Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TX-99/3930-1		

4. Title and Subtitle	5. Report Date
EVALUATION OF THE VERTICAL MOISTURE BARRIER INSTALLED ON IH 45 NEAR PALMER, TEXAS	November 1998 Revised: April 1999
	6. Performing Organization Code
7. Author(s) Sanet Bredenkamp, Tom Scullion, John Ragsdale and Stephen Sebesta	8. Performing Organization Report No. Report 3930-1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. Project No. 7-3930
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Research: February 1997 - September 1998
	14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation.
Research Project Title: Vertical Moisture Barriers, Field Monitoring and Future Directions

16. Abstract

To minimize problems with expansive clays, TxDOT decided to install vertical moisture barriers on a major widening project on IH 45 near Palmer, Texas. This 14 mile project required barriers on each side of the pavement in both directions. To evaluate the effectiveness of the barrier, the variation in moisture content with depth was measured at four locations, with measurements both inside and outside of the barrier.

The monitoring was performed with a Troxler AP-200 Sentry gauge. This report describes the gauge, the installation procedures and the measured moisture contents.

The barrier seems to be performing as designed at three of the four monitor locations. At these three locations, during wet and dry periods the moisture contents inside the barrier were relatively constant, whereas outside the barrier substantial variations were monitored. At the fourth location very little difference could be detected between the moisture fluctuations inside or outside of the barrier.

Concerns were expressed concerning the installation procedure, which requires the cutting of a 250 mm trench, which is backfilled with gravel. This trench appears to trap water, which may have a detrimental impact on long-term barrier performance. Future research work should be directed at "trench-less" barrier installation techniques.

17. Key Words	18. Distribution Statement
Vertical Moisture Barriers, Expansive Clays, Pavements, Rehabilitation	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	132	

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EVALUATION OF THE VERTICAL MOISTURE BARRIER INSTALLED ON IH 45 NEAR PALMER, TEXAS

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Report 3930-1
Project Number 7-3930
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Sponsored by the
Texas Department of Transportation

November 1998
Revised: April 1999

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DISCLAIMER

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ACKNOWLEDGMENT

The staff of the Dallas District of the Texas Department of Transportation is acknowledged for their support of this work. In particular Mr. Bill Hale, P.E., for initiating the project, and to the project director Mr. Hal Stanford, P.E., for providing on-site assistance with data collection. Because of the nature of expansive clays, a project of moisture changes is indeed a long-term monitoring effort, and the district staff is thanked for their patience in this project. Also, we would like to thank TxDOT for their assistance and support on the project. Mr. Ronny G. Vestal and the Ennis Fire Department were helpful in providing rain data for the area.

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CHAPTER 1
INTRODUCTION

Expansive clays are known to cause millions of dollars of damage to structures in the United States and elsewhere. Their impact on the riding quality of highways is well known. In Texas, the often recommended treatment for minimizing their damage is to replace approximately 1.5 m (4.8 ft) of swelling material with a non-swelling low PI fill material. On most projects this strategy is cost prohibitive. Therefore, for the past 20 years the TxDOT has been experimenting with various methods of minimizing damage by encapsulating clays with impermeable fabrics. Both horizontal and vertical moisture barriers have been used. The use of a vertical moisture barrier installed in the shoulder of a pavement proved to be successful in stabilizing moisture conditions beneath Interstate Highway Loop 410 in San Antonio in 1987 (*1*,*2*,*3*). More references on the performance of these barriers can be found in the following: Steinberg (*4*), Lytton, Steinberg and Picornell (*5*).

To evaluate the effectiveness of these barriers, both long-term pavement performance and short-term instrumentation experiments have been conducted. The long-term studies have generally shown that these barriers have been successful in limiting the roughness induced in the highways by expansive subgrades (Steinberg (*4*)). The short-term instrumentation studies have been less successful primarily because of the poor durability of the available field moisture and suction measuring equipment. Thermal moisture sensors have been used but proved not to be reliable when the soil was too dry. Thermocouple psychrometers are not accurate in measuring soil suction in extremely wet soil conditions. Other soil moisture instruments, such as moisture blocks, have given durability problems within the first few months after installation (*6*).

For a vertical moisture barrier to be working correctly it must stabilize the moisture content beneath the highway. It is fluctuations in moisture content that are responsible for the large volume changes of swelling clays. Expansive clay damage could possibly be minimized by limiting the infiltration of water, particularly from the edge of the highway. Therefore, a quick and inexpensive method of judging the barrier effectiveness is to monitor the moisture content both inside and outside the barrier with depth. Once a barrier system has reached an equilibrium condition, the moisture content inside the barrier should show significantly less variation than that on the outside.

In the past 20 years, numerous efforts have been made to monitor moisture contents with various types of devices. In this research, efforts are made to use a relatively new moisture measuring device, the Troxler Sentry 200-AP, to evaluate the effectiveness of the vertical moisture barrier being installed on a major interstate widening project on IH 45 near Palmer, Texas. In the next section of this report the device will be described, together with a discussion of the field installation and laboratory calibration work. This will be followed by a discussion of the data collected since barrier installation.

CHAPTER 2

DESCRIPTION AND INSTALLATION PROCEDURE OF THE MOISTURE SENSOR

DESCRIPTION OF DEVICE

The Troxler Sentry 200-AP moisture measurement device was chosen to perform moisture measurements on the inside and the outside of vertical moisture barriers located along IH 45. The Sentry 200-AP responds to changes in the electrical properties of the material from which the moisture content is determined. The electrical property measured is the dielectric constant, which is related to the electrical conductivity of the material. It has been found for highway materials that the dielectric constant of a soil is related to its moisture content. Most dry solid highway materials like sand, clay and aggregates have a dielectric constant of between 2 and 4, while water has a dielectric constant of 81 (*7*). The addition of moisture to any soil will cause an increase in the measured dielectric. The Sentry measures the soil dielectric and then uses a laboratory determined calibration factor to relate it to volumetric moisture content.

The probe operates inside a PVC access tube, which is installed vertically to the desired depth. The probe count, calculated moisture content, date, and time are stored for each field measurement. The device is capable of storing up to 1,000 field measurements, and the data can be stored and downloaded to a computer.

The gauge consists of a calibrated moisture probe which measures volumetric moisture contents, a control unit, an access tube mount, and cable stops. Figure 1 is a photograph of the probe.

INSTALLATION PROCEDURE OF ACCESS TUBE

The moisture probe is connected to a long cable and is lowered into a PVC access tube through which it makes the moisture measurement. The access tube consists of a 50 mm (2 in) PVC pipe which is installed to the desired depth at which moisture measurements will be taken.

Figure 1. Troxler Sentry 200-AP Moisture Measuring Device.

The end of the access tube is sealed. A summarization of the installation procedure of the access tube follows:

1. Locate the area where moisture measurements are to be taken.
2. Determine the maximum depth of measurement.
3. Obtain a section of PVC access tube.
4. Ensure that the access tube is the correct length. The bottom of the tube must be sealed with an end cap and should extend at least 150 mm below the lowest point at which a measurement will be made.
5. Auger a hole with the same diameter as the PVC tube into the soil to the desired depth of installation (Figure 2). A smooth- walled shelby tube sample should also be taken to the desired depth and the excavated soil can be saved for subsequent calibration.
6. Drive the PVC tube into the augured hole (Figure 3). The PVC pipe must fit tightly against the earth walls of the augured hole to prevent air voids forming between the access tube and the surrounding soil. The formation of air voids could lead to unreliable moisture readings.
7. Seal off the top end of the access tube with an end cap to prevent rainwater and debris from contaminating the access tube. Then apply loop sealant over the top of the end cap to provide waterproofing. Figure 4 is a photograph of the finished hole.
8. Perform a moisture measurement by removing the loop sealant and the end cap, then lowering the probe into the access tube. After moisture measurements at the desired depths, replace the end cap and reapply the loop sealant. Figure 5 shows the probe being lowered into the PVC access tube to take moisture measurements.

Figure 2. A Hole Being Augured on IH 45 Shoulder.

Figure 3. A PVC Access Tube Being Pushed into the Tight Fitting Augured Hole.

Figure 4. Finished Hole Sealed Off with Loop Sealant.

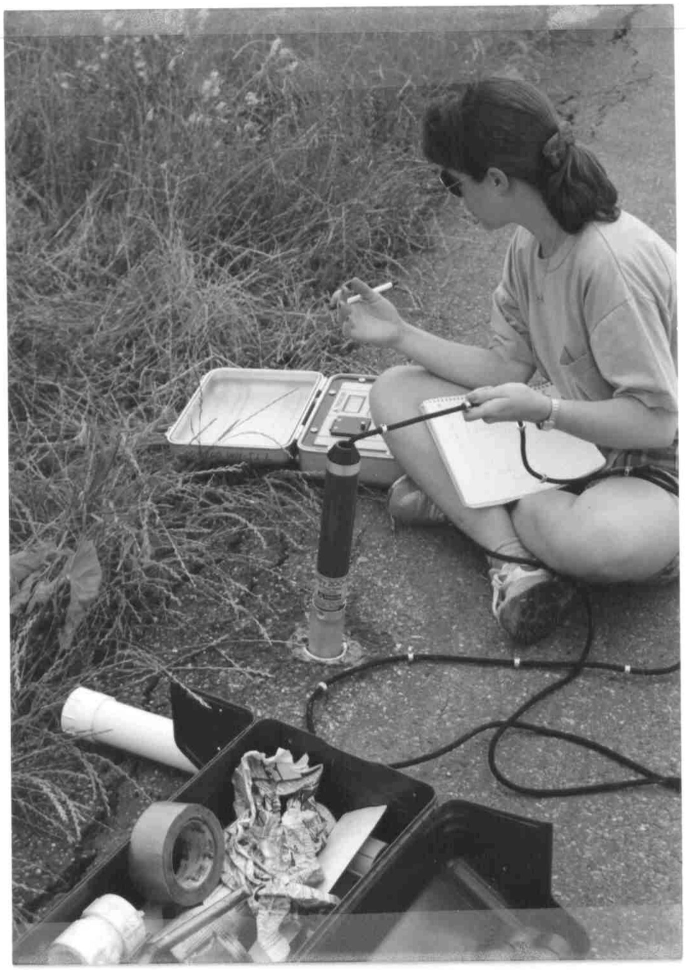


Figure 5. Sentry 200-AP Moisture Gauge Being Lowered into the PVC Access Tube.

CHAPTER 3
CALIBRATION PROCEDURE

INTRODUCTION

To ensure an accurate moisture content measurement, a calibration procedure is performed for each soil type encountered on a site. One of two possible calibration procedures can be used. The first is the field calibration procedure, which is done in the field at the time of probe installation. The second is a laboratory calibration procedure. This calibration is performed on soil that was returned from the test site to the laboratory. Each of these calibration procedures has its own advantages and disadvantages. A description of both procedures is given below, together with a discussion about the advantages and disadvantages of each procedure.

The first calibration procedure discussed under the heading Field Calibration Procedure is recommended by the manufacturer Troxler, and is described in the user's manual for the Sentry 200-AP moisture measurement device (*7*). The second calibration procedure described under the heading Laboratory Calibration Procedure was developed by the Texas Transportation Institute (TTI).

FIELD CALIBRATION PROCEDURE

The field calibration procedure is performed by taking undisturbed shelby tube samples while the access tube is being installed. The depths of these samples are accurately recorded. Probe readings are then taken at the locations where the core samples were removed. The moisture contents of the core samples are determined in the laboratory by use of ASTM standard D-4959 (*8*). These moisture contents are then plotted against the field-obtained gauge readings to obtain a calibration curve.

LABORATORY CALIBRATION PROCEDURE

When performing calibrations it is essential to obtain gauge readings over a wide range of possible field moisture contents. If the range of moisture contents over which the calibration is performed is not sufficient, the data may not fit a regression line well enough to obtain a calibration curve. This problem leads to a poor calibration factor resulting in scattered data and inconsistent moisture measurements. If the core samples obtained as described for the field calibration procedure do not correspond to at least a 15 percent variation in volumetric moisture content, an alternate calibration procedure is recommended. The calibration factor is generated automatically by the Sentry for each soil type under project. The user inputs the volumetric moisture content that corresponds to gauge readings. Rather than using field data this procedure, developed by TTI, uses laboratory prepared samples, and ensures that a wide range of moisture contents are used. With this procedure it is necessary to excavate soil from the location where moisture measurements are to be taken and to hand mix at least three samples at a variety of moisture content values. The procedure is as follows:

1. Take a representative sample of soil sufficient to fill at least three, 20 liter containers for calibration purposes, as well as enough additional soil to determine the optimum moisture content and corresponding maximum dry density of the soil.
2. Determine the optimum moisture content of the soil by using the standard Proctor compaction method as described by ASTM standard D-698 (*9*).
3. Thoroughly dry and crush the remaining soil fine enough to pass through a no. 40 sieve.
4. The calibration test set-up is shown in Figure 6. The test container is a 20 liter (approximately 5 gallon) plastic bucket with an airtight lid. A section of 50 mm diameter PVC pipe is installed vertically at the center of the bucket by gluing it to the base. Prepare three of these containers for three batches of soil at different moisture contents.
5. Weigh exactly 27 kg of the dried crushed soil.
6. Determine the weight of water that should be added to the soil to yield a moisture content of 10 percent less than the optimum moisture content determined in step 2 of this procedure.

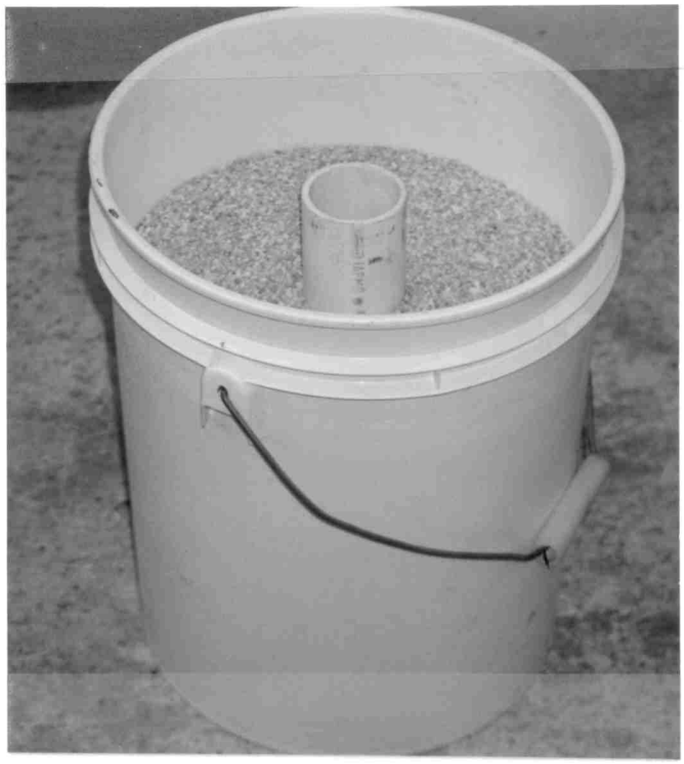


Figure 6. 20 Liter Bucket with PVC Pipe Glued to Bottom for Calibration Purposes.

7. Mix the water into the soil until it reaches a uniform consistency and color. Save a sample of this soil in an airtight container for laboratory analysis to obtain the actual gravimetric moisture content.
8. Carefully place the soil around the PVC pipe until the bucket is filled to one third of its depth. Compact the soil by applying 25 blows using a standard proctor hammer while moving cautiously around the PVC pipe. It is important to ensure that the soil is tightly compacted against the PVC pipe, since the presence of air voids between the PVC pipe and the compacted soil would result in unreliable moisture readings.
9. Repeat step 7 by first filling the bucket to two-thirds of its depth and then to its full depth.

10. Seal the bucket airtight for subsequent calibration with the moisture probe.
11. Determine the weight of the water needed to yield the optimum moisture content. Mix and compact soil into the second bucket by repeating steps 5, 7, 8, 9 and 10.
12. Determine the weight of the water needed to yield a moisture content 10 percent higher than the optimum moisture content. Mix and compact soil into the third bucket by once again repeating steps 5, 7, 8, 9 and 10.
13. Determine the exact moisture content of each of the three samples saved as described in step 7. These moisture contents should be determined by the direct heat method as described in ASTM standard D-4959. This procedure yields a gravimetric moisture content. The Sentry 200-AP device is calibrated to compute volumetric moisture content values. Therefore it is necessary to convert the obtained gravimetric moisture content to volumetric moisture contents.
14. Once the volumetric moisture contents of the soil in the three buckets is known, take gauge readings by lowering the probe into the PVC access tube that has been installed into the plastic containers. These gauge readings are related to the dielectric of the soil surrounding the PVC tube. The calibration factor is calculated by plotting the gauge reading against volumetric moisture content. The data points for such a calibration are shown in Figures 7 and 8. The computation of the calibration factor is done automatically by the Sentry device; it fits a regression line through the data points.
15. The calibration is now complete and can be saved under an appropriate name.

CALIBRATION CURVES FOR VARIOUS SOIL TYPES

It was found that a reasonable correlation between gauge reading and actual moisture content could be obtained by performing a laboratory calibration on major soil types. It is, therefore, not necessary to perform a calibration on each access hole from each site that is to be monitored. The Sentry 200-AP, as received from the manufacturer, is only equipped with a calibration factor for sandy soils. Therefore, it was necessary to obtain a standard calibration for gravel and clay soils in order to be able to make moisture measurements without calibrating the probe for every test location.

The initial assumption is that a single calibration factor is appropriate for sand, clays, etc. This assumption is based on the limited amount of work done in this project, and must be checked on all subsequent studies. On all subsequent work, calibration factors should be generated for every soil type encountered. However, it does not appear necessary to generate a new factor for each access hole.

Repeatability tests were performed with the Sentry 200-AP on a black clay and on gravel. These tests aided in determining the reliability and accuracy of measurements made with the moisture probe and provided calibration curves for clay and gravel in general. These tests were performed by repeatedly obtaining gauge readings from clay and gravel soils that were used for calibration purposes.

The results from the calculation of the actual moisture contents for the black clay and the sandy gravel are presented in Table 1. The gauge-derived repeatability results are presented in Table 2. The results in Table 2 are graphically presented in Figures 7 and 8.

It is evident from the data in Table 2 that the repeatability of the moisture probe is very good. The difference between readings at the same moisture content was insignificantly small. A regression was performed on the moisture data obtained from the repeatability tests. For both the clay and the sandy gravel, the data can be presented by the equation of a straight line. The equation constants are tabulated in Table 3.

The equation is given by:

$$y = mx + c$$

where:

y = gauge reading

x = moisture content (% by volume)

m = slope of the curve

c = intercept on y-axis

Table 1. Laboratory Determined Water Content.

Volumetric water content of a black clay		Volumetric water content of a sandy gravel	
Sample no.	% moisture	Sample no.	% moisture
1	44	1	8.9
2	53	2	18.9
3	67	3	19.7

Table 2. Gauge Derived Moisture Content.

Volumetric water content of a black clay			Volumetric water content of a sandy gravel		
Sample no.	Gauge reading	% moisture	Sample no.	Gauge reading	% moisture
1	4424	44.6	1	3652	8.9
	4417	44.3		3655	9
	4424	44.6		3646	8.8
	4419	44.5		3651	8.8
2	4575	51.2	2	4073	17.9
	4575	51.2		4071	17.9
	4574	51.2		4070	17.9
	4570	51		4072	17.9
3	4958	69.7	3	4196	20.6
	4959	68		4196	20.6
	4955	67.8		4197	20.6
	4952	67.8		4194	20.5

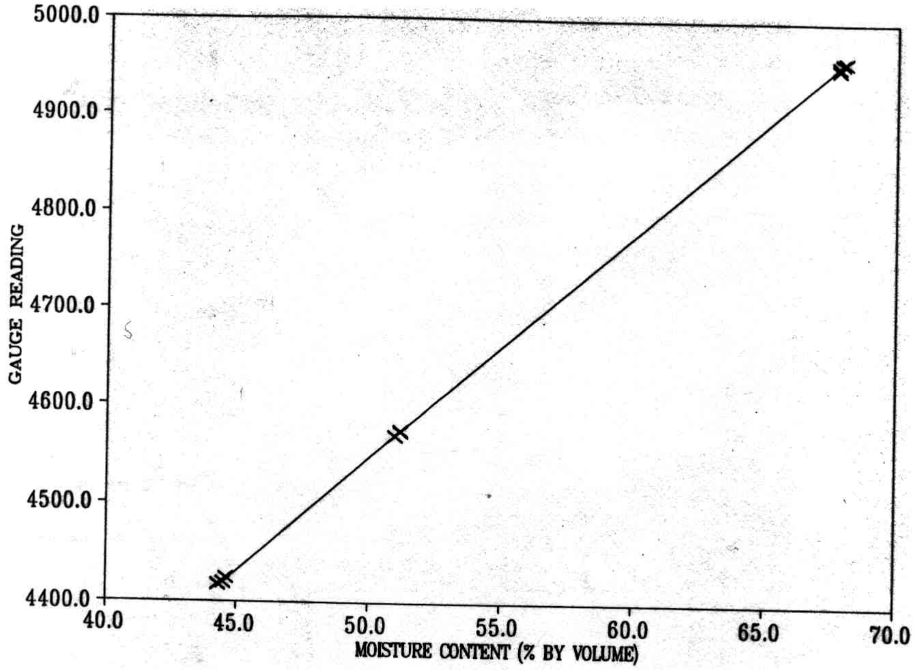


Figure 7. Repeatability Data Used for Calibration of Black Clay Soil.

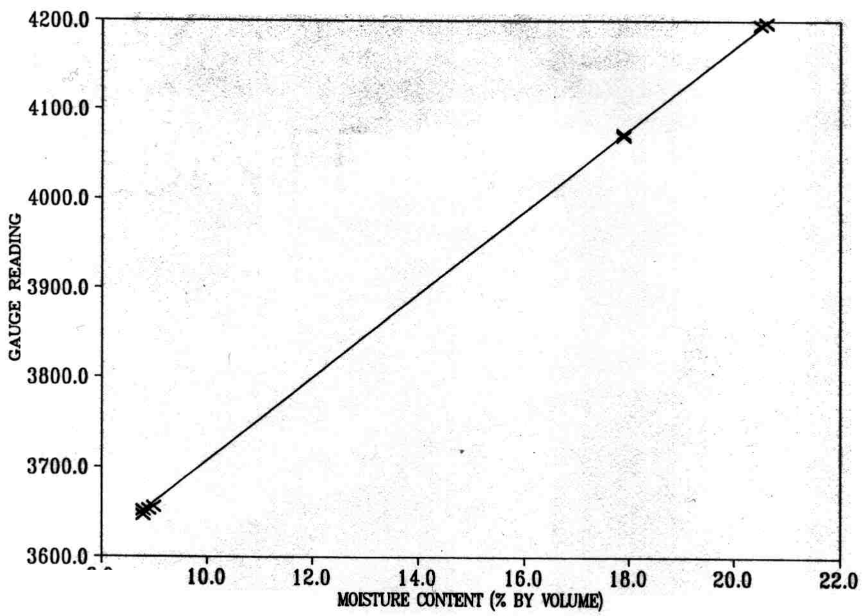


Figure 8. Repeatability Data Used for Calibration of Gravel.

Table 3. Regression Constants.

	Clay	Sand/Gravel
Slope	22.884447	46.566363
Intercept	3403	3238

ADVANTAGES AND DISADVANTAGES OF DIFFERENT CALIBRATION PROCEDURES

The major advantage that the field calibration procedure has over the laboratory calibration procedure is the time it takes to complete the calibration. The laboratory calibration procedure calls for large quantities of soil to be hauled to the laboratory where it has to be dried, crushed, re-wetted and compacted, while the field calibration simply needs laboratory-obtained moisture contents for each of the core samples. Since the gauge-derived reading for the field calibration process is obtained from the actual location where moisture measurements are to be made, it has the advantage that the density of the soil used for calibration purposes is the same as the density of the soil on which the subsequent moisture measurement is to be taken. It is problematic to re-compact the excavated soil to the field density since it has to be compacted around the PVC pipe in the 20 liter plastic container. However, one of the great advantages of excavating the soil and re-compacting it in the laboratory is the wide range of moisture contents that can be used for the re-compacted soil. It was found that field moisture contents seldom vary enough within a localized area to obtain a wide enough range of moisture contents and corresponding gauge readings to fit a reasonable curve. A calibration performed over a wide range of moisture contents facilitates a more accurate calibration curve.

The advantages and disadvantages of the field and laboratory calibration procedures are summarized in Table 4.

Table 4. The Advantages and Disadvantages of the Laboratory and Field Calibration Procedures.

Measurement	Field	Laboratory
Time	Advantage	Disadvantage
Density	Advantage	Disadvantage
Moisture Range	Disadvantage	Advantage
Accuracy	Disadvantage	Advantage

CHAPTER 4
PERFORMANCE OF BARRIER ALONG IH 45

OBJECTIVE OF PROJECT

The objective of this project was to evaluate for effectiveness the moisture barrier installed on Interstate 45 by performing long-term monitoring of moisture variations both inside and outside the barrier. To be effective, the barrier must stabilize the moisture content of the soils inside the barrier and thereby minimize the damage caused by their shrinking and swelling. To perform the evaluation TTI instrumented four test locations along the highway. Two additional sites were installed the last year of the project. Neither site contains any physical moisture barrier. One site, at RM 263.2, is a control site, constructed with the same materials as used at locations where the moisture barrier is. The other site, a "select material" site at RM 254.4, was constructed with select materials for optimal performance. Moisture measurements were taken at regular intervals on both sides of the barrier to a depth of 2.5 m (8.2 ft). In this chapter, the moisture measurements obtained from both the inside and outside of the vertical moisture barrier will be discussed.

DESCRIPTION OF TEST LOCATIONS

The material underlying the pavement is a grayish, brown, and tan colored mixed clay with calcarious and limestone deposits. No seepage was encountered during drilling. This indicates that the groundwater table is below the maximum depth of drilling, which was approximately 3.5 m (11.5 ft).

The pavement was initially constituted of 250 mm (10 in) thick concrete main lanes with an asphalt shoulder. The initial jointed concrete pavement had exhibited typical roughness wavelengths associated with expansive clay. The pavement was scheduled for widening and a concrete overlay. An initial geotechnical investigation recommended replacing 1.5 m (4.9 ft) of the subgrade soil under the widened section to minimize the damage from the expansive clay subgrade. In lieu of this recommendation, the district opted for a vertical moisture barrier, which had been reported to have performed well in other districts in Texas, most noticeably in San Antonio. A moisture barrier was installed next to the new asphalt shoulder. In order to evaluate the effectiveness of the moisture barrier, access tubes were installed at four locations on the inside and outside of the moisture barrier. During August 1993, a new 330 mm (13 in) thick concrete overlay was subsequently added on top of the existing concrete lanes and asphalt shoulder. Access tubes were re-installed at the same locations along the highway. The locations of the original four test sites along IH 45 are shown in Figure 9. Figure 10 shows a detailed location of each test site, including the two sites added in 1997, according to reference markers. A cross section of the pavement after the new overlay is shown in Figure 11.

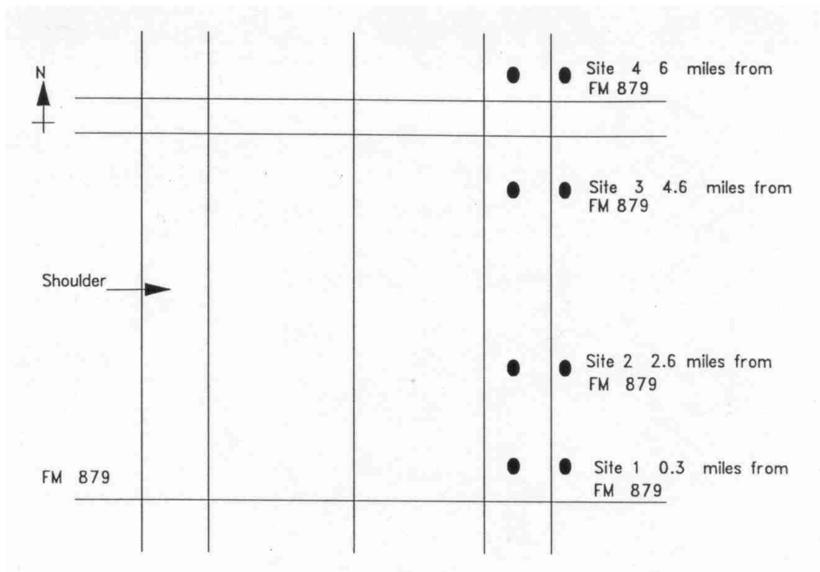


Figure 9. Location of Access Tubes Along IH 45, Near Palmer, Texas.

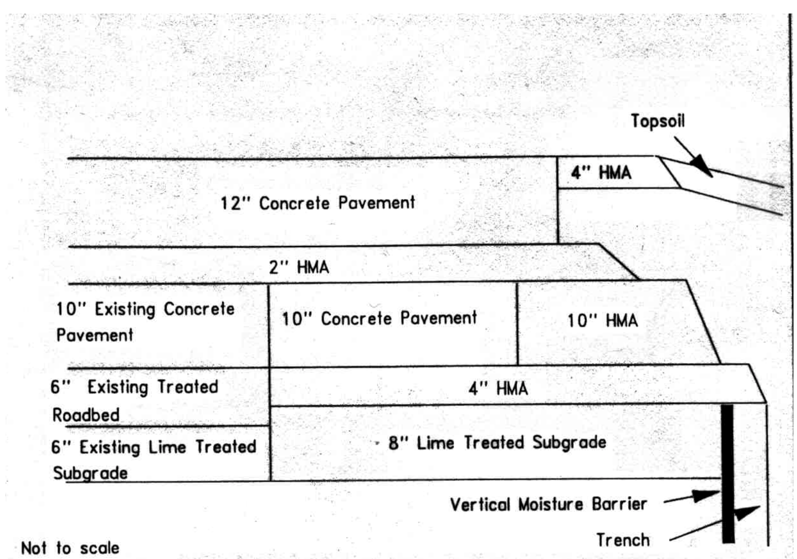


Figure 10. Typical Completed Cross-Section of Pavement with Barrier Installed.

