SEASONAL INSTRUMENTATION OF SHRP PAVEMENTS - THE UNIVERSITY OF TOLEDO

PB99-123218

ODOT PROJECT NO. 14584(0)

Final Report

By

Andrew G. Heydinger

and

Brian W. Randolph

Department of Civil Engineering

The University of Toledo

Report No. UT-CE/GG 98-101

October, 1998

Prepared in cooperation with the Ohio Department of Transportation and the U. S. Department of Transportation, Federal Highway Administration

REPRODUCED BY: NTIS
U.S. Department of Commerce
National Technical Information Service
Springfield, Virginia 22161

1. Report No.
FHWA/OH-98/012

2. Government Accession No.

3. R[illegible]
PB99-123218

5. Report Date
May, 1998

6. Performing Organization Code

8. Performing Organization Report No.

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
State Job No. 14584(0)

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

4. Title and Subtitle

SEASONAL INSTRUMENTATION OF SHRP PAVEMENTS - THE UNIVERSITY OF TOLEDO

7. Author(s)

Andrew G. Heydinger, Brian W. Randolph

9. Performing Organization Name and Address

The University of Toledo
Department of Civil Engineering
Toledo, OH 43606-3390

12. Sponsoring Agency Name and Address
Ohio Department of Transportation
1600 West Broad Street
Columbus, OH 43216-0899

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract: Seasonal Monitoring Program (SMP) instrumentation was installed in five sections at the Ohio Test Pavement in Delaware County, Ohio using Strategic Highway Research Program (SHRP) protocols developed for the Long-Term Pavement Performance (LTPP) group of the Federal Highway Administration (FHWA). The SMP instrumentation monitors pavements for temperature and pavement bases and subgrade soils for variations of moisture, temperature and frost penetration. Time Domain Reflectometry (TDR) instrumentation was installed onsite in two sections for monitoring the moisture. Thermal conductivity sensors (TCS) were installed in four sections to measure soil moisture suction. Laboratory soil-water characteristic tests were conducted on remolded subgrade soil.

The TDR volumetric moisture contents typically varied by 10% to 15% from the driest to the wettest periods, but sometimes the variations were larger. The lower water contents occurred during the late winter/early spring months and the higher contents occurred during the late summer/early fall months. This reflects the climatic conditions that occurred. Some of the TDR moisture contents exceeded 40%, which is greater than the soil porosity and therefore not possible. An equation for TDR volumetric water content developed for the FHWA yields lower water contents. Most of the thermal conductivity sensors are no longer within calibration. Data from sensors in calibration indicate very low matric suctions, which is consistent with high water contents. Soil-water characteristic relationships were obtained for the subgrade soil using triaxial and pressure plate apparatus. The relationships from the two tests are comparable. The soil exhibits some hysteresis when comparing drying and wetting curves.

17. Key Words
Seasonal Instrumentation, Time Domain Reflectometry, Volumetric Water Content, Soil Matric Suction, Soil-Water Characteristic Relationship.

18. Distribution Statement
No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
59

22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

SEASONAL INSTRUMENTATION OF SHRP PAVEMENTS - THE UNIVERSITY OF TOLEDO

ODOT PROJECT NO. 14584(0)

Final Report

By

Andrew G. Heydinger

and

Brian W. Randolph

Department of Civil Engineering

The University of Toledo

Report No. UT-CE/GG 98-101

October, 1998

Prepared in cooperation with the Ohio Department of Transportation and the U. S. Department of Transportation, Federal Highway Administration

EXECUTIVE SUMMARY

Report No. FHWA/OH-98/012

Seasonal Instrumentation of SHRP Pavements - The University of Toledo

Andrew G. Heydinger and Brian W. Randolph
Department of Civil Engineering, University of Toledo

Sponsoring Agency: Ohio Department of Transportation
1600 West Broad Street
Columbus, OH 43216-0899

October, 1998

The objectives were to install and monitor Seasonal Monitoring Program (SMP) instrumentation and additional instrumentation to measure soil moisture and moisture suction at the Ohio Test Pavement in Delaware County, Ohio. Laboratory soil-water characteristic testing was to be conducted on remolded samples of the subgrade soil.

Strategic Highway Research Program (SHRP) protocols developed for the Long-Term Pavement Performance (LTPP) group of the Federal Highway Administration (FHWA) were used for the SMP installation and monitoring. Five pavement sections were monitored for the seasonal variations of volumetric moisture content, temperature and frost penetration since September 1996. Time Domain Reflectometry (TDR) instrumentation was installed onsite for monitoring moisture content. Six thermal conductivity sensors (TCS) were installed in the subgrade soil at each of four of the pavement sections to measure moisture suction. Laboratory soil-water characteristic tests were conducted on compacted subgrade soil using pressure plate and triaxial apparatus.

The TDR volumetric moisture contents typically varied by 10% to 15% from the driest to the wettest periods, but in some instances the variations were larger. The lower water contents occurred during the late winter/early spring months and the higher contents occurred during the late summer/early fall months. This reflects the climatic conditions that occurred during the monitoring period. Some of the TDR moisture contents exceeded 40%, which is greater than the soil porosity and therefore not possible. An equation for TDR volumetric water content developed for the FHWA yields lower computed water contents. Most of the thermal conductivity sensors are no longer within calibration. Data from sensors in calibration indicate very low matric suctions, which are consistent with the high water contents. Soil-water characteristic relationships obtained for the subgrade soil using triaxial and pressure plate apparatus are comparable. The soil exhibits some hysteresis when comparing drying and wetting curves.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

ACKNOWLEDGEMENTS

The authors acknowledge the collaborative efforts of other university researchers in the Ohio who are also responsible for SMP pavement instrumentation and monitoring at other test sections at the Ohio Test Pavement. These include Dr. Shad Sargand and Mr. Issam Khoury of the Ohio University; Dr. Ludwig Fugueroa of Case Western Reserve University; Dr. William Wolff of The Ohio State University. The authors express their gratitude to Mr. William Edwards (retired), Mr. Roger Green and Mr. Brad Young of the Ohio Department of Transportation. The assistance with the laboratory testing and field instrumentation by former University of Toledo graduate students Mr. Brad Lowery, Ms. Chandrika Manepally and Mr. Pirasanna Venugopal is also acknowledged.

PROTECTED UNDER INTERNATIONAL COPYRIGHT
ALL RIGHTS RESERVED.
NATIONAL TECHNICAL INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

The Long-Term Pavement Performance (LTPP) group of the Federal Highway Administration (FHWA) is sponsoring pavement testing identified by the Strategic Highway Research Program (SHRP) research. The testing is a national initiative to evaluate the long-term effects of climate and traffic loading on pavements. Included in the SHRP program is the Seasonal Monitoring Program (SMP) which includes instrumenting and monitoring pavements, pavement bases and subbases, and subgrade soils for seasons variations of moisture, temperature and frost penetration. The SMP program specifies instrumentation sensors and installation and data acquisition protocols for collecting the data (Rada, et al., 1994). Computer software is provided for preparing the data for the LTPP Information Management System (Elkins and Zhou, 1996). Specific Pavement Studies (SPS) pavement testing has been designed to measure a number of pavement structural parameters.

The Ohio Department of Transportation (ODOT) is participating in the SHRP pavement testing at the Ohio Test Pavement on U. S. Route 23 in Delaware County, Ohio (DEL-23). Pavement sections were instrumented for both SMPP and SPS testing. The test sections consist of different pavement, base, subbase, and drainage designs for asphalt (southbound sections) and Portland cement concrete (northbound sections) pavements (Sargand, 1994). An on-site weather station monitors daily temperatures, precipitation, solar radiation, relative humidity, wind speed, and wind direction. Additional instrumentation was installed on some of the SMPP pavement sections by researchers at the University of Toledo, that allow for more frequent reading of the Time Domain Reflectometry (TDR) soil moisture measurements and measurement of soil moisture suction.

Pavement performance is dependent on the condition of the pavement base and subgrade soil. Pavements can experience distress if the supporting layers do not have adequate strength or stiffness. Pavement design procedures require material stiffness parameters for pavement, base and subgrade soils. The stiffness parameters vary because of seasonal variations of moisture and other climatic factors. Laboratory testing conducted on subgrade soils from several sites in Ohio including the Ohio Test Pavement site has shown the dependence of soil stiffness on soil moisture and stress (Jin et al., 1994; Figueroa, et al., 1994; DeButy, 1997).

For subgrade soils, soil moisture changes result in variations of the soil moisture suction and effective soil stresses. Soil moisture suction is the negative pore water pressure that occurs in unsaturated soils. The component of the total soil moisture suction that is most relevant to seasonal variations is the moisture suction caused by capillary surface tension. This is the soil matric suction and is defined as the difference between the pore air pressure and the pore water pressure. The relationship between soil matric suction and soil moisture content is the soil-water characteristic curve. The relationship is unique for each soil. The relationship differs for wetting and drying conditions, which is the hysteresis effect. Negative pore water pressure increases the effective soil stress, which increases the soil shear strength and stiffness. An understanding of the variation of soil moisture and moisture suction is desirable if one is to investigate the climatic effects on pavements.

This report discusses results from field monitoring and laboratory testing on the subgrade soil at the Ohio Test Pavement project. Time domain reflectometry (TDR) soil moisture sensors, electrical resistivity and temperature probes were installed in five pavement sections according to SHRP guidelines (Rada, et al, 1994). Temperature data is uploaded to personal computers from onsite CR10 dataloggers, and TDR and soil resistivity data is collected at least fourteen times each year using a mobile data acquisition system. In addition to this instrumentation, two sections were equipped with a cable tester and CR10 datalogger for more frequent monitoring of soil moisture.

Thermal conductivity sensors (TCS) were installed in four of the sections to measure soil moisture suction. The sensors are sensitive to the amount of moisture in the soil so they can be calibrated for soil matric suction. Calibrated sensors were purchased and installed adjacent to TDR moisture probes. CR10 dataloggers are used to store the data for later collection. The TCS sensors can be used with the TDR sensors to enable measurement of both soil moisture and moisture suction for comparison with the laboratory soil-water characteristic hysteresis curves. This information will be useful in evaluating the extent of the season variations of soil moisture and soil moisture suction in the subgrade soil.

Laboratory testing was conducted at the University of Toledo to investigate the soil-water characteristic behavior of the subgrade soil at the Ohio Test Pavement test site. Bag samples were obtained from several locations at the site. The soil was carefully recompacted to approximate properties of the compacted soil. Soil-water characteristic studies were conducted using a pressure plate extractor test device with hysteresis apparatus attached (Lowery, 1996). For the testing, soil volumetric content and matric suction were measured using two methods: 1) by measurement of the flow of water from or to the soil and the air and water pressures; and 2) by measurements from TDR soil moisture and TCS soil matric suction sensors placed in the soil during compaction. Free draining soil-water characteristic testing was conducted on soil compacted with TDR, TCS and tensiometers. For this testing, the moisture content was varied through cycles of wetting and drying and readings were obtained from the sensors. Soil-water characteristic testing was also conducted on compacted soil using a modified triaxial cell and volume change apparatus which allowed for very accurate measurements of volume changes (Manepally, 1997). Laboratory test results are compared with field measurements obtained from the site to gain a better understanding of the seasonal variations of soil moisture and moisture suction in the subgrade soil.

CHAPTER 2

RESEARCH OBJECTIVES

The objectives of the research was to install and monitor Seasonal Monitoring Program (SMP) and additional soil moisture instrumentation in test pavements at the Ohio Test Pavement and to conduct laboratory soil-water characteristic testing on soil obtained from the site. The research required literature review, laboratory soils testing and installation and monitoring of the sensors. The major tasks required for the research are as follows.

1) Literature review on instrumentation and laboratory testing of unsaturated soils. Research was required on SMP instrumentation installation and data collection, TDR soil moisture instrumentation, soil matric suction sensors and laboratory soil moisture characteristic testing.
2) Additional soil moisture instrumentation including capabilities to measure the soil matric suction and to install onsite Time Domain Reflectometry (TDR) instrumentation to measure soil moisture.
3) Soil-water characteristic testing was to be were conducted in the Environmental Geotechnology Laboratory at The University of Toledo to evaluate the use of TDR and TCS sensors for soil moisture and soil moisture suction measurements, and to determine the soil-water characteristic relationship for the subgrade soil.
4) SMP seasonal instrumentation was to be installed in five test sections by The University of Toledo researchers.
5) Seasonal instrumentation monitoring including collection of data from the ONSITE and MOBILE data collection systems at least fourteen times per year. Data from the onsite TDR systems and the TCS sensors are also to be monitored.
6) Evaluation of seasonal variation of subgrade soil moisture condition. Computer programs written for personal computers are to be used to evaluate and process the SMP data.

CHAPTER 3

LABORATORY SOIL - WATER CHARACTERISTIC TESTS

3.1 Soil-Water Characteristic Relationship

The soil-water character relationship is the relationship between soil matric suction and the volumetric water content. It is typically obtained by plotting the soil volumetric water content on the vertical axis and the matric suction on the horizontal axis. Soil matric suction is defined as the difference between soil air pressure and soil water pressure, u_a - u_w. For unsaturated soils, the soil air pressure is approximately equal to atmospheric pressure or zero gage pressure while the soil water pressure is less than atmospheric pressure or negative gage pressure, resulting in positive matric suction values. Negative pore water pressures are caused by capillary surface tension and, for soils at low degree of saturation, adsorptive forces between soil particles. Capillary surface tension is inversely proportional to the radii of the menisci formed within the soil pore spaces.

The soil moisture characteristic relationship exhibits hysteresis or partial irreversibility for many soils. The matric suction for a particular moisture content is somewhat greater if the moisture content is arrived at because of drying than if the soil is wetting. Thus the drying curve lies above the wetting curve. Hysteresis behavior is attributed to differences in the soil water menisci and to air entrapment during soil wetting. A consequence of hysteresis behavior is that it is necessary to measure soil matric suction as well as soil moisture content. Pavement subgrade soils can be expected to experience cycles of wetting and drying depending on seasonal climate changes.

Subgrade soils that may not undergo large seasonal variations of the soil moisture content could be subject to significant variations of the soil matric suction depending on the shape of the soil moisture characteristic curves. The slope of the soil characteristic curve is an indication of magnitude of the soil matric suction changes that could occur. The spacing of the hysteresis curves determines the magnitude of the variations in soil matric suction. This chapter discusses results of laboratory soil characteristic testing conducted on the Ohio

Test Pavement subgrade soil and the following chapter presents results of seasonal instrumentation at the site.

3.2 Axis Translation Technique

A major difficulty arises when attemoting to measure pore water pressures that are lower than -1 atmosphere. At these low pressures water cavitates, i.e. water molecules change from liquid to vapor. The water vapor fills the measuring system making it impossible to measure the pore water pressure. The axis translation technique is a method that has been adopted for investigating the soil-water moisture characteristic behavior for soils at low suction pressures. The technique involves raising the soil air pressure to a high positive value while maintaining the soil water pressure near atmospheric pressure. At each increment of applied air pressure the soil water is allowed to drain from the soil until equilibrium is reached. The water content is determined and the soil matric pressure is computed as defined previously, except in this case both the air and water pressures are translated to higher values. The technique can be used for both drying and wetting cycles by reversing the steps taken to dry the soil. This technique has been shown to be a valid method for determining the soil moisture characteristic relationship (Fredlund, 1993).

3.3 Pressure Plate Extractor Tests

The pressure plate extractor is an apparatus available for determining soil-water characteristic relationships for soils. Soil compacted in a ring is placed on a large ceramic plate. Air pressure is applied and soil water flow occurs using connections through the side of the chamber. Soil moisture content determinations are made by measuring the volume of water flow out from or into the soil or by quickly removing the soil from the extractor and conducting a destructive moisture content test. A hysteresis attachment to the pressure plate extractor is designed to remove diffused air from the water before measuring the volume of water flow.

3.3.1 Apparatus Description

The pressure plate extractor used for the testing is the type designed for use by soil scientists for testing agricultural soils. A hysteresis attachment was also required for some of the testing. A schematic of the apparatus used for the testing is shown in Figure 3.1 and a description of the components follows.

1) The apparatus includes a chamber and a lid that bolts down to the chamber. There are four ports with tubing fittings through the side of the chamber which allow for the application of air pressure and for the flow of water.
2) A water-saturated ceramic plate is placed in the chamber. The capillary forces in the saturated ceramic material prevent air from passing through the plate. Ceramic plates have a specified air entry value of 1 to 15 bars depending on the size of the openings. The air entry value is the maximum air pressure that can be applied to a saturated plate before the air enters the plate. A rubber membrane and water compartment on the bottom of the plate collects the soil water. Ports extending though the plate to the water compartment are connected to the chamber ports with small diameter tubing.

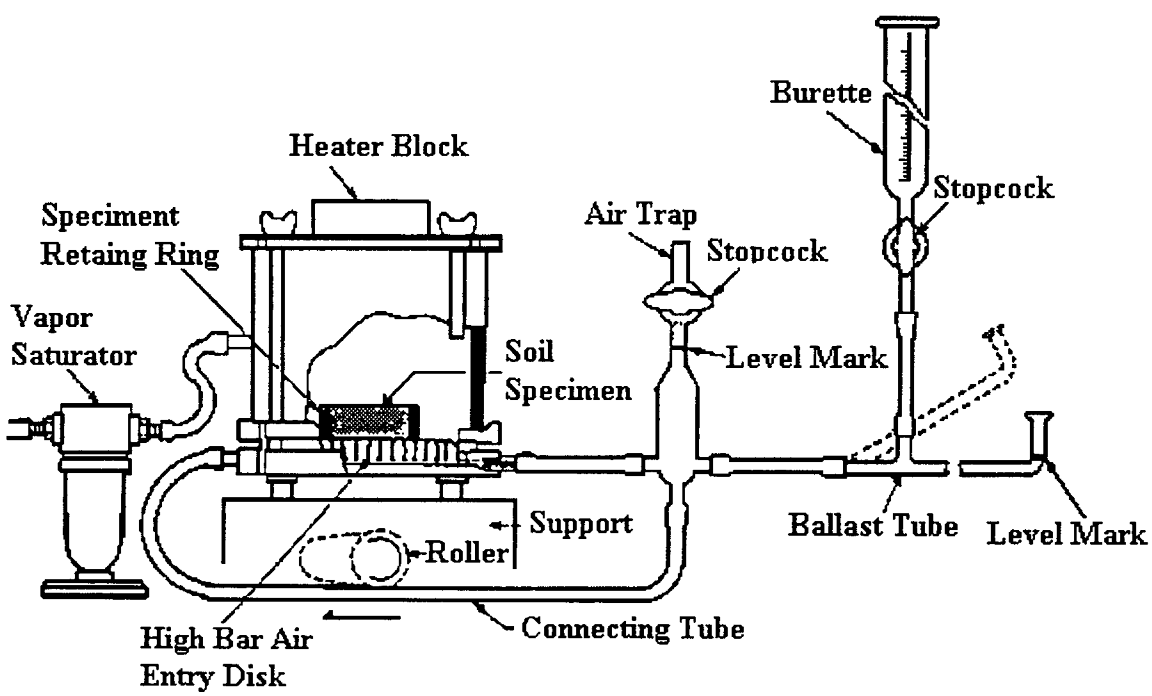


Figure 3.1 - Pressure Plate Extractor (From Fredlund, 1993)

3) The hysteresis apparatus enables measurement of the volume of water flowing to or from the soil. A tubing pump was used in place of the roller to circulate water through the water compartment to remove diffused air. Water flow measurements were made using the burette. The small diameter tubing was connected to the ballast tube to collect the water.

