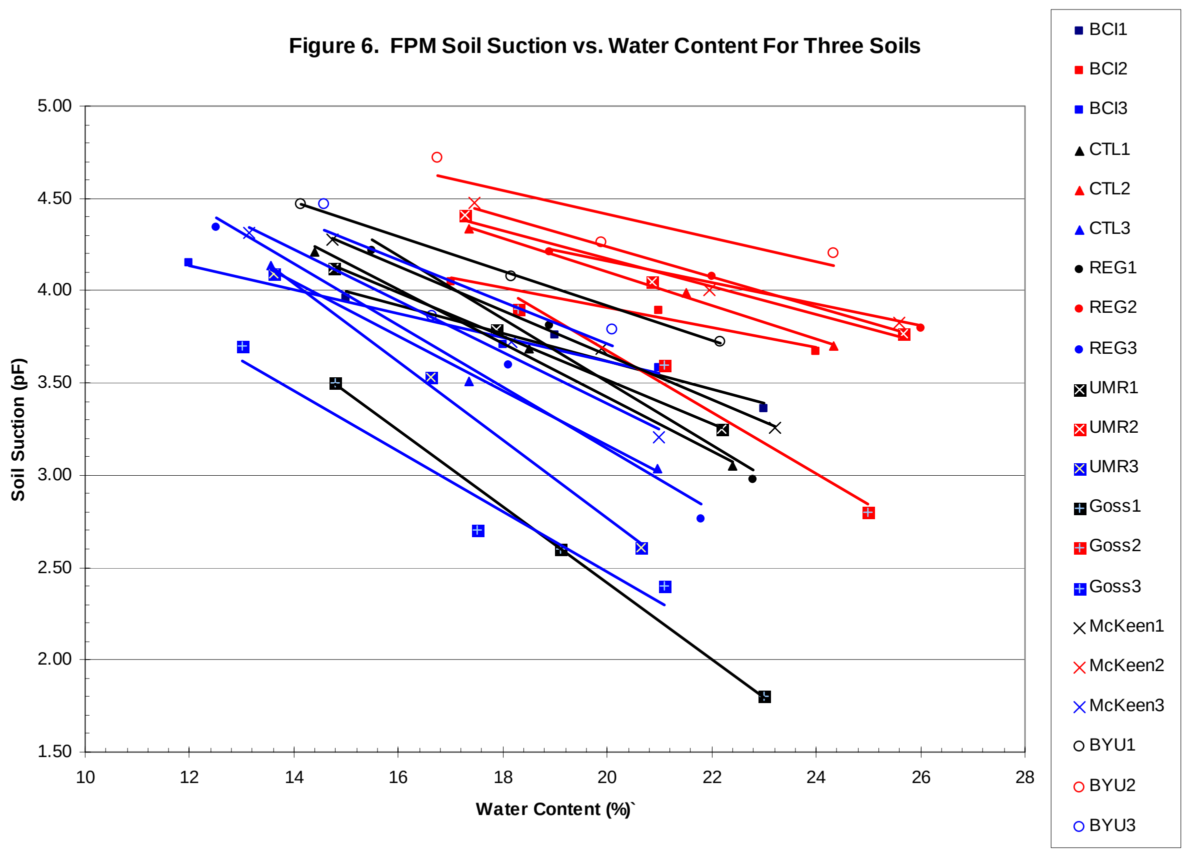


Figure 6. FPM Soil Suction vs. Water Content For Three Soils
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
Soil Suction (pF)
10
12
14
16
18
20
22
24
26
28
Water Content (%)`
BCI1
BCI2
BCI3
CTL1
CTL2
CTL3
REG1
REG2
REG3
UMR1
UMR2
UMR3
Goss1
Goss2
Goss3
McKeen1
McKeen2
McKeen3
BYU1
BYU2
BYU3