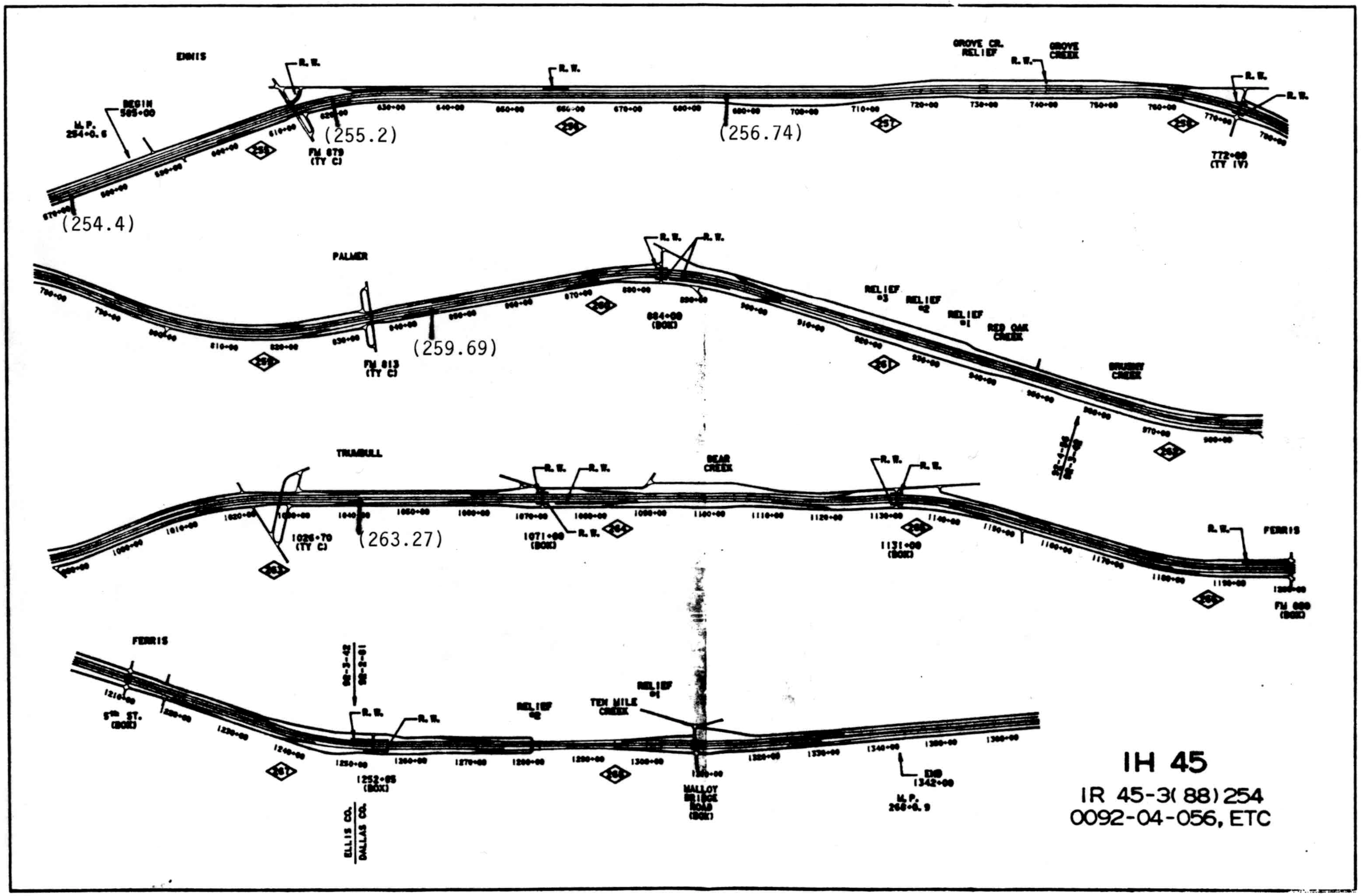


Figure 11. Locations of Texas Sites.

DIFFICULTIES REPORTED DURING CONSTRUCTION

The following problems were encountered during the construction of the vertical moisture barrier:

1) The installation of the barrier was performed by cutting a 250 mm (10 in) wide trench with a trenching machine to a depth of 2.5 m (8.2 ft). The moisture barrier which consists of a thick block of polypropylene fabric, was placed against the inside wall of the trench. The trench was then backfilled with sand and sealed at the surface. The district expressed the following concerns:
   a) The density of the backfilled material was low due to the inability to achieve adequate compaction. The backfill material was changed several times until a material which "self compacted" during the backfilling operation was found. Whichever material is used will be problematic because it is difficult to apply any compaction in such a narrow trench.
   b) Because of the low-density, high-permeability backfill, it was thought that moisture would be trapped in the trench on the outside of the barrier.
   c) It was unclear whether this construction technique could be used on flexible pavements as it could cause the highway to crack and possibly collapse into the trench.
2) Before the final overlay was placed, the widened pavement consisted of three concrete mainlanes with an asphalt shoulder (See Figure 10). The barrier was installed beneath the asphalt shoulder. The bond between the concrete-asphalt interface was such that it allowed the infiltration of surface moisture. This moisture would be trapped on the inside of the barrier. Figure 12 shows water accumulating at the concrete/asphalt interface.

Vertical Moisture Barrier near Palmer, Texas. Barrier installed at edge of asphalt shoulder 8 foot deep. Moisture seeping from concrete/asphalt joint.

Figure 12. Water Accumulating on the Concrete-Asphalt Interface.

3) The primary function of the moisture barrier is to keep water from seeping into the low-permeability clay soil underneath the pavement. However, at the northern end of the project, a sand seam was encountered. Several test holes were drilled through the concrete and it was clear that water that would otherwise have easily drained from the high-permeability soil was getting trapped inside the barrier. It was recommended that the barrier be removed at this location.

MEASUREMENTS WITH SENTRY 200-AP DEVICE

Moisture measurements were taken with the Sentry 200-AP immediately after installation of the access tubes in August 1993, and again in November 1993, May 1994, June 1995, March 1996, June 1996, July 1996, March 1997, May 1997, July 1997, September 1997, December 1997, March 1998, and July 1998. It should be noted that all the access tubes extend to a depth of 3.5 m (10 ft) except at location 2. At this location the depth of the hole was limited to 2.5 m (8 ft) due to researchers having encountered a stiff layer during drilling, probably a large boulder.

PRESENTATION AND DISCUSSION OF RESULTS

With moisture data collected over several years for the six test sites used in evaluating the vertical moisture barrier on IH 45 near Palmer, Texas, it is possible to examine the data for long term trends. Of key significance is the fact that the moisture content of the soil inside the moisture barrier appears to have remained consistently low to a depth of between 762 and 1016 mm (30 and 40 in). At this depth the moisture content inside the barrier approaches that of the soil outside the barrier. Overall, the moisture barriers appear to be effective in stabilizing soil moisture beneath the road as compared to moisture variability outside the barrier. Some notable trends from the data taken are:

- At comparable depths, moisture variability inside the barrier was less than that outside the barrier 72 percent of the time.
- With the exception of RM 254.4, moisture variability inside the barrier generally decreased with depth.
- In general, moisture levels measured in the soil parallel the average monthly rainfall trends. However, moisture levels inside the barrier are effected less by changes in rainfall amounts than moisture levels outside the barrier.

- Drastic changes from "normal" weather patterns can cause significant changes in moisture inside the barrier, but the long-term variability is still generally less than that outside the barrier.

A. Evaluation Methods

The performance of the vertical moisture barrier is best evaluated by determining if soil moisture inside the barrier varies less than the moisture outside the barrier, as the purpose of the barrier is to stabilize moisture levels underneath the road. In other words, the moisture barrier needs to maintain relatively constant moisture levels at each depth in the soil profile below the pavement, especially in the crucial zone of approximately 0 to 1,016 mm (0 to 40 in) of depth. If over time the benefits of the barrier are lost, then its performance is not acceptable.

In order to evaluate the barrier's performance, volumetric moisture contents at selected depths throughout the soil profile were taken both inside and outside the barrier from 1996 to 1998 at each site. Moisture measurements were taken with the Sentry 200-AP by using the laboratory calibration factor for clay soils. Three evaluation methods were used in this analysis:

1. Graphical analysis: The moisture data was graphed for each site in order to make inferences about the variability of soil moisture inside the moisture barrier relative to that outside the barrier. If the moisture readings taken inside the barrier were more similar over time than the readings taken outside the barrier, the moisture barrier was judged to be effective.
2. Statistical analysis: Besides a graphical evaluation of the data, a statistical analysis was also performed to determine if moisture levels were less variable inside the moisture barrier. The standard deviation of moisture readings at each depth was determined for moisture contents both inside and outside the barrier. By comparing the standard deviation of moisture readings inside the barrier to those outside the barrier, it was determined statistically if, and how many times, the barrier was effective at reducing soil moisture variability.
3. Laboratory analysis: The final evaluation method in determining if the moisture barrier was effective was to verify results from the field with a laboratory determination of soil moisture levels both inside and outside the barrier at determined depths. If, for each

comparable depth, the moisture level inside the barrier varied less than that outside the barrier, the moisture barrier was deemed effective. However, the laboratory analysis determines the moisture content on a mass basis, while the field measurements are determined on a volumetric basis. Because of this, it is necessary to show that the mass basis measurements are valid decision criteria when field measurements were made on a volumetric basis. More importantly, it must be determined that trends over time are similar for both the mass and volumetric basis soil moisture contents.

In order to determine a relationship between the mass and volumetric basis soil moisture contents, one must first understand a few fundamentals involved in such soil calculations. These necessary relationships are given below:

- Mass basis soil moisture = Mass of water (g) / Mass of dry soil (g)
- Volume basis soil moisture = Volume of water (cc) / Bulk volume of soil (cc)
- Soil bulk density = Mass of dry soil (g) / Bulk volume of soil (cc)

Recalling that the density of water is 1 g/cc, the volume of water has the same numerical value as the mass of water as determined by a soil test. Thus, if the soil sample being tested is of a known volume, the volumetric moisture content is:

(Mass of water (g) * 1 cc water/g water) / Bulk volume of soil (cc)

Sometimes the soil sample may not be of a known volume. In these circumstances, it is necessary to know the soil's bulk density in order to convert the mass basis moisture content to a volumetric basis:

$$\text{Volume Basis Moisture Content} = \text{Mass Basis Moisture Content} \quad \frac{\text{Soil Bulk Density}}{\text{Density of Water}}$$

With these fundamentals in mind, it is now possible to move on to the establishment of a relationship between the mass basis and volumetric basis soil moisture content.

A. The Relationship Between Mass Basis and Volumetric Basis Water Content.

The simplest way to determine the relationship between mass and volumetric basis soil moisture content is to use hypothesized values for soil bulk density and the mass basis soil moisture content. Then determine the corresponding volumetric basis soil moisture content by the method given above. An important assumption in this analysis is that a constant soil bulk density of 3 g/cc was used in each calculation. The results of the analysis are in Table 5.

Table 5. Hypothetical Data Used in The Determination of the Relationship Between Mass Basis and Volumetric Basis Soil Moisture Content.

Mass Basis Soil Moisture Content (%)	Soil Bulk Density	Volumetric Basis Soil Moisture Content (%)	Ratio of Mass Basis to Volumetric Basis Soil Moisture Content
7.5	3 g/cc	22.5	1/3
15	3 g/cc	45	1/3
21.5	3 g/cc	64.5	1/3
23	3 g/cc	69	1/3
25	3 g/cc	75	1/3

It is easy to see that there is a direct relationship between the mass basis and volumetric basis soil moisture content. The exact factor is a function of the soil bulk density, which in this instance gives a ratio of 1 to 3. The principle, however, remains the same for any soil bulk density so long as that value remains constant:

$$\frac{\text{Mass Basis Soil Moisture Content 1}}{\text{Volumetric Basis Soil Moisture Content 1}} = \frac{\text{Mass Basis Soil Moisture Content 2}}{\text{Volumetric Basis Soil Moisture Content 2}}$$

This positive relationship between mass and volumetric basis soil moisture content can be graphically illustrated, as shown in Figure 13.

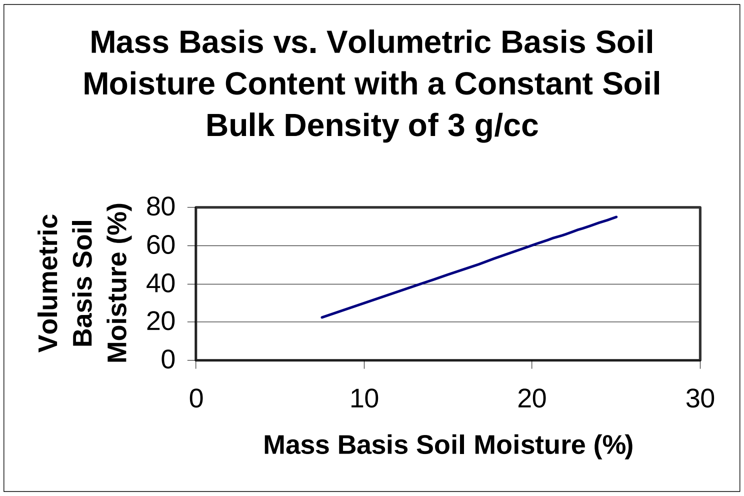


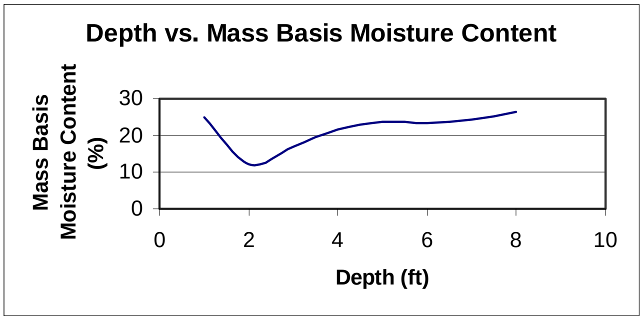
Figure 13. Graph of Mass Basis vs. Volumetric Basis Soil Moisture.

B. Comparing Mass and Volumetric Basis Soil Moisture.

Now that the relationship between the two methods of measuring soil moisture has been determined, it is important to determine if trends of the moisture curves for a given soil are comparable between the two methods. For example, if one wants to determine soil moisture at various depths in a soil, will the data look different depending on which moisture-measuring method is used? This is what we will examine next. In this instance, the mass basis soil moisture is from an actual soil test. However, the soil bulk density was not known, nor was the volume of the samples obtained, so a soil bulk density of 3 g/cc was again assumed throughout the soil profile. The data used in this analysis is given in Table 6 and appears graphically in Figure 14.

Table 6. Data Used in a Graphical Comparison of Depth vs. Moisture Content for Mass Basis and Volumetric Basis Soil Moisture Content.

Depth (feet)	Mass Basis Soil Moisture Content (%)	Volumetric Basis Soil Moisture Content (%)
1	24.97	74.91
2	12.18	36.54
3	16.88	50.64
4	21.65	64.95
5	23.70	71.10
6	23.33	69.99
7	24.30	72.90
8	26.45	79.35



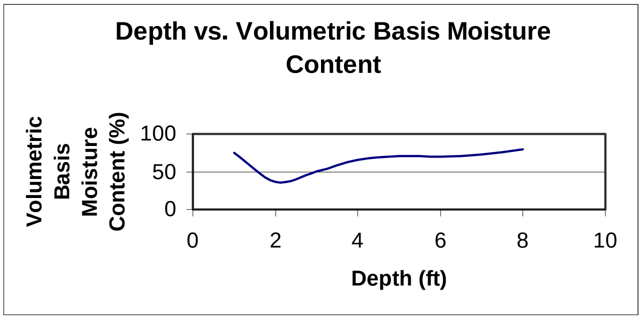


Figure 14. Comparison of Depth vs. Moisture Content for Mass and Volumetric Basis Soil Moisture Measuring Methods.

It is clear to see that the trends followed by the mass basis and volume basis moisture content are the same, so it is possible to look at trends in moisture contents between the two methods and compare them. It is important to realize, however, that the numerical magnitude of changes in moisture content will be greater for the volumetric basis moisture method. If the graphs are scaled the same, the volumetric basis measurement would appear to have much larger changes, although the actual change in soil moisture is the same as in the mass basis method, even though the percent change is different. This magnitude factor is a function of the soil's bulk density. This can be illustrated by putting both mass and volumetric basis data onto one graph, as in Figure 15. In this instance, the volumetric basis moisture content has a numerical magnitude three times greater than the mass basis moisture content as a result of the soil bulk density of 3 g/cc.

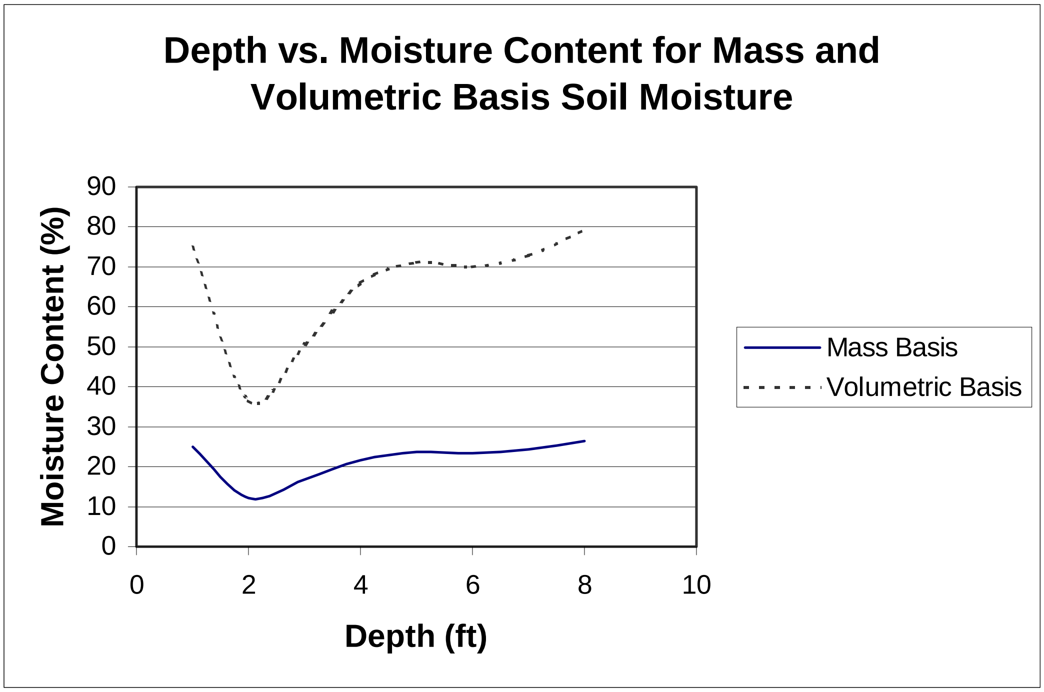


Figure 15. A Graphical Comparison of Mass and Volumetric Basis Soil Moisture Contents When Scaled the Same.

It is possible to compare trends between mass basis and volumetric basis soil moisture readings. However, one must realize that, if graphed on equivalent scales, the volumetric basis measurements will appear to have a much greater change in moisture. If the volumetric moisture percent is scaled down by a factor of the soil's bulk density, the graphs will appear the same. The important concept is that the same measuring methods can be used for data sets being compared. In the case of the laboratory moisture measurements, mass basis moisture readings will be made for all samples to make the comparison valid.

C. Graphical Evaluation of Soil Moisture Trends

By graphically examining the moisture contents through the soil profiles at the six test sites from 1996 to 1998, the moisture barrier appears to be performing consistently at all four sites. Most importantly in the evaluation, the variability in moisture levels inside the barrier appears to be less than the moisture variability outside the barrier. This can be seen in Figures

16, 17, 18, 19, 20 and 21 (following six pages), which graphically show all data obtained from 1996 through 1998. Since the main concern is the comparison of moisture levels inside the barrier to those outside the barrier, and because of the numerous data sets, moisture levels inside the barrier are all displayed as solid lines and readings outside the moisture barrier are displayed as dotted lines.

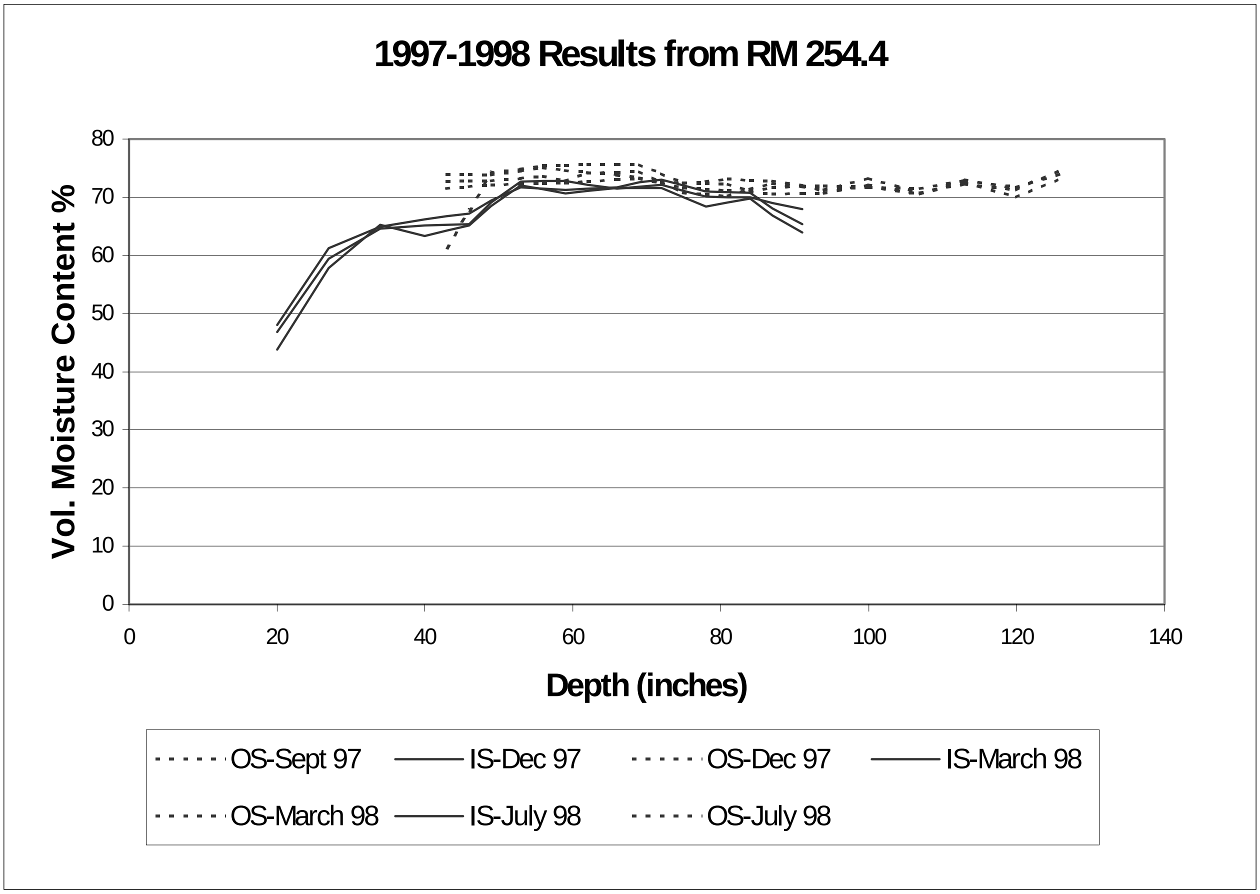
At Reference Marker (RM) 254.4, where the select material was used, moisture variability also appears to be small. At RM 263.2, the control site, moisture levels beneath the pavement clearly fluctuate substantially. The moisture readings taken at each reference marker from 1996 to 1998 are in Appendix A.

D. Statistical Test of Soil Moisture Variability

1. Statistical Evaluation with All Data:

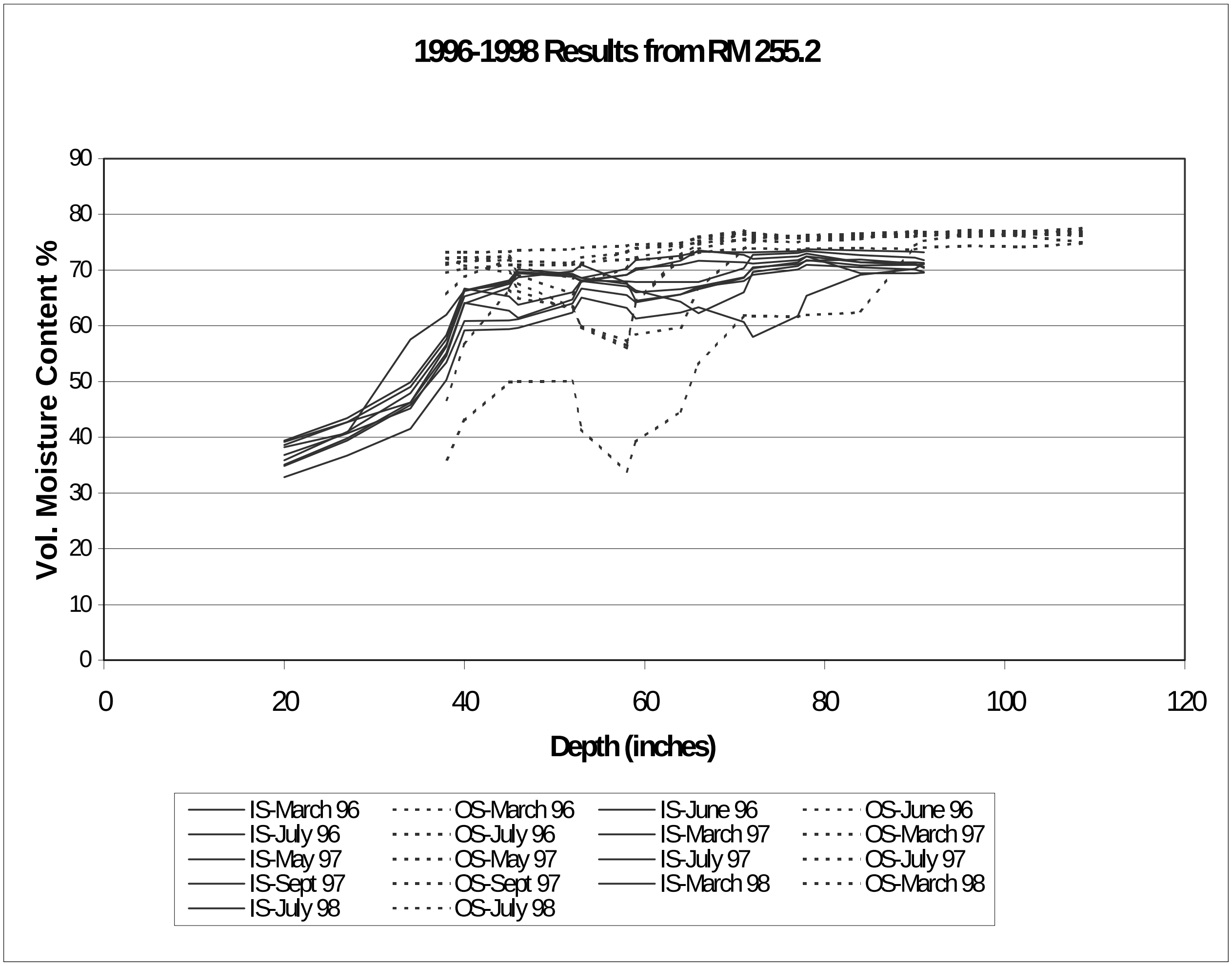
Instead of relying solely on a graph of data to evaluate the moisture barrier, it is more appropriate to statistically test the variability of readings inside the moisture barrier and to compare them to the moisture variability outside the barrier. By determining the standard deviation of all readings taken at each depth, it is possible to determine if the moisture barrier is actually maintaining more stable soil moisture levels. In 18 out of 25 comparable moisture readings, the moisture levels inside the moisture barrier had less variance, and thus a smaller standard deviation (72 percent of the time). This is reassuring evidence of the effectiveness of the moisture barrier. At RM 254.4, where no physical barrier was installed but select material was used, moisture varied less beneath the pavement in six out of eight times, or 75 percent of the time. At RM 263.2, the control site with no barrier, moisture varied less beneath the pavement in three out of eight times, or 38 percent of the time.

Tables 7 and 8 present the first two statistically comparable results for each site. A complete statistical evaluation is in Appendix B.