3.3.2 Test Procedures

Two types of tests were conducted using the pressure plate extractor apparatus; 1) soil-water test with water volume measurements, and 2) soil-water test with direct measurement of soil water content. The former test was conducted on a large soil sample. Special precautions were required to measure the water volumes. The later soil test used fourteen small soil specimens. One water content sample was removed from the pressure chamber at the end of each chamber pressurization period.

3.3.2.1 Test with Water Volume Measurements

Soil sample preparation consisted of obtaining approximately 500g of subgrade soil passing a #10 sieve. The soil was wetted to a moisture content of 11%. A PVC sample ring 7.7 cm high with a volume of 3,166.6 cc was placed in the chamber on a saturated ceramic plate. Soil was compacted in the sample ring around a TDR soil moisture probe and a TCS matrix suction sensor. A description of the TCS sensors is given in Chapter 4. The soil was trimmed flush with the top of the ring. Water was then placed in the pressure chamber up to the top of the sample ring. The soil was allowed to saturate for a period of forty-eight hours. The dry density of the soil was calculated to be 1.4 g/cm^3 (13.7 kN/m^3).

Modifications were needed for this testing. Holes were placed in the side of the pressure chamber to allow for the electronic sensor wires to exit the chamber. A seal was placed around the wires to maintain air pressures in the chamber. An extra fitting was added to the 5 Bar ceramic plate diametrically opposite to the other fitting to allow the area under the plate to be flushed free from diffused air. A long length of tubing was attached to the end of the ballast tube to collect soil water.

The test was conducted by first pressurizing the chamber from 0 to 200 kPa in increments of approximately 20 kPa and then returning the chamber pressure 0 in similar increments. The pressure was regulated manually using a pressure gauge and regulator. The water volume changes were measured manually using the burette and a graduated cylinder. The TDR probe and TCS sensor were connected to a CR10 datalogger to monitor the water content and pressure changes electronically. A CR10 program was written to read the TDR trace and TCS voltage change at five-minute intervals. Measurements were continued for each pressure level until no detectable changes were observed. The last five data points from the electronic sensors were averaged to compute the equilibrium values. The soil sample was removed from the pressure chamber at the end of the test in order to determine the final gravimetric water content.

3.3.2.2 Test with Direct Measurement of Soil Water Content

Soil from the Ohio Test Pavement site was hand compacted and statically compressed in a triaxial mold to attain a dry density of 17.0 kN/m^3 (108 lb/ft^3) and gravimetric moisture content of 20%. These values are equivalent to average values from undisturbed samples tested by DeButy (1997). Soil specimens were obtained by pressing stainless steel rings into the soil and then carefully trimming the ends of the rings. Each compacted soil sample was large enough to provide seven soil specimens 19.1 mm high by 47.5 mm diameter. A total of fourteen soil specimens were obtained in this manner.

A ceramic plate with an air entry value of 3 bars was used for the test. The plate was first saturated. The soil specimens were then placed on the ceramic plate in the pressure chamber and saturated by gradually increasing the depth of the water in the chamber in increments of 3 mm until the water reached the top of the rings. The excess water was removed from the top of the plate. The hysteresis apparatus was attached to the chamber in order to observe the movement of water. It was not necessary to measure the water volume for this test. Instead, after ensuring that the soil samples reached equilibrium with the applied air pressures, the pressure chamber was quickly depressurized and one sample was removed for a moisture content determination. A drying soil-water characteristic curve was obtained using half of the specimens and a wetting curve was obtained using the other half of the specimens in order to investigate the hysteresis behavior.

3.3.3 Test Results

Soil moisture characteristic curves were obtained from the pressure plate extractor tests. Results from the tests are compared wherever possible.

3.3.3.1 Test with Water Volume Measurements

A soil sample size larger than the typical pressure plate sample was required in order to accommodate the TDR and TCS sensors. A sample height of 7.7 centimeter was selected after consultation with the sensor manufacturers in order to provide adequate cover for the sensors. Since drainage time is a function of the square of the drainage depth, the time required for the soil to reach equilibrium was very long. Special precautions had to be taken to measure the large volume of outflow generated by the sample and to determine when water flow had ceased. There was some air leakage around the pressure plate at 200 kPa pressure so the drying cycle was terminated and water was reintroduced into the hysteresis attachment in order to begin the wetting process.

Soil-water characteristic relationships were obtained using measured water volume changes and air pressures and the TDR and TCS instrumentation. The initial and final gravimetric water contents were determined at the beginning and the end of the test. The

$$\theta = w \times \left(\frac{\gamma_{dry}}{\gamma_w} \right) \qquad 3.1$$

gravimetric water contents, w, were then converted to volumetric water content, θ, using the following equation. The dry unit weight, γ_{dry}, determined initially and the unit weight of water, γ_w, are used in the calculations. The volumetric water contents were then computed for the applied air pressures using the water volume changes and the initial or final water contents. For the axis translation technique, the soil matric suction is equal to the applied air pressure since the water pressure was kept at atmospheric and the static water level in the hysteresis apparatus was kept at center of the soil specimen. The TDR and TCS sensors were calibrated to give volumetric water content and soil matric suction, respectively. A discussion of these sensors is provided in Chapter 4.

The data from the pressure plate extraction tests was used in different ways to obtain the soil-water characteristic curves. Table 3.1 shows the computed pressures and water contents. The calculated water contents were computed using the water volume change measurements and the initial and final gravimetric water contents as described above. Four different soil moisture characteristic curves are shown in Figure 3.2. The calculated volumetric moisture contents are consistently lower than the TDR water contents. Therefore, the two curves plotted using calculated water contents fall below the other two curves. The matric pressures computed using the applied air pressures and the TCS measurements vary. However, both sets of curves obtained from plots of calculated water content and TDR water content overlie

Table 3.1 - Pressure Plate Test Results, Water Volume Measurements

Applied Air Pressure (kPa)	TCS Matric Suction (kPa)	Calculated Volumetric Water Content (%)	Calculated Gravimetric Water Content (%)	TDR Volumetric Water Content (%)	TDR Gravimetric Water Content (%)
0.0	30.8	31.4	22.4	50.9	36.1
20.3	7.8	16.1	11.5	25.6	18.2
38.9	26.8	14.0	10.0	23.5	16.7
63.7	51.6	12.9	9.2	21.9	15.5
81.3	81.4	11.8	8.4	21.4	15.2
122.6	125.7	10.8	7.7	19.7	14.0
142.9	161.2	10.8	7.7	19.1	13.5
207.3	189.4	10.5	7.5	19.3	13.7
151.0	105.0	11.5	8.2	18.5	13.1
132.1	98.3	11.9	8.5	18.8	13.3
101.6	103.3	12.6	9.0	17.0	12.7
78.9	82.8	13.0	9.3	17.2	12.2
63.7	77.1	13.4	9.6	18.3	13.0
40.6	67.6	14.7	10.5	18.4	13.0
20.3	31.8	17.1	12.2	19.0	13.5
0.0	1.6	26.9	19.2	27.7	19.6

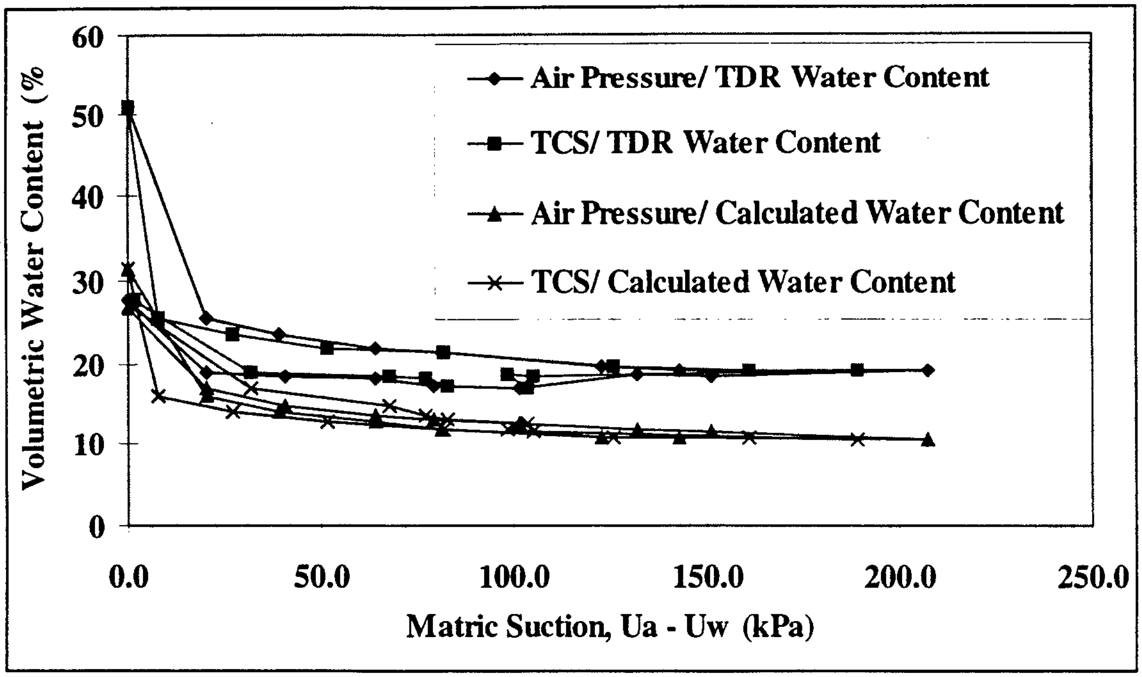


Figure 3.2 - Soil Moisture Characteristic Curves, Pressure Plate Extractor Test With Water Volume Measurements

each other. The curves obtained using the TDR water contents exhibit more hysteresis effect. There appears to be no hysteresis effect between the air pressure/calculated water content wetting and drying curves. In fact, the wetting curve plots slightly above the drying curve where the drying curve should be above the wetting curve, as it is in for the other three plots.

3.3.3.2 Test with Direct Measurement of Soil Water Content

One soil sample was removed from the pressure chamber after each change in matric suction and the required moisture content measurements were made. The computed relationships are shown in Table 3.2 for both the drying and wetting cycles. The soil-water characteristic curve is shown in Figure 3.3. The shape of the curve is similar to curves from the test with water volume measurements. However, the volumetric water contents are consistently higher for this test. Thus the soil moisture characteristic curve would plot above

Table 3.2 - Pressure Plate Test Results, Direct Measurement of Water Content

Applied Air Press. kPa (psi)	Grav. Water Content (%)	Wet Unit Weight (g/cc)	Dry Unit Weight (g/cc)	Volum. Water Content (%)	Void Ratio	Porosity n	Degree of Saturation (%)
0.0	21.3	2.17	1.79	38.2	0.51	33.8	112.9
35. (5)	19.9	2.17	1.81	36.0	0.49	33.0	109.1
69. (10)	17.7	2.08	1.76	31.2	0.53	34.7	90.0
138. (20)	16.7	2.06	1.77	29.6	0.53	34.5	85.7
207. (30)	17.0	2.01	1.72	29.3	0.57	36.4	80.5
276. (40)	16.2	2.08	1.79	29.0	0.51	33.7	85.9
345. (50)	15.1	2.09	1.82	27.4	0.49	32.7	83.9
414. (60)	15.4	2.01	1.74	26.7	0.55	35.6	75.0
345. (50)	15.9	2.04	1.76	28.1	0.53	34.7	80.9
276. (40)	17.2	1.93	1.65	28.3	0.64	39.0	72.7
207. (30)	16.2	2.03	1.74	28.2	0.55	35.4	79.8
138. (20)	16.4	2.00	1.72	28.3	0.57	36.3	77.8
69. (10)	16.0	2.09	1.80	28.8	0.50	33.3	86.4
35. (5)	16.3	2.11	1.81	29.6	0.49	32.9	89.8

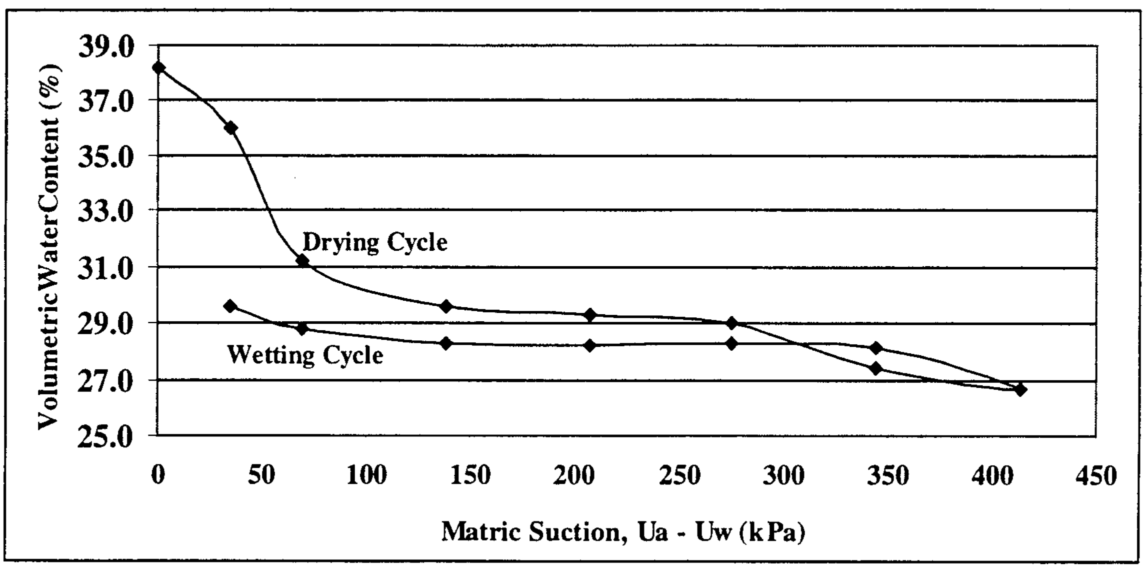


Figure 3.3 - Soil Moisture Characteristic Curves, Pressure Plate Extractor Test With Direct Measurement of Water Content

the other four curves from the previous test. A hysteresis effect can also be seen from the results of this test.

3.4 Free-draining Test

The free-draining test was conducted by compacting soil in a large plastic container with three types of sensors and varying the moisture content. The soil was moistened by immersing the container in water. The soil was subjected to drying cycles by removing the container from the water bath and allowing the water to drain and evaporate from the soil. In contrast to the axis translation technique, the air pressure is atmospheric and the pore water pressures takes on negative values as the soil dries. There was no way to measure the volume changes for the water. Therefore a TDR moisture probe, TCS matric suction and tensiometer probe was placed in the soil for measurement of the soil water content and matric suction.

3.4.1 Apparatus Description

The apparatus consisted of two large plastic containers of different diameters and the sensors and instrumentation. The soil was compacted in the container with the smaller diameter. The larger container provided a water bath. A cable tester was used to obtain the TDR traces for the moisture content. A CR10 datalogger was used to collect the TDR and TCS data. A personal computer was used with an optical isolated interface to read the data from the data logger. A type 2100F Soilmoisture Equipment Corporation tensiometer probe was placed in the soil. The tensiometer consists of a ceramic probe and a pressure gage connected by small diameter tubing. The soil moisture suction pressure is read directly from the pressure gage.

3.4.2 Test Procedure

For the free-draining test, subgrade soil from the Ohio Test Road was carefully compacted around the sensors and the soil was subjected to wetting and drying cycles. Small diameter holes were drilled in the bottom of the container to allow for water passage and a filter cloth was placed in the bottom to prevent loss of soil. The tensiometer was saturated by forcing water into the sensor tubing until the sensor was completely deaired. The optimum moisture content was estimated and the soil was manually compacted. Wetting was achieved by placing the smaller container inside the larger container on several layers of filter cloth. Water was added to the larger container. The water level in the larger container was maintained at the top of the soil layer. For drying cycles, the water was removed from the larger container and the smaller container was placed on a porous material so that water could drain from the bottom of the container. The container was open to the atmosphere during drying so that water could also evaporate from the soil. The testing took place over a period of 14 days during which two cycles of wetting followed by drying were completed.

3.4.3 Test Results

Soil moisture and matric suction readings were obtained over two complete cycles of wetting and drying. Soil moisture characteristic curves are shown in Figure 3.4 as determined from TDR volumetric water contents and TCS matric suction pressures. The first three cycles (wetting #1/drying #1/wetting #2) have volumetric water contents that are higher

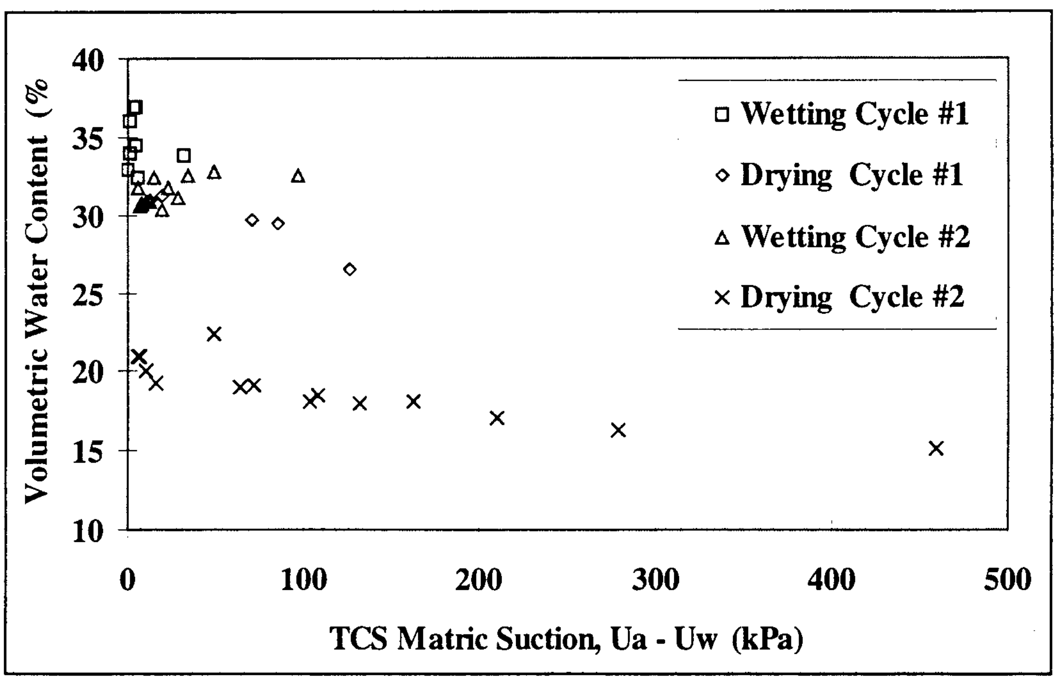


Figure 3.4 - Soil Moisture Characteristic Measurements, Free Draining Test

than the last drying cycle. Comparing the curves with the pressure plate extractor tests, the first three cycles are closer to the curves obtained from the test with direct measurement of water content, Figure 3.3. The final drying curve is closer to the test with water volume measurements, Figure 3.2. During the drying cycles, large changes in matric suction occurred in a matter of a few hours. The wetting cycles required longer periods of time. Thus, vaporization occurring at room temperatures took place at a much faster rate than the flow of water required for soil wetting. The maximum suction pressure obtainable from the tensiometer was just over 80 kPa. A comparison between TCS and tensiometer matric suction pressures is shown in Figure 3.5. The figure indicates that there is some agreement between the measurements obtained from the two sensors. The differences can be attributed in part to the fact that the soil was constantly changing water content and the response times of the two sensors differed.