Figure 7. FPM vs. WP4 For Soil#1

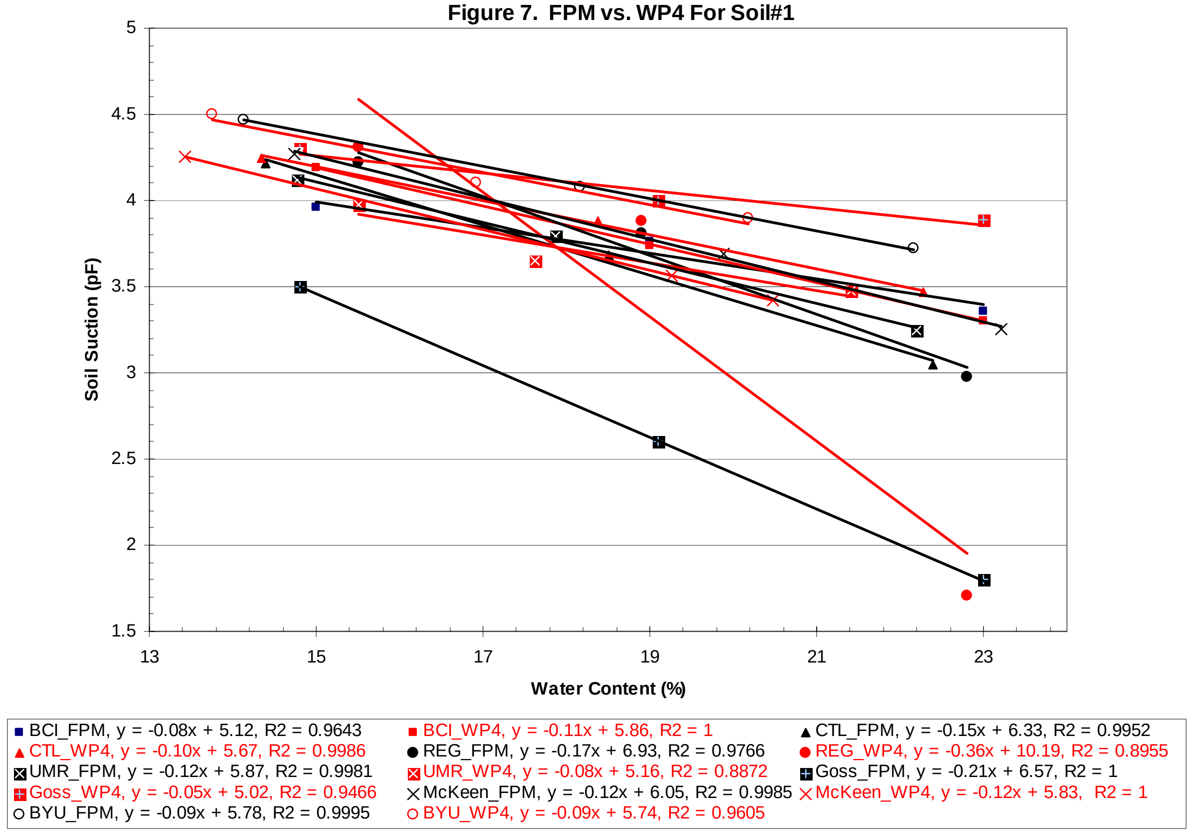
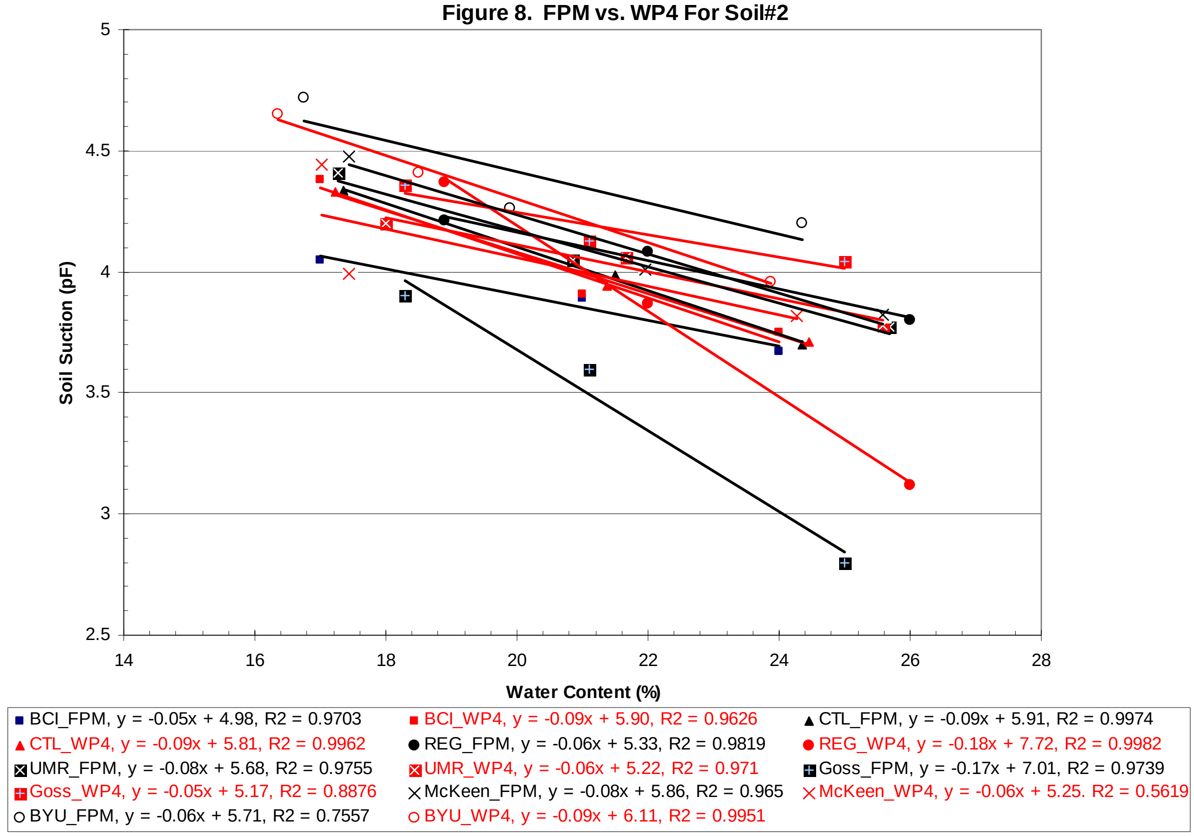
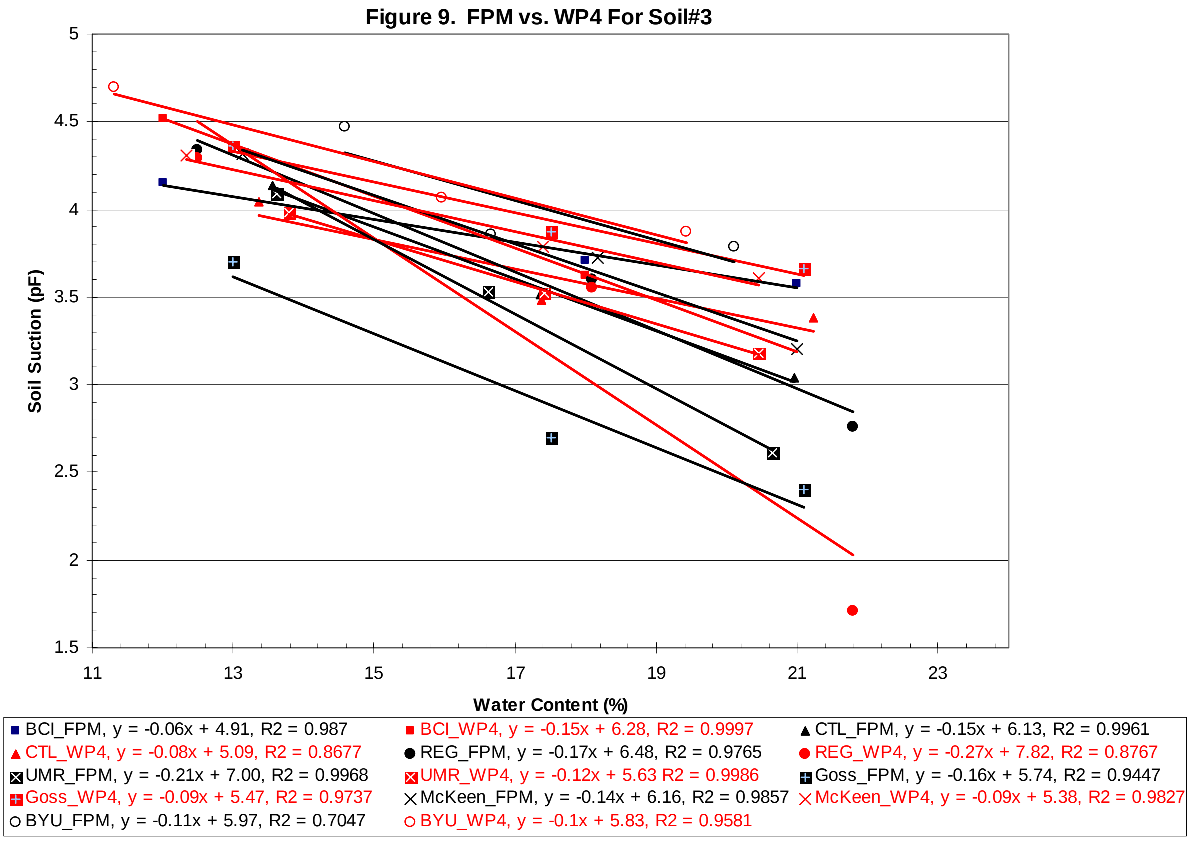


Figure 8. FPM vs. WP4 For Soil#2





Figures 10 and 11 are interpretations of the soil suction results versus the specimen water contents for all data submitted. Figure 10, showing the results from use of the WP 4 Dewpoint Potentiameter, illustrates the variance of all the data when analyzed together. The soil suction response of the three respective soils appears to track with the nature of their activity as shown by their Atterberg Limits and Linear Shrinkage. The correlation coefficients given in Figure 10 are fairly good but not exemplary. They are an indication of the variance of the specimens as tested, and the particular devices and personnel who used them. The correlation coefficient for soil #2 of 70% is the best of all plotted data and supports the use of the WP 4 device on highly active soils. Figure 11, containing the results from filter paper testing shows similar results to those in Figure 10. However, the correlation coefficients shown in Figure 11 are lower than those found in Figure 10, in all cases. In fact, for soil #2, the most active of all of those tested, the correlation coefficient is the smallest of all. When comparing the data from both test types on the same graph, as in Figures 7 through 9, and analyzing the data as done in Figures 10 and 11, it is clear that use of the WP 4 for measurement of total suction within the ranges shown here is superior to the use of the filter paper method.

All the data returned is shown in Table 6 below. One of the laboratories did not return dry unit weight data, but all have done a valuable service to those seeking methods to better predict the behavior of active clay soils.

Table 6. Round-Robin Data

From	Sample#	DUW (pcf)	WC_FPM (%)	FPM (pF)	WC_WP4 (%)	WP4 (pF)
Bryant Consultants, Inc.	1A	109	15	3.96	15	4.19
	1B	101	19	3.76	19	3.74
	1C	98	23	3.36	23	3.30
	2A	106	17	4.05	17	4.38
	2B	101	21	3.89	21	3.91
	2C	99	24	3.67	24	3.75
	3A	111	12	4.15	12	4.52
	3B	107	18	3.71	18	3.62
	3C	100	21	3.58	21	3.20
CTL/THOMPSON, INC	1A	101.1	14.40	4.2132	14.35	4.25
	1B	98.6	18.50	3.6857	18.37	3.88
	1C	95.9	22.40	3.0479	22.28	3.47
	2A	106.9	17.35	4.3350	17.23	4.33
	2B	100.2	21.50	3.9855	21.38	3.94
	2C	93.6	24.35	3.6974	24.45	3.71
	3A	106.4	13.55	4.1349	13.37	4.04
	3B	105.0	17.35	3.5121	17.37	3.48
	3C	100.0	20.95	3.0385	21.23	3.38
Reed Engineering Group	1A	105.8	15.5	4.22	15.5	4.31
	1B	103.0	18.9	3.81	18.9	3.88
	1C	101.2	22.8	2.98	22.8	1.71
	2A	102.8	18.9	4.21	18.9	4.37
	2B	99.5	22.0	4.08	22.0	3.87
	2C	95.6	26.0	3.8	26.0	3.12
	3A	109.2	12.5	4.34	12.5	4.29
	3B	106.1	18.1	3.6	18.1	3.55
	3C	101.3	21.8	2.76	21.8	1.71
UMR Geo Clay Lab	1A	106.75	14.77	4.12	15.50	3.98
	1B	103.36	17.87	3.79	17.63	3.65
	1C	100.10	22.20	3.25	21.41	3.48
	2A	105.27	17.28	4.41	18.01	4.20
	2B	101.37	20.86	4.05	21.67	4.06
	2C	96.62	25.68	3.77	25.58	3.78
	3A	109.66	13.61	4.09	13.79	3.98
	3B	108.30	16.62	3.53	17.41	3.52
	3C	102.48	20.64	2.61	20.46	3.18