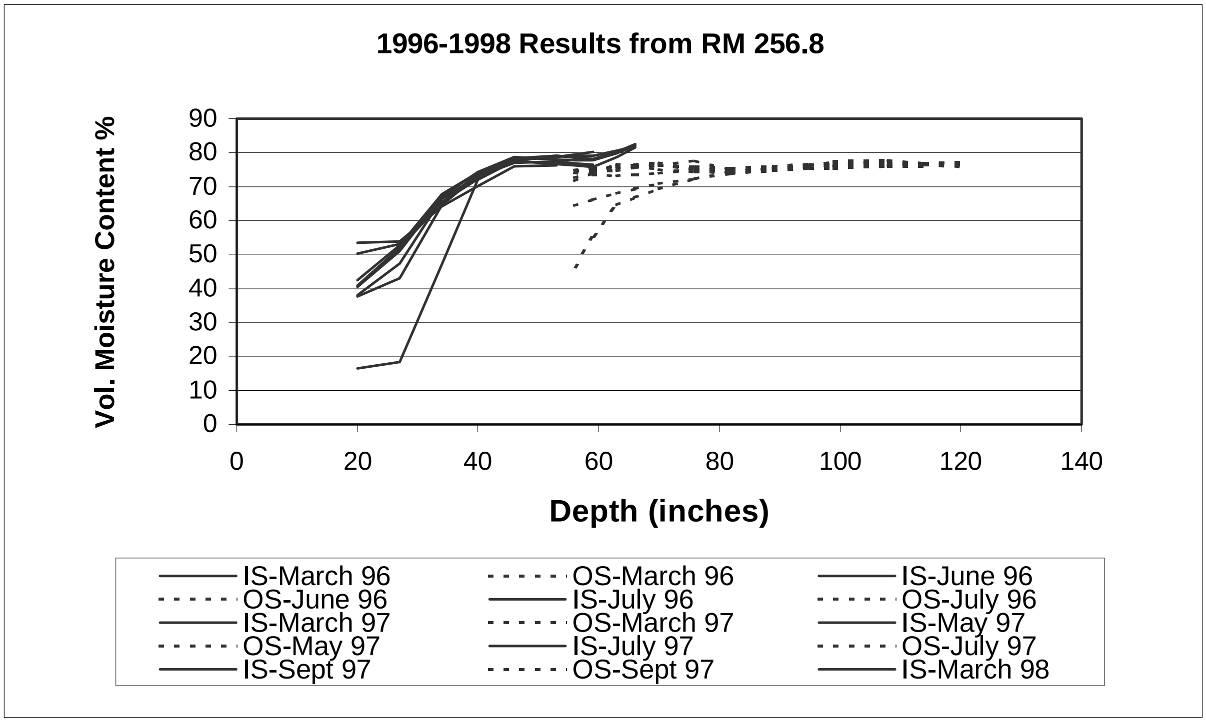
Note: Adjusted for grade separation

Figure 16. Graph of Reference Marker 254.4.



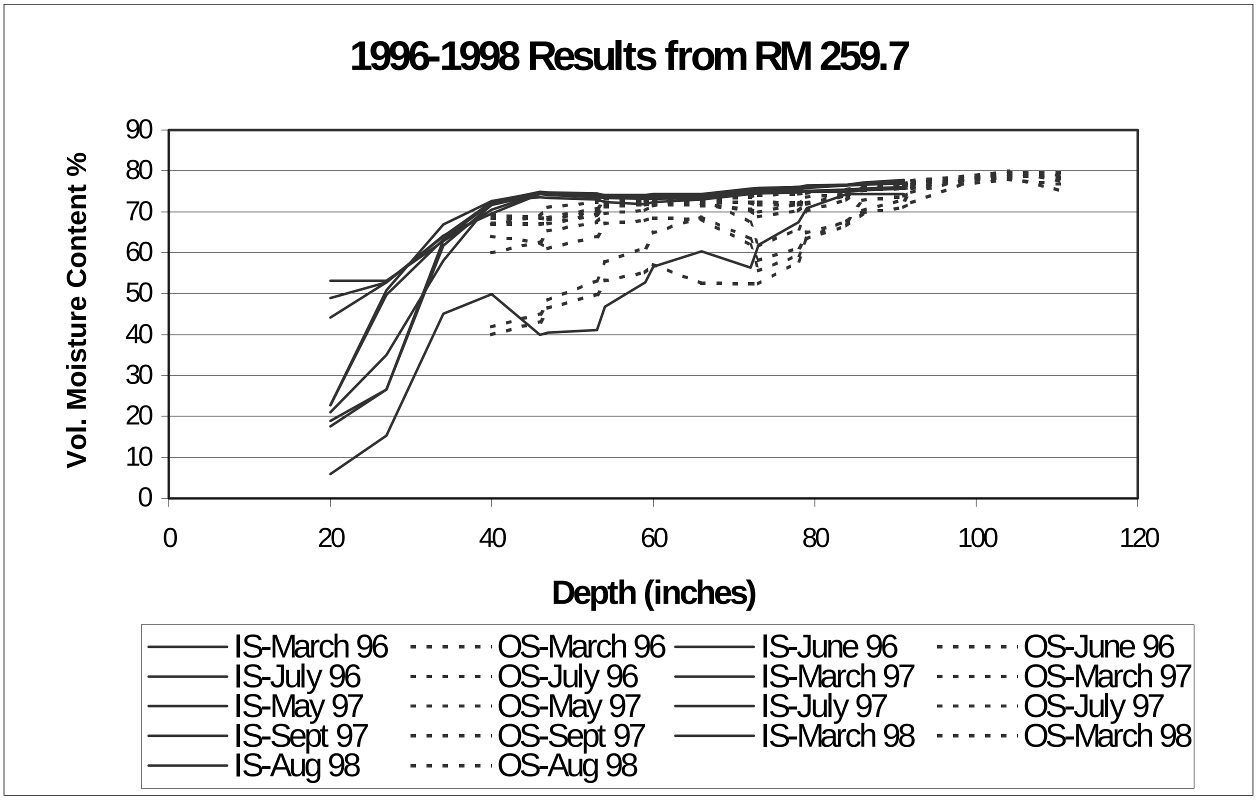
Note: Adjusted for grade separation

Figure 17. Graph of Reference Marker 255.2.



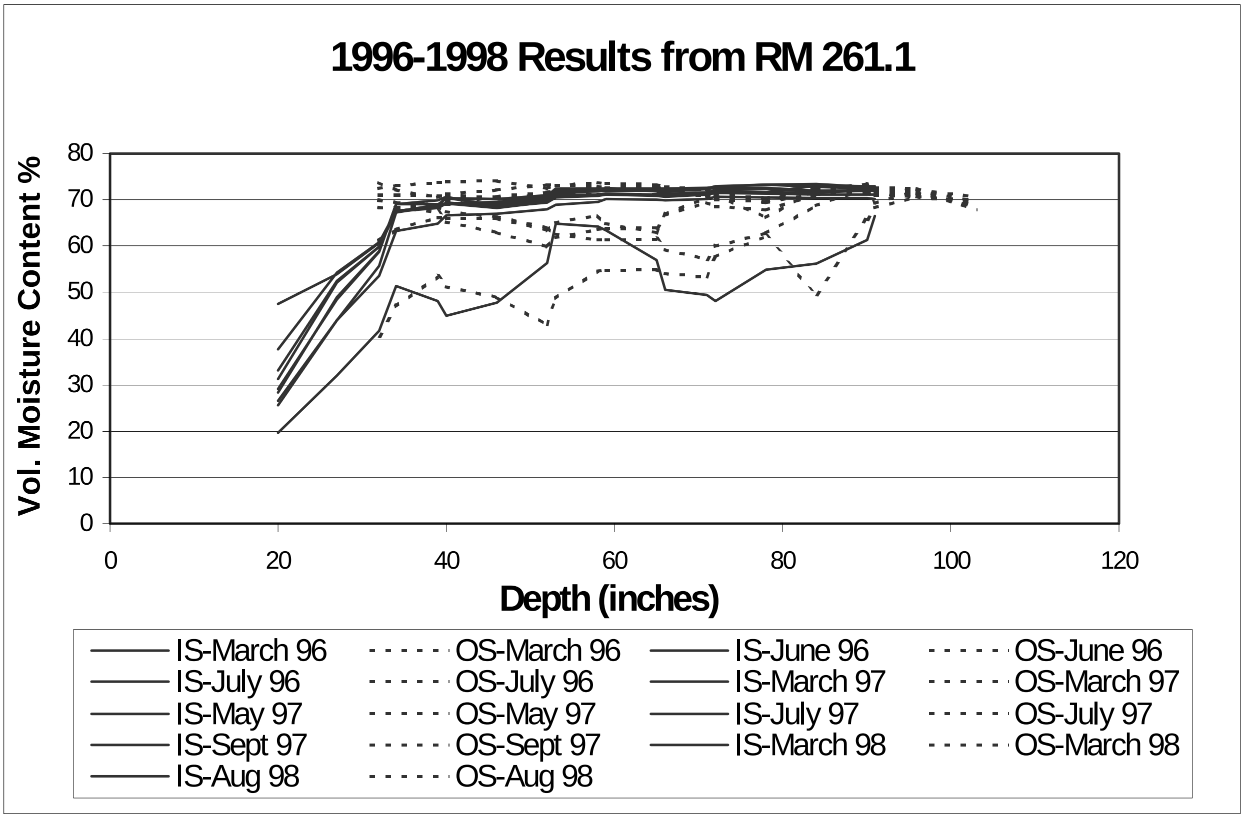
Note: Adjusted for grade separation

Figure 18. Graph of Reference Marker 256.8.



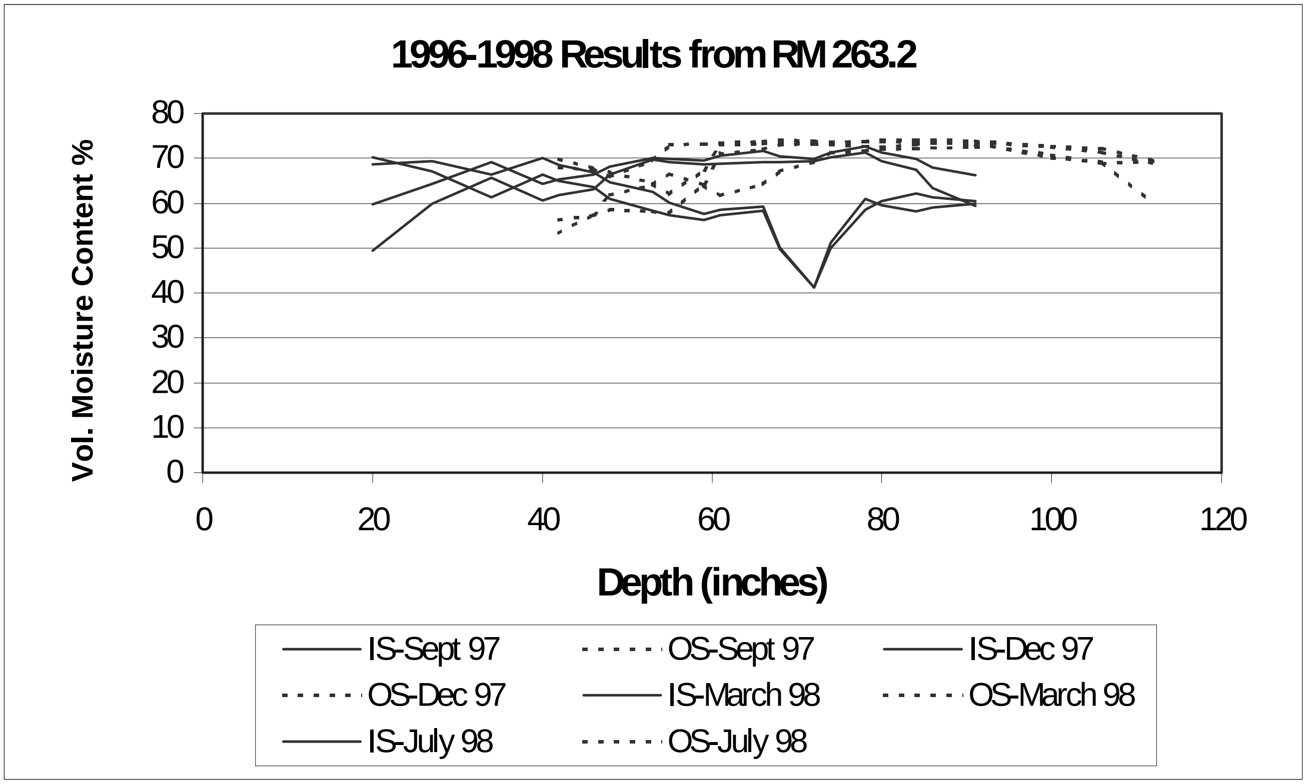
Note: Adjusted for grade separation

Figure 19. Graph of Reference Marker 259.7



Note: Adjusted for grade separation

Figure 20. Graph of Reference Marker 261.1.



Note: Adjusted for grade separation

Figure 21. Graph of Reference Marker 263.2.

Table 7. Selected Results from Statistical Comparisons of Soil Moisture Variability, 1996-1998.

Location	Depth (inches)	Standard Deviation of Moisture Readings, 1996-1998
RM 255.2 inside barrier	40	2.647
RM 255.2 outside barrier	38	13.368
RM 255.2 inside barrier	46	4.374
RM 255.2 outside barrier	45	7.282
RM 256.8 inside barrier	53	1.160
RM 256.8 outside barrier	56	10.358
RM 256.8 inside barrier	59	1.501
RM 256.8 outside barrier	63	4.610
RM 259.7 inside barrier	40	7.364
RM 259.7 outside barrier	40	11.432
RM 259.7 inside barrier	46	11.502
RM 259.7 outside barrier	47	9.016
RM 261.1 inside barrier	34	5.597
RM 261.1 outside barrier	32	10.149
RM 261.1 inside barrier	40	8.232
RM 261.1 outside barrier	39	5.756

Table 8. Selected Results from Statistical Comparisons of Soil Moisture Variability, 1997-1998.

Location	Depth (inches)	Standard Deviation of Moisture Readings, 1997-1998
RM 254.4 inside pavement	40	1.411
RM 254.4 outside pavement	43	5.784
RM 254.4 inside pavement	46	1.136
RM 254.4 outside pavement	49	.954
RM 263.2 inside pavement	40	3.941
RM 263.2 outside pavement	42	8.322
RM 263.2 inside pavement	46	1.936
RM 263.2 outside pavement	48	3.873

2. Statistical Evaluation with Trimmed Data:

When doing a statistical evaluation of data, more accurate results may be obtained by "trimming" off the data set that is most distant from the mean. By examining the data obtained in the test of the vertical moisture barrier, it is clear that September 1997 data is the most distant data set from the mean. For almost all cases, this particular data set had higher than normal variability and started off at much lower than typical moisture contents. This is most likely because of the drought-like conditions that existed at the time, as evidenced by vegetation at the test sites which showed signs of being permanently wilted. Another factor that could have affected the soil moisture is groundwater levels. However, no data on this is available, so it is impossible to determine exactly what caused the strange characteristics of soil moisture in September 1997.

Because September 1997 seems to have been an exception to what the normal trends in soil moisture have been, both inside and outside the barrier, a separate statistical analysis was done on the data without the September 1997 data set. Some significant differences in soil moisture standard deviations resulting from that analysis are given in Table 9. Generally, considering September 1997 data as non-typical, and thus not representative of what most moisture readings will be like, leads to a decrease in standard deviations both inside and outside the barrier. However, it also shows that under normal circumstances, the moisture barrier has an even higher rate of effectiveness in eliminating moisture variability. With September 1997 data, the standard deviations of moisture readings were less inside the barrier 72 percent of the time. Without September 1997 data, this goes up to 84 percent. The results of this separate analysis at each site will be discussed further in the site specific evaluations. A complete statistical data analysis with September 1997 omitted can be seen in Appendix C.

Table 9. Significant Changes in Standard Deviations of Soil Moisture Readings by Eliminating September 1997 Data.

Location	Depth (inches)	Standard Deviation with September 1997	Standard Deviation without September 1997
RM 255.2	38	13.37	8.79
RM 255.2	45	7.28	2.25
RM 256.8	20	11.05	6.13
RM 256.8	27	11.92	3.89
RM 256.8	34	6.73	1.34
RM 259.7	20	16.22	14.85
RM 259.7	40	7.36	1.16

E. The Relationship Between Rainfall Trends and Soil Moisture Contents

Another aspect investigated in the evaluation of the vertical moisture barrier was the effect of rainfall trends on the moisture content of the soil. In order to determine if there was a relationship between rainfall amounts and soil moisture, monthly rainfall amounts for Ennis, Texas (the nearest town to the test sites with rainfall data) were obtained from 1988 through September 1998. By graphically examining trends of monthly rainfall relative to trends in soil moisture, it is possible to see the effects of rainfall on the soil moisture contents. In order to do this, a bar graph was made for each site and year containing both monthly rainfall amounts and the soil moisture contents at one specific depth both inside and outside the moisture barrier. Each moisture content value was scaled down by a factor of 10 to put the moisture contents and rainfall amounts on a closer numerical scale and thus make interpretation of the data easier.

Figure 22 shows the way each site was examined for trends between rainfall and soil moisture. The monthly rainfall data for Ennis and the analysis for each site and year used in making inferences about the relationship between rainfall and soil moisture can be found in Appendix D.

When examining all the data, it appears that soil moisture rather closely reflects trends in rainfall. If rainfall amounts increased from one month to the next, soil moisture both inside and outside the moisture barrier usually followed the same pattern. Similarly, if rainfall amounts decreased, soil moisture levels tended to decrease also. It is important to note that moisture levels inside the barrier seemed to be less effected by changes in rainfall amounts than moisture contents outside the barrier.

In some instances, soil moisture changes seemed to "lag" behind the trends in rainfall. This is reasonable because more time is required for moisture to percolate deeper into the soil profile. In addition, data used in the analysis was monthly rainfall totals, and it is entirely possible that most, if not all, of any certain month's rainfall occurred at the end of the month. The important issue is that soil moisture does tend to follow the same trends as rainfall amounts (which logically makes sense), and that changes in rainfall levels from month to month has less impact on moisture levels inside the moisture barrier. This analysis further demonstrates that the vertical moisture barrier is effective at maintaining a more stable soil moisture environment underneath the pavement.

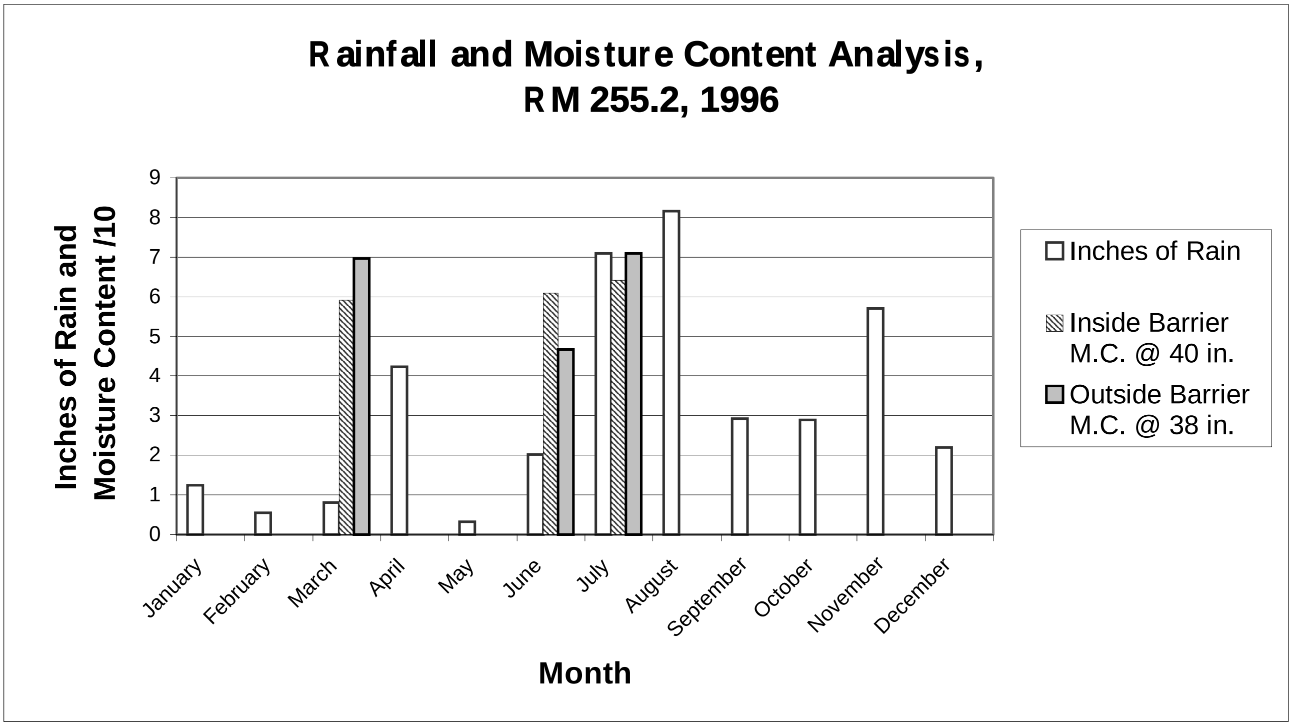


Figure 22. Rainfall and Moisture Content Analysis.

F. Ride Analysis of the Test Sites

A ride analysis was also performed at each test site. Figure 23 shows the data collected. Data was taken from PMIS Data. This data is graphed in Figure 23. At the time of this report no significant information has been obtained regarding the difference between the select field site RM 254.4, the control site at RM 263.2, and the four moisture barrier sites.

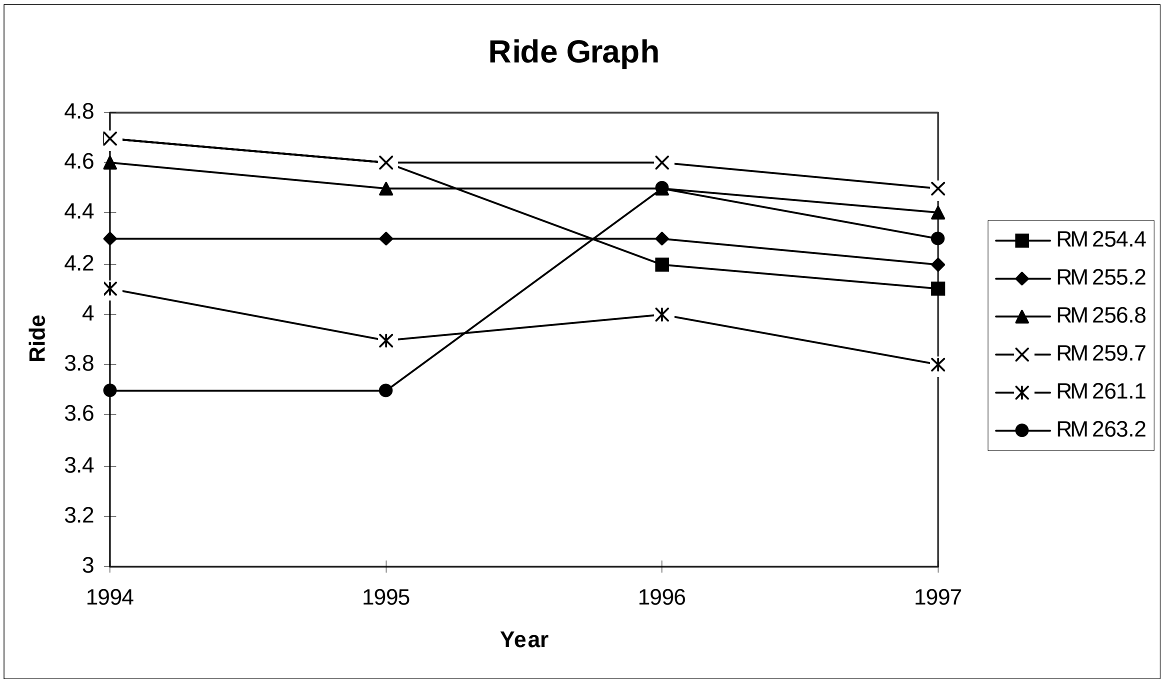


Figure 23. Ride Graph.

SITE SPECIFIC EVALUATIONS

RM 254.4:

1. General Evaluation:

RM 254.4 has no physical moisture barrier but was constructed with select materials. Moisture variability was negligible at RM 254.4 beneath the pavement. The standard deviation of moisture readings was between 0.1 and 2.2, which is negligible. Outside the road the deviations ranged from 0.77 to 5.78. Of eight comparable moisture readings, the moisture variability under the road was less six times out of the eight readings. Because of a lack of traffic control, no moisture readings were taken beneath the pavement in September 1997, and variations outside the barrier remained nearly identical with or without this data set. Figure 24 shows the standard deviation of the moisture readings for this site.

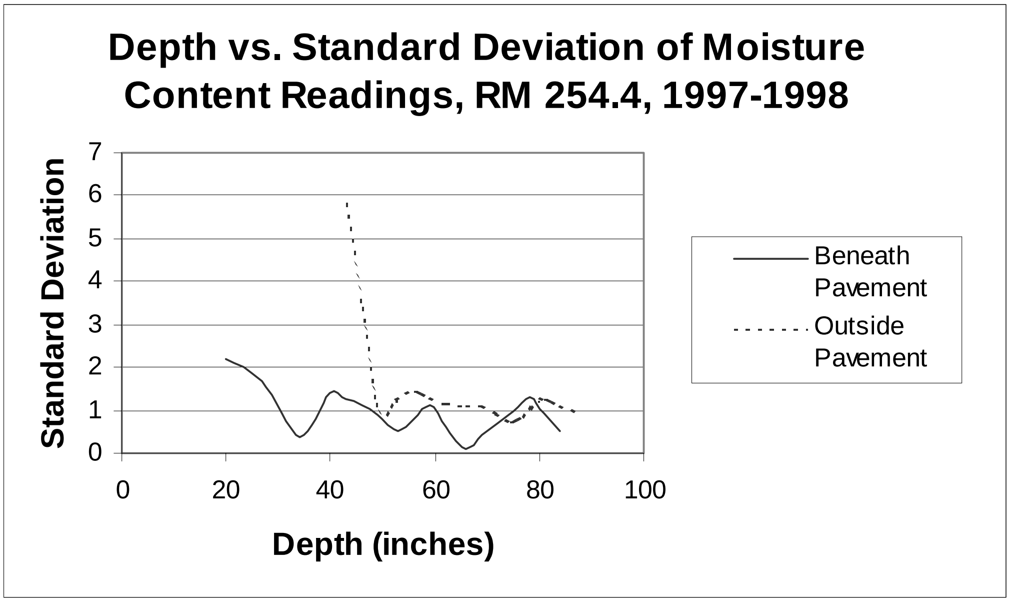


Figure 24. Depth vs. Standard Deviation of Moisture Content.

2. Site Specific Concerns:

RM 254.4 has only four data sets, which could possibly be too few. However, the data was taken over a one-year period and thus should still be fairly representative of moisture trends since there was ample time for changes in soil moisture to take place.

RM 255.2:

1. General Evaluation:

RM 255.2 exhibits the most promising results in that the moisture content inside the barrier remained very similar over time, even when moisture levels outside the barrier were fluctuating. With all data, the standard deviation of moisture readings inside the barrier at this site ranged from 1.432 to 4.577. Outside the barrier, the standard deviations of moisture measurements were between 4.730 and 13.368 and were always higher than the comparable deviations inside the barrier. This lends credibility to the effectiveness of the moisture barrier. From Figure 25, it is clear that the standard deviation, and thus variability, of moisture levels inside the moisture barrier is less than that outside the barrier, meaning the moisture barrier is performing as intended.

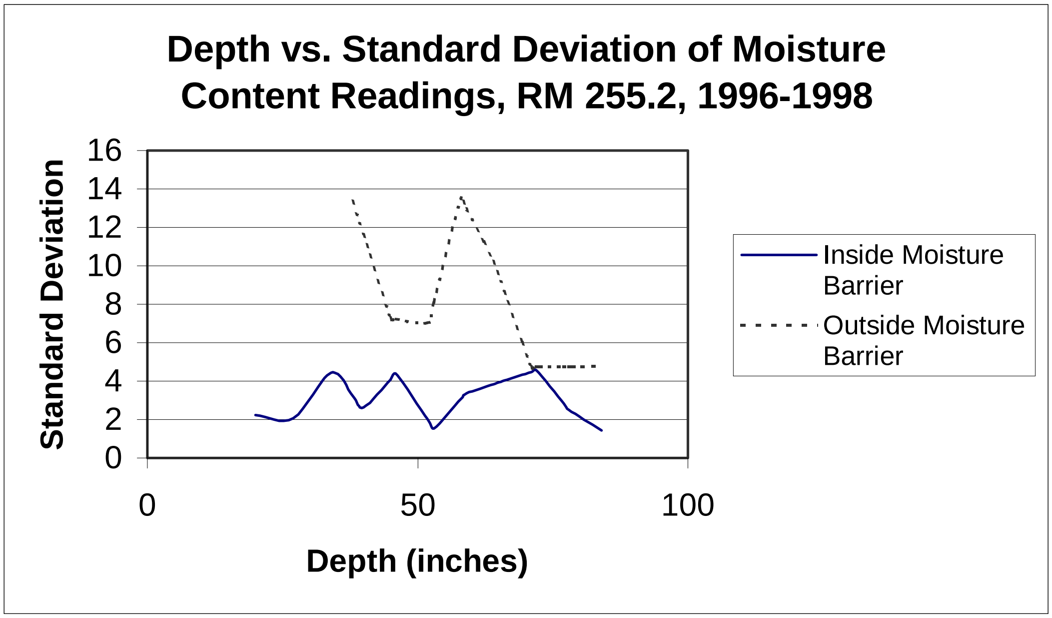


Figure 25. Depth vs. Standard Deviation of Moisture Content.