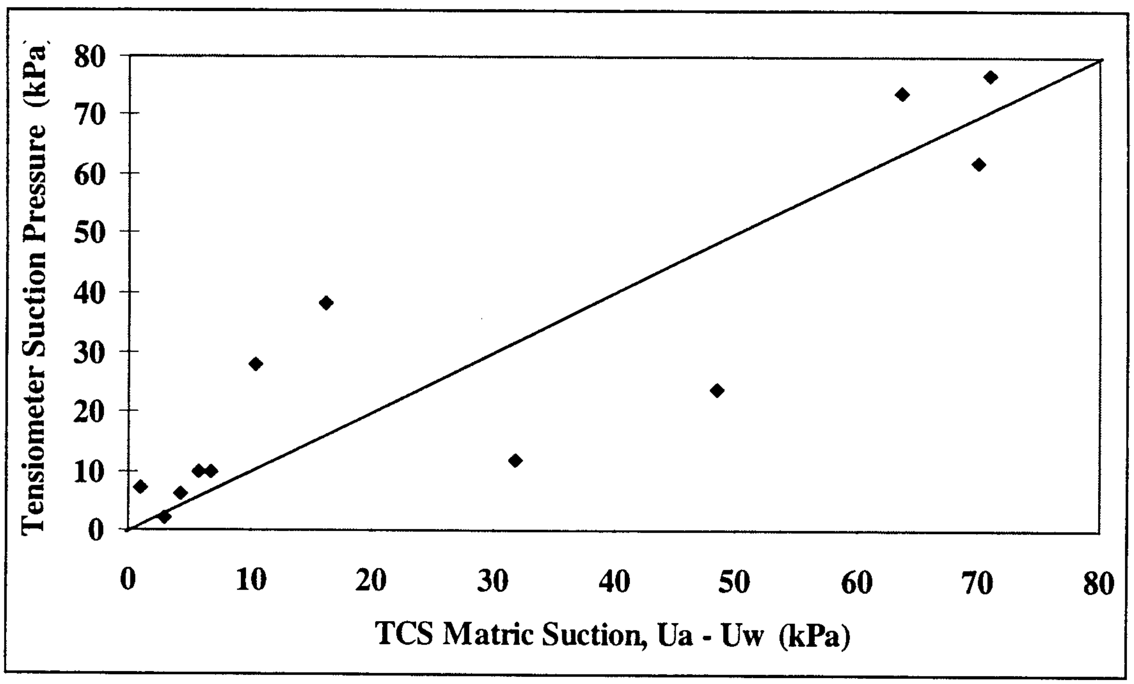


Figure 3.5 - Tensiometer Suction versus TCS Matric Suction From Free Draining Test

3.5 Modified Triaxial Cell/Volume Change Apparatus Test

A conventional triaxial cell was modified and volume change apparatuses were constructed to enable additional soil moisture characteristic testing. The number of outlets in the base of the triaxial cell was increased to allow for air and water flow. The sample base pedestal was machined to accommodate a pore-air pressure channel, a high air entry disk and a grooved water compartment below the disk. An electronic load cell was attached to the load piston inside the cell to measure the vertical load applied to the soil specimen. A Lucite cylinder was machined for one-dimensional testing. Two types of volume change apparatuses were fabricated, water volume change indicators (WVCI) and diffused air volume change indicators (DAVI). The volume change indicators are equipped with burettes capable of measuring to the nearest 0.1 ml. Consequently, precise volume change measurements can be made for accurate determinations of the volumetric water content.

3.5.1 Apparatus Description

A complete triaxial test set is available in the Environmental Geotechnology Laboratory at The University of Toledo for testing unsaturated soils. The triaxial apparatus, including the modified triaxial cell and volume change apparatus, consists of the following components.

3.5.1.1 Triaxial Equipment

1) A regulated pneumatic press capable of maintaining constant loads;
2) Water de-ionization apparatus for removing water ions;
3) Deairing chamber for deairing water;
4) Vacuum pump;
5) Compressed air supply;
6) Pressure regulator and pressure gage for applying the soil air pressure.

3.5.1.2 Triaxial Cell

1) Load piston with electronic load cell and analog-to-digital converter with display;
2) Mechanical dial indicator for measuring vertical displacement of the load piston to compute soil volume changes;

3) Base pedestal with spiral groove below a 5 bar high air entry disk. The spiral groove acts as a water compartment for flushing diffused air from below the disk. The high air entry disk is epoxied into the pedestal to prevent air from flowing around the disk.
4) Soil cap with porous stone;
5) Seven inlet/outlets in the base - one for applying cell pressure, two for both the base pedestal and the soil cap for the soil water, one for both the base pedestal and the cap for the soil air;
6) Lucite cylinder that fits over the base pedestal and also accommodates the soil cap for one-dimensional testing.

3.5.1.3 Water Volume Change Indicator (WVCI)

1) Lucite cylinder with aluminum ends;
2) Pressure fitting in the top;
3) Four burettes press fit into the base and open at the top, three measuring to 0.1 ml and one measuring to 0.01ml;
4) Manifold with five zero-volume valves connected together, one for the water supply and one each for the burettes;
5) Small diameter tubing (1/8 inch outside diameter).

3.5.1.4 Diffused Air Volume Indicator (DAVI)

1) Lucite cylinder with aluminum ends;
2) Pressure fitting in the top;
3) One burette measuring to 0.1 ml to measure the volume of diffused air, press fit into the base and the top with a pressure relief valve at the top;
4) One exit tube press fit into base and open at the top connected in parallel to the burette;
5) Zero-volume valve;
6) Small diameter tubing (1/8 inch outside diameter), one tubing that extends through the base into the burette and connects to the valve.

3.5.2 Test Procedure

3.5.2.1 Sample Preparation

Soil from the Ohio Test Pavement site was hand compacted and statically compressed in the Lucite cylinder and the Lucite cylinder was slid over the base of the pedestal in the triaxial cell. The initial soil properties were γ_{wet} = 20.3 kN/m^3 (129.1 lb/ft^3), γ_{dry} = 17.0 kN/m^3 (108.3 lb/ft^3) and gravimetric moisture content of 19.2%. The high air entry disk in the pedestal was saturated before soil compaction. The triaxial cell was closed and all connections to the volume change apparatuses were completed. The initial reading on the dial indicator was recorded. A vertical pressure equal to 34.5 kPa (5 lb/in^2) was applied throughout the test. The sample was saturated by allowing water to flow into the soil from the burette in the WVCI. The volume of water flowing into the soil was carefully monitored.

3.5.2.2 Moisture-Suction Variation

Soil moisture-suction variations were accomplished by varying the soil pore air and water pressures. The openings in the soil cap were left open so that the soil air pressure could be applied simply by varying the air pressure in the triaxial cell. The air pressure in the WVCI was maintained at atmospheric so the pore water pressure acting on the soil was due to the hydrostatic head in the WVCI burette used for measuring soil water volume changes. After the saturating the soil, the soil air pressure was increased and then decreased incrementally for one drying and one wetting cycle. The soil air pressure was maintained constant for each increment of matric suction but the pore water pressure increased during the drying cycle and decreased during the wetting cycle as the water flowed out of and back into the soil. Therefore the matric suction was corrected for each water volume measurement to account for the water pressure changes. Final water contents were computed for each increment after water stopped flowing from the soil.

3.5.2.3 WVCI Measurements

The water volume change indicator (WVCI) measured the changes in soil water volume. The WVCI was connected to one of the valves connected to the base pedestal using the small diameter tubing. The other valve was connected to the DAVI. The system was saturated initially by flushing water from burettes into the WVCI through the water compartment below the high air interface material and back out to the DAVI. After saturation the valve connected to the DAVI was kept closed during water volume measurements. Water volume changes were obtained directly from the burettes. However, in order to compute the soil water pressure, it was necessary to make accurate measurements of the height of the WVCI, the height of the zero reading on the burette and the change in height of water per unit volume for the burettes. The values were input into an MS Excel spreadsheet program designed to make all necessary computations. Occasionally it was necessary to adjust the height of water in the burette. The spreadsheet program was designed so that the cumulative change in soil water volume could be computed using the water volume adjustments.

3.5.2.4 DAVI Measurements

The diffused air volume indicator (DAVI) design described by Fredlund (1993) was used for the measurements. The DAVI was saturated as described in the previous section. The air vent at the top of the DAVI was kept open to the atmosphere at all times. The air vent at the top of the burette was kept open during saturation to maintain the air pressure at atmospheric. As water was flushed though the DAVI, the water spilled out the top of the exit tube and raised the water level in the burette to the top of the exit tube. After saturation, the air vent at the top of the burette was closed so that the diffused air volume could be measured. Diffused air volumes were measured by closing the manifold valve connected to the WVCI burette and opening the valve to the DAVI. Water was then flushed from one of the other burettes in the WVCI through the water compartment and to the DAVI. Water enters the DAVI though the small diameter tubing which extends into the bottom of the DAVI burette. The diffused air bubbles then flow to the top of the burette increasing the air pressure in the burette and displacing water from the burette. The flush water and the displaced water spills out the top of the exit tube. The diffused air volume is measured in the burette. The volume of diffused air is corrected for the pressure at the base of the cell. The volume of diffused air is subtracted from the water volume measurements to give the actual water volume changes.

3.5.3 Test Results

The soil sample was tested for one drying and wetting cycle in order to determine the soil-moisture characteristic curve. For the test, the air pressure was varied incrementally and the volume change measurements were entered into the spreadsheet program. The computed volumetric water contents were used to monitor the progress of the test to determine the conclusions of the stress periods, i. e. constant water content, and to ensure that the test apparatus was functioning properly. For the drying cycle, water was expelled from the soil and the test progressed without any problems. However for the wetting cycle, water did not flow back into the soil as the soil air pressure was decreased and air diffused through the high air entry disk. The computed volumetric water contents decreased as the air pressure was decreased. Therefore the results of the wetting cycle cannot be used. The results from the testing are shown in Table 3.3. The soil moisture characteristic curve for the drying cycle is shown in Figure 3.6.

Table 3.3 - Soil Moisture Characteristic Data, Triaxial Test

Ua (kPa)	Ua-Uw (kPa)	Water Volume Change (ml)	V_t (cm^3)	Using Initial Water Content: Water Content Volum.	Grav.	n (%)	S (%)	Using Final Water Content: Water Content Volum.	Grav.	n (%)	S (%)
0.0	-5.3	0.0	353.2	33.3	19.2	35.5	93.6	38.1	21.8	35.1	108.2
-34.5	-39.1	6.4	341.7	36.3	20.2	33.3	108.6	41.3	22.8	32.9	124.9
34.5	30.7	-1.2	341.2	34.1	19.0	33.3	102.4	39.1	21.6	32.9	118.7
68.9	65.1	-3.4	340.1	33.6	18.6	33.3	101.3	38.5	21.2	32.9	117.8
103.4	99.2	-7.8	339.5	32.4	17.9	32.9	98.0	37.3	20.5	32.4	114.5
137.9	133.3	-11.8	339.0	31.2	17.2	32.9	94.9	36.2	19.9	32.4	111.4
172.4	167.7	-13.6	338.8	30.7	16.9	32.9	93.4	35.7	19.6	32.4	109.9
206.8	202.1	-14.8	338.6	30.4	16.7	32.9	92.5	35.3	19.4	32.4	109.0
275.8	270.9	-16.9	338.4	29.8	16.4	32.9	90.8	34.7	19.0	32.4	107.3
344.7	339.6	-21.0	338.0	28.6	15.7	32.9	87.4	33.6	18.4	32.4	104.0
413.7	408.5	-21.9	337.8	28.3	15.6	32.9	86.7	33.3	18.2	32.4	103.3
344.7	339.5	-22.4	337.8	28.2	15.5	32.9	86.3	33.2	18.1	32.4	102.9
275.8	271.6	-25.5	337.8	27.3	15.0	32.9	83.5	32.3	17.6	32.4	100.1
206.8	203.2	-33.5	337.8	24.9	13.7	32.9	76.3	29.9	16.4	32.4	92.7
172.4	168.7	-35.1	337.4	24.5	13.4	32.4	75.1	29.5	16.1	32.0	91.6
137.9	132.4	-35.3	337.4	24.4	13.4	32.4	74.8	29.4	16.1	32.0	91.4
103.4	98.7	-42.7	336.5	22.3	12.2	32.4	68.7	27.3	14.9	32.0	85.3

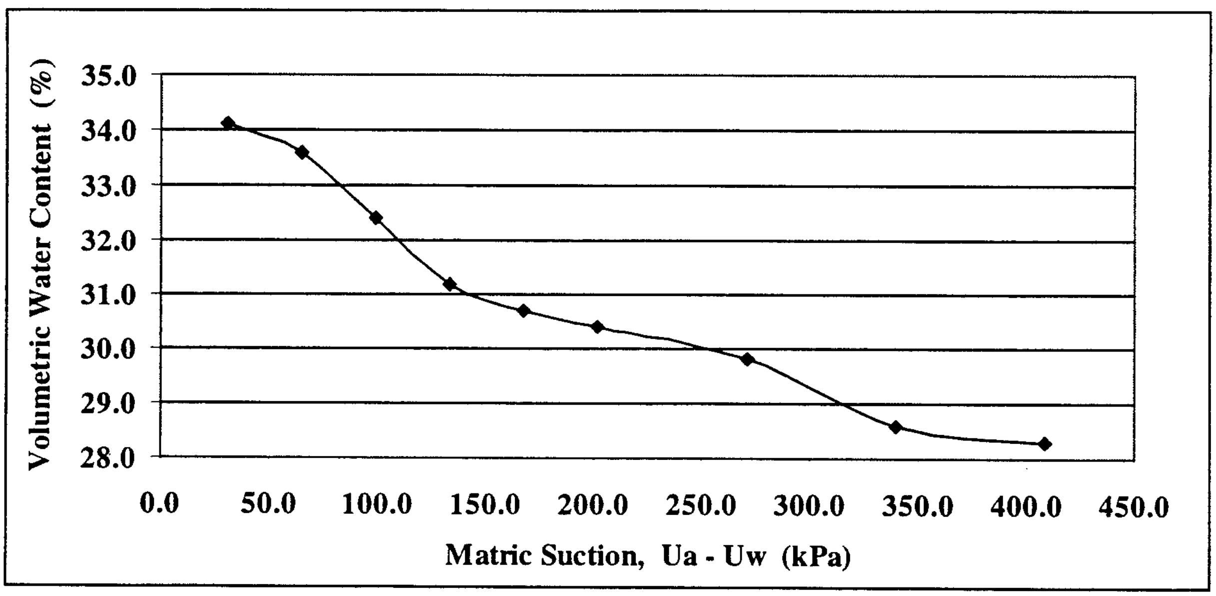


Figure 3.6 - Soil Moisture Characteristic Curve, Triaxial Test

3.6 Summary of Laboratory Testing

Soil moisture characteristic curves were obtained using different test apparatus and procedures to measure soil matric suction and volumetric water content. The results from all the tests are shown in Figure 3.7. According to the figure, there is close agreement between curves obtained from the triaxial test and the pressure plate extractor test with direct measurements of water contents. For these two tests it was possible to make accurate measurements of water content and matric suction. Volumetric water contents obtained from TDR measurements are low except for some of the free draining values. The volumetric water contents computed from water volume changes with the pressure plate apparatus also are low. The results from the former two tests are recommended. The soil–water characteristic curves can be used for comparisons with measured field values. The curves can also be used to determine the Gardner parameters for modeling the climatic effects on pavements (Gardner, 1958; Lytton, et al., 1993).

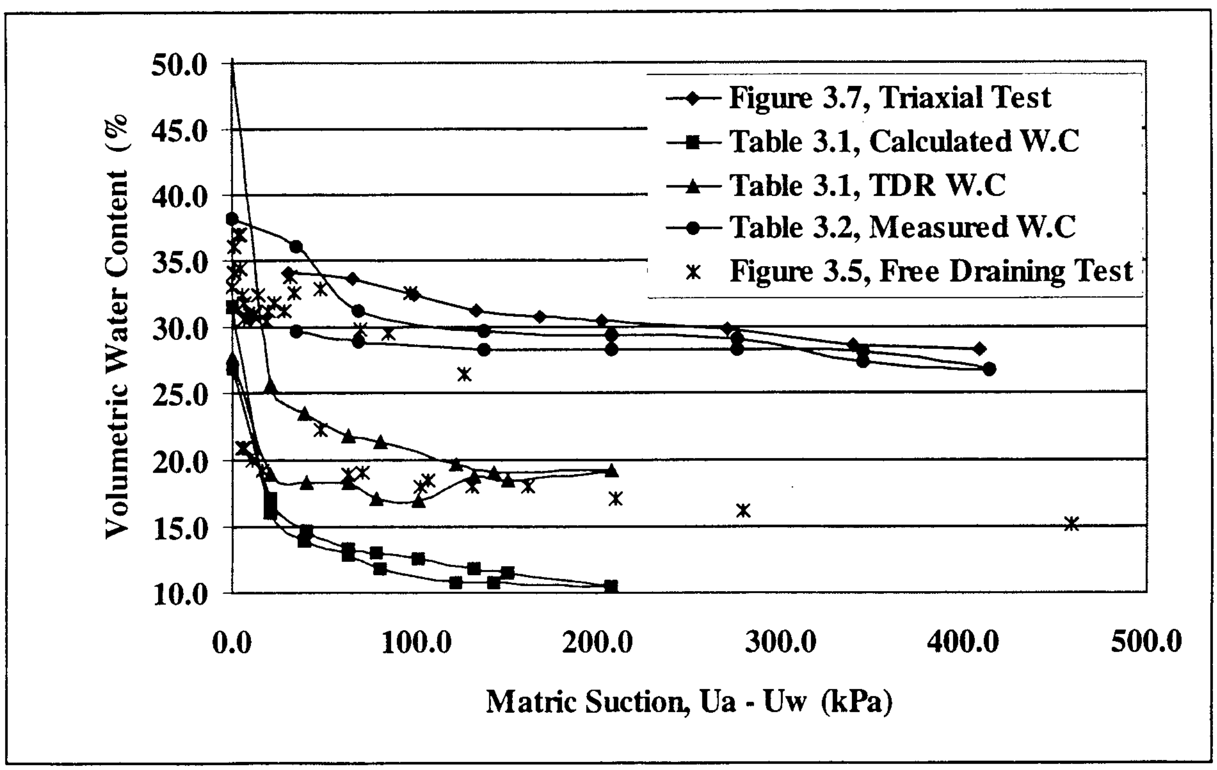


Figure 3.7 - Soil Moisture Characteristic Curves, All Tests

CHAPTER 4

SEASONAL INSTRUMENTATION MONITORING OF SUBGRADE SOIL

4.1 Overview of Instrumentation

Five pavement sections were instrumented with seasonal instrumentation according to FHWA guidelines (Rada et al., 1994) and the instrumentation plan by Sargand (1994). The five pavement sections included three asphalt sections, 390101, 390104 and 390112, and two Portland cement concrete sections, 390202 and 390204. The seasonal instrumentation required for each pavement section included the following: ten time domain reflectometry (TDR) probes to measure volumetric moisture content; a MRC thermistor probe to measure pavement, base and subgrade temperatures; and a CRREL resistivity probe to measure frost penetration. The probes were installed to a depth of 1.88 meter below the bottom of the pavement or stabilized base, where applicable. Data from the seasonal instrumentation probes is collected 14 time each year. A weather station was installed at the site to continuously monitor climatic conditions and piezometers were installed at various locations throughout the site. TDR cable testers and CR10 dataloggers were installed in sections 390112 and 390202 for more frequent measurements of volumetric moisture content.