Glenn Goss	1A	106.40	14.80	3.50	14.80	4.30
	1B	103.40	19.10	2.60	19.10	4.00
	1C	98.90	23.00	1.80	23.00	3.89
	2A	106.40	18.30	3.90	18.30	4.36
	2B	102.70	21.10	3.60	21.10	4.13
	2C	96.60	25.00	2.80	25.00	4.04
	3A	111.50	13.00	3.70	13.00	4.36
	3B	107.50	17.50	2.70	17.50	3.87
	3C	100.50	21.10	2.40	21.10	3.66

Gordon McKeen	1A		14.74	4.27	13.42	4.250
	1B		19.89	3.69	19.27	3.567
	1C		23.21	3.25	20.48	3.420
	2A		17.45	4.48	17.03	4.442
	2B		21.96	4.01	17.45	3.990
	2C		25.59	3.82	24.27	3.817
	3A		13.13	4.31	12.34	4.307
	3B		18.16	3.72	17.39	3.786
	3C		21.00	3.20	20.46	3.605

Brigham Young University	1A	105.88	14.13	4.47	13.75	4.50
	1B	100.57	18.16	4.08	16.91	4.10
	1C	97.39	22.17	3.72	20.18	3.90
	2A	105.57	16.74	4.72	16.36	4.65
	2B	100.76	19.89	4.26	18.50	4.41
	2C	94.02	24.35	4.20	23.88	3.96
	3A	107.25	14.59	4.47	11.31	4.70
	3B	100.45	16.65	3.86	15.96	4.07
	3C	98.45	20.10	3.79	19.42	3.87

Soil#1: Missouri Soil
Soil#2: Texas Soil
Soil#3: New Mexico Soil

CONCLUSIONS

It is the opinion of the researchers, at this time, that the WP4 Potentiameter provides a slightly more conservative measure of total suction and that the scatter of data is significantly less using the WP4 than using the Filter Paper Method. Therefore, it has excellent merit as a replacement device for determination of total soil suction over the previously standardized filter paper method, which is still in use today.

ACKNOWLEDGEMENTS

The authors sincerely appreciate the generous and long-standing support of Decagon Devices Inc. Others who assisted in providing the soils used are Gordon Mckeen, Hayward-Baker, Inc. and The Chemical Lime Company.
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APPENDIX

1992 REPORT OF INITIAL WP4 DEWPOINT POTENTIAMETER RESEARCH

Evaluation and Use of the Decagon WP4 Dewpoint Potentiameter

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Abstract

Determination of clay soil suction using the filter paper method, a process taking over 7 days, is the ASTM specified method of choice. Issues regarding the difficulty of its use and the variability of its results have kept it from becoming widespread in use. Decagon is producing, at reasonable cost, a dewpoint potentiameter, the WP4, that supposedly can provide acceptable accuracy in measuring total suction of clays in 5 minutes.

The ongoing study discussed in this paper has been aimed at evaluating how well the WP4 can read soil suction in the ranges needed for geotechnical engineering. In addition, protocols for sampling and equilibration of soils in WP4 test cups have been developed. Results show fairly accurate measurement of total suction in clays within 16 hours or less after sampling, depending on sample type and wetness. Data to support the use of the WP4 and the protocols developed are included.

Introduction and Background

Since well before 1960 geotechnical engineers have been searching for better ways to predict the behavior of expansive clay soils. This is especially true for prediction of swelling and heave of the ground surface upon expected wetting. By early in the 1970's geotechnical engineers had applied ideas from soil science dealing with the negative water stresses found in clays to predictions of volume change that would occur. These negative stresses were identified as soil suction stresses and characterized by their source within the soil. The sum of both kinds of soil suction was called Total Suction, and its constituents were named Matric Suction and Osmotic Suction. Osmotic Suction is that due to the dissolved salts within the pore water system of the clay soil, while Matric Suction is that due to the physico-chemical need of the clay present and the nature of the structure of the soil as a whole. Progress has been made in predicting swelling potential of clay soil subgrades using soil suction as the basis for these predictions.

Johnson (1973) was among the first to research how suction related to clay soil swelling. During the 1970's Snethen worked on a FHWA study of applying many expansive soil concepts, including soil suction, for prediction of the behavior of these materials in highway subgrades (1979). At about the same time Mckeen studied airport pavements on expansive soils and began his studies of the use of soil suction to predict clay behavior (1980). Shortly thereafter Wray published information on applying soil suction in geotechnical engineering (1984) and using soil suction to predict moisture changes that would occur in expansive soils under covered surfaces (1987). Mckeen and Johnson later discussed climate-controlled soil design parameters for expansive soils, including soil suction (1990) and Mckeen introduced a model for predicting expansive soil behavior, including soil suction, two years after that (1992). In that same year, Snethen and Huang (1992) added their evaluation of the methods using soil suction for heave prediction. Design methods are available for design of conventionally reinforced and post tensioned reinforced slabs-on-ground that utilize soil suction for predicting expansive soil behavior. It would be appropriate, therefore, for geotechnical engineers to readily measure this property of expansive clay soils.

Progress in the measurement of soil suction has not matched the progress in the use of this parameter for predictions of clay soil behavior. Most of the methods and devices used to this time have limitations of what ranges of soil suction they can effectively measure, of their application situations, and in their effective longevity, especially when placed in situ. The three most used devices and/or methods by geotechnical engineers have become the pressure plate apparatus, which measures Matric Suction only, and the dew point potentiometer measuring Total Suction only

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and the filter paper method (FPM), which can be used to measure both Total and Matric Suction. When ASTM standard test method D 5298 (1994) became adopted, the method of choice for most all practicing geotechnical engineers had become the filter paper method, the subject of this standard. The use of this method, as well as others proposed, has not become as widespread as one would expect. Difficulties with the complexity of the FPM test method and consistency of results, as well as the time it takes to complete it, have kept many geotechnical engineering firms from its use.

The measurement of soil suction continues to be the subject of research and publications. Snethen (1984) wrote of expedient methods for identification and classification of potentially active soils. A decade later, Houston, et. al. (1994) discussed the use of the filter paper method for suction measurements. More recently, Ridley and Wray (1996) published a review of current theories and practices for suction measurements. Others, too, have contributed to the overall knowledge and reviews of soil suction and its measurement. The reality, however, is that many are not measuring soil suction, and, therefore, not using it in design considerations because of the lack of a more convenient and consistent way to measure expansive clay soil suction.

The research reported here was aimed at evaluating a promising new device, the Decagon WP4 dewpoint potentiameter, for use in effectively measuring Total Suction of clay soils. This device was originally developed for use in the soil science and food service industries. The following report describes further details of those who developed the background for use of soil suction and the sources of information about the WP4 device. Following these sections is the discussion of the testing program utilized to determine how well this device measured expected Total Suction of fluids, how well it measured the suction of undisturbed and disturbed clay soils and what equilibration time was needed for consistent measurements. This is followed by descriptions of the testing used to compare the results obtained by testing undisturbed samples of clay soils using the WP4 device and the filter paper method. The results of all testing done are discussed and summarized in the conclusions. Recommendations for the use and future testing of the WP4 are also included.

The WP4 Dewpoint Poteniameter

The WP4 model Dewpoint Poteniameter is manufactured and sold by Decagon Devices, Inc. of Pullman, Washington. It is part of a line of devices provided to measure soil water potential. A picture of the device and the cup in which soil samples are placed is shown in Figure 1. The drawer shown is pushed into the machine and the activation knob is then turned to start the process. This slightly lifts the cup and seals it against the inside of the device to form a chamber in which the measurements are made.

The WP4 uses the chilled-mirror dewpoint technique to measure the water potential of the sample. In this type of instrument the sample is equilibrated with the headspace of a sealed chamber that contains a mirror and a means of detecting condensation on the mirror. At equilibrium, the relative humidity of the air in the chamber is the same as the water potential of the sample. In the WP4, the mirror temperature is precisely controlled by a thermoelectric (Peltier) cooler. Detection of the exact point at which condensation first appears on the mirror is observed with a photoelectric cell. A beam of light is directed onto the mirror and reflected into a photodetector cell. The photodetector senses the change in reflectance when condensation occurs on the mirror. A thermocouple attached to the mirror then records the temperature at which condensation occurs. The device then signals by flashing a green LED and/or beeping. The final water potential and temperature of the sample is then displayed. The readings are of the water potential in MPa of negative or positive pressure and the temperature is in degrees Celsius. This process has been taking, during the research reported, from 5 to 10 minutes. Since this is a type of psychrometer and no direct contact is made with the sample, the measurements are of Total Suction.