When September 1997 data is excluded off, the standard deviation of moisture measurements inside the barrier range from 1.406 to 4.66. Outside the barrier they are between 0.855 and 8.79. Without September 1997 data, the moisture levels inside the barrier were more stable than those outside the barrier up to a depth of 72 inches. Since the moisture barrier is still reducing moisture level variability in the critical area of the soil profile, its performance is still acceptable. Another observation is that soil moisture variability inside the barrier remained virtually the same both with and without September 1997 data. This substantiates even further the fact that the barrier is consistent in its performance, especially since eliminating that particular data set caused significant changes in moisture variability outside the barrier.

2. Site Specific Concerns:

As mentioned earlier, September 1997 readings for all sites seem to be non-typical in relation to other readings. RM 255.2 for September 1997 outside the barrier shows a significant change in soil moisture content within small depth changes that one may think are erroneous readings. For example, soil moisture increases 13.8 percent from 38” to 45”, decreases 16.3

percent from 52” to 58”, increases 10.8 percent from 58” to 64” and increases 17.3 percent from 64” to 71”.

Some possible reasons for these characteristics are:

- Differences in soil textures resulting in water not percolating further until the layer above reaches saturation. This could be the cause for the rapid decrease in soil moisture.
- Percolation occurring through the soil profile.
- Abnormal weather conditions. Combined with the possibility of a difference in soil textures and the possibility of a rare percolation event occurring, this factor most likely accounts for the readings obtained.
- The possibility that the drying of soil could have created air gaps between the soil and PVC at that depth, causing erroneous moisture readings.

When examining other sites, there are several instances of a large percent moisture change in a small depth interval:

- OS June 96 RM 255.2 from 58 to 64”, change of 16.3 percent
- OS May 97 RM 255.2 from 58 to 64”, change of 16.1 percent
- OS June 96 RM 256.8 from 56 to 63”, change of 18.1 percent
- OS July 96 RM 259.7 from 66 to 73”, change of 11.8 percent
- OS June 96 RM 261.1 from 52 to 58”, change of 8.9 percent

Because of these other cited instances of rapid soil moisture changes and the possibility of the soil dynamics and weather occurrences mentioned above, the readings for this location are most likely valid. Given the weather conditions, the moisture readings for the other three sites for September 1997 appear reasonable, indicating that the moisture meter was probably functioning and being operated correctly. Only a mistake in the actual data collection process would make the readings invalid. If there were a mistake it would probably be somehow related to the PVC pipe and not the moisture reading instrument.

However, the most probable explanation is that drought-like conditions existed and a rare percolation event was occurring through the soil profile at this site.

RM 256.8:

1. General Evaluation:

The moisture barrier also appears to be performing fairly consistently at RM 256.8, with the exception of September 1997. Excluding this outlier, the moisture levels inside the barrier seem have been maintained fairly well. At the three comparable depths of moisture readings at RM 256.8, the variability of soil moisture was many times less inside the moisture barrier than outside. The standard deviation of moisture measurements inside the barrier at this location ranges from 0.414 to 11.052. Outside the barrier, the standard deviation of moisture readings ranges from 2.859 to 10.358. Figure 26 shows the standard deviation of moisture readings for RM 256.8.

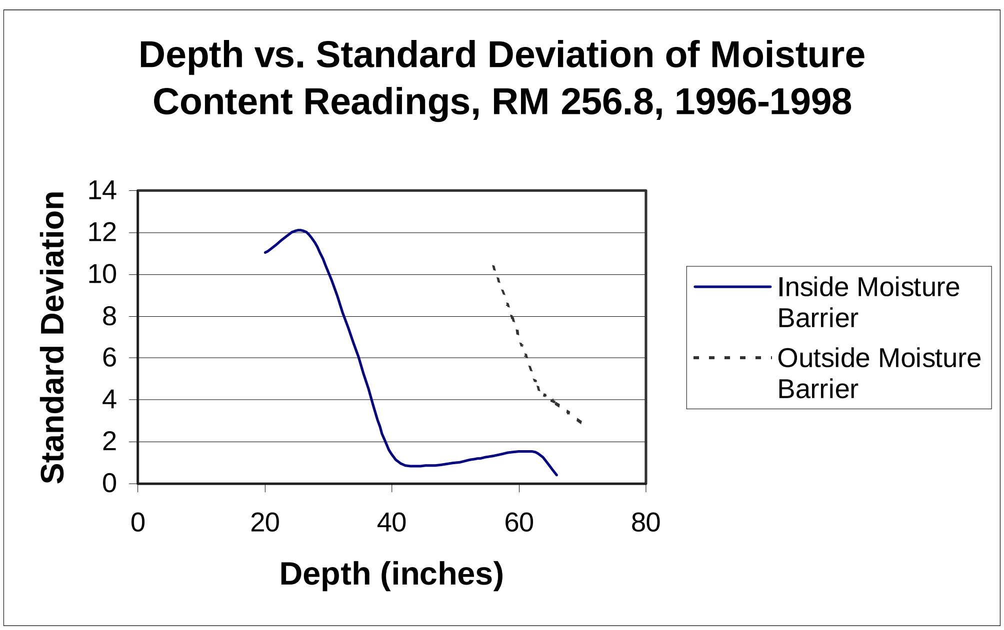


Figure 26. Depth vs. Standard Deviation of Moisture Content.

2. Site Specific Concerns:

It can be seen from the graph above that RM 256.8 exhibits rather large, undesirable standard deviations inside the moisture barrier up through a depth of about 34 in. The principle cause of the large deviations at this site inside the moisture barrier is the September 1997 data. Unfortunately, these large deviations in moisture levels are at the upper part of the soil profile, meaning that moisture content in the most crucial soil area was not consistently maintained during this abnormal weather period. However, as mentioned before, it would be more reasonable to omit this data set as an outlier and regard it as an exception rather than a normal occurrence. If this is done, the standard deviation of moisture measurements for RM 256.8 at depths of 20, 27 and 34 in fall to 6.13, 3.89, and 1.34, from 11.05, 11.92 and 6.73, respectively. For each comparable depth, the variability of soil moisture inside the moisture barrier was less than that outside the barrier both with and without September 1997 data included.

In terms of a long-term evaluation of the moisture barrier, the best approach is to consider the data both with and without this outlier. By doing this, it can be seen that the moisture levels inside the barrier can vary significantly, even in the most important region of soil, if weather patterns differ significantly from the norm for extended periods of time. On a long-term basis, however, it is apparent that moisture levels inside the barrier will be consistent much more often than not. Furthermore, without the non-typical September 1997 data, the standard deviations in the crucial first 40 in of soil depth inside the barrier are still not terribly high (maximum standard deviation of 6.13 percent).

Another problem at RM 256.8 was that the access tube was filled with water, which had to be pumped out before moisture measurements could be made. At this site the pavement cuts through a hill with a sloping embankment at the side of the pavement. This encourages poor drainage conditions and the possible accumulation of excessive moisture in the low-permeability backfill on the outside of the barrier. The surrounding soil at this site is a highly expansive clay and this is a problem area that exhibited sulfate swell problems when first stabilized with lime. The differential expansion at this site could have caused the PVC pipe to distort, crack and allow moisture to infiltrate the access tube.

RM 259.7:

1. General Evaluation:

At RM 259.7, the moisture barrier seems to have eliminated moisture variability at depths over 35 in (again with the exception of September 1997, probably because of a drought). Standard deviations of soil moisture inside the barrier at this site ranged from 2.75 to 16.22. Outside the barrier, the standard deviations of moisture levels were between 4.48 and 11.4. At comparable depths, standard deviations inside the moisture barrier were less four out of seven times, so the barrier was at least somewhat effective at this site. Unfortunately, soil moisture contents varied significantly in the crucial first 40 in of soil depth at this site, so it must be determined what is an acceptable variability in soil moisture. The standard deviations of moisture readings at RM 259.7 are in Figure 27.

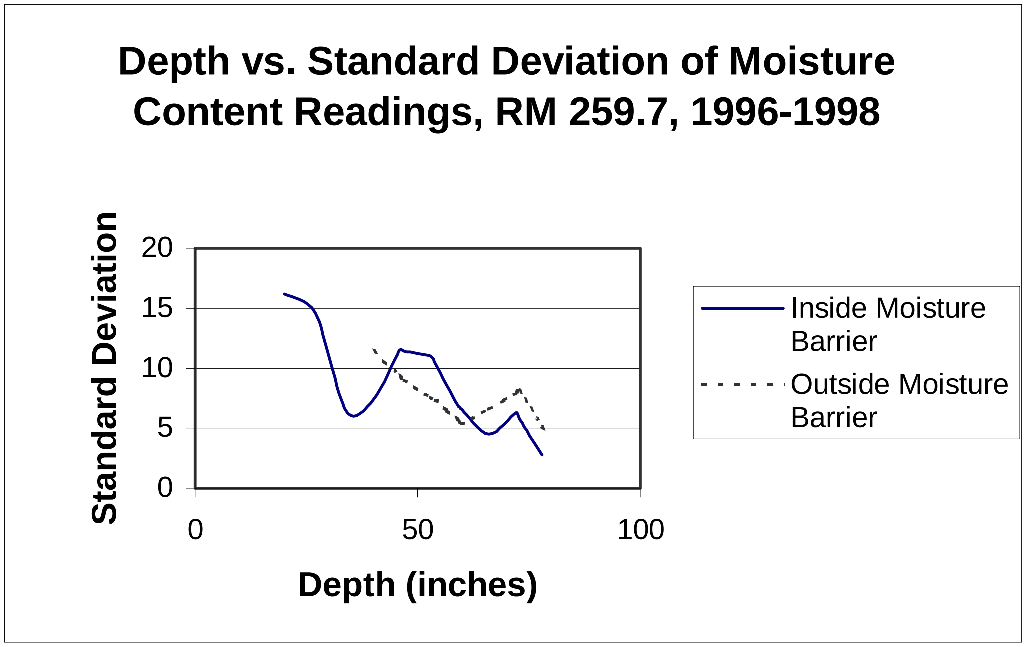


Figure 27. Depth vs. Standard Deviation of Moisture Content.

If September 1997 data is excluded, soil moisture standard deviations inside the barrier are smaller than those outside the barrier for every comparable data set. For depths over 27 in they range from 0.41 to 1.16 inside the barrier, which are negligible changes in moisture. (With September 1997 data the standard deviations inside the barrier are between 2.75 and 11.5 for the same depth range.) This indicates that significant weather variation could cause the soil moisture levels inside the barrier to change quite a bit. Standard deviations outside the barrier range from 1.89 to 9.05 when September 1997 data is omitted. Again, by evaluating barrier performance without this outlier of data, it is clear that in the long run moisture variability is less with the moisture barrier installed.

2. Site Specific Concerns:

A concern that arises from RM 259.7 is that soil moisture standard deviations were over 14 percent for depths of 20 and 27 in. With the exception of RM 255.2 inside the barrier, there was an obvious trend that soil moisture variability decreases with depth (this is probably because the upper part of the soil profile is more susceptible to weather and precipitation factors). However, at RM 259.7 from 0 to 35 in inside the barrier, the soil moisture ranged from 6 percent to 53 percent. Although September 1997 data is a clear outlier for depths over 40 in, there are no obvious outliers in the first 40 in of the soil profile at this site. Even with September 1997's data disregarded, this site still has a standard deviation of 14.85 and 11.96 at depths of 20 and 27 in, respectively. In the case of RM 259.7, it is necessary to determine if the barrier is cost effective when deviations of this magnitude are present.

RM 261.1:

1. General Evaluation:

When all data is considered, the moisture barrier at RM 261.1 only kept soil moisture variability less than the variability outside the barrier on three of seven comparable measurements. Standard deviations of moisture contents ranged from 2.34 to 8.23 inside the barrier and 3.21 to 10.15 outside the barrier. A summary of standard deviations of moisture readings at RM 261.1 is in Figure 28.

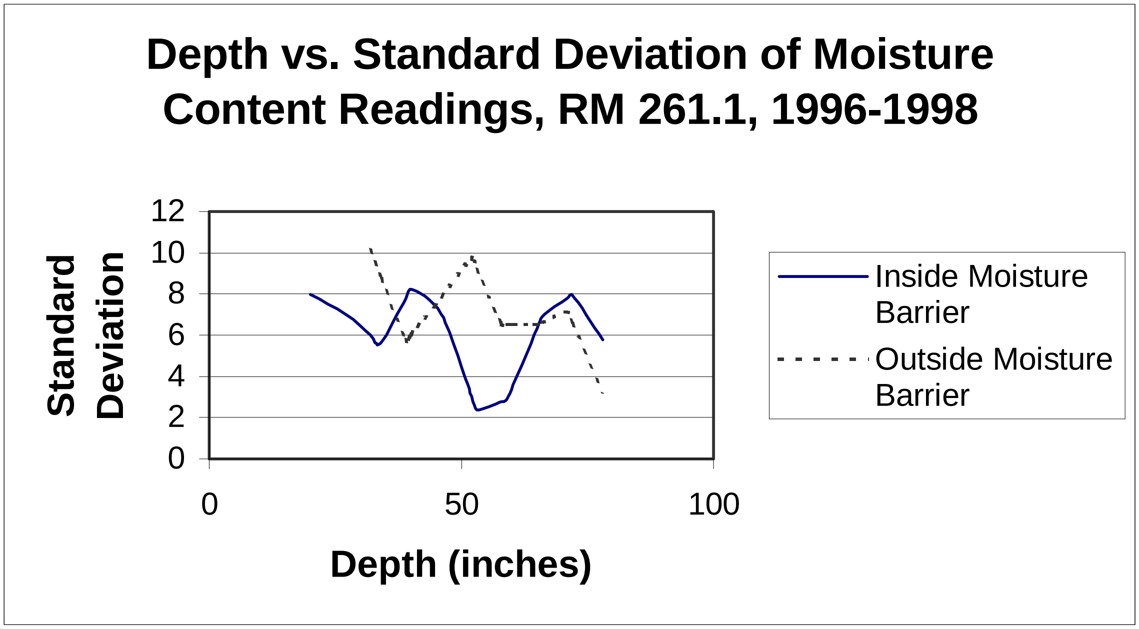


Figure 28. Depth vs. Standard Deviation of Moisture Content.

If September 1997 data is excluded from the evaluation, the moisture level inside the barrier had less variability for every comparable reading. This further reveals that a substantial weather change from the norm can significantly throw off the balance of moisture that the barrier has established. However, since September 1997 data was not typical of normal conditions, it is clear to see that the moisture barrier was quite effective at this site. Without consideration of the outlier, standard deviations inside the barrier were between 0.77 and 7.22, while outside the barrier they ranged from 2.82 to 10.92.

2. Site Specific Concerns:

An observation from RM 261.1 is that by estimating "normal" environmental conditions and eliminating the September 1997 data from the evaluation, the standard deviation of soil moisture beyond 34 in of depth is negligible. Outside the barrier, moisture levels still vary quite a bit, even without September 1997. This observation is also evident at RM 256.8 and RM 259.7, which lends a substantial amount of support to the effectiveness of the moisture barrier.

RM 263.2:

1. General Evaluation:

There are no moisture barriers installed at RM 263.2, since this is the control site. At this test site, moisture levels varied less beneath the pavement only three of five times for comparable readings. Beneath the road, the standard deviation of moisture readings was between 1.936 and 16.37. Standard deviations in the row ranged from 0.716 to 8.32. Overall, the examination of moisture trends at this site shows that the moisture barrier does provide more stability to soil moisture beneath the pavement, as moisture readings at the same depths varied much more at the control site than at the sites with a moisture barrier. Figure 29 shows the standard deviation of moisture readings at RM 263.2.

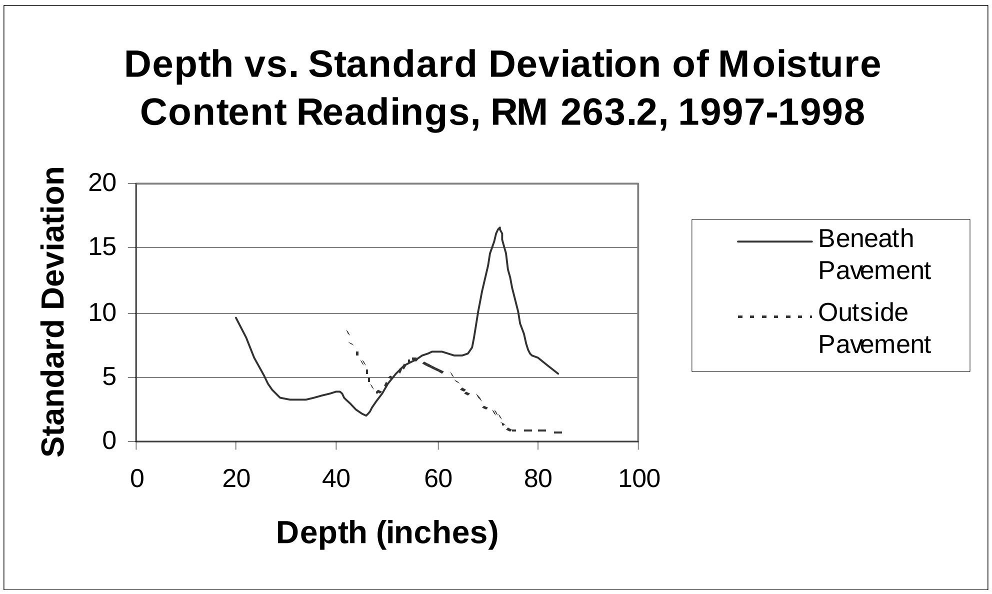


Figure 29. Depth vs. Standard Deviation of Moisture Content.

2. Site Specific Concerns:

RM 263.2 exhibited some rather strange behavior in moisture variability, as can be seen from Figure 29. It is not clear why this happened except that a few readings at certain depths were significantly different from the others. This is evidence to the fact that, with no moisture barriers, moisture levels beneath the road can be rather unpredictable. As mentioned before, there are only four data sets for RM 263.2. It is possible that with more data sets the moisture variability would approach a more stable trend.

CHAPTER 5
CONCLUSION

By evaluating the soil moisture variability both inside and outside the moisture barrier after its installation, it can be seen that the barrier is effective at reducing soil moisture variability. Moisture data was evaluated by graphical comparison of readings inside and outside the barrier, along with statistical analysis of moisture data. The standard deviation of moisture readings was used as the comparison measure for the statistical analysis. Laboratory determination of soil moisture was performed to verify readings taken in the field.

With all data considered, moisture levels varied less inside the barrier for 72 percent of the observations. To determine if the moisture barrier provided a significant reduction in soil moisture variability, the average standard deviation of moisture readings was determined for each site, both inside and outside the barrier. This provides a quantifiable way to estimate overall moisture variability throughout the soil profile. With all data, three of four test sites at the moisture barrier had less average moisture variation inside the barrier. At test sites located at RM 255.2, RM 256.8, and RM 261.1, the average moisture variations inside the barrier were less than those outside the barrier by 63.2 percent, 26.3 percent, and 11.7 percent, respectively. Being that a change greater than 10 percent is statistically significant, the barrier at these sites did significantly reduce moisture variation. At RM 259.7, the average moisture variability inside the barrier was greater than outside the barrier by 17.2 percent. At the site where the select material was used but no barrier installed, the average moisture variations were 40.3 percent less beneath the road than those outside the road. At the control site with no barrier, average moisture variability was 71 percent greater beneath the road than outside the road. A summary of the results is in Table 10.

A more accurate statistical evaluation often is obtained by eliminating outliers from the data set. As noted in the results section, September 1997 data, having much higher than normal moisture variability through the soil profile and much lower than normal moisture contents towards the profile surface, was a clear outlier. Because of this, a separate statistical analysis was performed without this data set. When this is done, moisture levels inside the barrier varied less than those outside the barrier for 84 percent of the observations.

With the trimmed data set, average standard deviations of moisture readings inside the barrier are smaller for each site where barrier performance was monitored. The average standard deviations of moisture levels were reduced by 21.2 percent, 67.5 percent, 37.4 percent, and 71.9 percent at RM 255.2, RM 256.8, RM 259.7, and RM 261.1, respectively. Each of these reductions in moisture variability easily qualifies as significant. At the select material site, average moisture variability was less inside the barrier by 43.7 percent. At the control site average moisture variability was 72.6 percent greater beneath the road than outside the road without September 1997 data.

Table 10. Percent Change in Average Moisture Variability from Outside to Inside the Barrier

Site	Avg. Standard Deviation Outside Barrier	Avg. Standard Deviation Inside Barrier	Percent Reduction	Percent Increase
RM 254.4	1.686	1.007	40.3	N/A
RM 255.2	8.203	3.021	63.2	N/A
RM 256.8	5.94	4.377	26.3	N/A
RM 259.7	7.474	8.757	N/A	17.2
RM 261.1	7.001	6.181	11.7	
RM 263.2 No Barrier	3.777	6.464	N/A	71.1

Note: Analysis based on all data taken. Moisture barriers show reduction in average moisture variability for all sites when outlier of data is omitted, as described in text.

The data was also analyzed for a relationship between rainfall and moisture trends. This was done by comparing monthly rainfall amounts in Ennis, TX, to moisture trends both inside and outside the moisture barrier. It was found that soil moisture rather closely resembles trends in rainfall levels, but that changes in rainfall levels from month to month have less impact on moisture levels inside the moisture barrier.

As mentioned, several methods of analysis were used to examine the performance of the vertical moisture barrier. This was done in order to approach the evaluation of the moisture barrier from as many perspectives as possible. In addition, a ride analysis was performed at each test site. Some specific findings from the complete project of the moisture barrier are:

- Soil moisture variability is significantly less inside the vertical moisture barrier.
- Utilization of select materials in construction also significantly reduces soil moisture variation beneath the road
- Soil moisture variability generally decreases with depth.
- With "normal" weather conditions, moisture variability inside the barrier is negligible beyond depths of approximately 34 inches.
- When abnormal weather conditions occur (such as a drought), moisture variability goes up.
- Soil moisture levels rather closely follow monthly rainfall trends, but moisture levels inside the moisture barrier are influenced less by rainfall amounts
- No significant difference was found in ride among the test sites over the course of the project

In summary, the moisture barrier did provide a significant reduction in moisture variation, but other factors must be considered before a large-scale implementation is attempted. For example, the cost effectiveness of the barrier should be determined. This could be done by a life cycle cost analysis of the protected area versus a non-protected area of the highway. This would insure that the benefits of the moisture barrier actually lower the equivalent uniform annual cost of the roadway.

REFERENCES

1. M.L. Steinberg. Deep Vertical Fabric Moisture Seals. Proc., Fourth International Conference on Expansive Soils, Denver, Colorado, ASCE, 1980, pp. 383-400.
2. M.L. Steinberg. Controlling Expansive Soil Destructiveness by Deep Vertical Geomembranes on Four Highways. Transportation Research Record 1032, TRB, National Research Council, Washington, D.C., 1985, pp. 48-53.
3. D.A. Gay. Development of a Predictive Model for Pavement Roughness on Expansive Clay. Ph.D. dissertation, Texas A&M University, College Station, Texas, August 1991.
4. M.L. Steinberg. Deep Vertical Fabric Moisture Barriers in Swelling Soils. TRB 790, 1981, pp. 87-94.
5. M. Picornell, R.L. Lytton and M.L. Steinberg. Matrix Suction Instrumentation of a Vertical Moisture Barrier. Paper presented at 1982 TRB Meeting, Washington, D.C., January 1982.
6. M. Picornell. The Development of Design Criteria to Select the Depths of a Vertical Moisture Barrier. Ph.D. dissertation, Texas A&M University, College Station, Texas, December 1985.
7. Troxler Sentry 200-AP User's Manual. Troxler Electronic Laboratories, Inc., Second Edition, March 1992.
8. Test Method for Determining Water (Moisture) Content by Direct Heat Method. ASTM Standard D-4959. Section 4, Volume 04.08 Soil and Rock; Dimension Stone; Geosynthetics. 1992.
9. Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort. ASTM Standard D-698. Section 4, Volume 04.08 Soil and Rock; Dimension Stone; Geosynthetics. 1992.

APPENDIX A

MOISTURE READINGS FOR ALL SITES,

1996-1998

Volumetric Moisture Contents for Site at RM 254.4, 1997

Depth in inches	IS – September Moisture Content (%)	OS – September Moisture Content (%)	IS – December Moisture Content (%)	OS – December Moisture Content (%)
20	N/A	N/A	46.8	N/A
27	N/A	N/A	59.4	N/A
34	N/A	N/A	64.6	N/A
40	N/A	N/A	65.1	N/A
43	N/A	73.9	N/A	72.7
46	N/A	N/A	65.4	N/A
49	N/A	73.8	N/A	72.8
53	N/A	N/A	72.7	N/A
56	N/A	75.1	N/A	73.6
59	N/A	N/A	72.8	N/A
62	N/A	74.3	N/A	74.1
66	N/A	N/A	71.5	N/A
69	N/A	73.4	N/A	74.4
72	N/A	N/A	72.1	N/A
75	N/A	72.3	N/A	70.8
78	N/A	N/A	70.1	N/A
81	N/A	73.1	N/A	70.2
84	N/A	N/A	70	N/A
87	N/A	72.8	N/A	72.4
91	N/A	N/A	68	N/A
94	N/A	71.2	N/A	71.1
100	N/A	73.3	N/A	71.8
107	N/A	70.8	N/A	70.6
113	N/A	72.2	N/A	73
120	N/A	71.2	N/A	71.4
126	N/A	74.7	N/A	74.6

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 254.4, 1998

Depth in inches	IS – March Moisture Content (%)	OS – March Moisture Content (%)	IS - July Moisture Content (%)	OS – July Moisture Content (%)
20	43.8	N/A	48.1	N/A
27	57.8	N/A	61.2	N/A
34	65.3	N/A	64.9	N/A
40	63.4	N/A	66.2	N/A
43	N/A	71.5	N/A	61.3
46	65.1	N/A	67.2	N/A
49	N/A	72.1	N/A	74.2
53	72	N/A	71.7	N/A
56	N/A	72.3	N/A	75.5
59	70.7	N/A	71.2	N/A
62	N/A	72.7	N/A	75.6
66	71.6	N/A	71.7	N/A
69	N/A	73.2	N/A	75.6
72	71.6	N/A	73	N/A
75	N/A	71.6	N/A	72.5
78	68.4	N/A	71	N/A
81	N/A	71.1	N/A	72.2
84	69.8	N/A	70.8	N/A
87	N/A	70.6	N/A	71.7
91	63.9	N/A	65.4	N/A
94	N/A	70.7	N/A	71.9
100	N/A	72.1	N/A	71.7
107	N/A	70.5	N/A	71.5
113	N/A	72.6	N/A	72.9
119	N/A	70	N/A	71.7
126	N/A	73.3	N/A	74

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 255.2, 1996

Depth in inches	IS – March Moisture Content (%)	OS – March Moisture Content (%)	IS – June Moisture Content(%)	OS - June Moisture Content (%)	IS – July Moisture Content (%)	OS – July Moisture Content (%)
20	32.9	N/A	34.9	N/A	39.2	N/A
27	36.7	N/A	39.4	N/A	42.7	N/A
34	41.5	N/A	45.8	N/A	46.2	N/A
38	N/A	69.6	N/A	46.7	N/A	71
40	59.2	N/A	60.9	N/A	64.1	N/A
45	N/A	71	N/A	66.6	N/A	72.5
46	59.6	N/A	61.2	N/A	61.4	N/A
52	N/A	70.9	N/A	63.4	N/A	65.7
53	65.1	N/A	66.7	N/A	68.1	N/A
58	N/A	71.9	N/A	56.5	N/A	70.3
59	61.3	N/A	64.2	N/A	66	N/A
64	N/A	72.1	N/A	72.8	N/A	74.1
66	63.4	N/A	67	N/A	67.1	N/A
71	N/A	74	N/A	76.4	N/A	76.4
72	58	N/A	69.1	N/A	70.3	N/A
77	N/A	73.7	N/A	75.8	N/A	75.9
78	65.4	N/A	71	N/A	72.5	N/A
84	69.1	73.9	70.5	75.7	69.4	N/A
90	N/A	73.7	N/A	76.8	N/A	76
91	71.2	N/A	69.7	N/A	69.6	N/A
96	N/A	74.4	N/A	76.8	N/A	76.4
102	N/A	74.2	N/A	76.4	N/A	76.1
109	N/A	74.8	N/A	76.5	N/A	74.9

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 255.2, 1997

Depth in inches	IS - March Moisture Content (%)	OS - March Moisture Content (%)	IS – May Moisture Content (%)	OS - May Moisture Content (%)	IS - July Moisture Content (%)	OS – July Moisture Content (%)	IS - Sept. Moisture Content (%)	OS - Sept. Moisture Content (%)
20	35.9	N/A	36.8	N/A	38.6	N/A	39.4	N/A
27	41	N/A	40.7	N/A	42.7	N/A	43.5	N/A
34	47.9	N/A	45.2	N/A	49	N/A	49.9	N/A
38	N/A	72.1	N/A	65.7	N/A	73.2	N/A	36.1
40	65.3	N/A	64	N/A	66.2	N/A	66.7	N/A
45	N/A	72.4	N/A	71.9	N/A	73.3	N/A	49.9
46	69.7	N/A	69.7	N/A	69.4	N/A	63.8	N/A
52	N/A	68.6	N/A	63.4	N/A	73.7	N/A	50.1
53	68.6	N/A	68	N/A	68.2	N/A	68.2	N/A
58	N/A	73.3	N/A	56	N/A	74.4	N/A	33.8
59	71.8	N/A	70.3	N/A	70	N/A	67.8	N/A
64	N/A	74.8	N/A	72.1	N/A	74.8	N/A	44.6
66	73.3	N/A	71.7	N/A	73.5	N/A	67.9	N/A
71	N/A	76.7	N/A	75.5	N/A	77.1	N/A	61.9
72	73.2	N/A	71.2	N/A	72	N/A	72.8	N/A
77	N/A	76.1	N/A	76	N/A	76.1	N/A	61.6
78	73.7	N/A	72.4	N/A	73	N/A	73.4	N/A
84	73.5	76.1	71.4	76.2	71.4	76.1	72.7	62.4
90	N/A	76.1	N/A	76	N/A	76.6	N/A	74.4
91	73.2	N/A	70.6	N/A	71.3	N/A	71.8	N/A
96	N/A	77.1	N/A	77.2	N/A	76.4	N/A	76.4
102	N/A	76.5	N/A	76.8	N/A	76.3	N/A	76.4
109	N/A	77.2	N/A	77.6	N/A	76.7	N/A	76.5