4.2 Soil Moisture Suction Instrumentation

Four of the pavement sections were instrumented with six thermal conductivity sensors (TCS) calibrated for soil matric suction. The TCS probes were placed in the subgrade soil adjacent to the TDR probes so that the matric suction pressures could be compared to the volumetric water contents. The depths that the TCS probes were installed are shown in Table 4.1. Prior to installing the sensors at section 390112, it was observed that sensor number 4 was broken and that sensor number 5 was cracked. No other probes were available for installation.

Table 4.1 - Depth of TCS Probes

Depth Below Pavement Surface, meter				
Sensor No.	**390101**	**390112**	**390202**	**390204**
1	0.43	0.66	0.43	0.51
2	0.58	0.81	0.58	0.66
3	0.74	0.97	0.74	0.81
4	0.89	Broken	0.89	0.97
5	1.04	1.27	1.04	1.12
6	1.35	1.57	1.35	1.42

4.2.1 Sensor Description

Thermal conductivity sensors consist of a miniature temperature-sensitive integrated circuit and a resistance heater surrounded by a porous ceramic material. The sensors are cylindrical shaped, about 2.5 cm. in diameter by 5.0 cm. long. The miniature integrated circuit and resistance heater are encapsulated in an epoxy material and placed at the center of the ceramic material. Four insulated wires extend out from one end of the block though an epoxy backing. Two of the wires are used for heating the resistor and two of the wires are used to measure the voltage difference across the integrated circuit. The sensors used for this project were made in the People's Republic of China and calibrated by the Unsaturated Soils Group at the University of Saskatchewan. A total of 32 sensors were purchased but only 24 were reading properly at the time of installation.

4.2.2 Sensor Calibration

The thermal conductivity of the ceramic block is inversely proportional to the water content of the block, which is controlled by the matric suction of the surrounding soil. Heat applied to a dry ceramic block is dissipated at a much smaller rate than a wet block due to the presence of the water. The voltage difference measured across the integrated circuit increases correspondingly to larger temperature changes, i.e. for less heat dissipation. Therefore, the sensors can be calibrated for the soil matric suction by measuring the output from the temperature-sensitive integrated circuit as known matric suctions are applied. In practice, the voltage difference is read across the integrated circuit. A controlled amount of electrical energy is then applied to the resistor for a period of 60 seconds using a precision 10-volt voltage controller. The voltage difference is read immediately after heating the resistor. The change in voltage difference is then used for the calibrations.

An example calibration is shown in Figure 4.1 for sensor no. 532. The calibration curve shows the measured changes in voltage difference as a function of applied matric suction. The calibration curves for the majority of the TCS sensors are bilinear with a break point at approximately 175 kPa. The break point can be explained in terms of the properties of the porous ceramic material and the pore water. For matric suctions below the breakpoint, the thermal properties of the pore water dominate. Conversely, the ceramic material dominates for high matric suctions. The voltage difference approaches a maximum value asymptotically for high matric suctions. Since the properties of the sensors were not uniform the curves for the other sensors, although similarly behaved, are different.

Calibrations provided by researchers at the University of Saskatchewan were approximated with curve fitting equations using an optimization routine available in spreadsheet software (Lowery, 1996). Mathematical expressions were derived for each calibration by inverting Equation 4.1 to obtain Equation 4.2.

$$dV = \frac{a}{1 + b \cdot e^{-kS}} \qquad 4.1$$

$$S = \frac{\ln\left(\frac{(a / dV - 1)}{b}\right)}{-k} \qquad 4.2$$

Equation 4.2 is the desired form of the equation for the seasonal monitoring program since the voltage difference, dV, is read with the data acquisition equipment in order to determine matric suction, S. The TCS curve fitting calibration for sensor no. 532 is shown in Figure 4.1. Values of the constants a, b and k were obtained by requiring that the voltage difference could not exceed maximum values estimated from the curves and by specifying values for voltage differences corresponding to zero matric suction. Table 4.2 contains a listing of the calibration

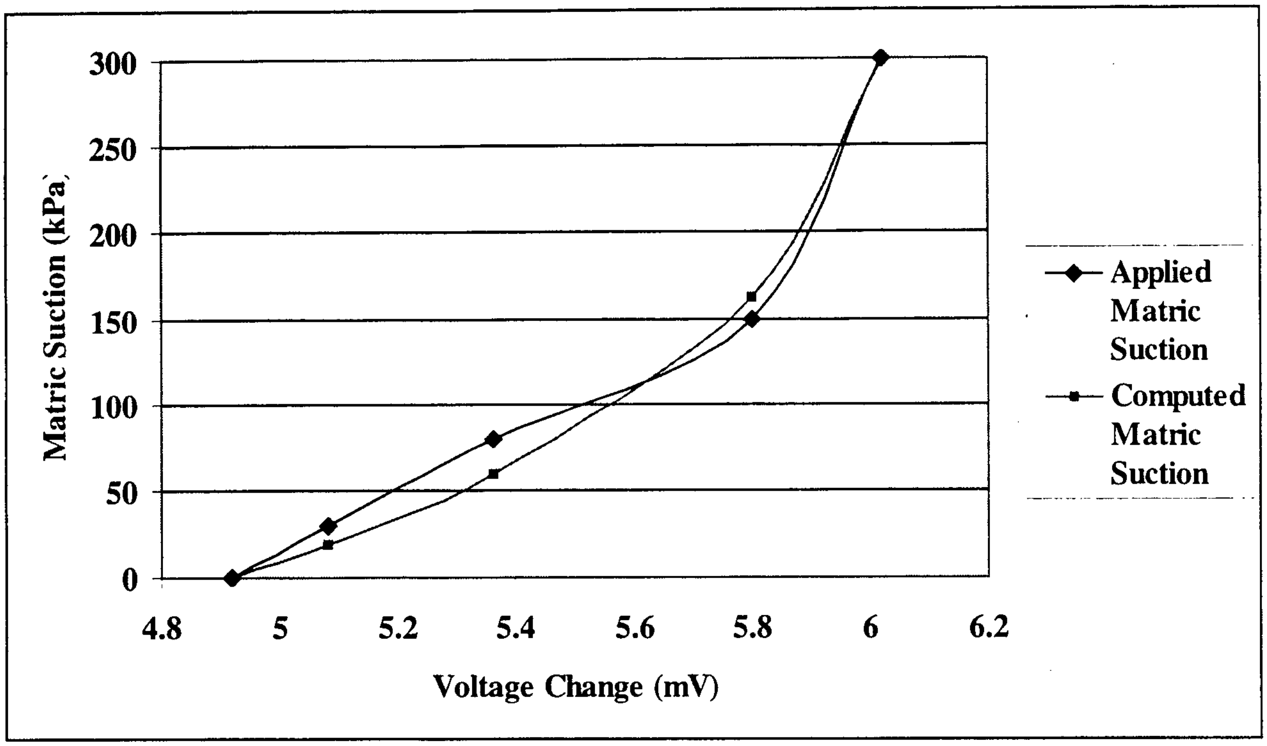


Figure 4.1 - TCS Sensor Calibration Curve

constants and the minimum and maximum voltage differences provided with the calibrations for the 24 sensors that were installed in the pavement sections

4.2.3 Sensor Installation

The TCS probes were installed as a part of the seasonal instrumentation installations. The MRC thermistor and resistivity probes were carefully placed in a 0.305-meter diameter hole. Soil was then compacted to the required elevation using a tamper designed specifically for this application. A TDR probe was placed in the hole and soil was carefully compacted above it. A length of galvanized metal pipe with a diameter slightly smaller than the TCS probes was used to cut a vertical hole beside the TDR probe in the compacted soil. A plastic insert was then placed in the end of the pipe to assist in placing the TCS probe in the hole and to prevent damage to the sensor as it was pushed into the soil. It was possible to push the probes into the holes without applying much pressure. The probes were pushed completely into the holes to

Table 4.2 - TCS Calibration Constants

Sensor No.	a	b	k	Minimum Volt. Diff. (mV)	Maximum Volt. Diff. (mV)
390101-1	6.111	0.242	0.009	4.92	6.02
390101-2	8.090	0.117	0.009	7.24	8.01
390101-3	4.618	0.452	0.008	3.18	4.44
390101-4	7.726	0.283	0.008	6.02	7.54
390101-5	5.553	0.212	0.007	4.58	5.35
390101-6	5.434	0.345	0.010	4.04	5.34
390112-1	6.219	0.285	0.011	4.84	6.15
390112-2	6.028	0.337	0.009	4.51	5.90
390112-3	7.444	0.404	0.010	5.30	7.30
390112-4	8.561	0.374	0.007	6.23	8.15
390112-5	5.581	0.316	0.011	4.24	5.52
390112-6	9.609	0.391	0.008	6.91	9.30
390202-1	4.369	0.340	0.007	3.26	4.20
390202-2	6.424	0.168	0.011	5.50	6.36
390202-3	4.506	0.224	0.007	3.68	4.40
390202-4	4.384	0.396	0.007	3.14	4.18
390202-5	5.302	0.259	0.009	4.21	5.20
390202-6	5.176	0.578	0.010	3.28	5.04
390204-1	7.513	0.200	0.008	6.26	7.36
390204-2	6.635	0.252	0.007	5.30	6.43
390204-3	4.948	0.302	0.007	3.80	4.78
390204-4	5.941	0.363	0.007	4.36	5.72
390204-5	7.875	0.232	0.009	6.39	7.76
390204-6	4.829	0.327	0.006	3.64	4.60

ensure that the end of the probe was in direct contact with soil. The installations took place between July 20 and September 14, 1995.

4.2.4 Data Acquisition Instrumentation

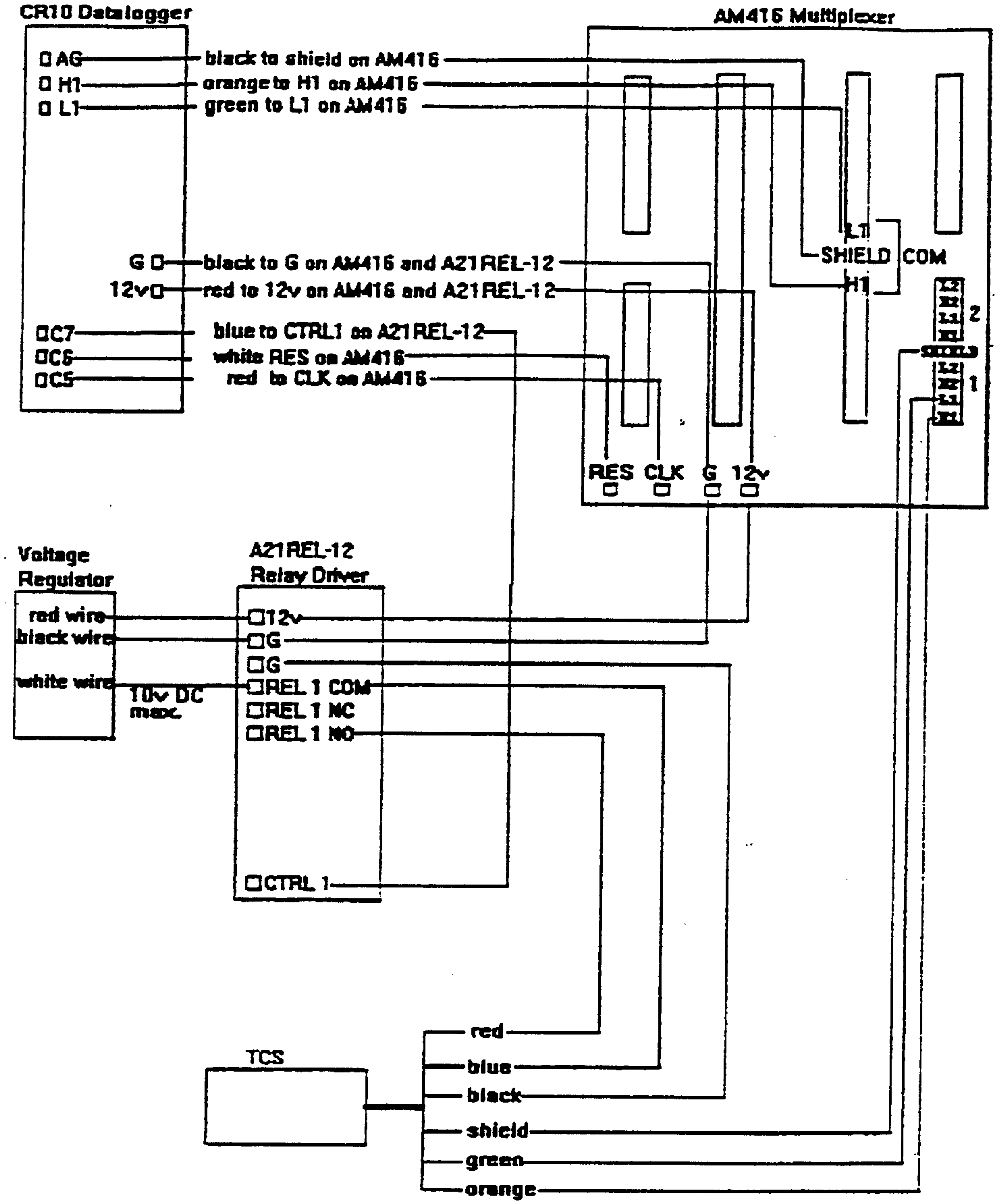
Data acquisition equipment for the seasonal monitoring program and the TCS probes was installed in instrumentation boxes adjacent to the old pavement. Instrumentation wiring and cables were buried in narrow trenches and fed into the instrumentation boxes though a hole near the bottom of the boxes. Due to construction delays caused by inclement weather, the instrumentation could not be installed at the site until starting in July of 1996. A schematic showing the wiring details for the TCS probes is shown in Figure 4.2. Controls C5 through C7 on the CR10 datalogger were used for the TCS instrumentation since controls C1 through C4 are used for the TDR sensor instrumentation. The TDR wiring schematic provided by Rada, et al. (1995) was used for sections 390112 and 390202. The instrumentation described below was required in addition to the data acquisition equipment specified by FHWA for the seasonal monitoring program.

1) **Sections 390101 and 390204 with TCS Probes:**

Campbell Scientific CR10 datalogger with 12 Volt power supply and charger;
10 Volt precision voltage controller;
A21REL-12 relay driver;
AM416 multiplexer;
Waterproof enclosure box.

2) **Sections 390112 and 390202 with TCS Probes and Tektronic cable tester:**

Campbell Scientific CR10 datalogger with 12 Volt power supply and charger;
Library Special PROM with instruction 100 for CR10;
Tektronix 1502B TDR cable tester;
Campbell Scientific SDM1502B communication interface;
Campbell Scientific PS1502B power control module;
Waterproof enclosure box.
Campbell Scientific TDR 50 Ohm coax multiplexer (2 each section);
Waterproof enclosure box.
10-Volt Precision voltage controller;
A21REL-12 Relay Driver;
AM416 multiplexer;
Waterproof enclosure box.



Note: Only the H1 and L1 positions on the AM416 are used.
The green, orange, and shield wires of additional TCS are connected to the next open H1 and L1 positions.

Figure 4.2 - TCS Wiring Schematic (from Lowery, 1996)

Table 4.3 - CR10 Datalogger Instructions for TCS Probes

```
* 1     Table 1 Programs
 01: 60     Sec. Execution Interval
05: P86    Do   ** Cycle every 6 hours.
 01: 1      Call Subroutine 1
06: P89    If X<=>F  **Read 4 times daily
                      if Minute == 0
 01: 65     X Loc Minute
 02: 01     =
 03: 0      F
 04: 30     Then Do
07: P86     Do
 01: 46     Set high Port 6
08: P87     Beginning of Loop
 01: 0      Delay
 02: 6      Loop Count
09: P86     Do
 01: 75     Pulse Port 5
10: P2      Volt (DIFF) ** Read voltage
                  difference before.
 01: 1      Rep
 02: 23     25 mV 60 Hz rejection Range
 03: 1      IN Chan
 04: 31--   Loc [:TSCB #1  ]
 05: 1      Mult
 06: 0.0    Offset
11: P95     End
12: P86     Do
 01: 56     Set low Port 6
13: P86     Do      ** Provide 10 volts to
                  relay driver.
 01: 47     Set high Port 7
14: P87     Beginning of Loop **Heat sensor
                                for 1 minute.
 01: 1      Delay
 02: 1      Loop Count
15: P95     End
16: P86     Do
 01: 57     Set low Port 7
17: P86     Do
 01: 46     Set high Port 6
18: P87     Beginning of Loop
 01: 0      Delay
 02: 6      Loop Count
19: P86     Do
 01: 75     Pulse Port 5
20: P2      Volt (DIFF) ** Read voltage
                  difference after.
    01: 1      Rep
    02: 23     25 mV 60 Hz rejection Range
    03: 1      IN Chan
    04: 37--   Loc [:TCSA #1  ]
    05: 1      Mult
    06: 0      Offset
21: P35     Z=X-Y ** Calculate change in
                  voltage difference.
 01: 37--   X Loc TCSA #1
    02: 31--   Y Loc TSCB #1
    03: 43--   Z Loc [:VDiff. #1]
    22: P95    End
*** 1: 6 Hour TCS Voltage Diff. (Before)
    23: P86    Do
    01: 10     Set high Flag 0 (output)
    24: P80    Set Active Storage Area
    01: 1      Final Storage Area 1
    02: 1      Array ID or location
    25: P77    Real Time     ** Timestamp.
    01: 1220   Year,Day,Hour-Minute
    26: P70    Sample        ** Voltage
                             differences.
    01: 6      Reps
    02: 31     Loc TSCB #1
*** 2: 6 Hour TCS Voltage Diff. (After)
   27: P86     Do
   01: 10      Set high Flag 0 (output)
   28: P80     Set Active Storage Area
   01: 1       Final Storage Area 1
   02: 2       Array ID or location
   29: P77     Real Time
   01: 1220    Year,Day,Hour-Minute
   30: P70     Sample
   01: 6       Reps
   02: 37      Loc TCSA #1
*** 3: 6 Hour TCS Voltage Differences
   31: P86     Do
   01: 10      Set high Flag 0 (output)
   32: P80     Set Active Storage Area
   01: 1       Final Storage Area 1
   02: 3       Array ID or location
   33: P77     Real Time
   01: 1220    Year,Day,Hour-Minute
   34: P70     Sample
   01: 6       Reps
   02: 43      Loc VDiff. #1
   35: P86     Do
   01: 56      Set low Port 6
 * 3     Table 3 Subroutines
  01: P85    Beginning of Subroutine
   01: 1       Subroutine Number
  02: P18    Time
   01: 1       Minutes into current day (1440 max)
   02: 360     Mod/by
   03: 65      Loc [:Minute  ]
  03: P95    End
```

4.2.5 Data Acquisition

Data is obtained from the TCS probes using the onsite CR10 dataloggers and datalogger software. Datalogger programs with instructions similar to the ONSITE program were written for the installations with TCS probes and the installations with TCS probes and onsite TDR cable testers. The instructions required for the TCS sensors are given in Table 4.3. The CR10 datalogger storage capacity for the two installations is shown in Table 4.4. Data is uploaded from the CR10 dataloggers using GraphTerm (GT) software program. The station name for the sections are obtained using the letter T and the pavement section number (i.e., T390101, T390112, T390202 and T390204). The program saves the data in a data file with the same station name as the filename and with 'dat' for the extension. The data files are then renamed according the file naming protocol specified by FHWA and given the extension 'ut'.