Since most geotechnical engineers use soil suction in units of pF or the log of the height of an equivalent column of water that would have the same pressure at its base, the WP4 measurement must be converted for use. The following simple equation is used:

$$pF = \log_{10} (\text{MPa} \times 10{,}200)$$

WP4 readings do not require any corrections for temperature, since the calculation to determine the readings displayed takes the sample temperature into account. The device is best cleaned about once a week when being used and calibrated to the reference solution twice daily when in use. The WP4 needs to have at least a half hour to warm up before the calibration process is done each morning.

Considerable concern about equilibration times for undisturbed samples of clays within the chamber was raised, especially since the filter paper method utilizes 7 days of equilibration time. Therefore, this subject became a necessary part of the research report here and will be discussed later.

The accuracy of the WP4 is given by Decagon as ± 0.1 MPa for the range of 0 to -10 MPa and ± 1% for the range of -10 to -40 MPa. The resolution provided by the device is ± 0.001. Readings are displayed in the form -X.XX or -XX.X, depending on the range utilized. A typical readout is shown in Figure 2. The device does have a standard RS232 serial port available and can provide continuous readings, if desired. Further information can be obtained and literature is available at www.decagon.com.

The Research Test Program

The research reported here had three basic goals during planning. First was the determination of whether the WP4 could do what it was suppose to be able to do. Second, to find out how samples of expansive clay soils should be prepared before placement into the device so that proper measurements of Total Suction were made. Third, to evaluate whether the WP4 measurements would be accurate enough to be used in making geotechnical engineering recommendations.

To address these goals the following processes were utilized:

1. Test multiple samples of standardized test solutions to evaluate whether the WP4 would provide accurate enough and correct measurements of pF.

2. Test both undisturbed and disturbed samples of clay soil to determine whether disturbance made a difference in the readings obtained with the WP4.

3. Determine the length of time that undisturbed samples of clay soils need to be equilibrated in the WP4 sample cups, sealed with the lids provided, before testing would provide consistent and conservative measurements of Total Suction, using the WP4.

4. Side-by-side testing for Total Suction using the WP4 and the protocol developed, and the Filter Paper Method as specified by ASTM D 5298. The results of this final part of the testing provide evaluation and validation of the WP4 for use in geotechnical engineering practice.

Two types of standard concentration solutions were used to evaluate the accuracy and repeatability of the WP4. These consisted of several differing concentrations of potassium chloride and of sodium chloride is demineralized water. The proper pF of each solution was determined and used as the expected value for that solution. In addition, the calibrating solutions, of a 0.5 Molal/kg solution of potassium chloride, one provided by Decagon and one made up in the testing lab, were read multiple times to ascertain the variability of measurements made with the WP4.

In order to test the difference in readings by the WP4 on samples of undisturbed and disturbed clay soils, two differing processes were done, each by the two laboratories doing this research. One laboratory tested samples of soils from several project borings. In each case the samples were split in two parts. One part was placed into the sample cup for equilibration and reading in the undisturbed state and the other part was broken down before being placed into the cup for equilibration. The other laboratory, using a project sample, remolded several cylinders of the soil, using static compaction, at a fairly uniform water content and dry unit weight. From each cylinder was taken three undisturbed WP4 samples and three later-to-be-disturbed samples. All the samples were equilibrated in sealed WP4 sample cups for prescribed times. Just before the later-to-be-disturbed samples were to be placed into the WP4 for testing, the samples were each, in turn, broken down to approximately minus #10 US Series sieve size. Comparisons of results for similarly equilibrated disturbed and undisturbed samples were used to determine the effects of disturbance on the Total Suction measured.

Determination of the time needed for equilibration in the WP4 sealed cups prior to testing them in the device was done for both the undisturbed and disturbed samples described above. The results provided by the WP4 for these samples, which had been equilibrated for as little as 2 hours to as long as 1 week, were compared and plotted.

Determination was then made of the shortest and proper equilibration times that would provide consistent and conservative results.

Evaluation of the WP4 continued with comparison of readings taken with this device with those determined using the Filter Paper Method as specified by ASTM D 5298 (1994). The protocol used by each laboratory followed for this test procedure and was used to develop a filter paper calibration curve, relating filter paper water content to the Total Suction measured. Solutions of potassium chloride and sodium chloride in demineralized were used for this process.

Following this, one laboratory used project samples for the comparison testing. The other laboratory used remolded specimens of one project soil that were made using static compaction. These samples of the soil were brought to four differing water contents, representing the range normally found in situ. Then the samples were allowed to equilibrate at these water contents for several days. Using project information, dry unit weights consistent with these water contents for the originally sampled soil were picked. The samples were then compacted to the dry unit weights picked for the appropriate water contents. One of the two cylinders prepared at each water content-dry unit weight was sampled for testing immediately. The other four representative cylinders were placed into consolidometer rings, had a 200 psf overburden pressure applied to them, were inundated with water and allowed to swell for several days.

When possible, multiple (at least three) samples of project samples or prepared specimens were tested using the WP4 and the Filter Paper Method to determine their Total Suction. These values were converted to pF units and compared using charts of data results. Determinations of the appropriateness of the results from WP4 testing were then made.

Test Results

The test results for the research reported here will be discussed in the same order as the tasks were previously listed. Figures of plotted results will be utilized for this purpose. If requested by individuals, tables of data may be provided electronically. Where possible, figures of data applicable to more than one task are provided. Several of the figures contain data points which fall at the same locations on a particular chart; therefore, the number of data points for each will be included in the discussion, unless it is obvious from the chart.

Initial testing to determine whether the WP4 would provide readings of soil suction as expected started with multiple readings of both the Decagon supplied standard solution and a similar solution prepared in the laboratory. Calibrations were carried out to set the device as specified in the instruction manual. The calibration solutions provided by Decagon is a 0.5 Molal/kg solution of potassium chloride, which is suppose to have a WP4 reading of 2.19 MPa (4.35 pF). The calibration process was continued until this reading was supplied $\pm$ 0.01 MPa, which continued to be the process during all of the testing reported here. Following calibration each day, and over a span of several days, both of the 0.5 Molal/kg solutions (standard and laboratory) were read using the WP4. The total number of readings was 45 for each solution. A plot of the results for these readings on the standard solution is shown in Figure 3. The values read during this part of the testing ranged from 4.32 pF to 4.39 pF , -0.03 to +0.04 relative to the 4.35 pF expected. The mean of this data is 4.353 pF. The results for the laboratory prepared solution were similar. Considering the relatively small range of the readings made, the performance of the WP4 would be considered acceptable.

Further verification of how well the WP4 read solutions was conducted using a set of potassium chloride and a set of sodium chloride solutions prepared using demineralized water. The solutions were made to provide relative humidities that represented soil suctions of from about 2.5 to 5.0 pF. The potassium chloride solutions were read 4 times and the sodium chloride solutions were read 3 times over a period of days. The results of this testing are shown in Figures 4 and 5. The plots are of the WP4 derived values of Total Suction in pF versus that expected by the concentrations of salts in the solutions. In both figures the results indicate that the WP4 provides reasonably accurate to very accurate for readings above the values of suction of 3.5 pF and above. Below that value, the readings shown are more erratic, although conservative. This was especially true when the potassium chloride solutions were read, as shown in Figure 4. Since the most important range of soil suction measurements for expansive clays is for values above 3.5, the data on these figures support the use of the WP4.

Once there was sufficient support for use of the WP4 when reading the Total Suction of prepared laboratory solutions, the next step was to determine how long an equilibration time would be required to obtain consistent and conservative measurements for undisturbed and intact expansive clay soils. Decagon had indicated, in its literature that readings of Total Suction could be made in about 5 minutes after the cup with soil was placed into the device. In reality, during the research reported here, the actual times varied from about 5 minutes most of the time and reached 10 minutes in some instances. There was an additional concern about whether these short times in the chamber would actually result in proper measurement of Total Suction for clay soils when 7 days are needed for equilibration for the Filter Paper Method. It was expected that an equilibration delay would be required and that for undisturbed and intact samples the length of the delay would be longest. Comparisons of results for disturbed versus undisturbed samples has, so far, shown that the intact samples exhibited higher Total Suctions. The results that follow are for undisturbed samples only, since these best represent the in situ situation.

Both of the laboratories involved in this research independently investigated the delay time for equilibration for undisturbed and intact samples of expansive clay soils. The results obtained are shown in Figures 6, 7 and 8. A delay time which resulted in reasonable results within a practical length of time was considered to be an optimal situation.

Figure 6 shows how the suction values measured by the WP4 varied in both MPa and pF for a remolded and undisturbed soil for equilibration times ranging from 2 hours to 96 hours. Three samples were taken from remolded cylinders of the soil at approximately the same moisture content for each equilibration time delay. These 21 samples were then sealed into the WP4 cups and allowed to equilibrate for the specified time before they were opened and read for Total Suction. As can be seen in Figure 6, the readings made became consistent at 24 hours of equilibration time.