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 255.2, 1998

Depth in inches	IS-March Moisture Content (%)	OS-March Moisture Content (%)	IS-July 98 Moisture Content (%)	OS-July 98 Moisture Content (%)
20	35.1	N/A	38.2	N/A
27	39.8	N/A	40.8	N/A
34	46.2	N/A	57.6	N/A
38	N/A	71.3	N/A	72.1
40	66.3	N/A	66.3	N/A
45	N/A	71.8	N/A	69.6
46	70.1	N/A	68.7	N/A
52	N/A	71.3	N/A	62.8
53	68.6	N/A	70.9	N/A
58	N/A	73.2	N/A	57.2
59	66.4	N/A	64.5	N/A
64	N/A	74.5	N/A	59.7
66	62.3	N/A	66.6	N/A
71	N/A	75.4	N/A	73.7
72	69.7	N/A	70.5	N/A
77	N/A	75	N/A	76.2
78	71.8	N/A	71.7	N/A
84	70.8	75.6	71.9	76.5
90	N/A	76.9	N/A	76.9
91	71.1	N/A	70.4	N/A
96	N/A	76	N/A	76.7
102	N/A	76.4	N/A	76.9
109	N/A	76.2	N/A	76.8

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 256.8, 1996

Depth in inches	IS - March Moisture Content (%)	OS – March Moisture Content (%)	IS - June Moisture Content (%)	OS - June Moisture Content (%)	IS – July Moisture Content (%)	OS - July Moisture Content (%)
20	53.5	N/A	38	N/A	40.5	N/A
27	53.8	N/A	47.4	N/A	51.1	N/A
34	64.2	N/A	66.5	N/A	67.1	N/A
40	70.1	N/A	72.9	N/A	74.3	N/A
46	76	N/A	77.1	N/A	78.7	N/A
53	76.2	N/A	77.4	N/A	78	N/A
56	N/A	64.3	N/A	46.4	N/A	74.1
59	N/A	N/A	76.4	N/A	77.7	N/A
63	N/A	68	N/A	64.5	N/A	73.1
66	N/A	N/A	N/A	N/A	82.1	N/A
70	N/A	70.8	N/A	69.4	N/A	73.9
76	N/A	72.2	N/A	72.4	N/A	74.9
82	N/A	74.6	N/A	73.8	N/A	74.9
89	N/A	75.4	N/A	75.1	N/A	75.3
95	N/A	76.1	N/A	75.6	N/A	76.4
99	N/A	77.3	N/A	76.6	N/A	76.5
108	N/A	77.7	N/A	76.8	N/A	76.1
114	N/A	76.8	N/A	76.9	N/A	76.8
120	N/A	77.2	N/A	76.2	N/A	76.6

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 256.8, 1997

Depth in inches	IS - March Moisture Content (%)	OS - March Moisture Content (%)	IS - May Moisture Content (%)	OS - May Moisture Content (%)	IS - July Moisture Content (%)	OS - July Moisture Content (%)	IS – Sept Moisture Content (%)	OS - Sept Moisture Content (%)
20	50.2	N/A	37.7	N/A	42.5	N/A	16.5	N/A
27	53.1	N/A	43	N/A	52.7	N/A	18.3	N/A
34	65.6	N/A	64.6	N/A	67.9	N/A	47.2	N/A
40	72.3	N/A	73.3	N/A	74.2	N/A	72	N/A
46	78	N/A	78.3	N/A	78.3	N/A	77.6	N/A
53	79.2	N/A	79.1	N/A	78.7	N/A	76.7	N/A
56	N/A	74.7	N/A	72.6	N/A	74.9	N/A	71.7
59	78.2	N/A	78	N/A	80.2	N/A	75.8	N/A
63	N/A	74.7	N/A	75.5	N/A	75.9	N/A	76.7
66	82.5	N/A	82.5	N/A	N/A	N/A	81.5	N/A
70	N/A	76.5	N/A	76.2	N/A	77.1	N/A	75.1
76	N/A	75	N/A	75.8	N/A	75.2	N/A	74.4
82	N/A	75.5	N/A	75.5	N/A	74.7	N/A	74.1
89	N/A	75.4	N/A	76	N/A	75.4	N/A	74.8
95	N/A	76.3	N/A	76.7	N/A	75.9	N/A	75.4
99	N/A	77.2	N/A	75.8	N/A	77	N/A	75.4
108	N/A	76.8	N/A	77.5	N/A	76.7	N/A	76
114	N/A	76.6	N/A	76.8	N/A	76.3	N/A	76.1
120	N/A	76.5	N/A	77	N/A	N/A	N/A	N/A

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 256.8, 1998

Depth in inches	IS-March 98 Moisture Content (%)	OS-March Moisture Content (%)
20	40.8	N/A
27	51.9	N/A
34	65.4	N/A
40	73.8	N/A
46	77.6	N/A
53	79	N/A
56	N/A	N/A
59	79.1	N/A
63	N/A	N/A
66	82	N/A
70	N/A	76.3
76	N/A	77.6
82	N/A	75
89	N/A	75
95	N/A	75.4
99	N/A	76.1
108	N/A	76.7
114	N/A	76.4
120	N/A	75.9

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 259.7, 1996

Depth in inches	IS - March Moisture Content (%)	OS – March Moisture Content (%)	IS – June Moisture Content (%)	OS - June Moisture Content (%)	IS - July Moisture Content (%)	OS - July Moisture Content (%)
20	53.1	N/A	22.8	N/A	17.5	N/A
27	53.1	N/A	49.6	N/A	26.6	N/A
34	62.8	N/A	63.3	N/A	61.7	N/A
40	70.5	64	72.3	41.8	71.6	67.2
46	74.6	N/A	74.6	N/A	74.4	N/A
47	N/A	60.9	N/A	48.4	N/A	67
53	73.9	N/A	74.2	N/A	74.2	N/A
54	N/A	67.1	N/A	57.7	N/A	72
59	73.7	N/A	73.7	N/A	73.8	N/A
60	N/A	68.4	N/A	64.8	N/A	72.6
66	74.1	68.3	73.6	68.8	73.7	73.3
72	75.4	N/A	74.9	N/A	75.5	N/A
73	N/A	55.7	N/A	58	N/A	61.5
78	75.8	N/A	75.8	N/A	75.5	N/A
79	N/A	63.2	N/A	64.8	N/A	70.2
84	76.6	N/A	76.6	N/A	76.4	N/A
86	N/A	72.8	N/A	70.4	N/A	75.6
91	77	N/A	77.7	N/A	77.2	N/A
92	N/A	74.8	N/A	75.7	N/A	76.7
98	N/A	77.6	N/A	77.7	N/A	77.9
104	N/A	78.9	N/A	79.4	N/A	79
111	N/A	78.6	N/A	79.5	N/A	78.5

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 259.7, 1997

Depth in inches	IS-March Moisture Content (%)	OS-March Moisture Content (%)	IS-May Moisture Content (%)	OS-May Moisture Content (%)	IS-July Moisture Content (%)	OS-July Moisture Content (%)	IS-Sept Moisture Content (%)	OS-Sept Moisture Content (%)
20	44.1	N/A	18.9	N/A	48.9	N/A	6	N/A
27	52.8	N/A	26.6	N/A	52.8	N/A	15.2	N/A
34	64.1	N/A	63.1	N/A	64.2	N/A	45.1	N/A
40	72.4	68.4	72.6	60	69.5	69.1	49.9	40
46	74.8	N/A	74.7	N/A	74.3	N/A	40	N/A
47	N/A	68.6	N/A	65.3	N/A	68	N/A	46.4
53	74.3	N/A	74.2	N/A	73.6	N/A	41	N/A
54	N/A	73.1	N/A	69.5	N/A	72.2	N/A	53.2
59	74.1	N/A	73.5	N/A	73.2	N/A	52.8	N/A
60	N/A	72.6	N/A	71.4	N/A	72.9	N/A	57.2
66	74.4	72	74	72.7	73.3	72.3	60.4	52.5
72	75.6	N/A	75.5	N/A	74.7	N/A	56.3	N/A
73	N/A	68.7	N/A	71.6	N/A	72.4	N/A	52.3
78	76.1	N/A	76	N/A	75.1	N/A	67.5	N/A
79	N/A	72	N/A	71.9	N/A	72.2	N/A	63.5
84	76.5	N/A	76.4	N/A	74.9	N/A	74.4	N/A
86	N/A	75.8	N/A	76.1	N/A	75.7	N/A	69.7
91	77.4	N/A	77	N/A	75.6	N/A	74.4	N/A
92	N/A	77.2	N/A	77.3	N/A	77	N/A	72.3
98	N/A	78	N/A	78.5	N/A	77.7	N/A	76.7
104	N/A	79.4	N/A	79.9	N/A	79.1	N/A	78
111	N/A	79	N/A	N/A	N/A	78	N/A	76.7

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 259.7, 1998

Depth in inches	IS-March Moisture Content (%)	OS-March Moisture Content (%)	IS-Aug Moisture Content (%)	OS-Aug Moisture Content (%)
20	22.8	N/A	21	N/A
27	50.9	N/A	35	N/A
34	66.9	N/A	58	N/A
40	72.7	66.9	72.4	66.9
46	73.6	N/A	74.9	N/A
47	N/A	67	N/A	71.1
53	73	N/A	74.5	N/A
54	N/A	71.3	N/A	73.6
59	71.8	N/A	73.4	N/A
60	N/A	71.9	N/A	73.5
66	73	71.4	74.2	72.9
72	74.3	N/A	75.5	N/A
73	N/A	70	N/A	74.1
78	74.8	N/A	76	N/A
79	N/A	73.6	N/A	74.6
84	75.4	N/A	76.7	N/A
86	N/A	75.2	N/A	76.2
91	76.1	N/A	76.9	N/A
92	N/A	76	N/A	77.5
98	N/A	77.4	N/A	78.5
104	N/A	78.5	N/A	79.8
111	N/A	75	N/A	77.3

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 261.1, 1996

Depth in inches	IS - March Moisture Content (%)	OS – March Moisture Content (%)	IS - June Moisture Content (%)	OS - June Moisture Content (%)	IS - July Moisture Content (%)	OS - July Moisture Content (%)
20	26.5	N/A	33.1	N/A	28.4	N/A
27	44	N/A	52.4	N/A	48.9	N/A
32	N/A	68.4	N/A	40.6	N/A	70
34	63.2	N/A	67.4	N/A	69	N/A
39	N/A	67.4	N/A	53.4	N/A	68.9
40	66.6	N/A	70.4	N/A	70.6	N/A
46	67	63	70.2	48.9	68.4	N/A
52	N/A	59.9	N/A	42.9	N/A	71.1
53	68.9	N/A	71.7	N/A	70.5	N/A
58	N/A	63.6	N/A	54.6	N/A	71.1
59	70.2	N/A	72.5	N/A	71.1	N/A
65	N/A	63.9	N/A	54.9	N/A	71.1
66	69.8	N/A	71.3	N/A	70.6	N/A
71	N/A	69.3	N/A	53.2	N/A	71
72	70.7	N/A	72.1	N/A	71.8	N/A
78	70.5	67.7	72.2	62.1	71.7	70.3
84	70.4	71.1	72	49.6	73	71.7
90	N/A	71.6	N/A	65.8	N/A	71.9
91	70.2	N/A	71.9	N/A	72.9	N/A
96	N/A	71.3	N/A	70.7	N/A	70.6
103	N/A	68.4	N/A	69.8	N/A	69.3

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 261.1, 1997

Depth in inches	IS-March Moisture Content (%)	OS-March Moisture Content (%)	IS-May Moisture Content (%)	OS-May Moisture Content (%)	IS-July Moisture Content (%)	OS-July Moisture Content (%)	IS-Sept. Moisture Content (%)	OS-Sept. Moisture Content (%)
20	31.2	N/A	25.6	N/A	47.5	N/A	19.6	N/A
27	52.1	N/A	44	N/A	53.9	N/A	32.1	N/A
32	N/A	71	N/A	61.2	N/A	72.4	N/A	68.2
34	67.6	N/A	67.3	N/A	67.6	N/A	51.3	N/A
39	N/A	70.9	N/A	66.1	N/A	73.7	N/A	68.7
40	69.3	N/A	70.3	N/A	69.2	N/A	44.9	N/A
46	68.5	70.7	68.9	66	69.5	74.1	47.8	66.3
52	N/A	71.6	N/A	63.4	N/A	72.5	N/A	63.9
53	71.3	N/A	71.7	N/A	72	N/A	64.8	N/A
58	N/A	72.2	N/A	66.7	N/A	73.8	N/A	61.3
59	72.6	N/A	72	N/A	72.4	N/A	63.5	N/A
65	N/A	73	N/A	63	N/A	73.3	N/A	61.5
66	71.1	N/A	72	N/A	71.8	N/A	50.6	N/A
71	N/A	71.2	N/A	70.5	N/A	72.2	N/A	57.1
72	71.5	N/A	72.9	N/A	72.6	N/A	48.2	N/A
78	71.6	69.5	73.3	69.6	72.6	70.4	54.9	62.7
84	71.6	72.4	73.4	73.1	71.9	72.5	56.1	68.8
90	N/A	72.8	N/A	72.9	N/A	72.8	N/A	72.4
91	72.4	N/A	72.2	N/A	72.2	N/A	66.4	N/A
96	N/A	72.3	N/A	72.4	N/A	71.3	N/A	71.7
103	N/A	69.5	N/A	67.7	N/A	68.5	N/A	68.4

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 261.1, 1998

Depth in inches	IS-March Moisture Content (%)	OS-March Moisture Content (%)	IS-Aug Moisture Content (%)	OS-Aug Moisture Content (%)
20	37.7	N/A	29.2	N/A
27	54.2	N/A	48.5	N/A
32	N/A	69.8	N/A	73.7
34	67.4	N/A	69	N/A
39	N/A	68.9	N/A	70.5
40	69.2	N/A	69.1	N/A
46	68.2	69.3	69.1	72.1
52	N/A	70.9	N/A	73.2
53	71	N/A	72.5	N/A
58	N/A	71.2	N/A	72.9
59	71.3	N/A	72.4	N/A
65	N/A	71.2	N/A	72.4
66	70.9	N/A	72.4	N/A
71	N/A	71.1	N/A	72.3
72	71.4	N/A	72.8	N/A
78	71.3	69.4	73.2	66.2
84	71.2	71.3	72.8	72.2
90	N/A	71.5	N/A	73.4
91	71.1	N/A	72.1	N/A
96	N/A	70.6	N/A	72.1
103	N/A	69	N/A	70.6

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 263.2, 1997

Depth in inches	IS - September Moisture Content (%)	OS – September Moisture Content (%)	IS - December Moisture Content (%)	OS – December Moisture Content (%)
20	68.6	N/A	70.3	N/A
27	69.4	N/A	67	N/A
34	66.3	N/A	61.3	N/A
40	70	N/A	66.4	N/A
42	N/A	56.2	N/A	53.2
46	66.9	N/A	63.6	N/A
48	N/A	58.5	N/A	61.8
53	62.5	N/A	58.3	N/A
55	N/A	57.8	N/A	66.5
59	57.7	N/A	56.3	N/A
61	N/A	70.9	N/A	61.6
66	59.2	N/A	58.3	N/A
68	N/A	73	N/A	67.1
72	41.2	N/A	41.3	N/A
74	N/A	73.4	N/A	71.2
78	58.6	N/A	61	N/A
80	N/A	74	N/A	72
84	62.2	N/A	58.1	N/A
86	N/A	74	N/A	72.3
91	60.4	N/A	59.9	N/A
93	N/A	73.6	N/A	72.7
100	N/A	72.6	N/A	70
106	N/A	72.2	N/A	69.1
112	N/A	69.5	N/A	59.9

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

Volumetric Moisture Contents for Site at RM 263.2, 1998

Depth in inches	IS – March Moisture Content (%)	OS – March Moisture Content (%)	IS - July Moisture Content (%)	OS - July Moisture Content (%)
20	49.5	N/A	59.7	N/A
27	59.9	N/A	64.2	N/A
34	65.7	N/A	69.2	N/A
40	60.6	N/A	64.2	N/A
42	N/A	68	N/A	69.8
46	63	N/A	66.3	N/A
48	N/A	66.9	N/A	65.9
53	69.7	N/A	70.1	N/A
55	N/A	62	N/A	73
59	68.6	N/A	69.6	N/A
61	N/A	73	N/A	73.4
66	69.2	N/A	71.7	N/A
68	N/A	73.5	N/A	74
72	69.3	N/A	69.9	N/A
74	N/A	73	N/A	73.6
78	71.2	N/A	72.6	N/A
80	N/A	72.5	N/A	73.7
84	67.5	N/A	69.8	N/A
86	N/A	73.4	N/A	73.5
91	59.4	N/A	66.2	N/A
93	N/A	73.4	N/A	72.7
100	N/A	72.5	N/A	70.8
106	N/A	71.2	N/A	68.8
112	N/A	68.9	N/A	69.4

Note: IS is inside the moisture barrier, OS is outside the moisture barrier

APPENDIX B

STATISTICAL EVALUATION OF SOIL MOISTURE CONTENTS

Statistical analysis of moisture contents beneath the pavement for site at RM 254.4, 1997 to 1998											
Depth	20 inches	27 inches	34 inches	40 inches	46 inches	53 inches	59 inches	66 inches	72 inches	78 inches	84 inches
	46.8	59.4	64.6	65.1	65.4	72.7	72.8	71.5	72.1	70.1	70
	43.8	57.8	65.3	63.4	65.1	72	70.7	71.6	71.6	68.4	69.8
	48.1	61.2	64.9	66.2	67.2	71.7	71.2	71.7	73	71	70.8
Mean	46.23333	59.46667	64.93333	64.9	65.9	72.13333	71.56667	71.6	72.23333	69.83333	70.2
Variance	4.863333	2.893333	0.123333	1.99	1.29	0.263333	1.203333	0.01	0.503333	1.743333	0.28
St. Dev.	2.205297	1.70098	0.351188	1.410674	1.135782	0.51316	1.096966	0.1	0.70946	1.320353	0.52915

Statistical analysis of Moisture Contents outside the pavement for site at RM 254.4, 1997 to 1998								
Depth	43 inches	49 inches	56 inches	62 inches	69 inches	75 inches	81 inches	87 inches
	73.9	73.8	75.1	74.3	73.4	72.3	73.1	72.8
	72.7	72.8	73.6	74.1	74.4	70.8	70.2	72.4
	71.5	72.1	72.3	72.7	73.2	71.6	71.1	70.6
	61.3	74.2	75.5	75.6	75.6	72.5	72.2	71.7
Mean	69.85	73.225	74.125	74.175	74.15	71.8	71.65	71.875
Variance	33.45	0.909167	2.149167	1.409167	1.21	0.593333	1.603333	0.929167
St. Dev.	5.783597	0.953502	1.466004	1.187083	1.1	0.770281	1.266228	0.963933

Statistical analysis of moisture contents inside the barrier for site at RM 255.2, 1996 to 1998

Depth	20 inches	27 inches	34 inches	40 inches	46 inches	53 inches	59 inches	66 inches	72 inches	78 inches	84 inches
	32.9	36.7	41.5	59.2	59.6	65.1	61.3	63.4	58	65.4	69.1
	34.9	39.4	45.8	60.9	61.2	66.7	64.2	67	69.1	71	70.5
	39.2	42.7	46.2	64.1	61.4	68.1	66	67.1	70.3	72.5	69.4
	35.9	41	47.9	65.3	69.7	68.6	71.8	73.3	73.2	73.7	73.5
	36.8	40.7	45.2	64	69.7	68	70.3	71.7	71.2	72.4	71.4
	38.6	42.7	49	66.2	69.4	68.2	70	73.5	72	73	71.4
	39.4	43.5	49.9	66.7	63.8	68.2	67.8	67.9	72.8	73.4	72.7
	35.1	39.8	46.2	66.3	70.1	68.6	66.4	62.3	69.7	71.8	70.8
	38.2	40.8	57.6	66.3	68.7	70.9	64.5	66.6	70.5	71.7	71.9
Mean	36.77778	40.81111	47.7	64.33333	65.95556	68.04444	66.92222	68.08889	69.64444	71.65556	71.18889
Variance	5.029444	4.291111	19.6725	7.0075	19.12778	2.412778	11.43194	16.17361	20.95278	6.235278	2.051111
St. Dev.	2.242642	2.0715	4.435369	2.647168	4.373531	1.553312	3.381116	4.021643	4.57742	2.497054	1.43217

Statistical analysis of moisture contents outside the barrier for site at RM 255.2, 1996 to 1998

Depth	38 inches	45 inches	52 inches	58 inches	64 inches	71 inches	77 inches	84 inches
	69.6	71	70.9	71.9	72.1	74	73.7	73.9
	46.7	66.6	63.4	56.5	72.8	76.4	75.8	75.7
	71	72.5	65.7	70.3	74.1	76.4	75.9	
	72.1	72.4	68.9	73.3	74.8	76.7	76.1	76.1
	65.7	71.9	63.4	56	72.1	75.5	76	76.2
	73.2	73.3	73.7	74.4	74.8	77.1	76.1	76.1
	36.1	49.9	50.1	33.8	44.6	61.9	61.6	62.4
	71.3	70.1	71.3	73.2	74.5	75.4	75	75.6
	72.1	68.7	62.8	57.2	59.7	73.7	76.2	76.5
Mean	64.2	68.48889	65.57778	62.95556	68.83333	74.12222	74.04444	74.0625
Variance	178.7175	53.02861	49.35694	181.2628	104.85	22.37444	22.41778	22.84268
St. Dev.	13.36853	7.282075	7.02545	13.46339	10.23963	4.730163	4.734742	4.779401

Statistical analysis of moisture contents inside the barrier for site at RM 256.8, 1996 to 1998

Depth	20 inches	27 inches	34 inches	40 inches	46 inches	53 inches	59 inches	66 inches
	53.5	53.8	64.2	70.1	76	76.2		
	38	47.4	66.5	72.9	77.1	77.4	76.4	
	40.5	51.1	67.1	74.3	78.7	78	77.7	82.1
	50.2	53.1	65.6	72.3	78	79.2	78.2	82.5
	37.7	43	64.6	73.3	78.3	79.1	78	82.5
	42.5	52.7	67.9	74.2	78.3	78.7	80.2	
	16.5	18.3	47.2	72	77.6	76.7	75.8	81.5
	40.8	51.9	65.4	73.8	77.6	79	79.1	82
Mean	39.9625	46.4125	63.5625	72.8625	77.7	78.0375	77.91429	82.12
Variance	122.137	141.9784	45.24268	1.945536	0.725714	1.345536	2.254762	0.172
St. Dev.	11.05156	11.91547	6.726268	1.394825	0.851889	1.159972	1.501586	0.414729

Statistical analysis of moisture contents outside the barrier for site at RM 256.8, 1996 to 1998

Depth	56 inches	63 inches	70 inches
	64.3	68	70.8
	46.4	64.5	69.4
	74.1	73.1	73.9
	74.7	74.7	76.5
	72.6	75.5	76.2
	74.9	75.9	77.1
	71.7	76.7	75.1
			76.3
Mean	68.38571	72.62857	74.4125
Variance	107.2948	21.25571	8.178393
St. Dev.	10.35832	4.610392	2.859789

Statistical analysis of moisture contents inside the barrier for site at RM 259.7, 1996 to 1998

Depth	20 inches	27 inches	34 inches	40 inches	46 inches	53 inches	59 inches	66 inches	72 inches	78 inches
	53.1	53.1	62.8	70.5	74.6	73.9	73.7	74.1	75.4	75.8
	22.8	49.6	63.3	72.3	74.6	74.2	73.7	73.6	74.9	75.8
	17.5	26.6	61.7	71.6	74.4	74.2	73.8	73.7	75.5	75.5
	44.1	52.8	64.1	72.4	74.8	74.3	74.1	74.4	75.6	76.1
	18.9	26.6	63.1	72.6	74.7	74.2	73.5	74	75.5	76
	48.9	52.8	64.2	69.5	74.3	73.6	73.2	73.3	74.7	75.1
	6	15.2	45.1	49.9	40	41	52.8	60.4	56.3	67.5
	22.8	50.9	66.9	72.7	73.6	73	71.8	73	74.3	74.8
	21	35	58	72.4	74.9	74.5	73.4	74.2	75.5	76
Mean	28.34444	40.28889	61.02222	69.32222	70.65556	70.32222	71.11111	72.3	73.07778	74.73333
Variance	263.1378	213.5836	41.23694	54.22444	132.3003	121.1119	47.58111	20.1125	39.78694	7.55
St. Dev.	16.22152	14.6145	6.4216	7.363725	11.50219	11.00509	6.897906	4.484696	6.307689	2.747726

Statistical analysis of moisture contents outside the barrier for site at RM 259.7, 1996 to 1998

Depth	40 inches	47 inches	54 inches	60 inches	66 inches	73 inches	79 inches
	64	60.9	67.1	68.4	68.3	55.7	63.2
	41.8	48.4	57.7	64.8	68.8	58	64.8
	67.2	67	72	72.6	73.3	61.5	70.2
	68.4	68.6	73.1	72.6	72	68.7	72
	60	65.3	69.5	71.4	72.7	71.6	71.9
	69.1	68	72.2	72.9	72.3	72.4	72.2
	40	46.4	53.2	57.2	52.5	52.3	63.5
	66.9	67	71.3	71.9	71.4	70	73.6
	66.9	71.1	73.6	73.5	72.9	74.1	74.6
Mean	60.47778	62.52222	67.74444	69.47778	69.35556	64.92222	69.55556
Variance	130.7019	81.29194	53.68778	28.84194	43.08528	66.09944	20.04528
St. Dev.	11.4325	9.016205	7.327194	5.37047	6.563938	8.130156	4.477195

Statistical analysis of moisture contents inside the barrier for site at RM 261.1, 1996 to 1998

Depth	20 inches	27 inches	34 inches	40 inches	46 inches	53 inches	59 inches	66 inches	72 inches	78 inches
	26.5	44	63.2	66.6	67	68.9	70.2	69.8	70.7	70.5
	33.1	52.4	67.4	70.4	70.2	71.7	72.5	71.3	72.1	72.2
	28.4	48.9	69	70.6	68.4	70.5	71.1	70.6	71.8	71.7
	31.2	52.1	67.6	69.3	68.5	71.3	72.6	71.1	71.5	71.6
	25.6	44	67.3	70.3	68.9	71.7	72	72	72.9	73.3
	47.5	53.9	67.6	69.2	69.5	72	72.4	71.8	72.6	72.6
	19.6	32.1	51.3	44.9	47.8	64.8	63.5	50.6	48.2	54.9
	37.7	54.2	67.4	69.2	68.2	71	71.3	70.9	71.4	71.3
	29.2	48.5	69	69.1	69.1	72.5	72.4	72.4	72.8	73.2
Mean	30.97778	47.78889	65.53333	66.62222	66.4	70.48889	70.88889	68.94444	69.33333	70.14444
Variance	63.86944	49.36111	31.3375	67.75944	49.445	5.633611	8.326111	47.93028	63.325	33.49278
St. Dev.	7.991836	7.025746	5.597991	8.231613	7.031714	2.373523	2.8855	6.92317	7.957701	5.787295

Statistical analysis of moisture contents outside the barrier for site at RM 261.1, 1996 to 1998

Depth	32 inches	39 inches	52 inches	58 inches	65 inches	71 inches	78 inches
	68.4	67.4	59.9	63.6	63.9	69.3	67.7
	40.8	53.4	42.9	54.6	54.9	53.2	62.1
	70	68.9	71.1	71.1	71.1	71	70.3
	71	70.9	71.6	72.2	73	71.2	69.5
	61.2	66.1	63.4	66.7	63	70.5	69.6
	72.4	73.7	72.5	73.8	73.3	72.2	70.4
	68.2	68.7	63.9	61.3	61.5	57.1	62.7
	69.8	68.9	70.9	71.2	71.2	71.1	69.4
	73.7	70.5	73.2	72.9	72.4	72.3	66.2
Mean	66.16667	67.61111	65.48889	67.48889	67.14444	67.54444	67.54444
Variance	103.015	33.12861	94.38861	42.28611	42.67278	51.11278	10.27278
St. Dev.	10.14963	5.755746	9.71538	6.502777	6.53244	7.14932	3.205117

Statistical analysis of moisture contents beneath the pavement for site at RM 263.2, 1997 to 1998