4.2.6 Soil Moisture Suction Monitoring

Data from the four pavement sections with TCS sensors were analyzed to investigate the seasonal variation of the soil moisture suction in the subgrade soil. After obtaining the initial data, it was necessary to increase the range specified in the datalogger software instruction P2 (See Table 4.3) from a voltage difference of ± 25 mV to ±250 mV. This change resulted in a reduction in the resolution but was necessary in order to obtain readings within range. The program was also modified so that the voltage difference before and after applying the heat to the sensor was stored in the datalogger along with the change in voltage difference, equal to the voltage difference after minus the voltage difference before. These data are stored in storage locations 2, 3 and 4 for Sections 390112 and 390202 and in storage locations 1, 2 and 3 for Sections 390101 and 390204 (See Table 4.4).

Representative data from the four pavement sections was tabulated to analyze the results of the soil moisture suction monitoring. Tables 4.5 through 4.8 show the measured voltage differences for each pavement section over several months. For comparison purposes, the tables provide the range of values obtained from each sensor calibration as shown in Table 4.2. According to the tables, the majority of the readings are outside the ranges obtained

Table 4.4 - CR10 Datalogger Storage Capacity

a) Pavement Sections 390112 and 390202

Output Records:

Loc.	Frequency (Descr.)	Memory Required
2	6 hour (TCS V. DiffB)	4 * 10 = 40 / day
3	6 hour (TCS V. DiffA)	4 * 10 = 40 / day
4	6 hour (TCS V. Diff. Diff)	4 * 10 = 40 / day
5	12 hour (Batt. & Temp)	2 * 15 = 30 / day
10-19	48 hrs. (TDR Waveform)	2600 / 4 = 650 / day
		896 / day

Storage Capacity:

All sensors	32.4 days

b) Pavement Sections 390101 and 390204

Output Records:

Loc.	Frequency (Descr.)	Memory Required
1	6 hour (TCS V. DiffB)	4 * 10 = 40 / day
2	6 hour (TCS V. DiffA)	4 * 10 = 40 / day
3	6 hour (TCS V. Diff. Diff)	4 * 10 = 40 / day
4	8 hour (Batt. & Temp)	3 * 15 = 45 / day
		165 / day

Storage Capacity:

All sensors	175 days

from the calibrations. Some of the data from the sensors are very erratic, varying from high positive and negative values. The tables also show the voltage differences before and after heating the sensors for some of the readings. The readings for some of the sensors was set to –6999 by the datalogger, the highest negative number for low resolution, which indicates a voltage difference greater than ±250 mV. Table 4.9 summarizes the conclusions from the monitoring. Low matric suctions occur in soil that is close to saturation. There has been above normal precipitation at the site and the water table is shallow. Therefore, the sensors that are consistently reading below range might be functioning properly.

The sensors that are not performing satisfactorily are more than likely defective. According to the suppliers of the sensors at the University of Saskatchewan, two plausible causes for the defects are that the ceramic material or the integrated circuits in the sensors are damaged. The ceramic material is formed at high temperatures and must be cooled properly to prevent the material from being overstressed. The integrated circuits are encapsulated in epoxy to waterproof the circuit. Very small amounts of water getting through or around the epoxy can cause erroneous readings. The sensors read properly during the several weeks required for calibration. However, eight of the thirty-two sensors supplied were reading out of calibration at the University of Toledo laboratory and consequently were not installed. The sensors will continue to be monitored with the seasonal instrumentation since very little effort is required to obtain the data.

Table 4.5 - TCS Data, Pavement Section 390101

				Voltage Difference Readings (mV)					
Calibration Range				4.9 - 6.0	7.2 - 8.0	3.2 - 4.4	6.0 - 7.5	4.6 - 5.4	4.0 - 5.3
Loc.	Year	Day	Time	1	2	3	4	5	6
3	1996	206	1	4.553	0	4.379	4.876	4.74	0
3	1996	216	1201	4.696	0	0	-6999	3.784	3.215
3	1996	226	601	4.729	3.052	0	0	4.089	3.637
3	1996	236	1201	0	3.061	0	0	3.901	3.632
3	1996	246	1201	0	0	0	0	3.716	3.434
3	1996	256	601	0	3.069	0	0	4.103	3.794
1	1996	265	1201	-6999	-0.617	-6999	-6999	14.12	-3.889
2	1996	265	1201	-6999	2.441	-6999	-6999	18.48	0.223
3	1996	265	1201	0	3.057	0	0	4.359	4.113
3	1996	279	1201	0	3.049	0	0	4.014	3.74
3	1996	291	601	104.1	2.366	4.393	4.224	3.886	3.211
3	1996	301	1201	0	2.705	4.057	4.395	4.057	3.888
3	1996	315	1201	0	3.046	4.061	3.892	3.554	3.046
3	1996	330	601	0	6.769	-0.677	5.754	4.231	4.4
3	1996	345	601	0	6.772	-0.339	5.417	4.232	3.894
3	1996	360	1201	0	6.774	-0.677	5.419	4.403	4.064
3	1997	10	601	0	6.604	-0.677	5.419	4.233	4.403
3	1997	24	601	0	6.605	-0.677	5.758	4.403	4.064
3	1997	36	601	0	6.774	-0.339	5.588	4.234	4.064
3	1997	48	1201	0	6.776	-0.678	5.59	4.235	4.066
1	1997	54	1201	2206	17.27	529	1.016	55.72	-16.6
2	1997	54	1201	2214	24.05	528.7	6.774	59.95	-12.53
3	1997	54	1201	8.13	6.774	-0.339	5.758	4.234	4.064
3	1997	66	601	6.435	6.774	-0.339	5.758	4.064	4.234
3	1997	76	1201	6.094	6.433	-0.677	5.756	4.063	4.063
3	1997	84	601	6.60	6.431	0	5.754	4.062	3.892
3	1997	92	1201	6.43	6.091	-0.677	5.584	4.061	4.061
3	1997	100	601	5.409	6.432	-0.006	5.755	4.4	4.232
3	1997	110	1201	4.737	6.767	-0.508	5.583	4.06	4.568
3	1997	114	601	4.736	6.428	-0.677	5.582	4.398	4.06
3	1997	107	601	4.908	6.431	-0.677	5.584	4.231	4.231
3	1997	116	1201	4.732	6.592	-0.338	5.747	4.225	4.056
3	1997	124	1201	57.81	6.762	8.11	5.917	4.057	4.057
3	1997	132	601	-7.44	6.427	7.27	5.412	4.397	4.397
3	1997	141	1201	3.208	6.422	-0.688	5.071	4.393	4.057
3	1997	150	601	7.44	6.761	10.82	5.409	4.733	4.057
3	1997	160	601	4.732	6.422	-0.338	4.732	4.563	4.056
3	1997	170	601	4.731	6.59	-0.507	43.93	4.393	4.393

Table 4.6 - TCS Data, Pavement Section 390112

				Voltage Difference Readings (mV)					
	Calibration Range			4.8 - 6.2	4.5 - 5.9	5.3 - 7.3	6.2 - 8.2	4.2 - 5.5	6.9 - 9.3
Loc.	Year	Day	Time	1	2	3	4	5	6
2	1997	24	1004	-4.48	392.5	2.987	33.19	128.3	18.92
3	1997	24	1004	-4.646	392.3	2.987	33.35	129.4	19.25
4	1997	24	1004	-0.166	-0.176	0	0.165	1.158	0.331
2	1997	51	1320	20.74	9.29	-1.162	-10.95	-20.25	-28.71
3	1997	51	1320	-40.49	-45.14	-51.28	-57.09	-62.56	-67.71
4	1997	51	1320	-61.23	-54.43	-50.12	-46.13	-42.32	-39
2	1997	60	1320	-11.94	-20.57	-29.2	-36.83	-44.29	-50.93
3	1997	60	1320	-58.73	-62.71	-67.19	-71.8	-76.3	-80.1
4	1997	60	1320	-46.78	-42.14	-37.99	-35	-32.02	-29.2
2	1997	70	1320	-24.06	-32.02	-39.32	-46.29	-52.93	-58.9
3	1997	70	1320	-64.54	-68.03	-72.3	-76.5	-80.5	-84.3
4	1997	70	1320	-40.48	-36	-33.02	-30.2	-27.54	-25.39
2	1997	120	1	-21.1	-6999	-6999	-6999	-6999	-6999
3	1997	120	1	-6999	-6999	-6999	-6999	-6999	-6999
4	1997	120	1	-6999	0	0	0	0	0
2	1997	169	1	-6999	-6999	-6999	-6999	-6999	-6999
3	1997	169	1	-6999	-6999	-6999	-6999	-6999	-6999
4	1997	169	1	0	0	0	0	0	0
2	1997	185	601	-5.659	-6999	2.737	-6999	-6999	-6999
3	1997	185	601	-5.656	-6999	2.737	-6999	-6999	-6999
4	1997	185	601	0.003	0	0	0	0	0
2	1997	190	1201	-5.613	-6999	2.921	-6999	-6999	-9.52
3	1997	190	1201	-5.61	-6999	2.921	-6999	-6999	-15.3
4	1997	190	1201	0.003	0	0	0	0	-5.78
2	1997	200	1201	-5.561	-6999	3.182	-6999	-6999	3.239
3	1997	200	1201	-5.559	-6999	3.183	-6999	-6999	4.559
4	1997	200	1201	0.002	0	0.002	0	0	1.32
2	1997	210	1201	-5.372	-6999	3.724	-6999	-6999	-17.61
3	1997	210	1201	-5.374	-6999	3.724	-6999	-6999	-6999
4	1997	210	1201	-0.002	0	0	0	0	-6999
2	1997	218	1201	-5.219	-6999	4.133	-6999	-6999	-6999
3	1997	218	1201	-5.221	-6999	4.107	-6999	-6999	-6999
4	1997	218	1201	-0.002	0	-0.026	0	0	0

Table 4.7 - TCS Data, Pavement Section 390202

				Voltage Difference Readings (mV)					
Calibration Range				4.9 - 6.0	7.2 - 8.0	3.2 - 4.4	6.0 - 7.5	4.6 - 5.4	4.0 - 5.3
Loc.	Year	Day	Time	1	2	3	4	5	6
2	1996	257	1807	4.114	-6999	-6999	-6999	-6999	-6999
3	1996	257	1807	7.31	-6999	-6999	-6999	-6999	-6999
4	1996	257	1807	3.2	0	0	0	0	0
4	1996	263	1603	2.272	0	0	0	0	0
4	1996	297	1203	2.037	-14.43	-49.23	-41.59	-37.18	-35.65
4	1996	305	1203	1.868	-16.64	-44.48	-38.2	-34.29	-31.41
4	1996	315	1203	13.75	29.54	-42.78	-13.58	-11.71	-11.37
4	1996	325	1203	12.73	15.62	-30.9	-0.17	0.34	0
4	1996	335	1203	-0.679	-87.4	-21.9	-4.074	40.06	-42.78
4	1996	345	1203	-7.98	-21.06	48.91	15.62	7.13	24.28
4	1996	353	1203	-1.528	-63.85	51.28	5.434	10.02	18.68
4	1996	365	1203	-2.546	-175	39.38	-0.849	1.358	-63.66
4	1997	10	1203	-3.908	-5.607	-10.03	1.189	-27.7	106.7
4	1997	20	1203	2.889	81.1	54.38	9.01	-65.76	13.42
4	1997	30	1203	0.17	184.4	81.4	-4.928	-13.93	3.059
4	1997	40	1203	-9.86	143.7	92.1	-4.418	-12.23	-65.76
4	1997	50	1203	-11.89	32.43	-107.7	-12.74	-32.26	-50.94
4	1997	60	1803	-3.732	43.59	-22.22	11.7	-224.4	-21.2
4	1997	70	1203	8.49	67.39	-119.5	6.62	-16.3	-5.432
4	1997	80	1203	0.34	35.14	-93.2	1.358	82.2	-43.8
4	1997	90	1203	-2.037	24.45	-98.6	0.849	-72.7	47.2
4	1997	100	1258	13.58	34.8	163	-4.414	74.9	49.4
2	1997	118	1255	-4.628	-6999	-6999	-0.801	-6999	-6999
3	1997	118	1255	-7.04	-6999	-6999	-9.7	-6999	-6999
4	1997	118	1255	-2.408	0	0	-8.89	0	0
4	1997	120	1256	5.355	0	0	-2.421	0	0
4	1997	130	1257	0	0	0	0	0	0
4	1997	140	1255	0	0	0	0	0	0
4	1997	295	1209	6999	-92	-6999	-4.226	-6999	-126.4

Table 4.8 - TCS Data, Pavement Section 390204

				Voltage Difference Readings (mV)					
Calibration Range				4.9 - 6.0	7.2 - 8.0	3.2 - 4.4	6.0 - 7.5	4.6 - 5.4	4.0 - 5.3
Loc.	Year	Day	Time	1	2	3	4	5	6
3	1996	220	601	5.725	0	5.957	6.051	6999	0
3	1996	230	1201	5.759	0	5.905	5.894	6999	0
3	1996	240	1201	0	0	5.941	4.912	6999	0
3	1996	250	1201	8	0	5.972	5.196	6999	0
3	1996	255	1201	0	0	5.982	5.527	6999	0
1	1996	325	1801	-5.668	-2.667	397.9	126	48.67	6.334
2	1996	325	1801	39.17	1.834	54.68	-223.4	58.51	10
3	1996	325	1801	44.84	4.501	-343.2	-349.4	9.83	3.667
3	1996	335	1201	43.68	4.335	-328.3	-343.6	10.33	3.501
3	1996	355	1201	45.19	4.002	-297.3	-516.4	5.837	3.669
3	1996	365	1201	43.67	4.501	-247	-309.9	10.67	3.667
3	1997	10	1201	38.18	4.002	-287.6	-452.5	9	3.502
3	1997	31	1201	41.19	0.167	-0.167	-311.2	5.003	3.669
3	1997	50	1201	7.84	4.502	-1	-143.9	5.168	3.501
3	1997	60	1201	6.167	4.333	10.67	-146.3	5.667	3.667
3	1997	70	1201	8.84	4.501	-28.84	-218	5.668	3.501
3	1997	80	1201	-9.17	4.334	-6999	-215	5.668	3.501
3	1997	90	1201	24.17	4.167	608.4	-215.4	5.668	3.501
3	1997	100	1201	22.5	4.334	-3.834	-173.2	5.668	3.167
3	1997	110	1201	5	4.334	-1.334	-178.9	5.667	3.334
3	1997	120	1201	5.499	4.166	-1.5	-215	5.666	3.666
3	1997	140	1201	12.33	4.833	-46.49	-41.49	5.166	3.499
3	1997	150	1201	67.32	4.666	-1.5	-206.1	4.833	3.833
1	1997	160	1201	-126.3	-5.665	-3.666	-7.66	-2.999	10
2	1997	160	1201	-64.98	-1	-3.832	-213.8	2	13.33
3	1997	160	1201	61.32	4.666	-0.167	-206.1	4.999	3.333
3	1997	170	1201	37.31	4.998	0	-156.9	5.164	3.665
3	1997	180	1201	14.66	4.83	-1.166	-177.1	5.33	3.331
3	1997	190	1201	-11.33	4.998	-2.333	-199.8	5.165	3.665
3	1997	200	1201	17.66	5.331	-0.5	-188.4	5.497	3.332
3	1997	210	1	-4.331	4.997	-6.996	-186.9	5.164	3.332
3	1997	220	1201	-3.332	4.998	0	-199.2	5.331	3.498
3	1997	230	1201	-3.832	4.831	1.166	-191.3	4.665	3.332
3	1997	240	1201	13.99	4.831	0.333	-215.2	4.998	3.332
3	1997	250	1201	-20.49	4.664	-0.666	-214.2	4.998	3.831
3	1997	270	1201	-35.83	4.999	-0.667	-240	4.999	3.499
3	1997	280	1201	50.15	4.666	610	-241.8	4.999	3.666
3	1997	290	1201	0.167	5.001	-0.167	-250.4	4.001	3.501
1	1997	296	601	-1.5	-8	-7.17	-46.52	-5.335	25.34
2	1997	296	601	-1.334	-3.334	-5.835	-298.9	-1.5	28.84
3	1997	296	601	0.167	4.668	1.334	-252.4	3.835	3.501

Table 4.9 - Summary of Soil Suction Monitoring

Sensor	Monitoring Results	Assessment	Interpretation
390101-1	Readings above, below and within calibration	Acceptable	Positive matric suction
390101-2	Readings below calibration by a small amount	Acceptable	Zero matric suction
390101-3	Readings out of calibration, negative	Unacceptable	None
390101-4	Readings below calibration by a small amount	Acceptable	Zero matric suction
390101-5	Readings below calibration by a small amount	Acceptable	Zero matric suction
390101-6	Readings above, below and within calibration	Acceptable	Positive matric suction
390112-1	Readings out of calibration, negative	Unacceptable	None
390112-2	Readings out of calibration, positive and negative	Unacceptable	None
390112-3	Readings out of calibration, positive and negative	Unacceptable	None
390112-4	Sensor broken	Unacceptable	None
390112-5	Readings out of calibration, positive and negative	Unacceptable	None
390112-6	Readings out of calibration, positive and negative	Unacceptable	None
390202-1	Readings out of calibration, positive and negative	Unacceptable	None
390202-2	Readings out of calibration, positive and negative	Unacceptable	None
390202-3	Readings out of calibration, positive and negative	Unacceptable	None
390202-4	Readings out of calibration, positive and negative	Unacceptable	None
390204-5	Readings out of calibration, positive and negative	Unacceptable	None
390202-6	Readings out of calibration, positive and negative	Unacceptable	None
390204-1	Readings out of calibration, positive and negative	Unacceptable	None
390204-2	Readings below calibration by a small amount	Acceptable	Zero matric suction
390204-3	Readings out of calibration, primarily negative	Unacceptable	None
390204-4	Readings out of calibration, primarily negative	Unacceptable	None
390204-5	Readings below calibration by a small amount	Acceptable	Zero matric suction

4.3 TDR Soil Moisture Instrumentation

Five pavement sections were instrumented with TDR soil moisture probes according to FHWA guidelines (Rada et al., 1994) and the instrumentation plan by Sargand (1994). The five pavement sections included three asphalt sections, 390101, 390104 and 390112, and two Portland cement concrete sections, 390202 and 390204. Ten probes were installed beginning at a depth of 7.6 to 15.2 cm. below the bottom of stabilized material or pavement and then at vertical spacing of 15.2 cm, except for the bottom two probes, which were spaced at 30.5 cm. Data from the seasonal instrumentation probes is collected 14 time each year. Two TDR cable testers were installed in sections 390112 and 390202 for more frequent measurements of volumetric moisture content.