The results shown in Figure 7 where obtained at the other laboratory for multiples samples taken from project borings. In each case a sample for each delay time of equilibration was taken from field samples. These were then sealed in the WP4 cups and allowed to equilibrate until the appropriate delay had occurred. In this case the equilibration times varied to 24 hours. The results shown in Figure 7 indicate that a practical delay time for equilibration was somewhere between12 and 24 hours.

Since 12 hours would not be practical from the standpoint of a production laboratory, further investigation was done to determine how well a 16 hour equilibration time would work. In Figure 8 is displayed a comparison of the Total Suction determined for several project boring samples at delays of 16 and 24 hours. A line representing equality of results is provided for comparison purposes. Two things are believed to be important about these results. First, the values determined for the 16 and 24 hour equilibration times are nearly the same, with the 24 hour readings being slightly more conservative. Second, within the range of normal concern for soil suction there is better agreement of results. These results, coupled with those shown in Figures 6 and 7, support the use of an equilbration time delay of from 16 to 24 hours or more.

The practicality of the use of a 16 hour equilibration time is significant. In practice, field samples could be placed into WP4 cups even as late as 5 PM one day and could be placed into the device and read for Total Suction as early as 8 AM the following day. In reality, the most probable equilibration time in such circumstances would be more than 16 hours, and the results would favorably represent a conservative measure of suction.

Testing to determine how well use of the WP4 to measure Total Suction compared to use of the Filter Paper Method (FPM) started with recalibration of filter papers. Of the two laboratories involved in the reported research, one had a well-established calibration and the other was calibrating a new filter paper type. The calibration curves shown in ASTM standard D 5298 are known to be curves developed as the filter paper was caused to dry to the proper moisture content during the calibration process. During normal application of the FPM in production geotechnical laboratories, filter papers are kept dry until they are used for testing. It would follow, then, that a calibration curve for the wetting case would be most appropriate.

Figures 9 is a calibration curves for VWR Qualitative Papers, Grade 415. It shows two sets of data. The first is a plotting of the expected soil suction for the same potassium chloride solutions used before versus the filter paper water content determined for exposure to them for 7 days. The second is calculated water contents for the same soil suction levels, using the ASTM standard's curve for Whatman #42 filter paper. There appears to be good agreement between these two plots, especially at the lower water contents where higher soil suctions are present. This calibration curve was used for the remainder of testing done.

Two somewhat differing processes were used to accomplish the verification of WP4 readings of Total Suction against those found using the Filter Paper Method for undisturbed and intact samples of expansive clay soils.

That used by one of the laboratories involved in the research reported here was to use one clay soil, prepare it at four moisture levels common in situ, compact swell test cylinders at dry unit weights found in situ for this clay and test it two ways. One of the cylinders at each water content-dry unit weight configuration was sampled for suction testing as soon as it was compacted. The other one was placed into an oedometer and allowed to swell under an overburden pressure of approximately 200 psf as it was inundated with water. Following the swelling process, the cylinder, in each case was sampled for suction testing.

The other laboratory sampled several field samples from project borings and prepared these samples for suction testing. Both laboratories tested the samples used with the WP4 device and with the Filter Paper Method. The protocol used for WP4 testing included an equilibration time of at least 16 hours. Figures 10,11 and 12 detail the results of this part of the testing done.

The laboratory using one soil at four initial water contents and dry unit weights had results that would allow for the development of a Total Suction versus soil water content curve. This is what is shown in Figure 10. There are sets of data shown in this chart. The first was derived using the WP4 data and the FPM data for the recently calibrated VWR paper. It can be seen from this chart that the WP4 data is nearly the same in magnitude as that from the FPM. If one was to use the ASTM Whatman #42 paper line the agreement would be even better. The agreement of data shown on this chart has lower levels of agreement where the soil water content is higher, in fact the water content after swell, but is reasonable for higher suction levels. The scatter of data is slightly less, overall, for the WP4 data,which shows a more conservative measurement of suction.

Since the data determined by the other laboratory was for samples taken from different boring, different strata and different projects, development of a suction-water content curve was not possible. Figure 11 contains results for 17 samples with no replications and has a line of equality of readings provided. It is apparent that there is generally good agreement as to values of Total Suction and that the data determined using the WP4 is more conservative by about 0.25 pF at lower values to 0.1 pF at the highest levels of suction, as shown by the trend line. When other data is added, for equilibration times of 16 and 24 hours, the chart shown in Figure 12 emerges. The two trend lines for data of both sets show a possible range of +0.25 to -0.8 for the lower values of suction and +0.2 for values in the upper values of suction. Analyses of this data have not taken into account soil type differences and overburden-stress history differences. Considering what is shown in Figure 11, the use of the WP4 is well supported, while for the data shown in Figure 12 there is less support given.

Another facet of the testing presented needs to be discussed. This is that associated with the complexity of the test methods and the sources of error that are present in their use. The experiences gained in using the WP4 to date include that it is relatively simple to calibrate and operate. In addition, the preparation of samples for test is simple and direct, and the results appear not to be affected by operator handling techniques, nearly as much as for the FPM. The FPM is a complex and tedious methodology, requiring extreme care in how the filter paper is handled throughout. The results of the FPM are very much dependent on the same individual doing the test in the same way everytime. On the other hand, well-trained and normally competent individuals can obtain nearly the same resultswith the WP4, with little experience. Because of the factors discussed above, it is believed that a good deal of the variance seen in data shown in the figures discussed may be as a result of the FPM.

Systematic and Random Errors

As with any instrument, procedure or process, systematic and random measurement errors must be accounted for and if possible, quantified. Systematic and random errors are generated when the measured total soil suction values are not equal to the true representative total soil suction values. Systematic errors depend not only on the inherent characteristics of the instrument, procedure or process, but more importantly on the conditions (operator, temperature, relative humidity, etc.), under which it is used. Therefore, assuming constant conditions, systematic errors will affect the accuracy of the measurement set, but not necessarily the precision. On the other hand, random errors associated with the natural variations of samples, instrumentation limitations or repeatability of measurement will affect the precision of a measurement set.

Random and systematic errors occur in both the WP4 method and filter paper method. However, the random errors influence the precision of the measurements, which affect the resolution and repeatability of the measurements including the natural variability of the soil suction values. The same kinds of random error should be inherent due to variability in the soil samples in both techniques. In other words, the random errors contain the natural soil variability that we are trying to quantify and these errors do not affect the accuracy of the measurement.

Contrastingly, the accuracy of the measurement is directly related to the systematic error. Therefore, if follows that the more simple the technique and fewer measurement steps and calibrations, the lower the amount of systematic error. Because, a desirable outcome is to achieve higher accuracy in these measurements to have results consistent with the recognized moisture suction benchmarks, it is important to achieve accuracy in the values of soil suction, if calculations of soil volume change are to be predicted and modeled accurately.

As a result, we have found that as the number of measurement steps increase, as in the filter paper method, systematic errors are typically amplified and exacerbated due to the procedural complexities. Based upon thousands of measurements of the total soil suction using the filter paper method, it is our experience that the accuracy of the filter paper method is highly dependent on the individual tendencies and practices of the operator and the technique used. In comparison, based upon the limited research performed to date, it appears that the WP4 method effectively reduces the systematic errors through simple procedural steps such as calibration techniques, fewer procedural steps and much less complicated operator handling techniques.

Conclusions

Based on the results of the research reported here, the following conclusions can be made:

1. The Decagon WP4 is an acceptable device for determination of Total Suction of calibrating solutions.

2. When applying the WP4 for use in determination of the Total Suction of undisturbed expansive clay soils, an equilibration time of at least 16 hours is needed. There is appears to be no loss of water content of samples sealed in the WP4 cups for this equilibration time.

3. When compared to the use of the Filter Paper Method, ASTM D 5298, for determination of the Total Suction of potentially expansive clay soils, the WP4 provides acceptable results that are slightly more conservative, especially when the values of suction are in the range normally deemed important.

4. The methodology and devices used for determination of Total Suction using the WP4 are far less complex and time consuming than that used for the Filter Paper Method.

5. The use of the WP4 is more practical, less costly in time and expense, and less likely to contain errors than the Filter Paper Method.

Recommendations for Future Research

Further verification testing of the Decagon WP4 is warranted. This can best be done using a round-robin test program where several laboratories having Filter Paper Method capability and the resources to purchase this new device. Once further verification is done, as described above, development and submittal of a proposed ASTM standard for use of the Decagon WP4 should be done. Future research into random and systematic errors should be conducted to evaluate the of both methods.