Depth	20 inches	27 inches	34 inches	40 inches	46 inches	53 inches	59 inches	66 inches	72 inches	78 inches	84 inches
	68.6	69.4	66.3	70	66.9	62.5	57.7	59.2	41.2	58.6	62.2
	70.3	67	61.3	66.4	63.6	58.3	56.3	58.3	41.3	61	58.1
	49.5	59.9	65.7	60.6	63	69.7	68.6	69.2	69.3	71.2	67.5
	59.7	64.2	69.2	64.2	66.3	70.1	69.6	71.7	69.9	72.6	69.8
Mean	62.025	65.125	65.625	65.3	64.95	65.15	63.05	64.6	55.425	65.85	64.4
Variance	91.32917	16.64917	10.64917	15.53333	3.75	33.05	49.29667	46.80667	267.9692	50.09	27.76667
St. Dev.	9.556629	4.080339	3.263306	3.941235	1.936492	5.748913	7.021158	6.84154	16.36976	7.077429	5.269409

Statistical analysis of moisture contents outside the pavement for site at RM 263.2, 1997 to 1998

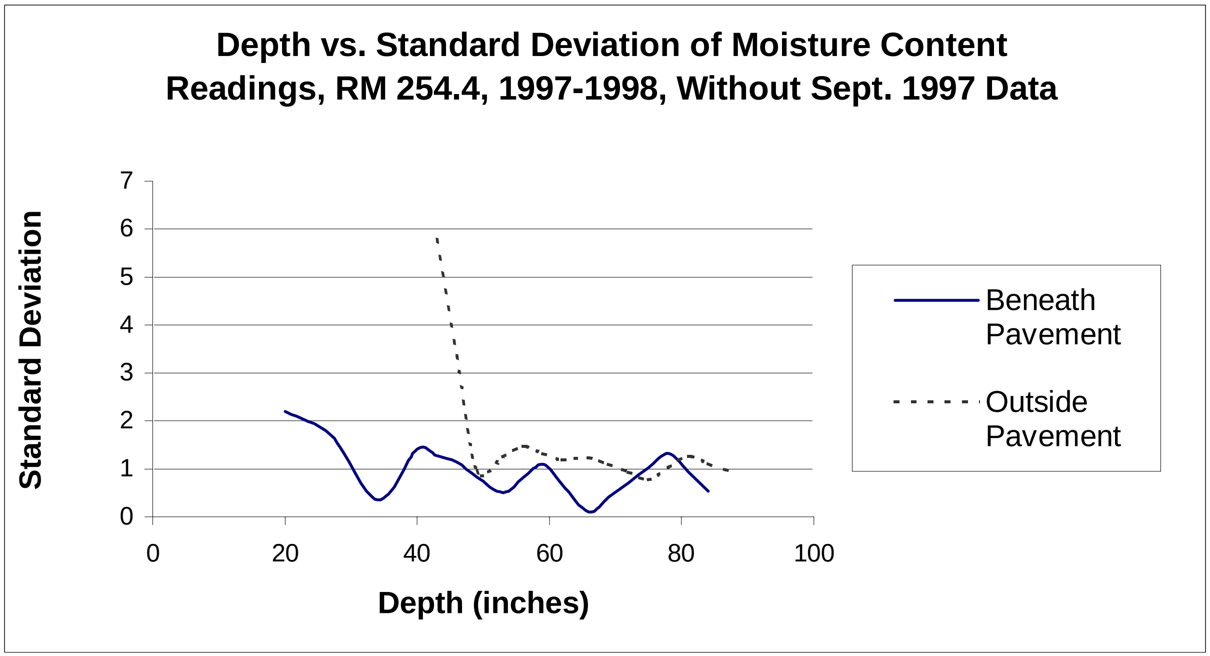
Depth	42 inches	48 inches	55 inches	61 inches	68 inches	74 inches	80 inches	86 inches
	56.2	58.5	57.8	70.9	73	73.4	74	74
	53.2	61.8	66.5	61.6	67.1	71.2	72	72.3
	68	66.9	62	73	73.5	73	72.5	73.4
	69.8	65.9	73	73.4	74	73.6	73.7	73.5
Mean	61.8	63.275	64.825	69.725	71.9	72.8	73.05	73.3
Variance	69.25333	15.0025	42.3225	30.5425	10.40667	1.2	0.91	0.513333
St. Dev.	8.321859	3.873306	6.505575	5.526527	3.225937	1.095445	0.953939	0.716473

APPENDIX C

STATISTICAL EVALUATION OF SOIL MOISTURE CONTENTS WITHOUT OUTLIER OF DATA

Statistical analysis of moisture contents beneath the pavement for site at RM 254.4, 1997 to 1998, without September 1997 data											
Depth	20 inches	27 inches	34 inches	40 inches	46 inches	53 inches	59 inches	66 inches	72 inches	78 inches	84 inches
	46.8	59.4	64.6	65.1	65.4	72.7	72.8	71.5	72.1	70.1	70
	43.8	57.8	65.3	63.4	65.1	72	70.7	71.6	71.6	68.4	69.8
	48.1	61.2	64.9	66.2	67.2	71.7	71.2	71.7	73	71	70.8
Mean	46.23333	59.46667	64.93333	64.9	65.9	72.13333	71.56667	71.6	72.23333	69.83333	70.2
Variance	4.863333	2.893333	0.123333	1.99	1.29	0.263333	1.203333	0.01	0.503333	1.743333	0.28
St. Dev.	2.205297	1.70098	0.351188	1.410674	1.135782	0.51316	1.096966	0.1	0.70946	1.320353	0.52915

Statistical analysis of moisture contents outside the pavement For RM 254.4, 1997 to 1998, without September 1997 data								
Depth	43 inches	49 inches	56 inches	62 inches	69 inches	75 inches	81 inches	87 inches
	72.7	72.8	73.6	74.1	74.4	70.8	70.2	72.4
	71.5	72.1	72.3	72.7	73.2	71.6	71.1	70.6
	61.3	74.2	75.5	75.6	75.6	72.5	72.2	71.7
Mean	68.5	73.03333	73.8	74.13333	74.4	71.63333	71.16667	71.56667
Variance	39.24	1.143333	2.59	2.103333	1.44	0.723333	1.003333	0.823333
St. Dev.	6.264184	1.069268	1.609348	1.450287	1.2	0.85049	1.001665	0.907377

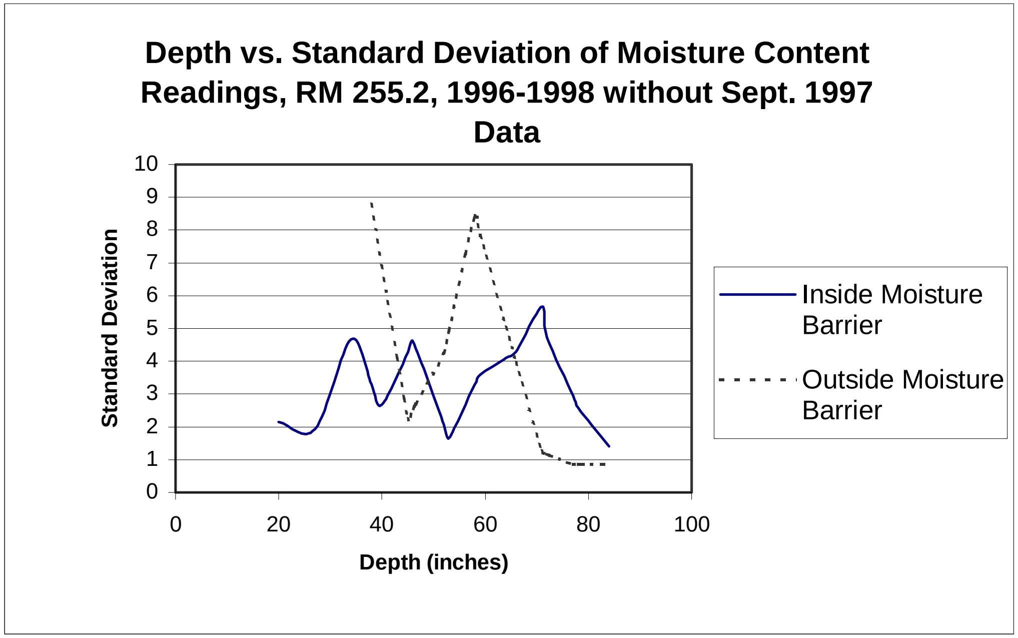

Depth vs. Standard Deviation of Moisture Content Readings, RM 254.4, 1997-1998, Without Sept. 1997 Data
Standard Deviation
0
1
2
3
4
5
6
7
0
20
40
60
80
100
Depth (inches)
Beneath Pavement
Outside Pavement

Statistical analysis of moisture contents inside the barrier for site at RM 255.2, 1996 to 1998, without September 1997 data

Depth	20 inches	27 inches	34 inches	40 inches	46 inches	53 inches	59 inches	66 inches	72 inches	78 inches	84 inches
	32.9	36.7	41.5	59.2	59.6	65.1	61.3	63.4	58	65.4	69.1
	34.9	39.4	45.8	60.9	61.2	66.7	64.2	67	69.1	71	70.5
	39.2	42.7	46.2	64.1	61.4	68.1	66	67.1	70.3	72.5	69.4
	35.9	41	47.9	65.3	69.7	68.6	71.8	73.3	73.2	73.7	73.5
	36.8	40.7	45.2	64	69.7	68	70.3	71.7	71.2	72.4	71.4
	38.6	42.7	49	66.2	69.4	68.2	70	73.5	72	73	71.4
	35.1	39.8	46.2	66.3	70.1	68.6	66.4	62.3	69.7	71.8	70.8
	38.2	40.8	57.6	66.3	68.7	70.9	64.5	66.6	70.5	71.7	71.9
Mean	36.45	40.475	47.425	64.0375	66.225	68.025	66.8125	68.1125	69.25	71.4375	71
Variance	4.642857	3.742143	21.705	7.108393	21.11357	2.753571	12.94125	18.47839	22.34571	6.636964	1.977143
St. Dev.	2.154729	1.934462	4.658863	2.666157	4.594951	1.659389	3.597395	4.29865	4.727125	2.576231	1.406109

Statistical analysis of moisture contents outside the barrier for site at RM 255.2, 1996 to 1998, without September 1997 data

Depth	38 inches	45 inches	52 inches	58 inches	64 inches	71 inches	77 inches	84 inches
	69.6	71	70.9	71.9	72.1	74	73.7	73.9
	46.7	66.6	63.4	56.5	72.8	76.4	75.8	75.7
	71	72.5	65.7	70.3	74.1	76.4	75.9	
	72.1	72.4	68.9	73.3	74.8	76.7	76.1	76.1
	65.7	71.9	63.4	56	72.1	75.5	76	76.2
	73.2	73.3	73.7	74.4	74.8	77.1	76.1	76.1
	71.3	70.1	71.3	73.2	74.5	75.4	75	75.6
	72.1	68.7	62.8	57.2	59.7	73.7	76.2	76.5
Mean	67.7125	70.8125	67.5125	66.6	71.8625	75.65	75.6	75.72857
Variance	77.34696	5.069821	17.90696	70.54286	25.44839	1.562857	0.731429	0.742381
St. Dev.	8.794712	2.251626	4.231662	8.39898	5.04464	1.250143	0.855236	0.861615

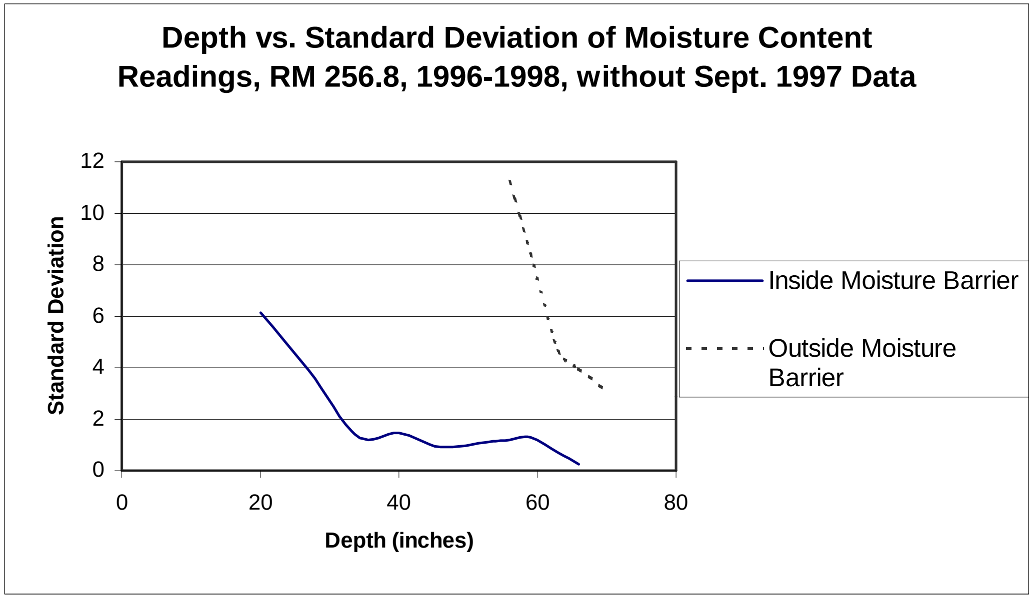

Depth vs. Standard Deviation of Moisture Content Readings, RM 255.2, 1996-1998 without Sept. 1997 Data
Standard Deviation
0
1
2
3
4
5
6
7
8
9
10
0
20
40
60
80
100
Depth (inches)
Inside Moisture Barrier
Outside Moisture Barrier

Statistical analysis of moisture contents inside the barrier for site at RM 256.8, 1996 to 1998, without September 1997 data

Depth	20 inches	27 inches	34 inches	40 inches	46 inches	53 inches	59 inches	66 inches
	53.5	53.8	64.2	70.1	76	76.2		
	38	47.4	66.5	72.9	77.1	77.4	76.4	
	40.5	51.1	67.1	74.3	78.7	78	77.7	82.1
	50.2	53.1	65.6	72.3	78	79.2	78.2	82.5
	37.7	43	64.6	73.3	78.3	79.1	78	82.5
	42.5	52.7	67.9	74.2	78.3	78.7	80.2	
	40.8	51.9	65.4	73.8	77.6	79	79.1	82
Mean	43.31429	50.42857	65.9	72.98571	77.71429	78.22857	78.26667	82.275
Variance	37.6381	15.10571	1.786667	2.128095	0.844762	1.229048	1.662667	0.069167
St. Dev.	6.134989	3.886607	1.336663	1.458799	0.919109	1.108624	1.289444	0.262996

Statistical analysis of moisture contents outside the barrier for site at RM 256.8, 1996 to 1998, without September 1997 data

Depth	56 inches	63 inches	70 inches
	64.3	68	70.8
	46.4	64.5	69.4
	74.1	73.1	73.9
	74.7	74.7	76.5
	72.6	75.5	76.2
	74.9	75.9	77.1
			76.3
Mean	67.83333	71.95	74.31429
Variance	126.1907	21.639	9.451429
St. Dev.	11.23346	4.651774	3.074318

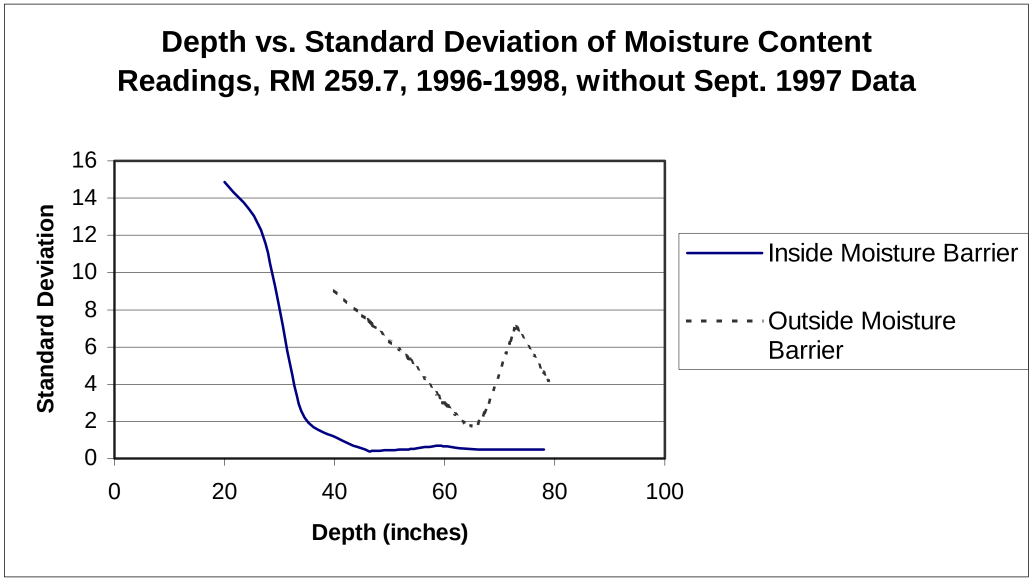

Depth vs. Standard Deviation of Moisture Content Readings, RM 256.8, 1996-1998, without Sept. 1997 Data
Standard Deviation
0
2
4
6
8
10
12
0
20
40
60
80
Depth (inches)
Inside Moisture Barrier
Outside Moisture Barrier

Statistical analysis of moisture contents inside the barrier for site at RM 259.7, 1996 to 1998, without September 1997 data

Depth	20 inches	27 inches	34 inches	40 inches	46 inches	53 inches	59 inches	66 inches	72 inches	78 inches
	53.1	53.1	62.8	70.5	74.6	73.9	73.7	74.1	75.4	75.8
	22.8	49.6	63.3	72.3	74.6	74.2	73.7	73.6	74.9	75.8
	17.5	26.6	61.7	71.6	74.4	74.2	73.8	73.7	75.5	75.5
	44.1	52.8	64.1	72.4	74.8	74.3	74.1	74.4	75.6	76.1
	18.9	26.6	63.1	72.6	74.7	74.2	73.5	74	75.5	76
	48.9	52.8	64.2	69.5	74.3	73.6	73.2	73.3	74.7	75.1
	22.8	50.9	66.9	72.7	73.6	73	71.8	73	74.3	74.8
	21	35	58	72.4	74.9	74.5	73.4	74.2	75.5	76
Mean	31.1375	43.425	63.0125	71.75	74.4875	73.9875	73.4	73.7875	75.175	75.6375
Variance	220.4884	142.9336	6.384107	1.345714	0.166964	0.232679	0.491429	0.226964	0.230714	0.219821
St. Dev.	14.84885	11.95548	2.526679	1.160049	0.408613	0.482368	0.70102	0.476408	0.480327	0.468851

Statistical analysis of moisture contents outside the barrier for site at RM 259.7, 1996 to 1998, without September 1997 data

Depth	40 inches	47 inches	54 inches	60 inches	66 inches	73 inches	79 inches
	64	60.9	67.1	68.4	68.3	55.7	63.2
	41.8	48.4	57.7	64.8	68.8	58	64.8
	67.2	67	72	72.6	73.3	61.5	70.2
	68.4	68.6	73.1	72.6	72	68.7	72
	60	65.3	69.5	71.4	72.7	71.6	71.9
	69.1	68	72.2	72.9	72.3	72.4	72.2
	66.9	67	71.3	71.9	71.4	70	73.6
	66.9	71.1	73.6	73.5	72.9	74.1	74.6
Mean	63.0375	64.5375	69.5625	71.0125	71.4625	66.5	70.3125
Variance	81.97982	51.13125	27.35982	8.735536	3.579821	49.93714	17.01554
St. Dev.	9.054271	7.150612	5.230662	2.955594	1.892042	7.066622	4.124989


Depth vs. Standard Deviation of Moisture Content
Readings, RM 259.7, 1996-1998, without Sept. 1997 Data
Standard Deviation
16
14
12
10
8
6
4
2
0
0
20
40
60
80
100
Depth (inches)
Inside Moisture Barrier
Outside Moisture Barrier

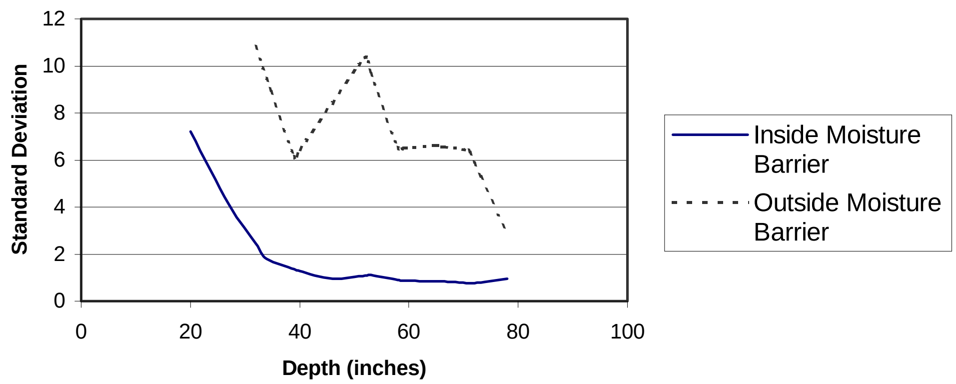
Statistical analysis of moisture contents inside the barrier for site at RM 261.1, 1996 to 1998, without September 1997 data

Depth	20 inches	27 inches	34 inches	40 inches	46 inches	53 inches	59 inches	66 inches	72 inches	78 inches
	26.5	44	63.2	66.6	67	68.9	70.2	69.8	70.7	70.5
	33.1	52.4	67.4	70.4	70.2	71.7	72.5	71.3	72.1	72.2
	28.4	48.9	69	70.6	68.4	70.5	71.1	70.6	71.8	71.7
	31.2	52.1	67.6	69.3	68.5	71.3	72.6	71.1	71.5	71.6
	25.6	44	67.3	70.3	68.9	71.7	72	72	72.9	73.3
	47.5	53.9	67.6	69.2	69.5	72	72.4	71.8	72.6	72.6
	37.7	54.2	67.4	69.2	68.2	71	71.3	70.9	71.4	71.3
	29.2	48.5	69	69.1	69.1	72.5	72.4	72.4	72.8	73.2
Mean	32.4	49.75	67.3125	69.3375	68.725	71.2	71.8125	71.2375	71.975	72.05
Variance	52.18857	16.85429	3.255536	1.605536	0.907857	1.237143	0.74125	0.694107	0.593571	0.928571
St. Dev.	7.224166	4.105397	1.80431	1.267097	0.952815	1.112269	0.860959	0.833131	0.770436	0.963624

Statistical analysis of moisture contents outside the barrier for site at RM 261.1, 1996 to 1998, without September 1997 data

Depth	32 inches	39 inches	52 inches	58 inches	65 inches	71 inches	78 inches
	68.4	67.4	59.9	63.6	63.9	69.3	67.7
	40.8	53.4	42.9	54.6	54.9	53.2	62.1
	70	68.9	71.1	71.1	71.1	71	70.3
	71	70.9	71.6	72.2	73	71.2	69.5
	61.2	66.1	63.4	66.7	63	70.5	69.6
	72.4	73.7	72.5	73.8	73.3	72.2	70.4
	69.8	68.9	70.9	71.2	71.2	71.1	69.4
	73.7	70.5	73.2	72.9	72.4	72.3	66.2
Mean	65.9125	67.475	65.6875	68.2625	67.85	68.85	68.15
Variance	117.067	37.67071	107.467	42.17125	43.64857	40.88286	7.968571
St. Dev.	10.81975	6.137647	10.36663	6.493939	6.606707	6.39397	2.822866

Depth vs. Standard Deviation of Moisture Content Readings, RM 261.1, 1996-1998, without Sept. 1997 Data

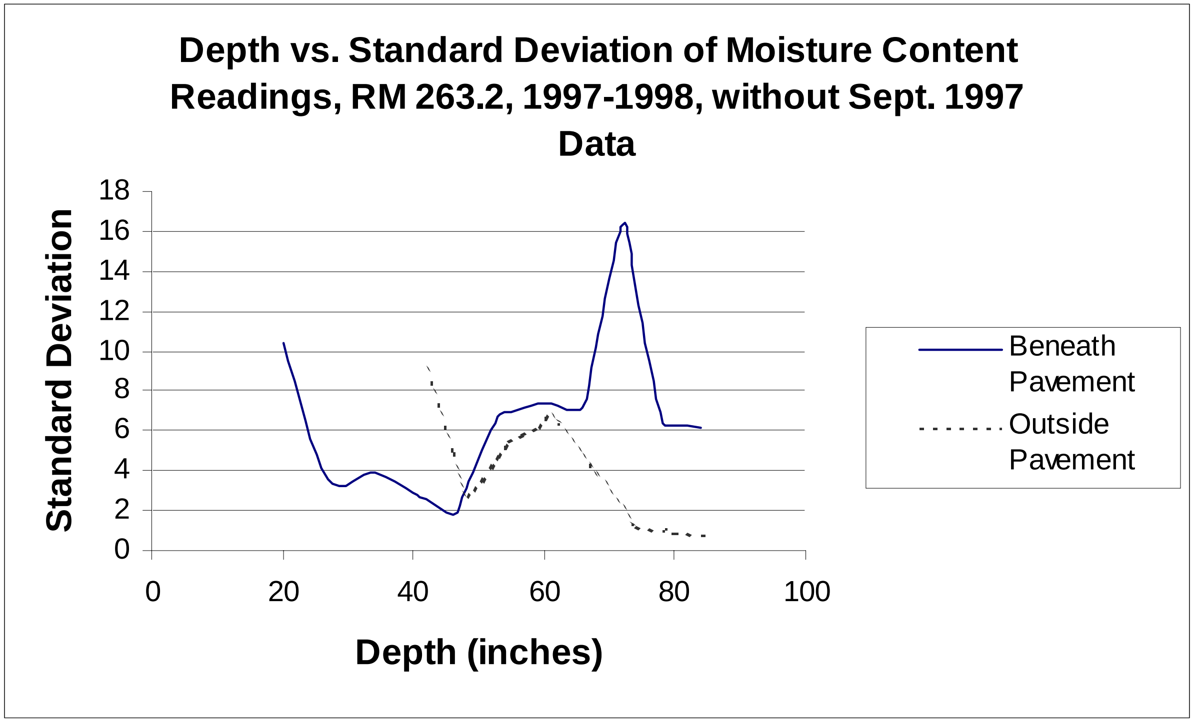


Statistical analysis of moisture contents beneath the pavement for site at RM 263.2, 1997 to 1998, without September 1997 data

Depth	20 inches	27 inches	34 inches	40 inches	46 inches	53 inches	59 inches	66 inches	72 inches	78 inches	84 inches
	70.3	67	61.3	66.4	63.6	58.3	56.3	58.3	41.3	61	58.1
	49.5	59.9	65.7	60.6	63	69.7	68.6	69.2	69.3	71.2	67.5
	59.7	64.2	69.2	64.2	66.3	70.1	69.6	71.7	69.9	72.6	69.8
Mean	59.83333	63.7	65.4	63.73333	64.3	66.03333	64.83333	66.4	60.16667	68.26667	65.13333
Variance	108.1733	12.79	15.67	8.573333	3.09	44.89333	54.86333	50.77	267.0533	40.09333	38.42333
St. Dev.	10.40064	3.576311	3.958535	2.928026	1.75784	6.700249	7.406979	7.125307	16.34177	6.33193	6.198656

Statistical analysis of moisture contents outside the barrier for site at RM 263.2, 1997 to 1998, without September 1997 data

Depth	42 inches	48 inches	55 inches	61 inches	68 inches	74 inches	80 inches	86 inches
	53.2	61.8	66.5	61.6	67.1	71.2	72	72.3
	68	66.9	62	73	73.5	73	72.5	73.4
	69.8	65.9	73	73.4	74	73.6	73.7	73.5
Mean	63.66667	64.86667	67.16667	69.33333	71.53333	72.6	72.73333	73.06667
Variance	82.97333	7.303333	30.58333	44.89333	14.80333	1.56	0.763333	0.443333
St. Dev.	9.10897	2.702468	5.53022	6.700249	3.84751	1.249	0.873689	0.665833


Depth vs. Standard Deviation of Moisture Content Readings, RM 263.2, 1997-1998, without Sept. 1997 Data
Standard Deviation
0
2
4
6
8
10
12
14
16
18
0
20
40
60
80
100
Depth (inches)
Beneath Pavement
Outside Pavement