4.3.1 Sensor Description

The TDR moisture probes installed at the site are three-rod probes developed by FHWA. The rods are 0.205 meter long. The center rod is connected to the signal lead of the 50 ohm RG58 cable. The two outside rods are connected to the shield of the cable. The circuit board connecting the rods to the cable and the end of the cable is encapsulated in epoxy that significantly improved the durability of the probes. The specified cable lengths was 30.5 meter (100 ft.) for all cables but the actual cable lengths varied as shown in Table 4.10. Therefore, the cable lengths have to be specified for each probe in MOBILE, the CR10 datalogger software program used for moisture measurements.

4.3.2 Sensor Calibration

The sensors do not require calibration as such but the sensors were checked at the University of Toledo to ensure that they were working properly. The procedure specified by the FHWA includes testing the probes in air, in pure water and with a metal short across the end of the rods. The TDR traces were obtained manually using a cable tester and a strip chart printer. According to the traces, all fifty probes were functioning properly.

4.3.3 Sensor Installation

The TDR probes were installed in a 0.305-meter diameter hole as required by SMP instrumentation installation protocols. The TDR probes were placed horizontally at the required elevations and soil was carefully compacted above it. Bag samples of the soil were obtained as each probe was placed and transported to the University of Toledo Soil Mechanics Laboratory. Gravimetric water contents were determined within 24 hours. A Tektronic 1502B cable tester with YT-1 strip chart recorder was used for TDR volumetric water content measurements. The TDR traces were used to determine the apparent lengths of the probes. The apparent dielectric constants and volumetric water contents of the soil were then computed. Table 4.10 shows the TDR volumetric water contents and the gravimetric water contents obtained by oven drying the soil. TDR gravimetric water contents were computed using Equation 4.3 and assuming a dry unit weight of the soil equal to 16.9 kN/m^3. Figure 4.3 shows the comparison between TDR and oven gravimetric contents.

$$w\ (\%) = \theta * \frac{\gamma_{water}}{\gamma_{dry}} \qquad 4.3$$

4.3.4 Data Acquisition Instrumentation

A mobile data acquisition system specified by FHWA is used to monitor the TDR moisture probes. The system consists of a Tektronix 1502B cable tester with a power module and communication interface; CR10 datalogger with PROM instruction P100; two SDMX50 multiplexers; a 12-Volt power supply and charger; and a SC32A optically isolated interface. The two mobile units at the Ohio Test Road site also have a multiplexer for reading the resistivity probes. A notebook computer is required to obtain the data. A wiring schematic for the instrumentation is provided in the SMP guidelines (Rada, et al., 1995). A description of the instrumentation for the two sections equipped with cable testers, 390112 and 390202, is provided in section 4.2.4. The wiring for these two sections is the same as for the mobile units.

Table 4.10 - TDR Probe Installation and Monitoring

Section Number	Sensor Number	Probe Length (mm)	Meas. Cable Length (Ft.)	MOBILE Cable Length (m)	TDR Apparent Length, (m)	Apparent Dielectric Constant	Volum. Water Content (%)	TDR Grav. Water Content (%)	Oven Grav. Water Content (%)
390101	1	201	97.5	43.75	0.55	7.6	14.1	8.1	11.8
	2	199	97.8	43.50	0.55	7.8	14.4	8.3	18.2
	3	201	98.0	43.75	0.7	12.4	23.4	13.5	15.9
	4	200	97.9	43.50	0.77	15.1	27.9	16.1	16.0
	5	200	98.3	43.75	0.73	13.6	25.4	14.7	16.9
	6	201	98.2	44.00	0.72	13.1	24.6	14.2	20.7
	7	202	98.0	43.50	0.72	13.0	24.4	14.1	21.4
	8	201	98.0	44.25	Shorted				20.9
	9	200	100.0	45.00	0.75	14.3	26.7	15.4	22.4
	10	203		45.00	0.77	14.7	27.2	15.7	21.6
390104	1	201	97.8	43.75	0.55	7.6	14.1	8.1	11.8
	2	200	97.6	43.50	0.68	11.8	22.3	12.9	16.9
	3	203	97.8	43.75	0.87	18.7	33.1	19.1	22.4
	4	201	97.8	43.50	0.85	18.2	32.5	18.8	22.5
	5	199	97.7	43.25	0.82	17.3	31.2	18.0	21.2
	6	200	98.0	43.25	0.88	19.8	34.4	19.9	20.7
	7	201	97.8	43.25	1.00	25.3	40.5	23.4	20.5
	8	200	100.2	45.50	1.17	34.9	48.3	27.9	22.0
	9	200	100.3	45.00	1.08	29.8	44.5	25.7	24.5
	10	200	100.2	45.00	1.10	30.9	45.4	26.2	24.6
390112	1	203	96.8	43.25	0.60	8.9	16.8	9.7	11.0
	2	203	98.1	43.25	0.67	11.1	21.1	12.2	13.3
	3	199	98.5	43.00	0.78	15.7	28.8	16.6	15.4
	4	200	98.2	43.25	0.85	18.4	32.7	18.9	16.3
	5	201	98.1	43.25	0.78	15.4	28.3	16.4	16.1
	6	201	97.8	43.50	0.70	12.4	23.4	13.5	14.8
	7	202	98.1	43.25	0.65	10.6	20.0	11.6	14.6
	8	201	98.0	43.00	0.70	12.4	23.4	13.5	14.2
	9	201	97.7	43.00	0.73	13.5	25.2	14.6	14.0
	10	200	98.0	43.00	0.72	13.2	24.8	14.3	15.2
390202	1	200	98.5	43.25	0.65	10.8	20.4	11.8	5.9
	2	201	98.3	44.50	0.88	19.6	34.2	19.8	13.3
	3	201	98.0	43.25	1.00	25.3	40.5	23.4	12.1
	4	202	98.0	43.25	0.95	22.6	37.8	21.8	13.4
	5	203	98.0	43.25	0.93	21.4	36.4	21.1	14.2
	6	202	97.3	43.25	0.87	18.9	33.4	19.3	16.6
	7	201	100.3	43.25	0.88	19.6	34.2	19.8	19.6
	8	200	100.7	43.25	0.87	19.3	33.9	19.6	22.0
	9	201	100.2	43.50	0.92	21.4	36.4	21.0	19.4
	10	201	98.0	43.50	0.87	19.1	33.6	19.4	16.2
390204	1	201	97.7	43.25	0.58	8.5	15.9	9.2	5.0
	2	201	97.7	44.50	0.62	9.7	18.4	10.6	14.6
	3	202	98.2	43.25	0.97	23.5	38.8	22.4	21.8
	4	203	97.7	43.25	0.93	21.4	36.4	21.1	19.9
	5	201	98.0	43.25	0.93	21.8	36.9	21.4	21.1
	6	199	97.5	43.25	0.85	18.6	33.0	19.1	21.2
	7	200	98.2	43.25	0.92	21.6	36.6	21.2	22.2
	8	201	98.1	43.25	0.93	21.8	36.9	21.4	21.9
	9	201	98.2	43.50	0.90	20.5	35.3	20.4	20.9
	10	200	97.8	43.50	0.80	16.3	29.7	17.2	20.0

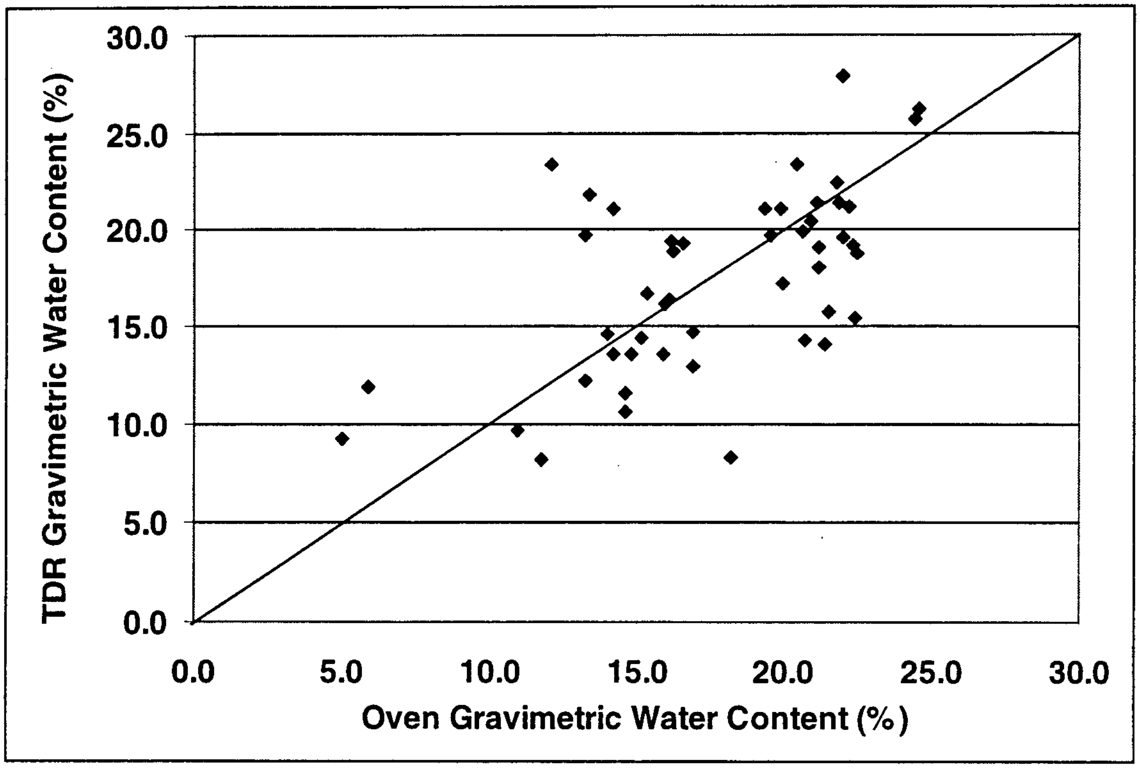


Figure 4.3 - Gravimetric Water Contents from Installation of TDR Probes

4.3.5 Data Acquisition

Data is obtained from the TDR probes using the onsite CR10 dataloggers and datalogger software. Datalogger program MOBILE provided by the FHWA was downloaded to the CR10 dataloggers. For each pavement section, the software had to be modified using software program EDLOG to account for the varying cable lengths. A couple of trial iterations were required to obtain the correct cable lengths. Datalogger programs with instructions similar to the MOBILE program were written for the installations with TCS probes and onsite TDR cable testers. Instruction P100 is used to collect TDR water content data with the cable testers. Two options for the P100 instruction were selected for the two sections with the onsite TDR cable testers. One option instructs the CR10 to read the cable tester waveforms and to compute the moisture content using a programmed equation. The other an option instructs the CR10 to store the raw waveform data for later use. Problems occurred during the execution of the moisture content option. The system locked up and was unable to collect any meaningful data. Therefore the former option had to be discontinued so that the raw waveform data could be collected without any further loss of data. The CR10 datalogger storage capacity for the two installations is shown in Table 4.4.

4.3.6 Soil Moisture Monitoring

Data from the five pavement sections instrumented with TDR probes were analyzed to investigate the seasonal variation of soil moisture. Data is collected at least fourteen times each year using the modified versions of SMP datalogger software. Dataloggers installed at the two sections with cable testers were programmed to measure the TDR raw waveform data every four days (Table 4.4 a). The TDR raw waveform data is then read using FHWA program MOBFIELD. MOBFIELD displays the waveform and computes the apparent length of the probe, the apparent dielectric constant of the soil and volumetric water content. Data obtained from the sections were imported into MS EXCEL spreadsheet programs for easy graphical display of the data. Figure 4.4 shows the seasonal variation of volumetric water content for pavement section 390101. The highest volumetric water contents were from the lowest probes, TDR 9 and TDR10, and the lowest water contents were from the highest probes, TDR 1 through TDR 3. Very low values of volumetric water content were measured in the top three probes during January 1997 due to freezing. The TDR probes measure moisture content of unfrozen water since the dielectric constant of ice is significantly lower than water. The variation of volumetric water content is shown as a function of depth below the pavement surface in Figures 4.5 through 4.9 for several months. Some trends can be observed from the figures. Some of the lowest volumetric water contents recorded during the spring months and some of the highest during late summer and fall months. This is not expected but may be a result of unseasonably wet periods during these two years.

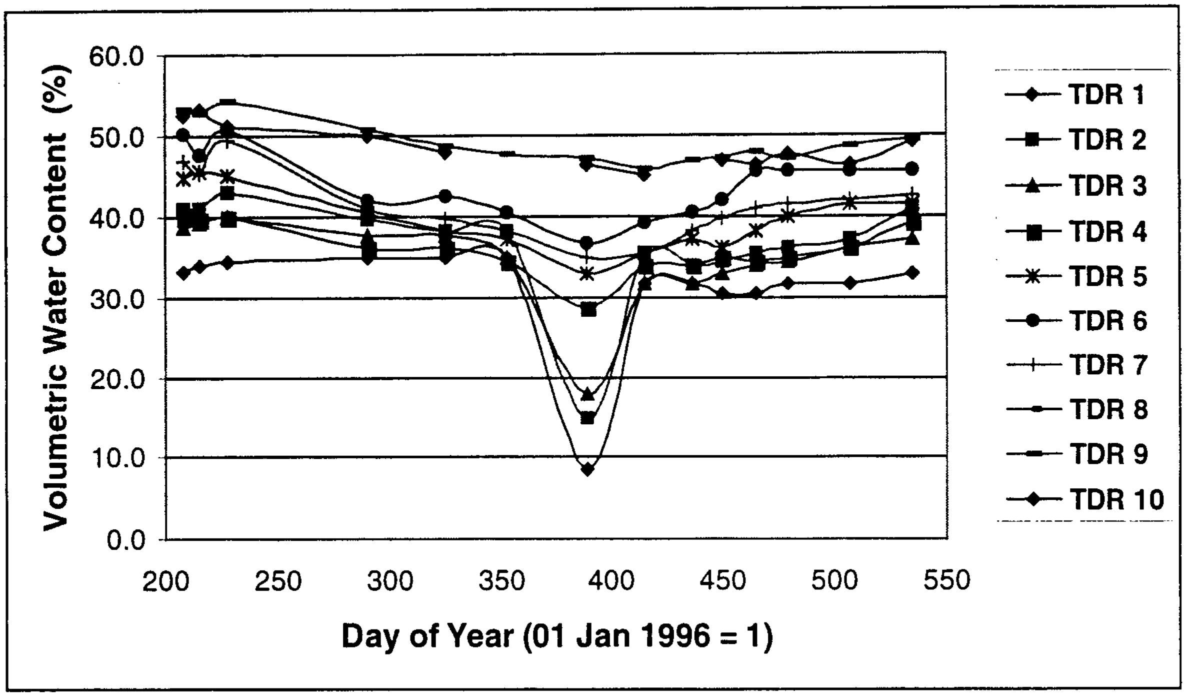


Figure 4.4 - Seasonal Variation of Volumetric Water Content (Section 390101)

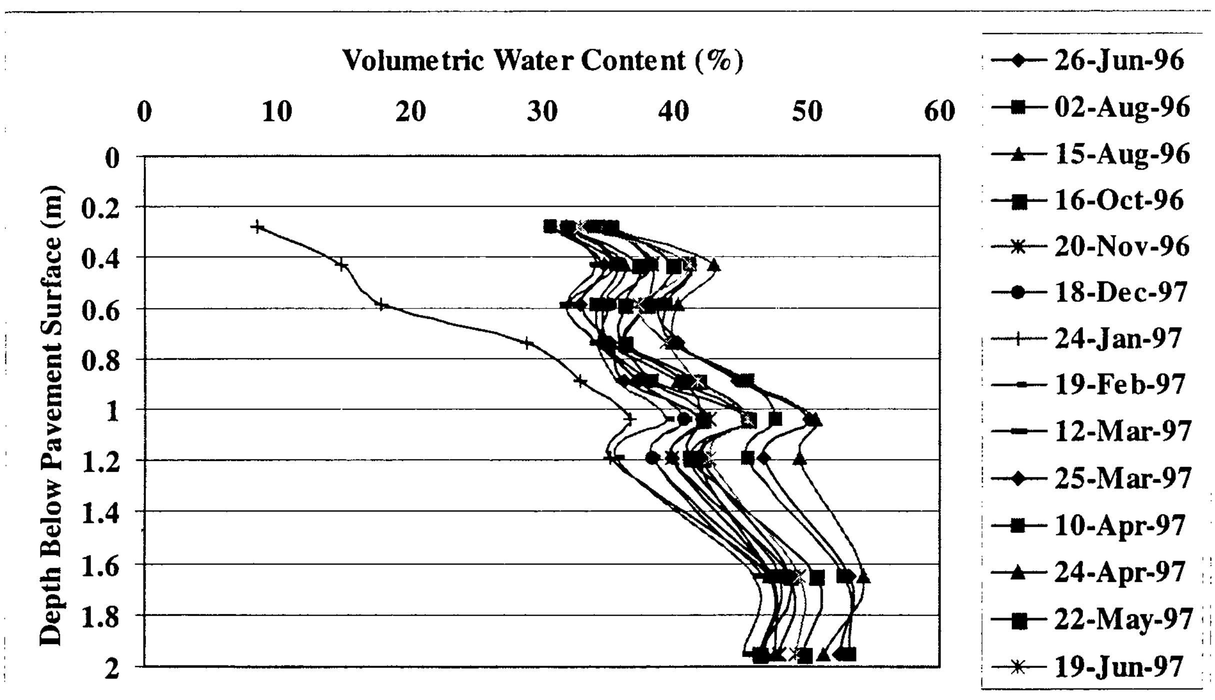


Figure 4.5 - TDR Volumetric Water Content (Section 390101)