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Protocol Used for WP4:

1. Turn on the WP4 at least one-half hour before intended calibration sequence.

2. Place all of one vial of 0.5 Molal/kg KCl Standard solution in WP4 Cup and allow to come to the temperature of the laboratory and device.

3. Once the WP4 is warmed up, place the standard solution cup in the device and read its Total Suction. This process is normally repeated until two consistent consecutive readings are taken.

4. Calibrate the WP4 using the calibration procedure specified in the device instructions, each time following the reset with a normal reading sequence. Once this normal reading is 2.19 MPa ± 0.01 MPa the calibration is complete.

5. Undisturbed sampling and preparation;

> **a. Obtain an intact sample of undisturbed soil approximately one inch thick.**
>
> **b. Push a sampling tube through the sample. Such a sampler (1.0 inch Diameter) and ejector device are shown in Figure 13. Care should be taken not to expose soil materials any more than necessary to preserve their natural water contents.**
>
> **c. Eject the sample from the tube and cut slices of it that are about 1/2 to 2/3 the depth of the WP4 cup in height. It is suggested that at least 3 samples be tested for each determination of Total Suction.**
>
> **d. Place each small disk cut into a WP4 cup and immediately place a lid for the cup on it and the cup should be marked with an identification label. This process is shown in Figure 14.**
>
> **e. Seal the edges of the WP4 cup with vinyl tape and place the cup into a container that can be sealed. This container is then placed into a cooler to provide a constant temperature environment for equilibration. This process is shown in Figures 14 and 15.**

6. After at least 16 hours of equilibration time, each WP4 cup is unsealed in turn and placed into the previously calibrated device to be read.

Figure 1. WP4 Device and Cup with Sample Ready to be Inserted

Figure 2. WP4 In Reading Mode with Normal Reading Shown

Figure 3. Total Suction Measured by WP4 for 0.5 M/kg Standard Solution of KCl

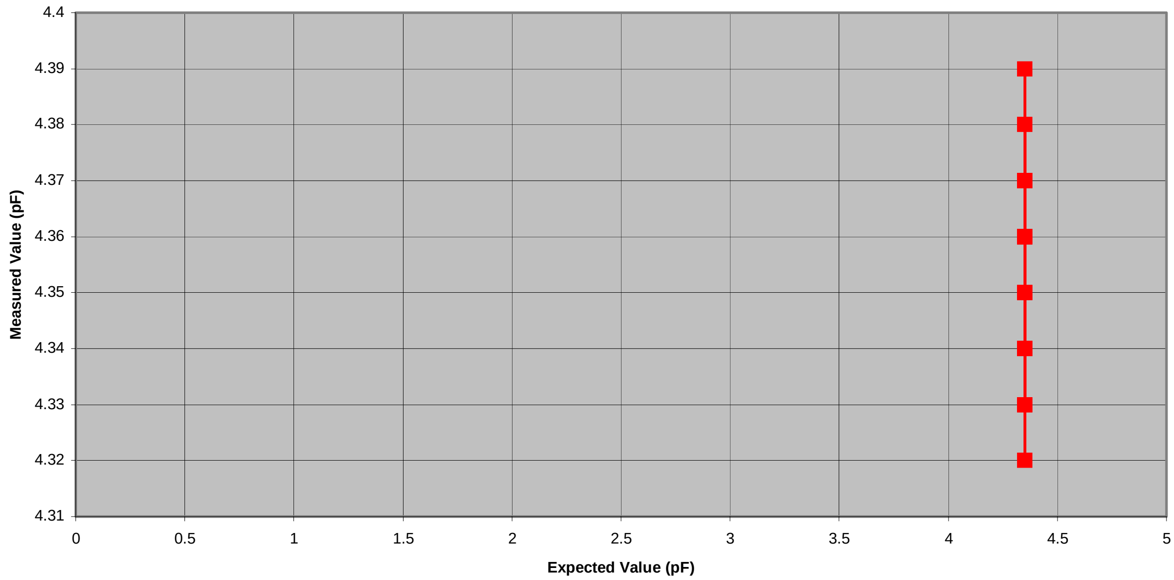

Figure 4. Expected Suction pF Versus WP4 Measured pF for Laboratory Solutions of KCl

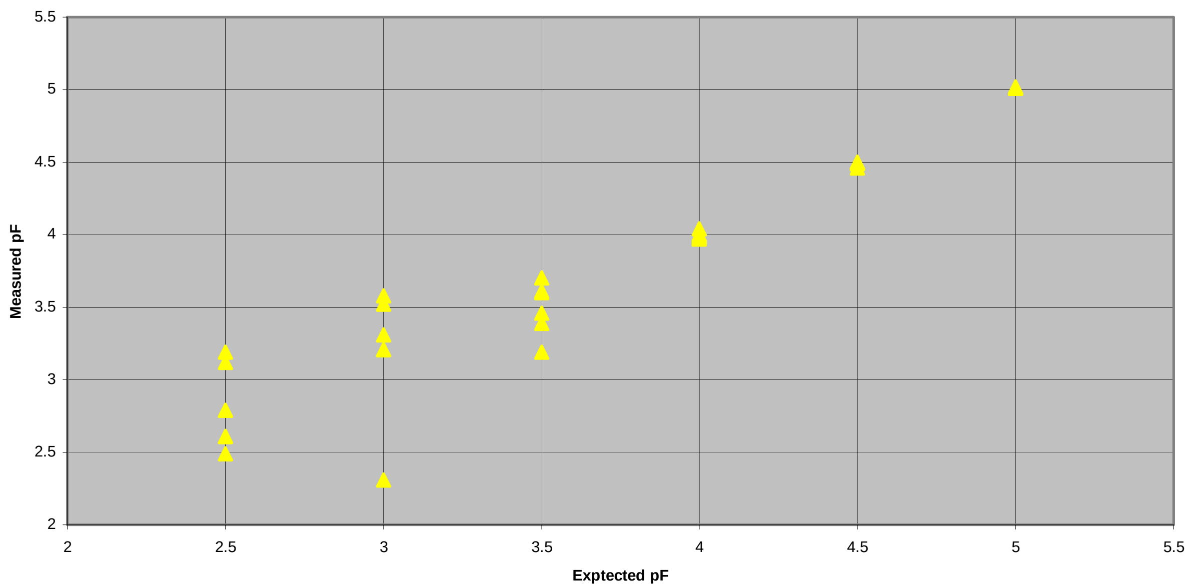

Figure 5. Expected Suction VS WP4 Measured Suction in pF for NaCl Solutions

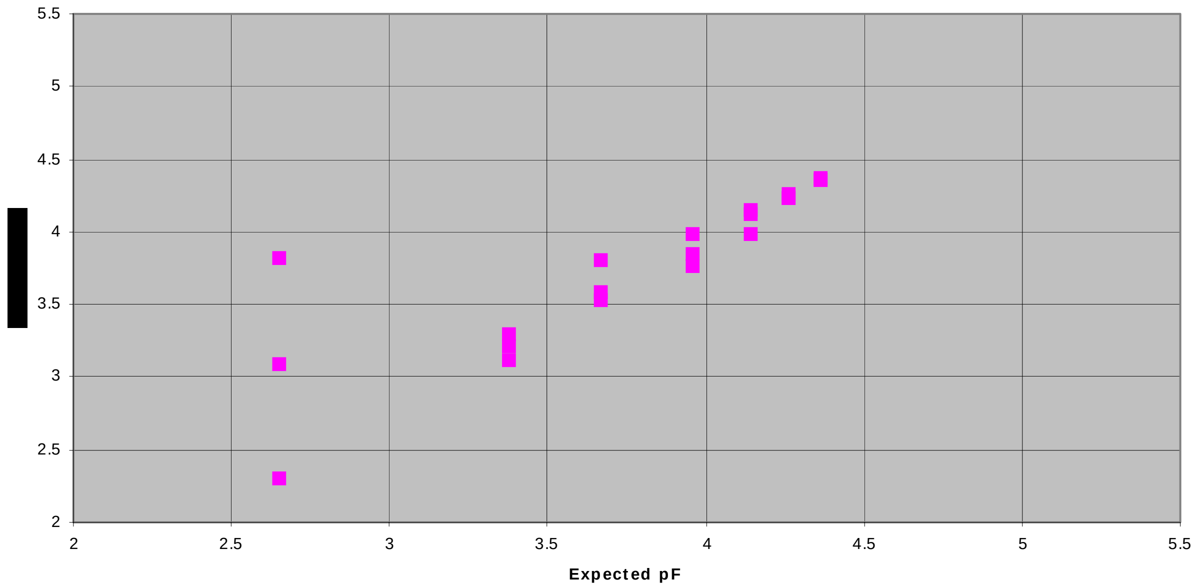

Figure 6. Total Suction in Remolded Undisturbed Soils with Equilibration Time Delays