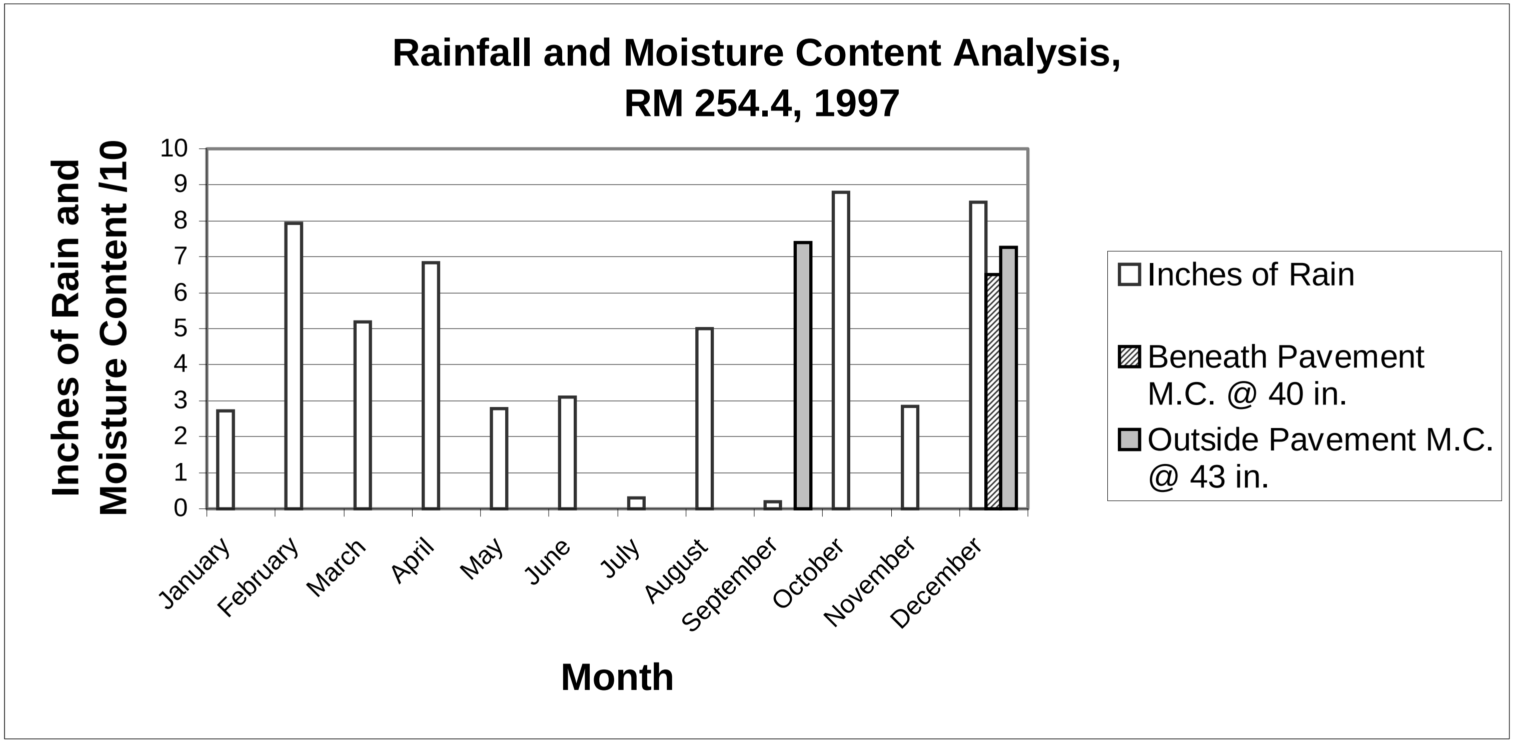
APPENDIX D

ANALYSIS OF THE RELATIONSHIP BETWEEN RAINFALL AND SOIL MOISTURE TRENDS

Monthly Inches of Rainfall in Ennis, TX,
1988-September 1998

Month	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
January	.50	3.37	11.86	5.05	4.80	3.47	1.58	3.99	1.25	2.72	6.62
February	3.08	3.71	4.46	3.17	3.51	5.09	3.91	.42	.55	7.94	3.23
March	3.54	4.36	6.54	1.33	1.20	3.74	4.01	4.60	.80	5.20	3.67
April	.98	3.51	2.13	2.17	2.61	6.13	3.73	7.40	4.23	6.84	1.68
May	2.54	8.10	4.05	1.94	3.55	2.59	6.52	6.56	.32	2.79	.57
June	1.72	4.81	1.38	2.13	2.39	6.82	2.77	3.00	2.02	3.10	.98
July	1.42	1.72	2.42	3.30	2.95	0.00	4.83	2.95	7.10	.30	.09
August	.44	3.20	1.62	4.84	5.07	.40	1.15	.92	8.16	5.00	4.69
September	4.05	4.06	2.57	2.50	3.66	3.20	2.78	3.25	2.92	.20	6.68
October	.93	1.57	1.30	4.98	7.22	12.84	10.63	1.03	2.90	8.79	N/A
November	3.89	.77	4.57	2.17	2.95	2.87	5.87	.42	5.71	2.84	N/A
December	2.47	.09	1.10	8.83	9.43	1.96	6.56	1.77	2.20	8.52	N/A

Source: Texas Climatological Data; Ronny G. Vestal


Rainfall and Moisture Content Analysis,
RM 254.4, 1997
Inches of Rain and
Moisture Content /10
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January
February
March
April
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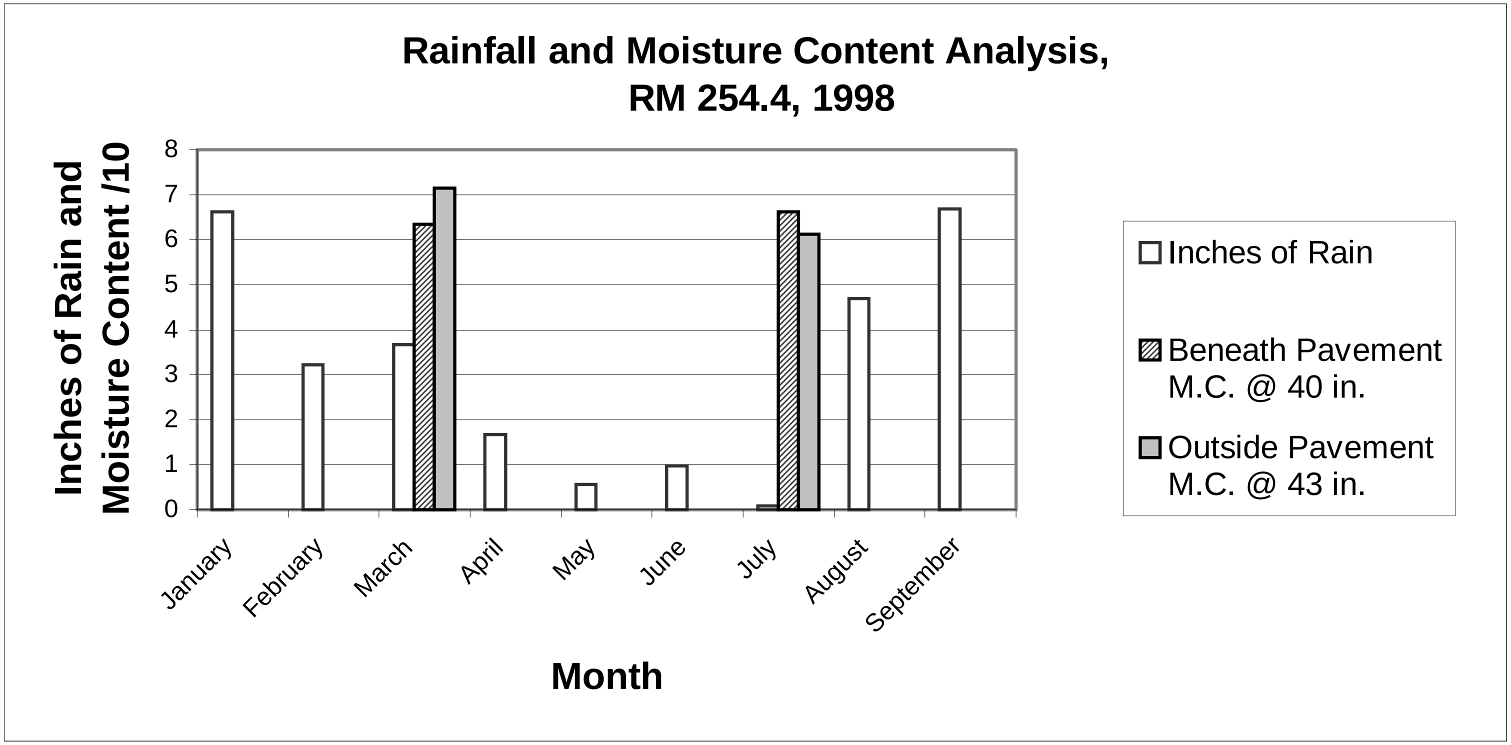
September
October
November
December
Month
Inches of Rain
Beneath Pavement M.C. @ 40 in.
Outside Pavement M.C. @ 43 in.


Rainfall and Moisture Content Analysis,
RM 254.4, 1998
Inches of Rain and Moisture Content /10
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January
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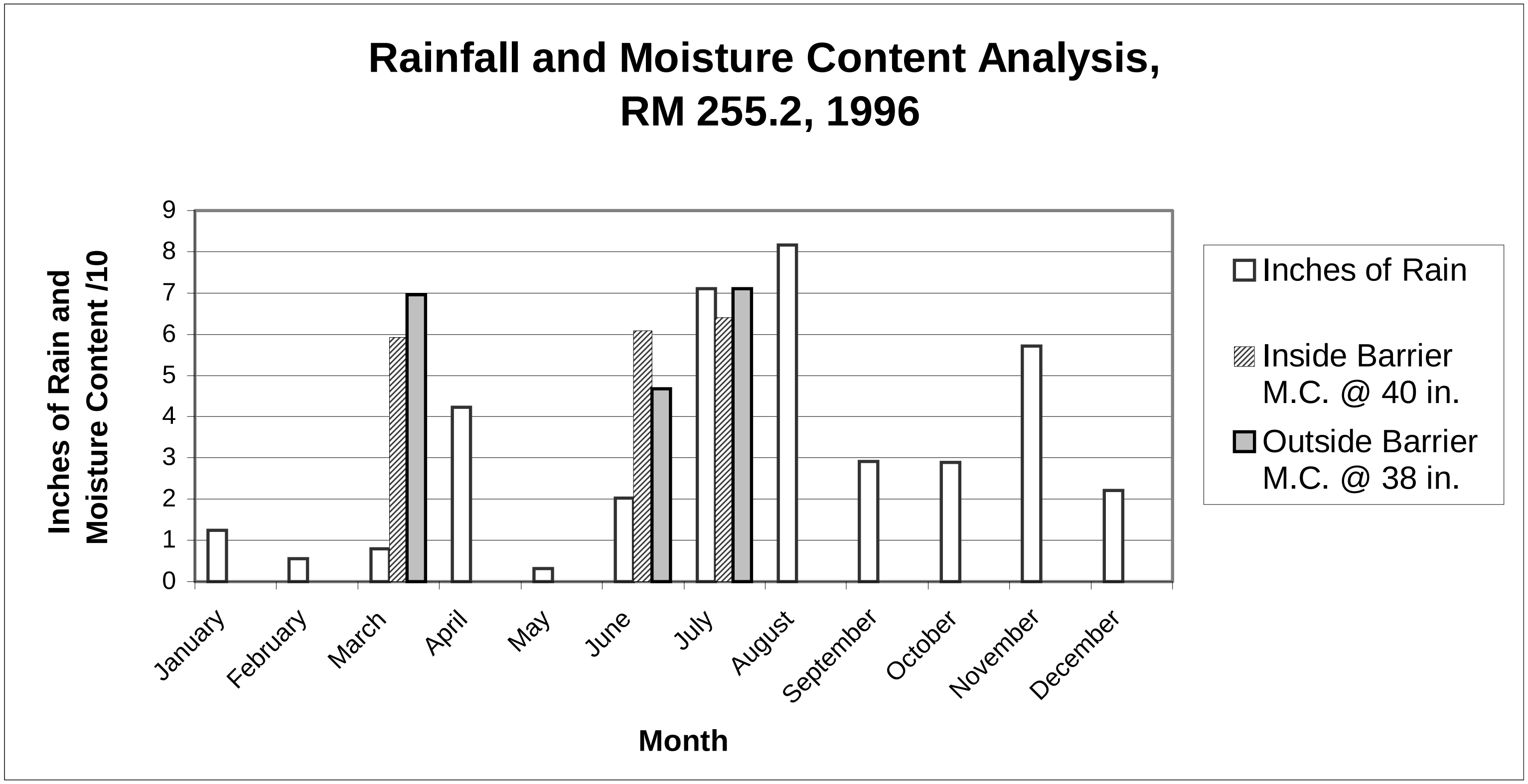
Month
Inches of Rain
Beneath Pavement M.C. @ 40 in.
Outside Pavement M.C. @ 43 in.


Rainfall and Moisture Content Analysis,
RM 255.2, 1996
Inches of Rain and
Moisture Content /10
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January
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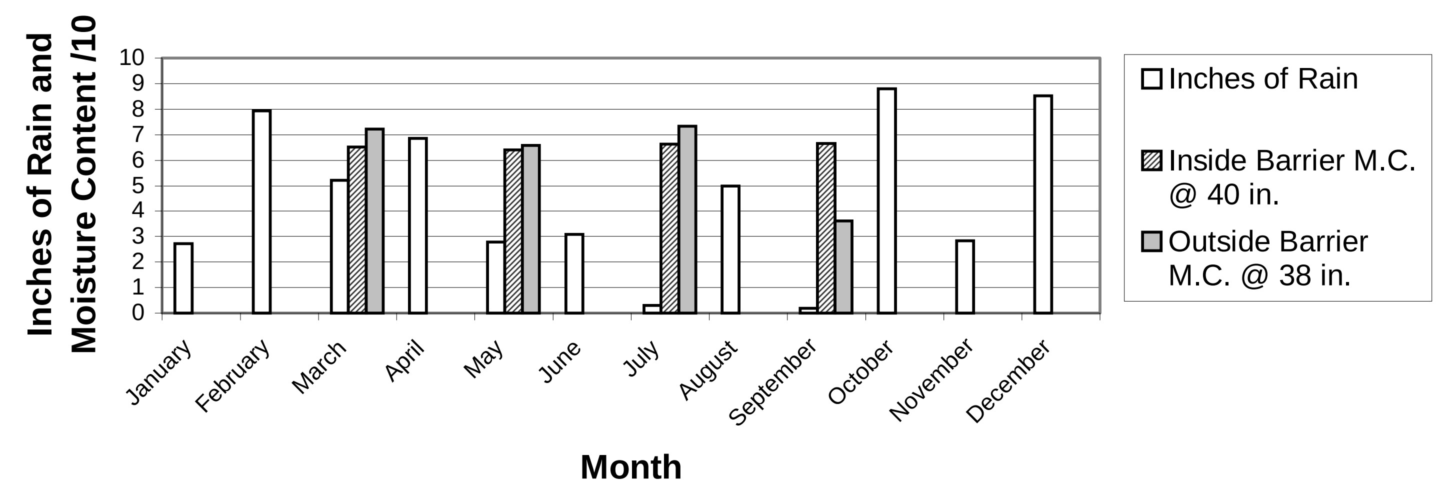
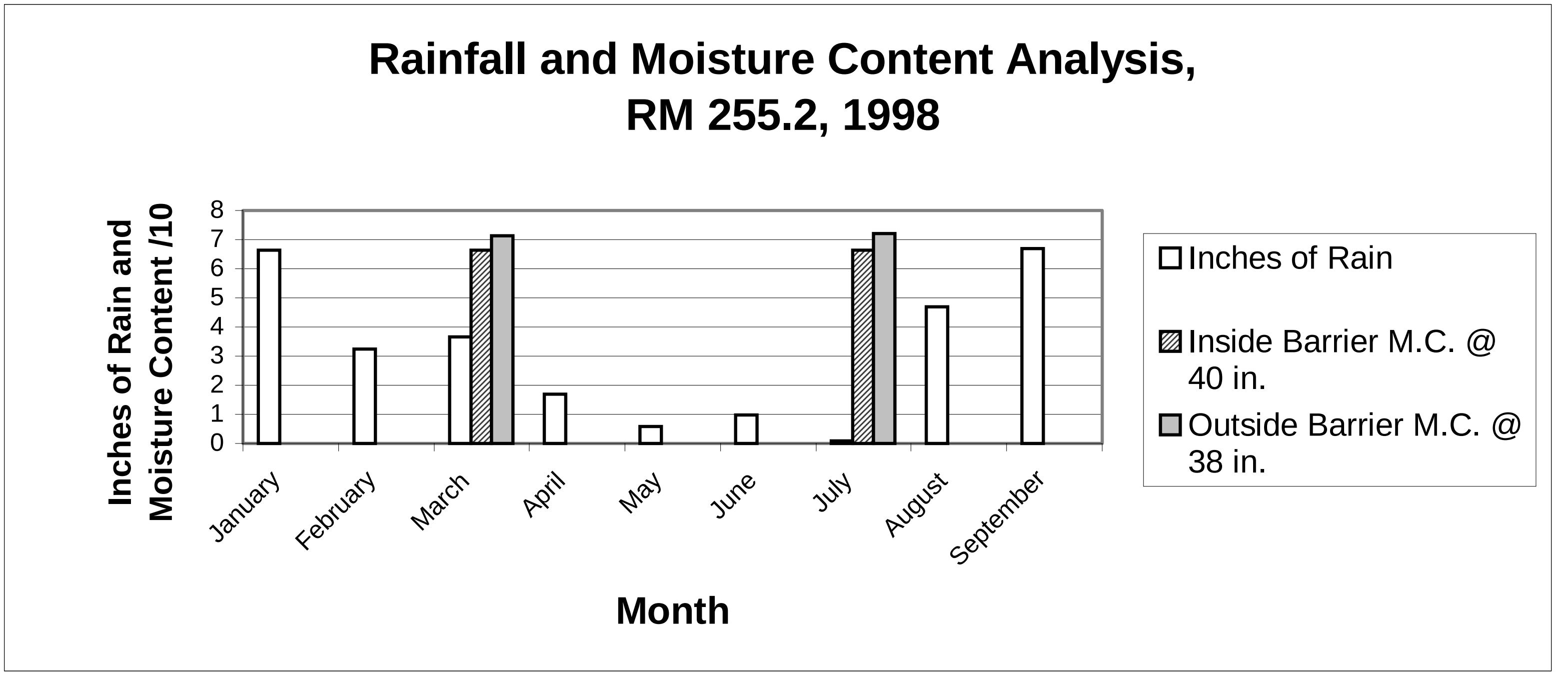
Month
Inches of Rain
Inside Barrier
M.C. @ 40 in.
Outside Barrier
M.C. @ 38 in.



Rainfall and Moisture Content Analysis, RM 255.2, 1997


Rainfall and Moisture Content Analysis,
RM 255.2, 1998
Inches of Rain and Moisture Content /10
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January
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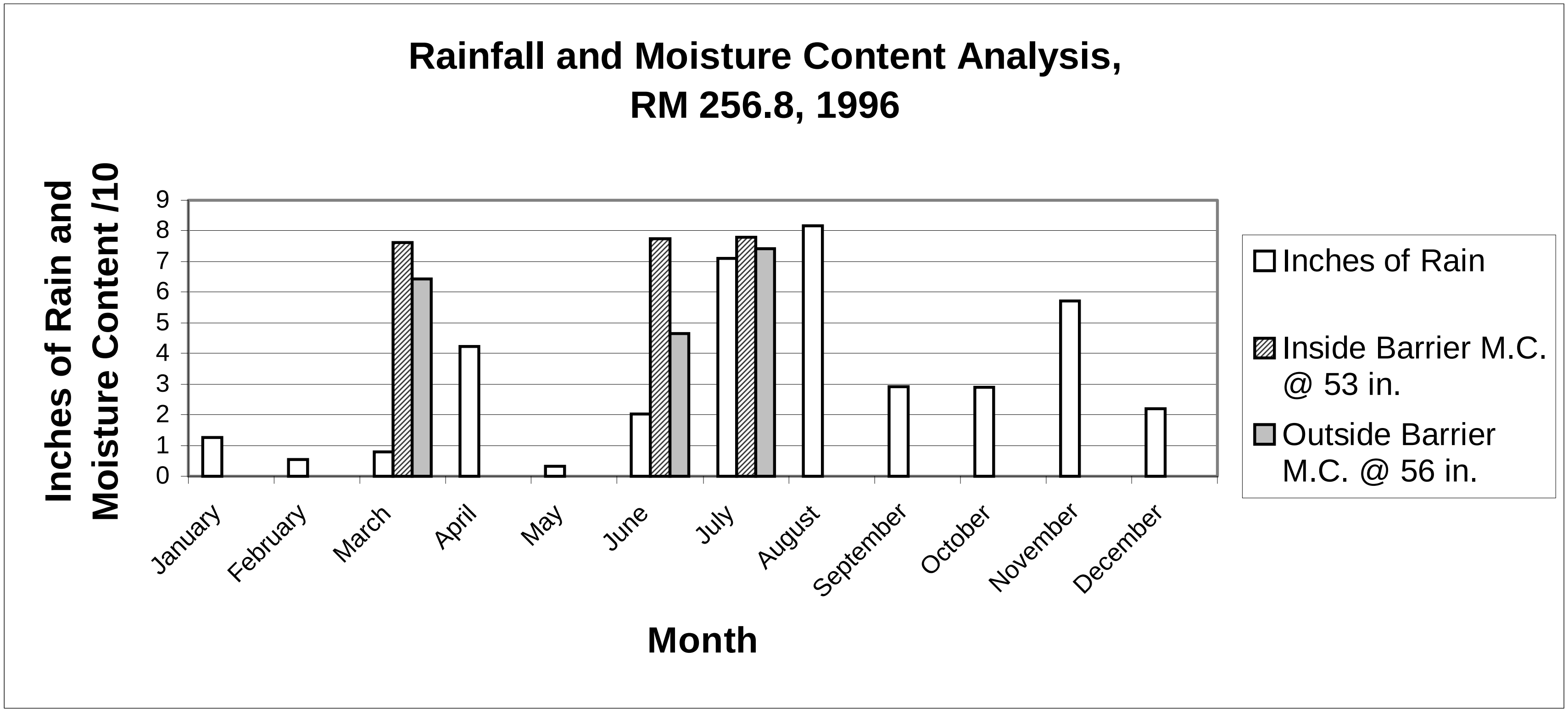
Month
Inches of Rain
Inside Barrier M.C. @ 40 in.
Outside Barrier M.C. @ 38 in.



Rainfall and Moisture Content Analysis,
RM 256.8, 1996
Inches of Rain and Moisture Content /10
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January
February
March
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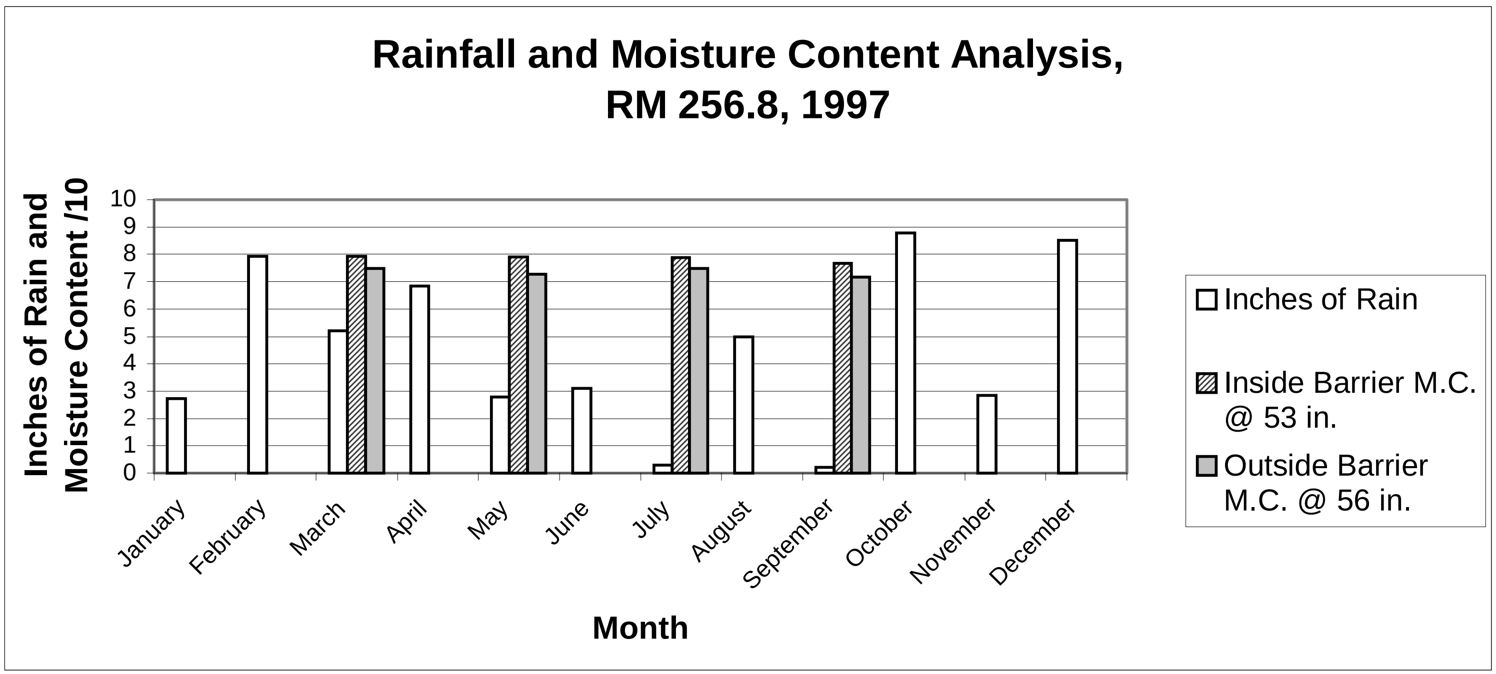
November
December
Month
Inches of Rain
Inside Barrier M.C. @ 53 in.
Outside Barrier M.C. @ 56 in.


Rainfall and Moisture Content Analysis,
RM 256.8, 1997
Inches of Rain and
Moisture Content /10
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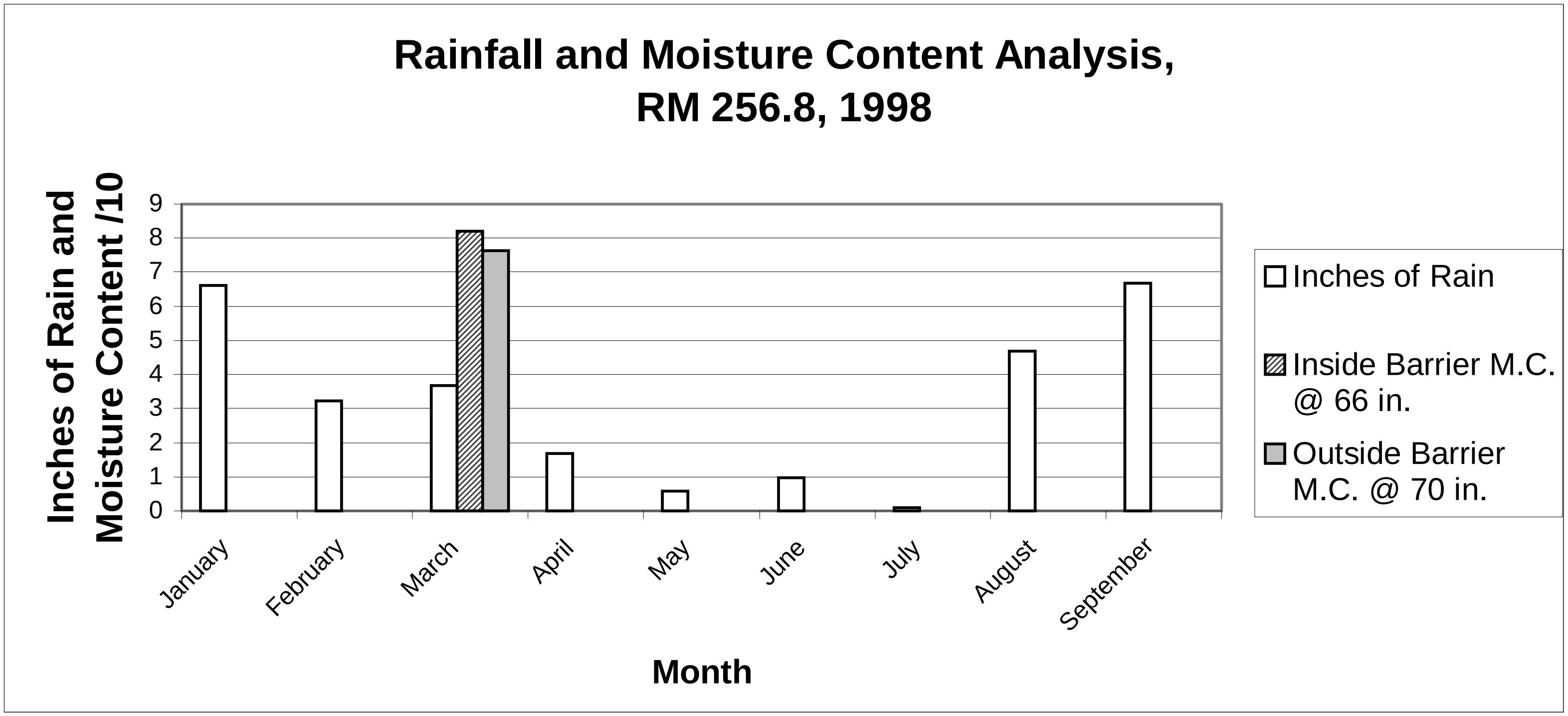
Month
Inches of Rain
Inside Barrier M.C. @ 53 in.
Outside Barrier M.C. @ 56 in.