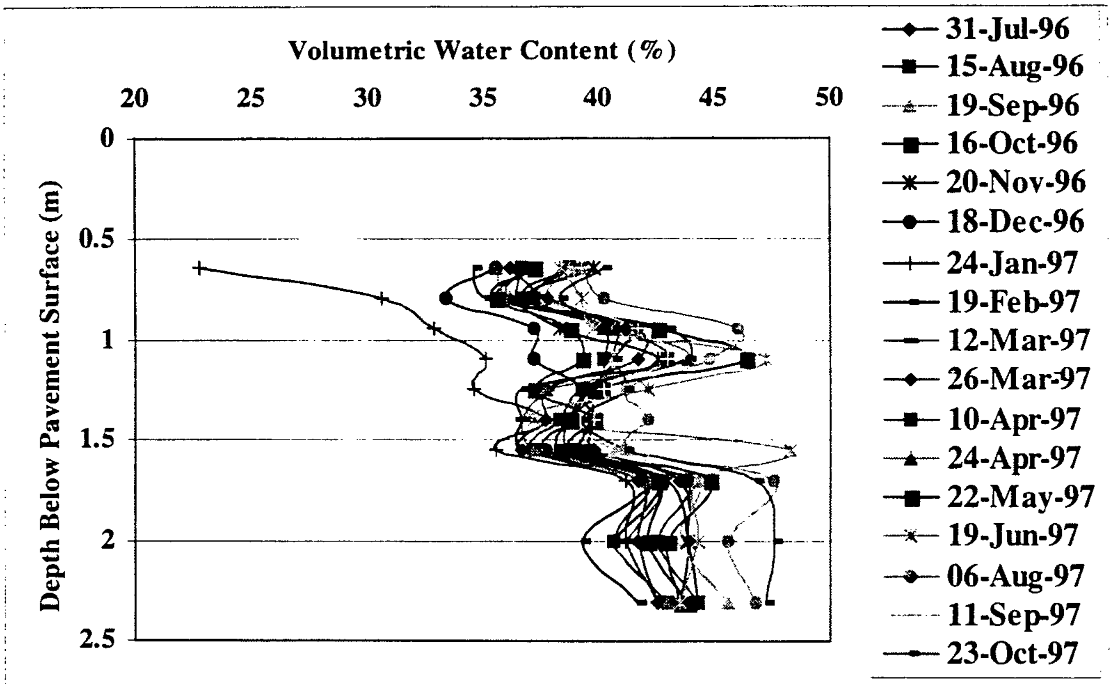


Figure 4.6 - TDR Volumetric Water Content (Section 390104)

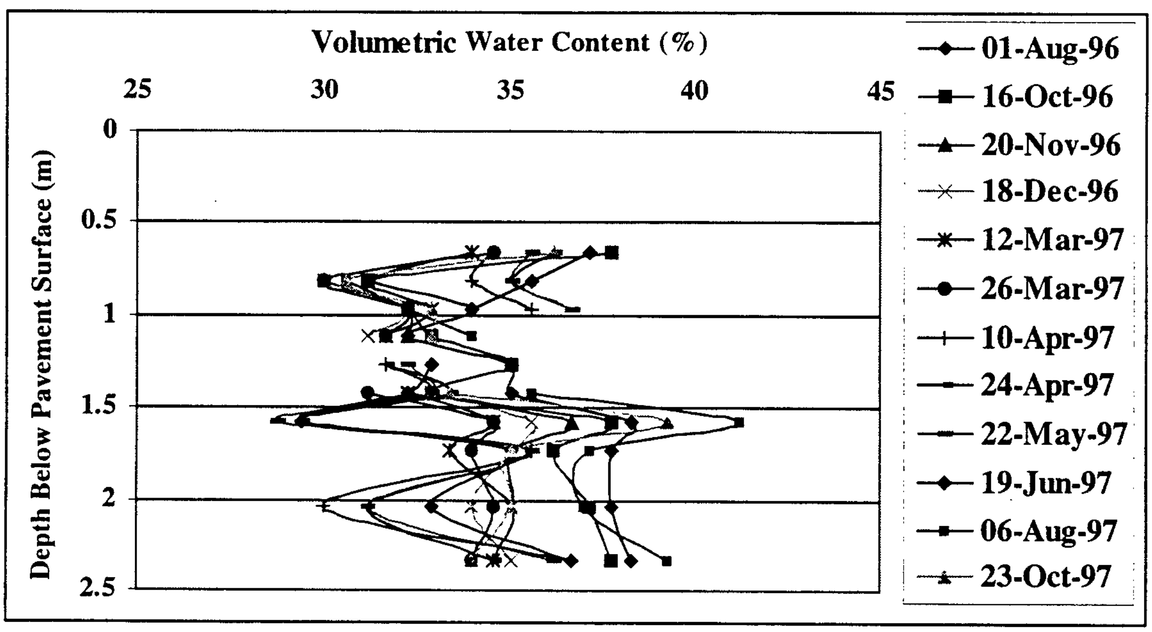


Figure 4.7 - TDR Volumetric Water Content (Section 390112)

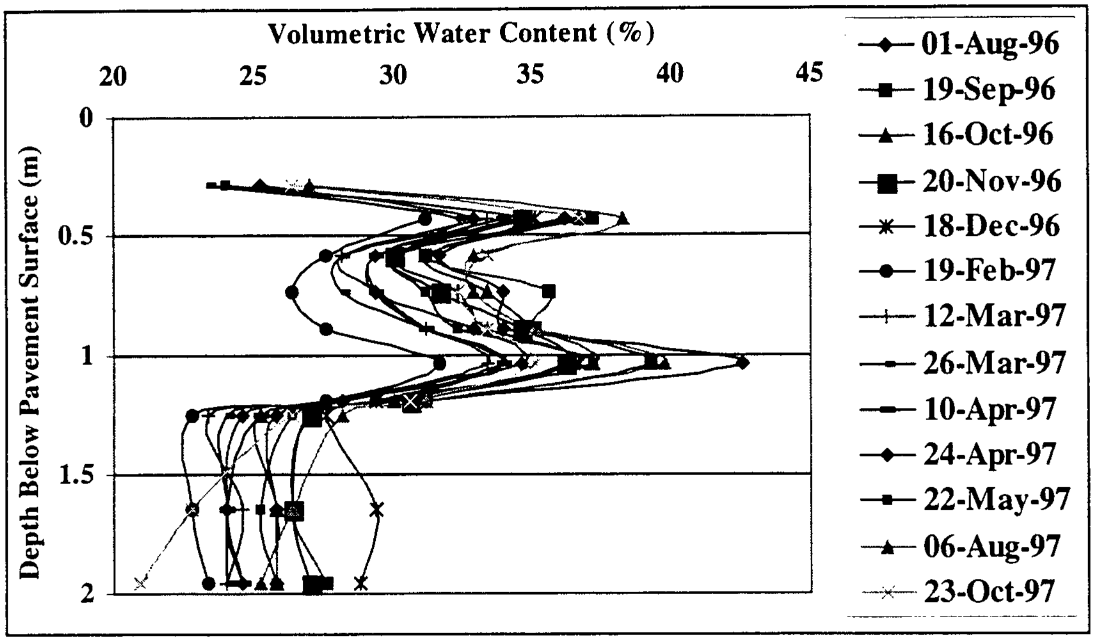


Figure 4.8 - TDR Volumetric Water Content (Section 390202)

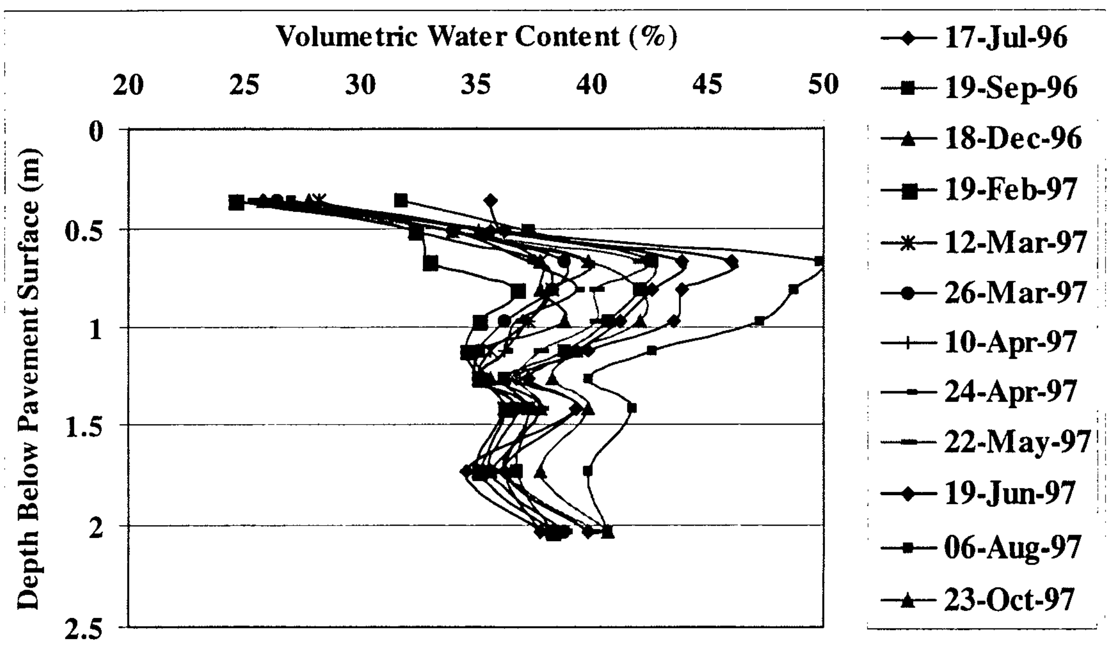


Figure 4.9 - TDR Volumetric Water Content (Section 390204)

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Literature Review

Research was required on SMP instrumentation installation and data collection, TDR soil moisture instrumentation, soil matric suction sensors and laboratory soil moisture characteristic testing. The reports on the Ohio Test Pavement test program (Sargand, 1994), protocols for SMP instrumentation installation and data collection (Rada, et al., 1994) and data processing (Elking and Zhou, 1996) were the primary sources of information for the Ohio Test Pavement SMP instrumentation. References on TDR instrumentation for measuring soil moisture content proved useful for this research (Topp, et al., 1980; Topp and Davis, 1985; Zegelin, et al., 1989; Zegelin, et al., 1992; Dalton, 1992; Klemunes, 1995; Klemunes, et al., 1995). Research was conducted on soil matric suction sensors that could be installed in the Ohio Test Pavement subgrade soil (Phene et al., 1971 a and b; Fredlund and Wong, 1989; Janoo and Eaton, 1989; Fredlund and Rahardjo, 1993). Procedures for the pressure plate extraction testing and modified triaxial shear fabrication and testing described in the reference by Fredlund and Rahardjo (1993) were adapted to this research.

5.2 Additional Soil Instrumentation

The research required purchase of electronic sensors and data acquisition equipment for onsite testing at the Ohio Test Pavement. A major objective was to install calibrated sensors to measure soil matric suction in the subgrade soil. Requirements for the sensors were that they should be able to survive freezing, should not be sensitive to dissolved ions in the soil water and could be monitored with some type of onsite datalogger. Thermal conductivity sensors (TCS) were purchased from the University of Saskatchewan for installation at the Ohio Test Pavement. The data acquisition equipment that was required for each of the four pavement sections instrumented with TCS matric suction sensors included a CR10 Datalogger, AM 416 multiplexer, A21REL-12 relay driver, precision voltage regulator and a waterproof enclosure. The research also included installation of two Tektronix 1502B Cable Testers for TDR measurements of soil moisture content at two pavement sections. Two SDMX50 multiplexers and one enclosure were required for each cable tester. The CR10 Dataloggers purchased for the TCS data acquisition was used for the TDR soil moisture measurements. Data acquisition instrumentation was purchased from Campbell Scientific, Inc. and cable testers were purchased from Tektronix, Inc.

5.3 Laboratory Soil-Water Characteristic Testing

Soil-water characteristic studies were conducted in the Environmental Geotechnology Laboratory at The University of Toledo. The purpose of the investigation was to evaluate the use of TDR and TCS sensors for soil moisture and soil moisture suction measurements, and to determine the soil-water characteristic relationship for the subgrade soil. For the testing, TDR and TCS probes were compacted in soil. One sample was tested in a pressure plate extractor with a hysteresis apparatus. Two other samples were tested in open buckets along with a soil tensiometer. Readings were obtained from the sensors as the soil moisture and moisture suctions varied and comparisons were made from the results. Additional soil-water characteristic testing was conducted using a modified triaxial cell and volume change apparatuses fabricated for the testing.

5.3.1 Overview of Soil-Water Characterization

A soil-water characteristic curve is used to depict the relationship between volumetric water content and soil matric suction for unsaturated soils. It is unique for each soil and is very sensitive to the conditions that exist during testing. Many soils exhibit a hysteresis effect depending upon whether the soil is wetting or drying. For the same volumetric water content, a soil will have higher matric suction during drying than during wetting. Thus it is necessary to measure both soil moisture and moisture suction to completely characterize the condition of the soil. The laboratory soil characteristic testing and seasonal monitoring was undertaken by researchers at the University of Toledo to better understand the behavior of the subgrade soil at the Ohio Test Pavement in Delaware County, Ohio.

Soil matric suction is an important stress state parameter for expressing unsaturated soil behavior. Soil properties that are highly dependent on the matric suction include permeability, shear strength and stiffness. Soil permeability, which increases as the matric suction decreases (increase in volumetric water content), affects the rate of water movement in subgrade soils. Soil shear strength and stiffness decrease as the matric suction decreases. Loss of shear strength in subgrade soils can lead to localized pavement failures. Testing at Case Western Reserve University (Figueroa, et al., 1994) has shown that the soil resilient modulus decreases significantly as the matric suction decreases. Loss of soil stiffness results in higher pavement deflections during traffic loading which decreases the pavement life. The soil-water characteristic behavior of the subgrade soil is required to model climatic effects on pavements.

5.3.2 Laboratory Soil Moisture Characteristic Relationship

Subgrade soil obtained from bag samples from the Ohio Test Pavement site was tested at the University of Toledo in order to investigate soil-water characteristic behavior. Pressure plate extraction, triaxial shear and free draining tests were conducted on prepared samples. Soil moisture characteristic curves from four types of tests were compared in Figure 3.8. The curves from the triaxial test and the pressure plate extraction tests, shown in Figure 5.1, are recommended for representing the soil water characteristic behavior. A recommended curve for drying is also shown. The hysteresis effect can be seen from the pressure plate test results. Mathematical expressions are used to approximate soil water characteristic curves for use in computer solutions that model the variation of soil moisture in unsaturated soils. The solutions can be expressed in terms of the slope of the curve that varies from point to point depending on the shape of the curve. Therefore it is necessary to define the curves as accurately as possible.

5.4 Installation of Seasonal Instrumentation

Five test sections (390101, 390104, 390112, 390202 and 390204) were instrumented with SMP instrumentation by The University of Toledo researchers. Calibration checks were

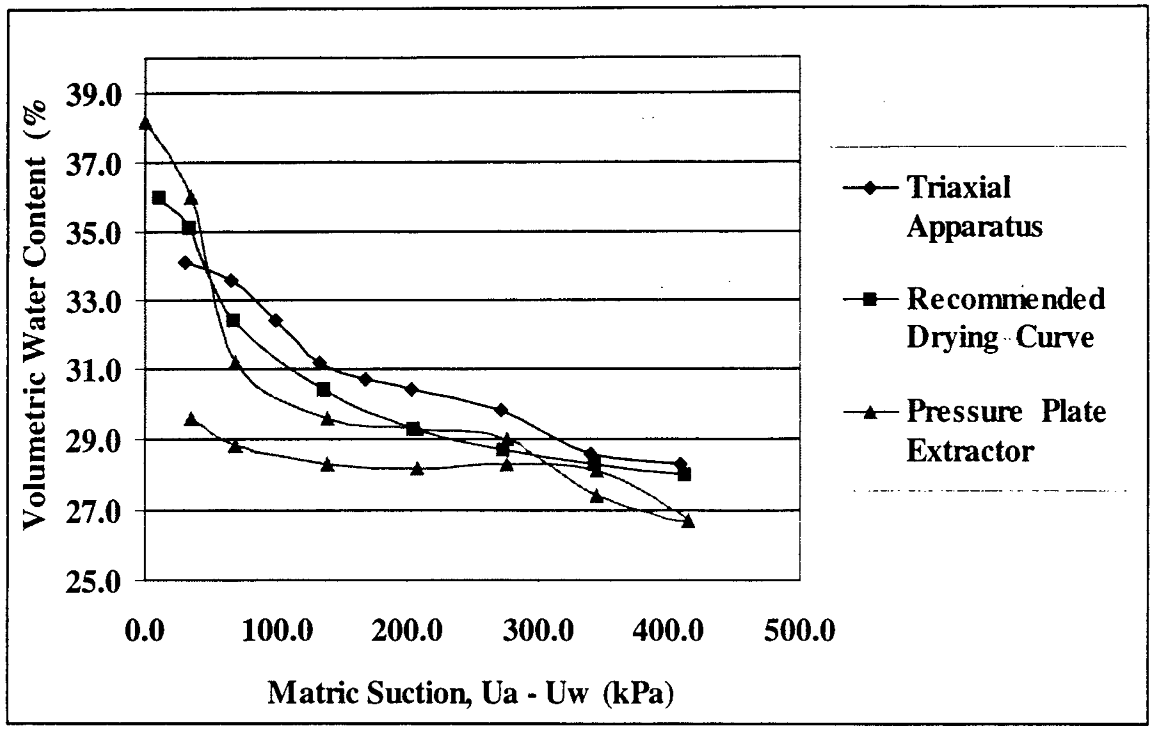


Figure 5.1 - Recommended Soil-Water Characteristic Behavior

performed on thermistor, electrical resistivity and TDR moisture probes and the sensors were installed in the test sections, all according to SMP protocols (Rada et al., 1995). Four of the test sections (390101, 390112, 390202 and 290204) were instrumented with TCS soil suction sensors and two of the sections (390112 and 390202) were instrumented with TDR cable testers for frequent readings of soil moisture. The probes were connected to the data acquisition equipment, which was installed in boxes along the side of the old pavement.

5.5 Field Monitoring

The SMP monitoring program requires data collection from onsite and mobile data acquisition systems at least fourteen times per year. The onsite data acquisition system installed at each pavement section stores readings from the thermistor probe. The mobile data acquisition system obtains readings from the TDR and electrical resistivity probes. Data is uploaded from the CR10 dataloggers using a portable computer and an optical isolated interface. CR10 datalogger programs were written under contract to FHWA for the seasonal monitoring (Rada, et al., 1994). Program ONSITE was downloaded to each onsite unit. Program MOBILE was modified to account for varying cable lengths of the TDR probes for each pavement section. Data is uploaded from data acquisition systems which were installed onsite at the two test sections with TCS sensors and the two test sections with both TCS sensors and TDR cable testers. CR10 datalogger programs were written by researchers at the University of Toledo for the data collection.

5.6 Evaluation of Seasonal Instrumentation Data

Computer programs written for personal computers are used to evaluate and process the SMP data. Software program Procedure Manager was developed to enable entering site information and to perform data checks (Rada et al., 1994). This software was superceded by program SMPCheck that performs data checks and prepares the data for the LTPP Information Management System (Elkins, et al., 1996). Programs ONSFIELD and MOBFIELD were written to provide checks on the onsite and mobile data during collection. The software programs provide useful plots of the data. Results from the programs are compared to the soil-water characteristic relationship to evaluate the seasonal variations of soil moisture and moisture suction in the subgrade soil.

5.6.1 Soil Moisture Suction

Results from soil matric suction measurements with the TCS sensors are tabulated in Tables 4.5 through 4.8. The readings shown in the tables are representative of the data from the sensors, however, the majority of the readings are out of calibration. An assessment for the sensors is provided in Table 4.9. Very few of the voltage differences indicate positive matric suction and some of these voltage differences would yield high positive matric suctions. Some of the sensors are behaving erratically so voltage differences that periodically fall within the calibration range are not reliable. The sensors will be monitored in order to determine if any useful data can be obtained from them.