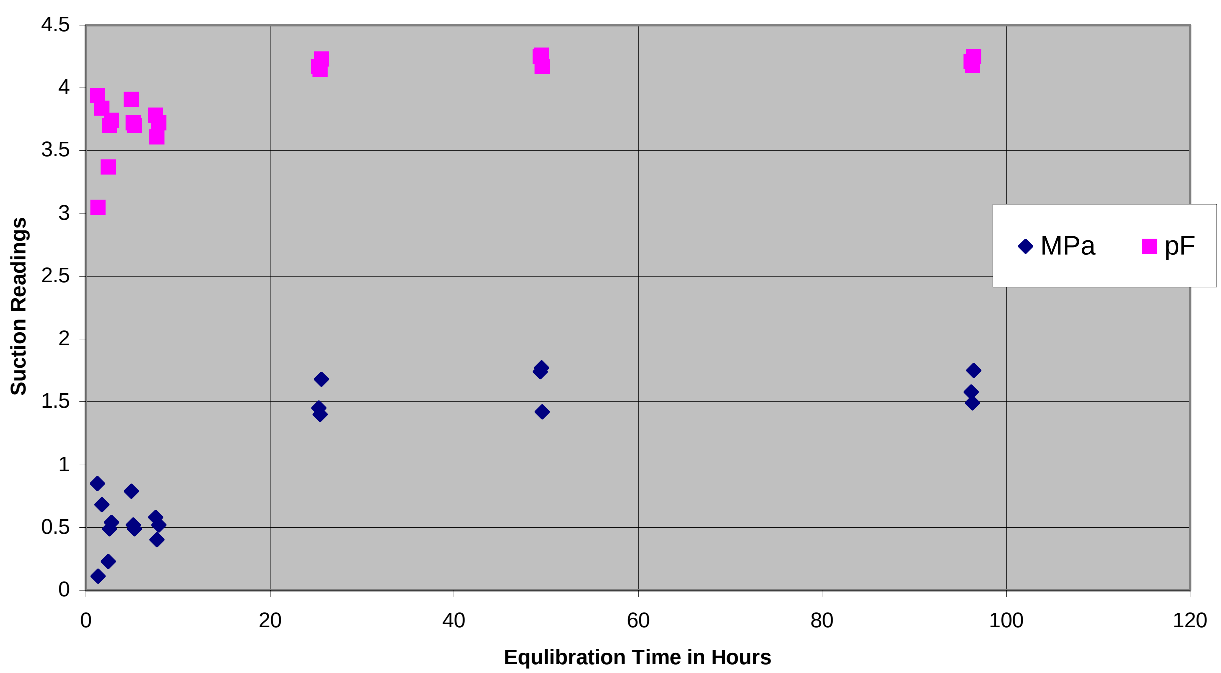

Figure 7. Total Suction by WP4 for Undisturbed Samples from Various Projects Versus Equilibration Time

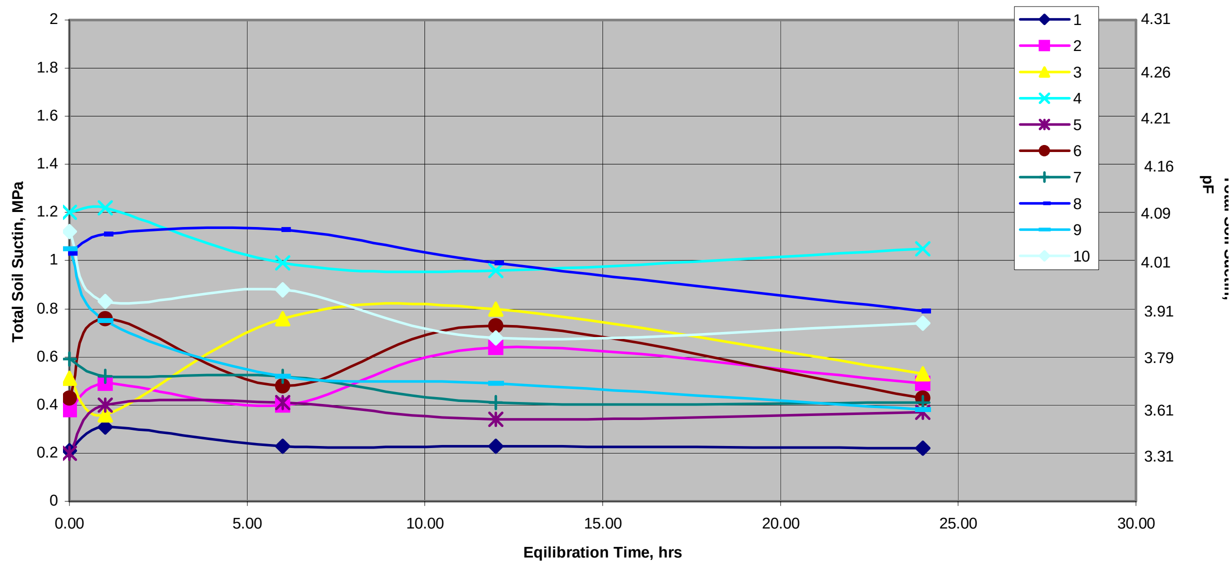

Figure 8. Total Suction by WP4 - Equilibration of 16 Hours VS Equilibration of 24 Hours

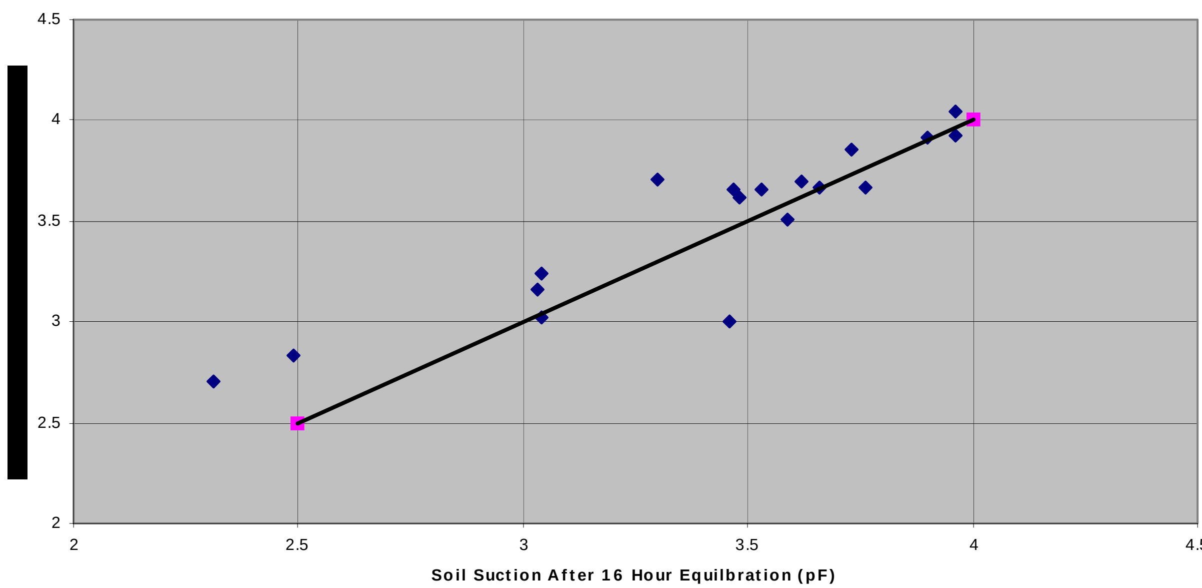

Figure 9. Calibration of VWR Filter Paper with Potassium Chloride Solutions (Whatman #42 ASTM)