Rainfall and Moisture Content Analysis,
RM 256.8, 1998
Inches of Rain and
Moisture Content /10
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January
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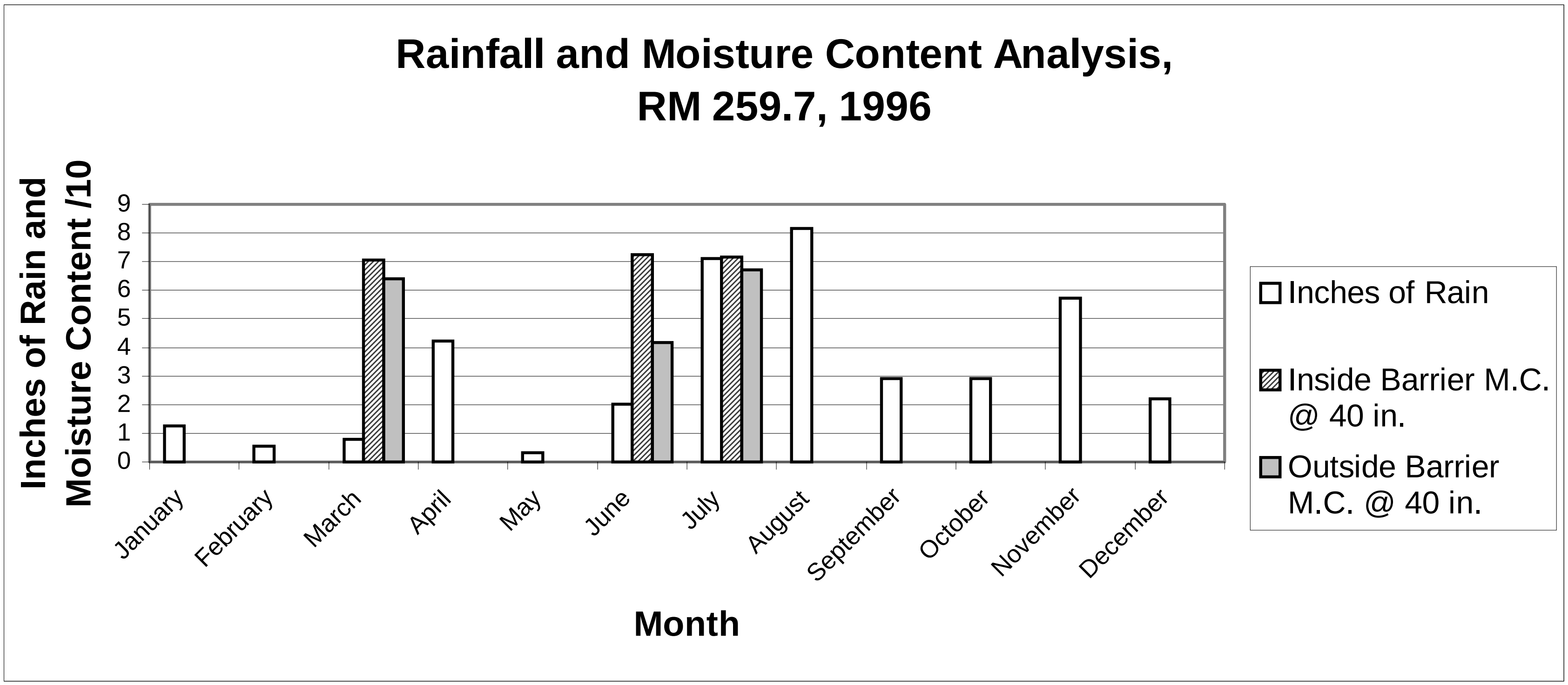
Month
Inches of Rain
Inside Barrier M.C. @ 66 in.
Outside Barrier M.C. @ 70 in.



Rainfall and Moisture Content Analysis, RM 259.7, 1996
Inches of Rain and Moisture Content /10
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January
February
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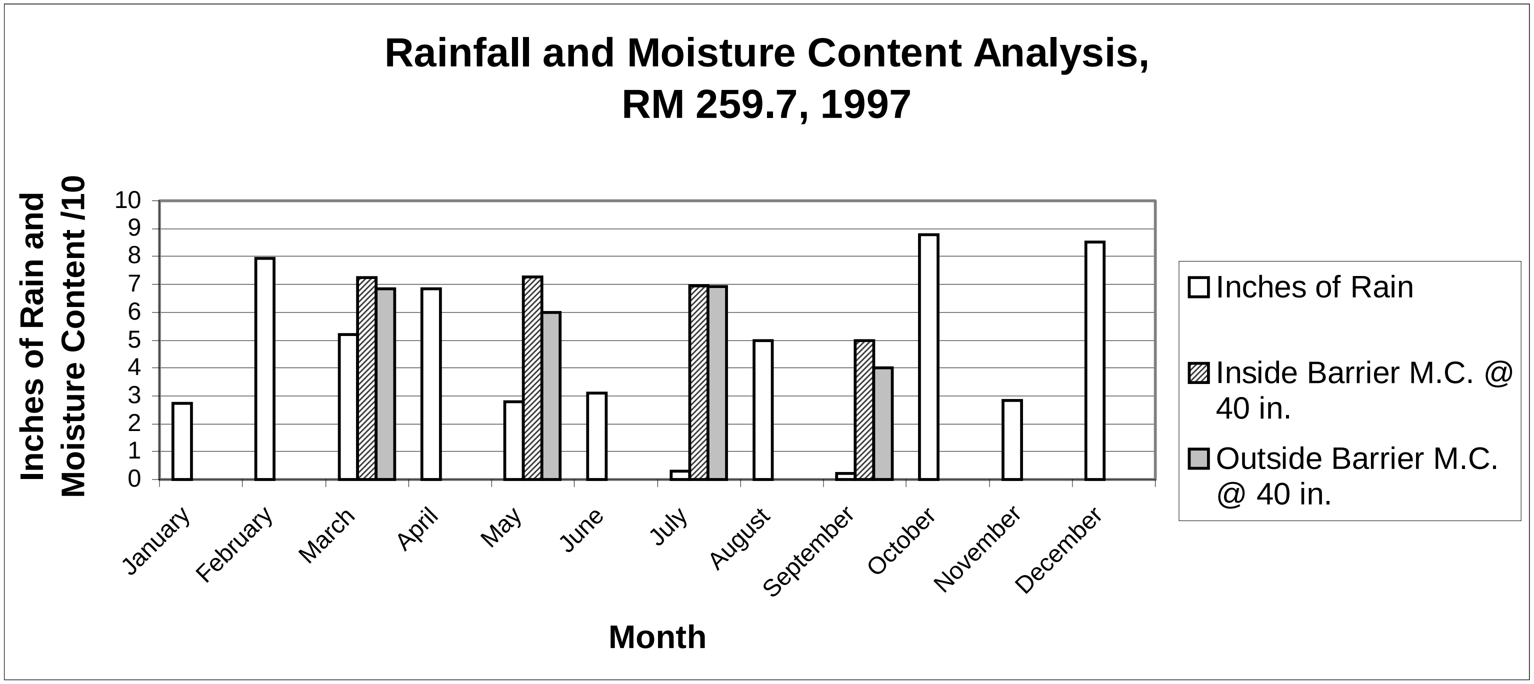
November
December
Month
Inches of Rain
Inside Barrier M.C. @ 40 in.
Outside Barrier M.C. @ 40 in.


Rainfall and Moisture Content Analysis,
RM 259.7, 1997
Inches of Rain and Moisture Content /10
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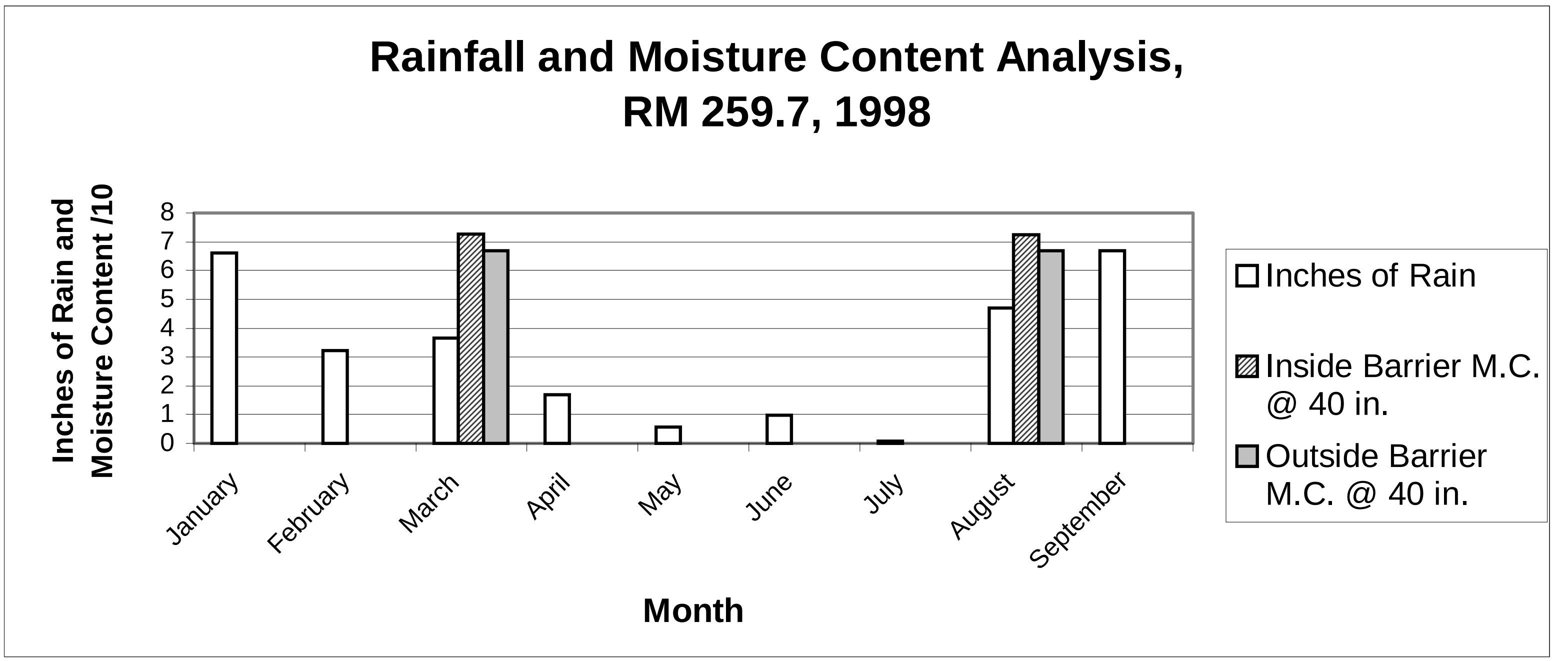
Month
Inches of Rain
Inside Barrier M.C. @ 40 in.
Outside Barrier M.C. @ 40 in.


Rainfall and Moisture Content Analysis,
RM 259.7, 1998
Inches of Rain and
Moisture Content /10
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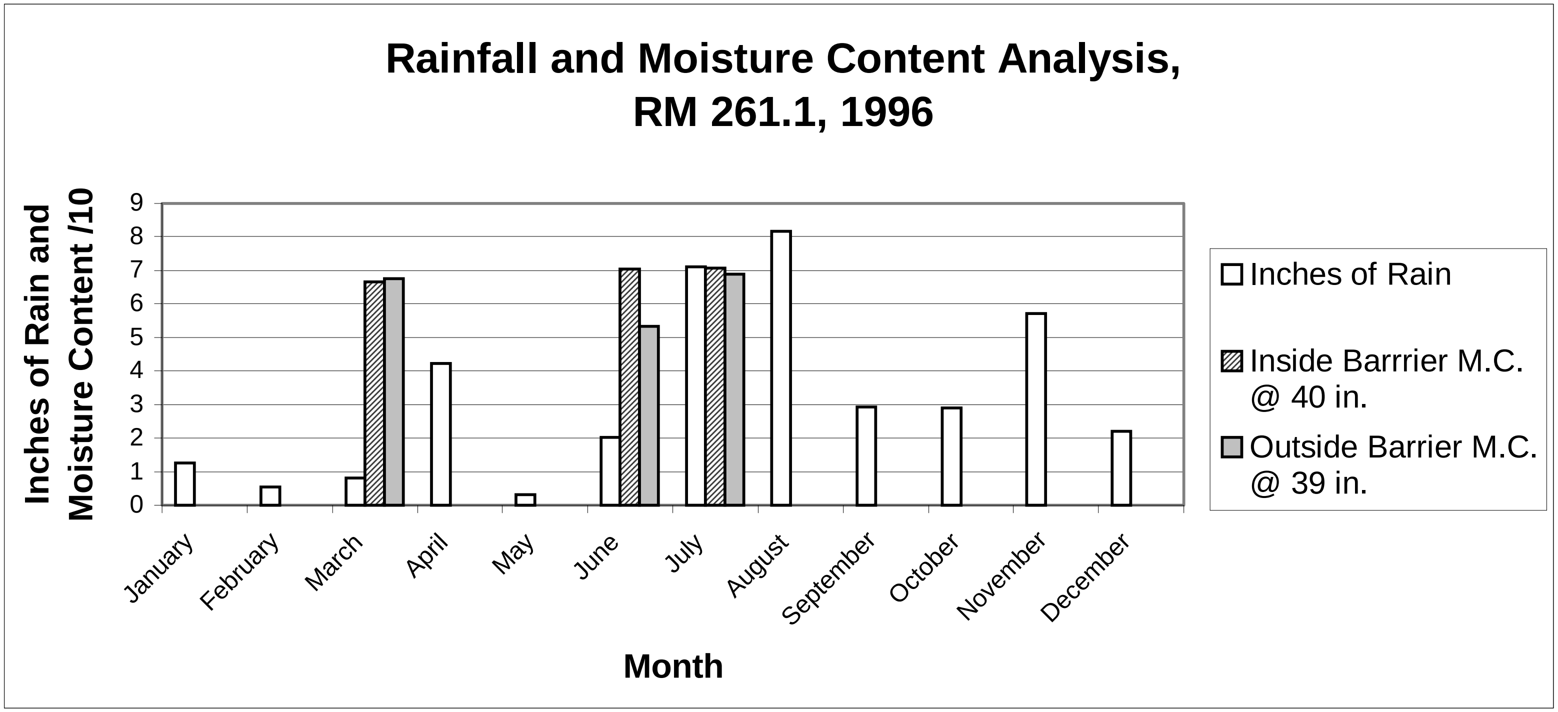
Month
Inches of Rain
Inside Barrier M.C. @ 40 in.
Outside Barrier M.C. @ 40 in.



Rainfall and Moisture Content Analysis,
RM 261.1, 1996
Inches of Rain and Moisture Content /10
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January
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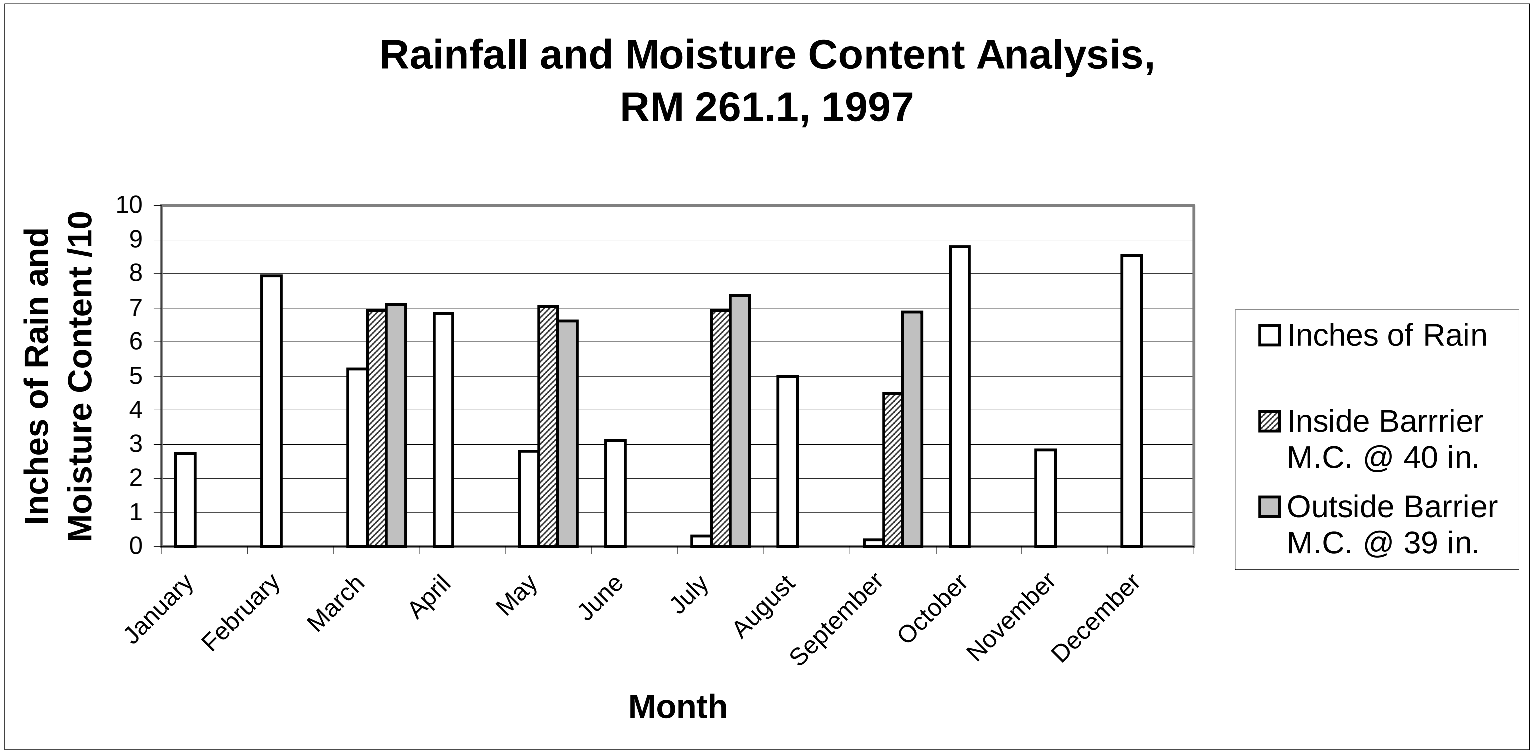
Month
Inches of Rain
Inside Barrrier M.C. @ 40 in.
Outside Barrier M.C. @ 39 in.


Rainfall and Moisture Content Analysis,
RM 261.1, 1997
Inches of Rain and Moisture Content /10
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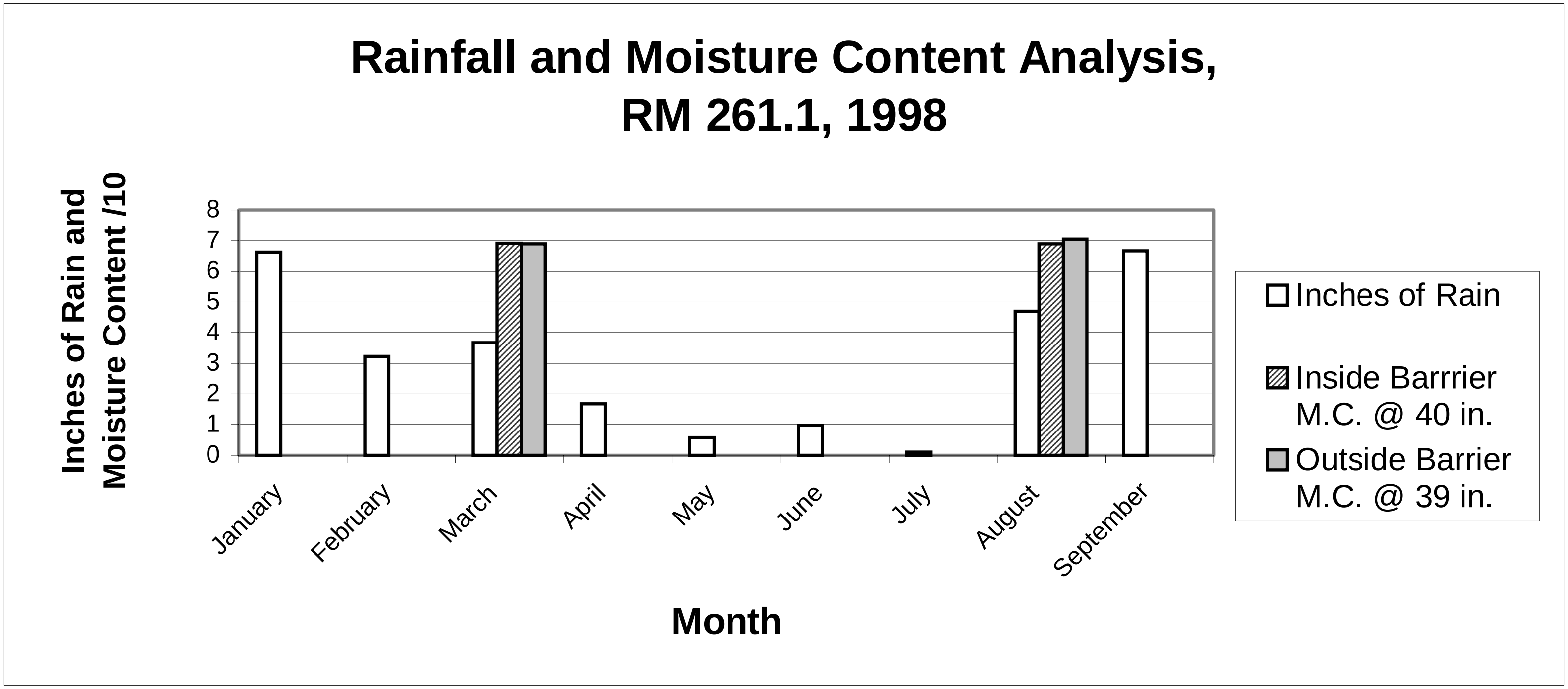
Inches of Rain
Inside Barrrier M.C. @ 40 in.
Outside Barrier M.C. @ 39 in.


Rainfall and Moisture Content Analysis,
RM 261.1, 1998
Inches of Rain and
Moisture Content /10
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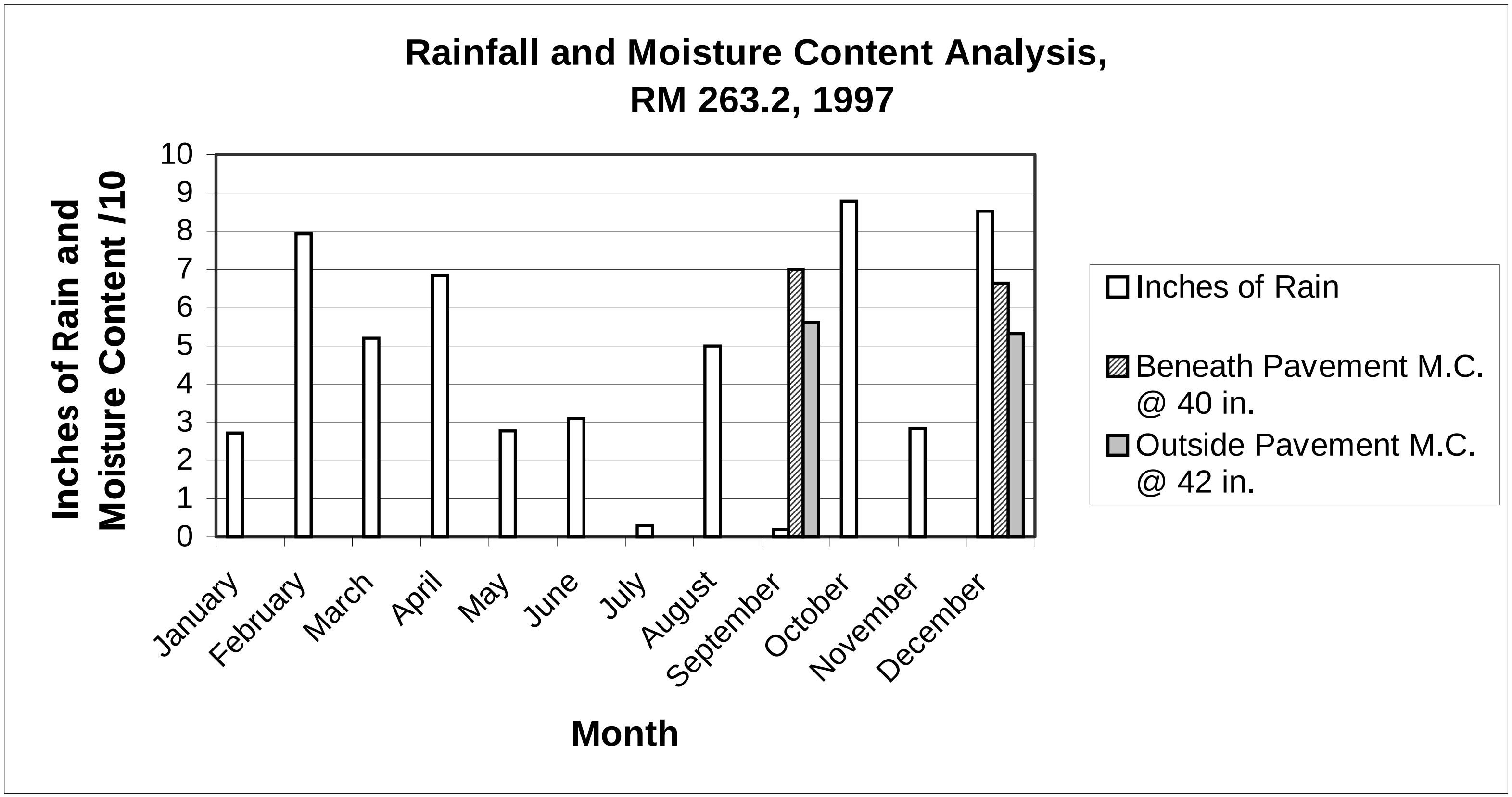
Inches of Rain
Inside Barrrier
M.C. @ 40 in.
Outside Barrier
M.C. @ 39 in.


Rainfall and Moisture Content Analysis,
RM 263.2, 1997
Inches of Rain and
Moisture Content /10
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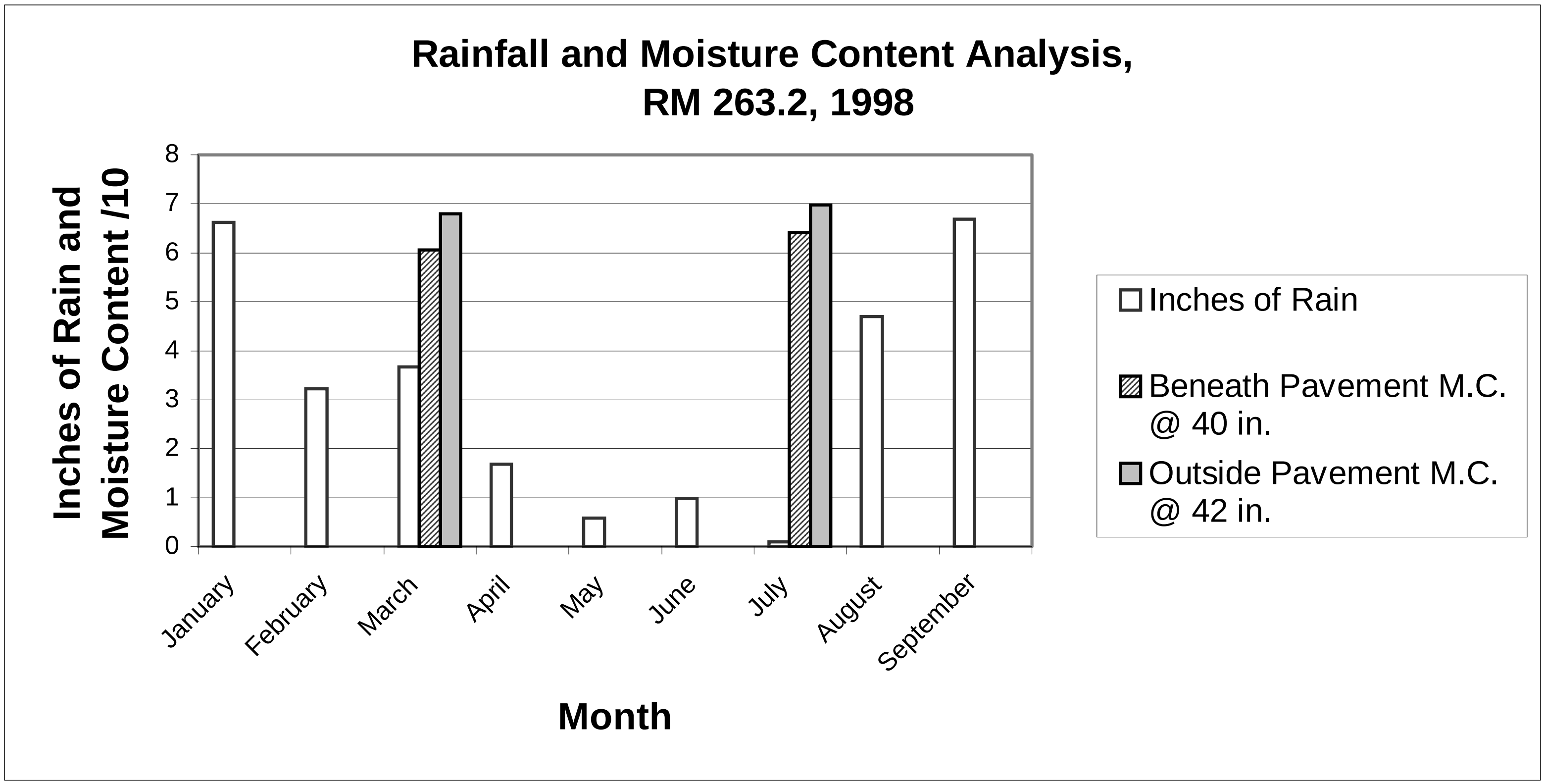
Month
Inches of Rain
Beneath Pavement M.C. @ 40 in.
Outside Pavement M.C. @ 42 in.


Rainfall and Moisture Content Analysis,
RM 263.2, 1998
Inches of Rain and Moisture Content /10
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January
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Month
Inches of Rain
Beneath Pavement M.C. @ 40 in.
Outside Pavement M.C. @ 42 in.