5.6.2 Volumetric Water Content

TDR volumetric moisture contents were measured at ten depths in five pavement sections. The water contents are shown in Figures 4.4 through 4.9 for several different months. The curves from one pavement section, 390112, behave erratically but the curves from the other sections are better. However, in many cases the volumetric water contents are too high. For example, volumetric water contents were computed using conventional phase relations for soils varying from 80 to 100% saturation as shown in Figure 5.2. Using these data, volumetric water contents greater than 45% would not be possible. Values of G_s = 2.68 to 2.72 and dry unit weights from 16 to 20 kN/m^3 were reported by DeButy (1997) from tests on soil from the test site. Data from compaction testing and undisturbed samples of soil from the site from DeButy (1997) were used to compute volumetric water content and porosity as shown in Table 5.1 and are also plotted in Figure 5.2. The volumetric water contents are consistently less than 40% and values of porosity vary from 28% to 40%.

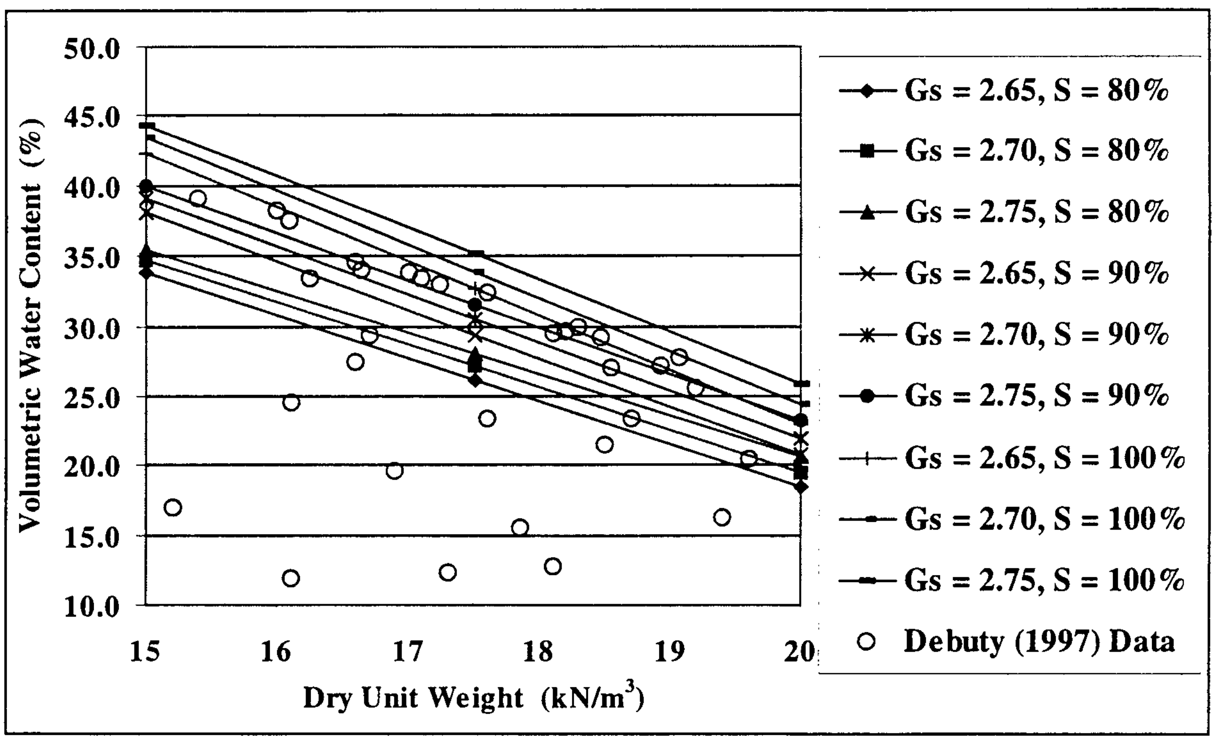


Figure 5.2 - Volumetric Water Contents Computed Using Assumed Properties

Table 5.1 - Volumetric Water Contents Computed From Compaction Testing

Input Soil Parameters					Calculated Soil Parameters					
Source	**Dry Unit Wt. (lb/ft^3)**	**Dry Unit Wt. (kN/m^3)**	**Specific Gravity**	**Grav. Water Content (%)**	**Void Ratio**	**Porosity (%)**	**Degree of Saturation (%)**	**Vol. Water Content (%)**	**Wet Unit Wt. (kN/m^3)**	**Wet Unit Wt. (lb/ft^3)**
	110.2	17.3	2.69	7	0.5	34	36	12.4	18.5	117.9
Subgrade	113.7	17.9	2.69	9	0.5	32	48	15.5	19.4	123.4
Soil	117.8	18.5	2.69	11	0.4	30	72	21.5	20.6	131.3
	119.1	18.7	2.69	12	0.4	29	80	23.3	21.0	133.7
Modified	115.3	18.1	2.69	16	0.5	31	94	29.5	21.0	133.7
Proctor	108.3	17.0	2.69	20	0.6	36	95	33.8	20.3	129.4
	96.8	15.2	2.69	11	0.7	42	40	17.0	16.9	107.4
Subgrade	102.5	16.1	2.69	15	0.6	39	63	24.6	18.5	117.9
Soil	105.7	16.6	2.69	16	0.6	37	74	27.5	19.3	122.9
	106.4	16.7	2.69	17	0.6	37	80	29.4	19.6	124.7
Standard	108.9	17.1	2.69	19	0.5	35	95	33.4	20.4	129.8
Proctor	101.9	16.0	2.69	23	0.6	39	97	38.2	19.7	125.8
	98.1	15.4	2.69	25	0.7	42	94	39.1	19.2	122.5
Embank.	115.3	18.1	2.71	7	0.5	32	40	12.8	19.4	123.3
Soil	123.6	19.4	2.71	8	0.4	27	60	16.2	21.0	133.7
	124.8	19.6	2.71	10	0.4	26	78	20.5	21.6	137.6
Modified	122.3	19.2	2.71	13	0.4	28	92	25.6	21.7	138.3
Proctor	116.6	18.3	2.71	16	0.5	31	96	29.9	21.2	135.3
Embank.	102.5	16.1	2.71	7	0.7	39	30	11.8	17.3	109.9
Soil	107.6	16.9	2.71	11	0.6	36	54	19.7	18.8	119.9
	112.1	17.6	2.71	13	0.5	34	69	23.3	19.9	126.7
Standard	115.9	18.2	2.71	16	0.5	32	94	29.6	21.1	134.4
Proctor	112.1	17.6	2.71	18	0.5	34	96	32.4	20.8	132.4
	105.7	16.6	2.71	20	0.6	38	92	34.6	20.0	127.3
[1]0.19	103.5	16.2	2.71	20	0.6	39	86	33.4	19.5	124.4
[1]0.37	106.0	16.6	2.71	20	0.6	37	91	34.0	20.0	127.3
[1]0.56	109.8	17.2	2.71	19	0.5	35	94	33.0	20.5	130.4
[1]0.95	102.5	16.1	2.71	23	0.7	39	95	37.5	19.8	125.9
[1]1.19	117.6	18.5	2.69	15	0.4	30	97	29.1	21.3	135.8
[1]1.50	118.1	18.5	2.69	14	0.4	30	91	27.1	21.2	135.0
[1]1.69	120.6	18.9	2.69	14	0.4	28	96	27.1	21.6	137.5
[1]1.88	121.5	19.1	2.69	14	0.4	28	100	27.7	21.8	138.8

[1]Data obtained from thin wall samples, where the numbers indicate the depth below the ground surface in meter.

The same ranges of values for volumetric water content and porosity are reported in this report in Tables 3.2 and 3.3 from soil moisture characteristic testing at the University of Toledo. It is not possible to have a volumetric water content greater than the porosity. Many of the TDR water contents shown in the figures are greater than 40%. Therefore, the procedures for determining volumetric water content need to be examined further.

5.6.3 Computation of Volumetric Water Content From TDR Measurements

Volumetric water content is computed using the apparent length of the TDR probe as measured with a cable tester. The apparent dielectric constant of the soil surrounding the TDR probe is computed using Equation 5.1.

$$K_a = \left[\frac{L_a}{L\ V_p} \right]^2 \qquad 5.1$$

where K_a = apparent dielectric constant

L_a = apparent probe length

L = actual probe length (= 0.205 m)

V_p = velocity of wave pulse (= 0.99 times the speed of light)

The soil volumetric water content is computed from the apparent dielectric constant using an empirical equation. The equation used in the FHWA software MOBFIELD is Topp's Equation given in equation 5.2.

$$\theta = (-0053 + 0.0293 K_a - 0.00055 K_a^2 + 0.0000043\, K_a^3)\ X\ 100\% \qquad 5.2$$

An extensive laboratory testing program was conducted at the University of Maryland to investigate the use of time domain reflectometry for measuring volumetric water content (Klemunes, 1995 and Klemunes, et al., 1995). Coarse and fine-grained soil samples were obtained from several locations. The samples were compacted to varying densities using a shake table. The shake table was stopped during compaction to obtain the TDR traces. The research involved investigating different methods for determining the apparent length of the probe and the use of empirical equations for computing volumetric water content. Errors resulting from the use of the equations were computed. One equation that resulted in relatively low error is given in Equation 5.3.

$$\theta = 6.043 \cdot (K_a - 0.54749)^{0.5634} \qquad 5.3$$

A plot of volumetric water content versus apparent dielectric constant obtained using the two equations is shown in Figure 5.3. Volumetric water contents computed using Equation 5.3 are lower than those from Equation 5.2. Topp's equation was obtained from tests on organic soils so this result is not unexpected. Comparing the two curves, a volumetric water content of 50% obtained from Equation 5.2 would give about 40% using Equation 5.3. Therefore an empirical equation other than Topp's equation should be used for the moisture content interpretations.

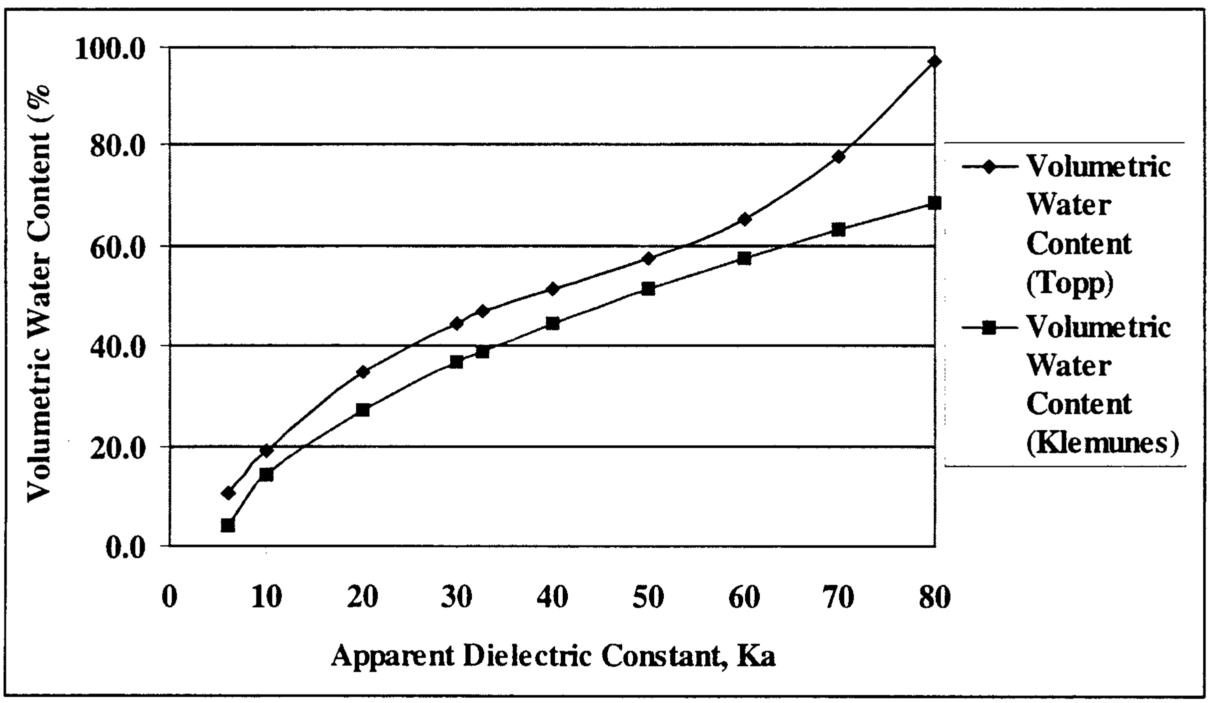


Figure 5.3 - Volumetric Water Content versus Apparent Dielectric Constant

5.6.4 Field Soil-Water Characteristic Behavior

The in situ soil-water characteristic behavior was not completed at this time because of difficulties in determining in situ soil matric suction and moisture contents. The moisture suction measurements are not reliable. It is possible that the subgrade soil at the test site has remained nearly saturated throughout the monitoring period. Therefore the low matric suction values inferred by some of the TCS measurements are plausible. An improved equation should be adopted for computing volumetric water contents. The monitoring should be continued throughout wetting and drying periods to investigate the in situ behavior.

5.6.5 Comparison of Laboratory and Field Behavior

Laboratory and field behavior can be compared using moisture suction and water content measurements or only water content measurements. If both moisture and suction readings are available, then data from field measurements can be plotted over the laboratory soil-water characteristic curves to determine if the data points from the in situ measurements fall within the laboratory curves. Matric suction pressures can be determined from the laboratory curves using TDR water contents. The in situ matric suction is greater than the value obtained from the wetting curve and less than the value obtained from the drying curve. The comparison between field and laboratory behavior would provide valuable insights into the seasonal variation of subgrade conditions. The variation of matric suction pressures could be used to determine the seasonal variation of soil properties such as permeability, shear strength and stiffness that are necessary to investigate climatic effects on pavements.

5.7 Recommendations for Climatic Modeling

Information from this research can be used in modeling climatic effects on pavements using a computer program (Lytton, et al., 1993). The required program inputs include pavement geometry and material properties, drainage conditions, weather information, and subgrade soil properties. The important soil properties are the soil-water characteristic relationship and a relationship between unsaturated permeability and matric suction. The integrated model can be used to predict soil moisture and temperature profiles that can then be compared with profiles obtained from the seasonal instrumentation monitoring.

BIBLIOGRAPHY

1) Dalton, F.N. (1992), "Development of Time-Domain Reflectometry for Measuring Soil Water Content and Bulk Soil Electrical Conductivity," *Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice,* SSSA Special Publication No. 30, 143 - 167.

2) DeButy, P.W. (1997), "Ohio Test Road Seasonal Instrumentation and Material Characterization," M. S. Thesis, Department of Civil Engineering, Case Western Reserve University, Cleveland, Ohio.

3) Elkins, G.E. and Zhou, H. (1996), "LTPP Seasonal Monitoring Program: SMPCheck Users Guide Version 2.3," PCS/Law Engineering, Beltsville, Maryland.

4) Figueroa, L.J., Angyal, E. and Su, X. (1994), "Characterization of Ohio Subgrade Types," Report No. FHWA/OH-94/006, Case Western Reserve University, Cleveland, OH, 181 pp.

5) Fredlund, D.G. and Wong, D.K.H. (1994), "Calibration of Thermal Conductivity Sensors for Measuring Soil Suction," *Geotechnical Testing Journal*, ASTM, 12(3), 188-194.

6) Fredlund, D.G. and Rahardjo, R. (1993), "Soil Mechanics for Unsaturated Soils," John Wiley and Sons, Inc., New York, NY.

7) Gardner, W.R. (1958), "Some Steady State Solutions of the Unsaturated Moisture Flow Equation with Application of Evaporation from a Water Table," *Soil Science*, Vol. 85, 223-232.

8) Manepally, C. (1997), "Properties of Unsaturated Sub-Grade Soils," M. S. Thesis, Department of Civil Engineering, University of Toledo, Toledo Ohio.

9) Jin, M.S., Lee, K.W. and Kovacs, W.D. (1994), "Seasonal Variation of Resilient Modulus of Subgrade Soils," *Journal of Transportation Engineering*, ASCE, 120(4), 606-616.

11) Klemunes, J.A., Jr. (1995), "Determining Soil Volumetric Moisture Content Using Time Domain Reflectometry," M. S. Thesis, Department of Civil Engineering, University of Maryland.

12) Klemunes, J.A., Jr., (1998), "Determining Soil Volumetric Moisture Content Using Time-Domain Reflectometry," Report No. FHWA-RD-97-139, Federal Highway Administration, U. S. Department of Transportation, 74 pp.

13) Lowery, B.F. (1996), "Moisture Characteristic studies on a Fine Grained Subgrade Soil," M. S. Thesis, Department of Civil Engineering, University of Toledo, Toledo, Ohio.

14) Lytton, R.L., Pufahl, D.E., Michalak, C.H., Liang, H.S. and Dempsey B.J. (1993), "An Integrated Model of the Climatic Effects on Pavements," Report No. FHWA-RD-90-033, Federal Highway Administration, U. S. Department of Transportation.

15) Phene, C.J., Hoffman, G.J. and Rawlins, S.L. (1971), "Measuring Soil Matric Potential in situ by Sensing Heat Dissipation With a Porous Body: I. Theory and Sensor Construction," *Soil Science Society of America Proceedings*, Vol. 35, 27-33.

16) Phene, C.J., Hoffman, G.J. and Rawlins, S.L. (1971), "Measuring Soil Matric Potential in situ by Sensing Heat Dissipation With a Porous Body: II. Experimental Results," *Soil Science Society of America Proceedings*, Vol. 35, 225-229.

17) Sargand, S. (1994), "Development of an Instrumentation Plan for the Ohio SPS Test Pavement (DEL-34-17.48)," Ohio University, Athens, Ohio.

18) Rada, G.R., Elkins, B.E., Henderson, B., Van Sambeek, R.J. and Lopez, A. Jr. (1995), "LTPP LTPP Seasonal Monitoring Program: Instrumentation Installation and Data Collection Guidelines," Report No. FHWA-RD-94110, Federal Highway Administration, U. S. Department of Transportation.

19) Topp, G.C., Davis, J.L. and Annan, A.P. (1980), "Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines," *Water Resources Research*, 16(3), 574-582.

20) Topp, G.C. and Davis, J.L. (1985), "Measurement of Soil Water Content Using Time-Domain Reflectometry (TDR): A field Evaluation," *Soil Science Soc. of America*, Vol. 29, 19-24.

21) Zegelin, S.J, White, I. and Jenkins, D.R. (1989), "Improved Field Probes for Soil Water Content and Electrical Conductivity Measurement Using Time Domain Reflectometry," Water *Resources Research*, 25(11), 2367-2376.

22) Zegelin, S.J, White, I. and Russell, G.F. (1992), "A critique of the Time Domain Reflectometry Technique for Determining Field Soil Water Content," *Advances in Measurement of Soil Physical Properties: Bring Theory into Practice, SSSA Special Publication No. 30, 187- 208.*

23) Zhou, H, Rada, G.R. and Elkins, G.E. (1996), "LTPP-SPS Automated Weather Stations: AWSCheck Users Guide Version 1.1," PCS/Law Engineering, Beltsville, Maryland.