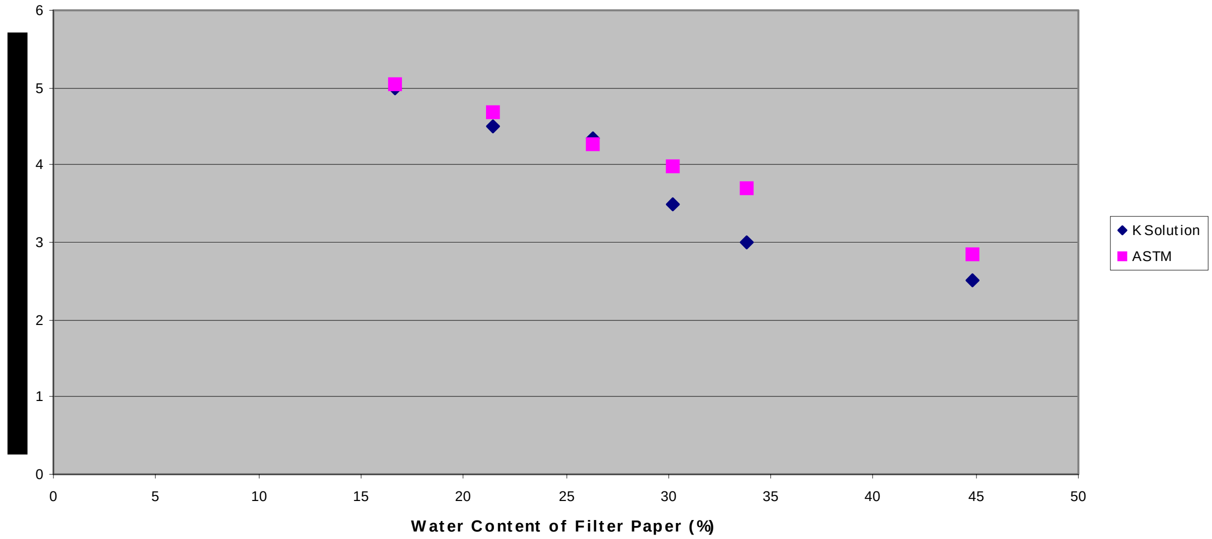

Figure 10. Soil Suction by WP4 and Filter Paper Method (Lab Curve) VS Soil Water Content for a Clay Soil

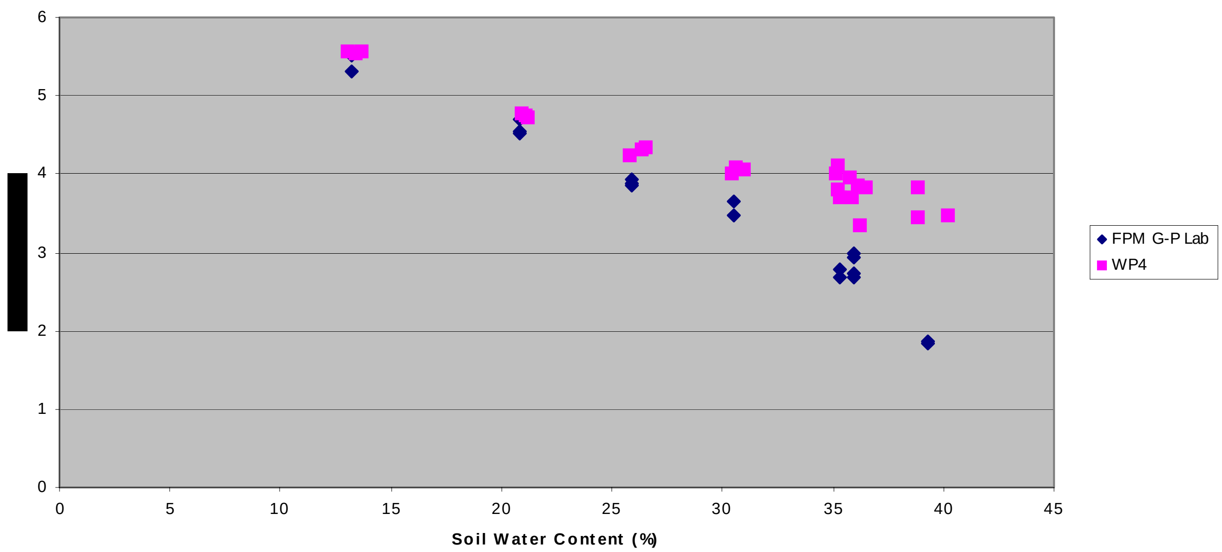

Figure 11. Total Soil Suction by WP4 VS Soil Suction by Filter Paper Method - Project Soil Set I - 24 Hour Equiibrations

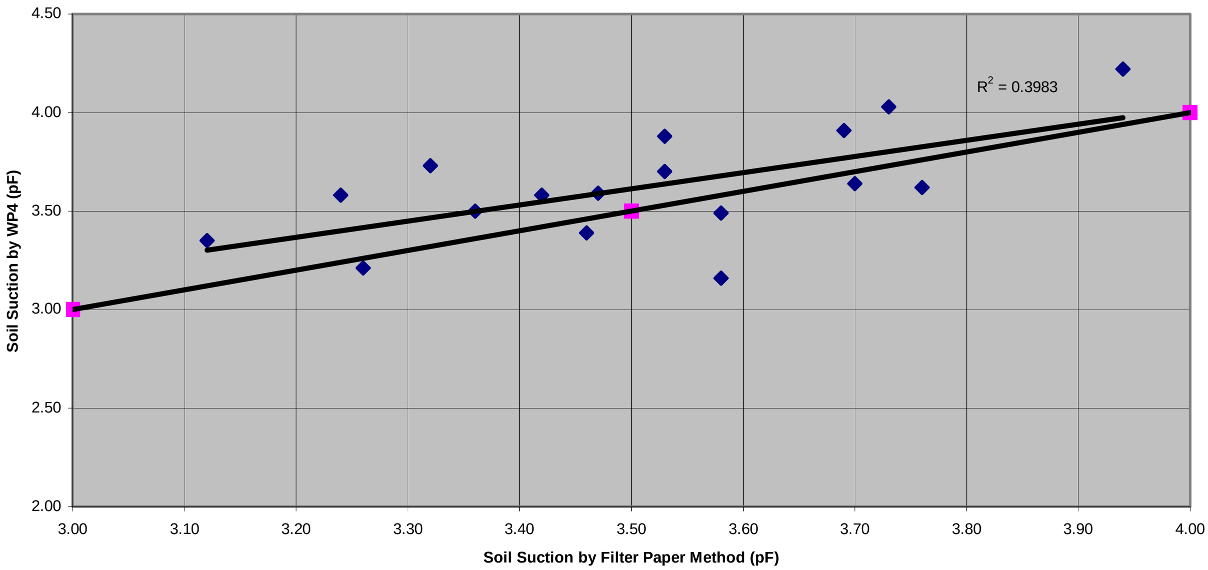

Figure 12. Total Soil Suction by WP4 VS Soil Suction by Filter Paper Method - Project Soil Sets I & II

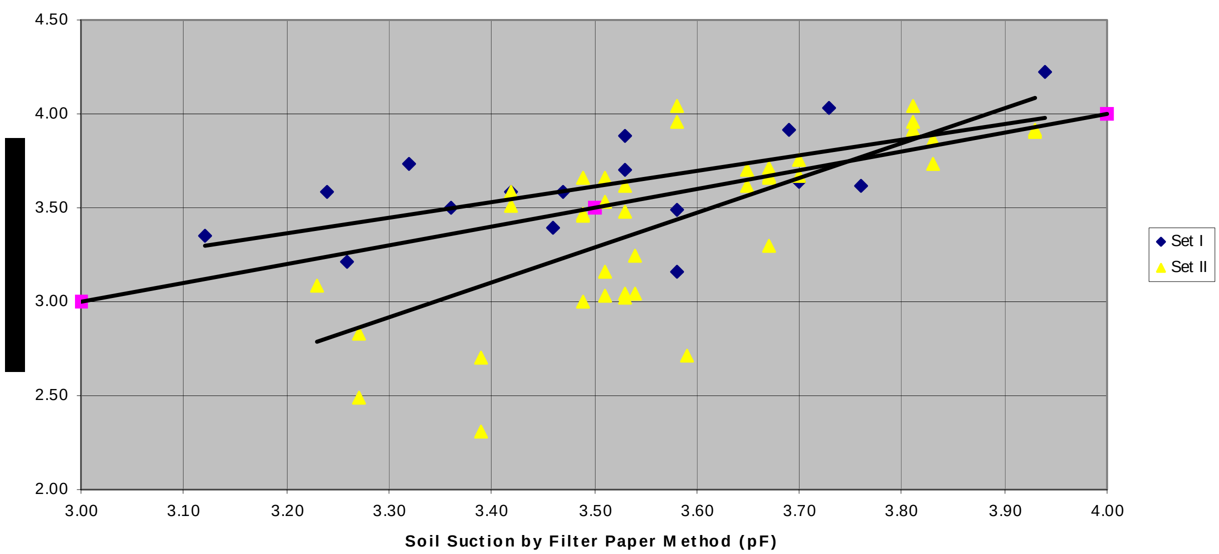

Figure 13. Sampling of Undisturbed Soil for WP4 Testing

Figure 14. WP4 Cup and Lid and Sealing of Cup for Equilibration

Figure 15. Sealing Chamber for Equilibration