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Evaluation Of Non-Nuclear Devices In Measuring Moisture Content And Density Of Soils

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by

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THESIS

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Abstract

The objective of this report was to assess the ability of several different devices to measure moisture content and dry density of various compacted geomaterials. The experimental research involved the testing of different subgrade soils and one base material. More than a dozen specimens, 2 ft in height and 1.5 ft in diameter, were constructed to evaluate the Transtech SDG 200, Purdue TDR, and the Decagon 10 HS moisture content sensor. The Speedy Moisture Tester and DOT600 Roadbed Water Content Meter were also evaluated using individual soil samples. All materials were tested at five different moisture contents, but at their corresponding maximum dry densities.

The Transtech SDG 200 and Purdue TDR estimate both the moisture content and dry density. Conversely, the DOT600 Meter, Speedy Moisture Tester, and the Decagon 10 HS Sensor only estimate the moisture content. The estimated quantities of each device were compared with oven-dry moisture contents measured from samples extracted from each specimen.

Overall, the Purdue TDR was slightly more accurate in determining the moisture content and dry density of the materials tested, when compared to the SDG 200. The Speedy Moisture Tester was the most accurate in determining the moisture content, while the DOT600 Meter overestimated or underestimated the moisture content for a majority of the specimens.

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Chapter 1: Introduction

Moisture content and density are important soil properties which are monitored during construction of pavements or other types of transportation infrastructure. Density and/or moisture content of soils are used as quality control/quality assurance items in demonstrating that proper construction was performed. Therefore, accurate readings of these soil properties are necessary in many construction projects involving earthwork.

Several field and laboratory devices are available for estimating the moisture content and/or density of geomaterials. Soil parameters and calibration procedures required for accurate measurements for each device vary. The required set-up and the time necessary for obtaining these soil parameters also vary. In this paper, five devices will be described and their corresponding performance evaluation on various soils will be discussed.

1.1 Objective

The main objectives of this research were the following items:

- Document device accuracy related to moisture content and dry density readings
- Compare the performance of different devices with different soil types, and
- Provide recommendation on most suitable device(s)

1.2 Organization of Report

This report has been divided into six chapters. Chapter 1 includes the introduction of objectives, and scope of work. Chapter 2 contains a review of relevant literature regarding non-nuclear moisture/density studies. That chapter also contains an overview of the devices used in

this particular study and other devices available for moisture content measurements. Chapter 3 illustrates the experimental design and describes the geomaterials tested. That chapter also explains the experimental approach along with testing protocols. Chapter 4 explains the data analysis procedures for all devices studied. Chapter 5 contains performance evaluations of all devices. Chapter 6 presents the conclusions and recommendations of this study. All supporting test data and additional graphical plots are included in the appendices.

Chapter 2: Background

INTRODUCTION

Numerous devices that are capable of measuring moisture content and density of geomaterials are currently available. Based on their principles of operation, these devices may be grouped into electrical conductivity, dielectric permittivity, gravimetric, chemical, and suction. Devices from each of these categories will be discussed in the subsequent paragraphs. Additionally, relevant studies corresponding to the devices used will be noted.

2.1 Electrical Conductivity Devices

These devices operate on the premise of an alternating current voltage that is measured in a porous material in contact with soil (Evett et al. 2008). The magnitude of this current is a measure of the conductivity and the amount of water in the porous material. Two devices which use electrical conductivity to determine moisture content are the Veris Technologies mapping system devices and the Geonics EM38-MK2 (both are shown in Figure 2.1). Both devices are effective in determining variances in salt or mineralogy content of soils.

Figure 2.1 – Geonics EM38-MK2 (left) and a Veris Technologies device (right)

2.2 Dielectric Permittivity Devices

These devices transmit radio frequency energy through tapered darts driven into the soil in a specific geometry. They then analyze the radio frequency transmitted through the soil to produce a soil dielectric constant (Berney et al. 2011). The dielectric constant is then converted into a density and moisture content, based upon a comparison with results from a calibration soil model. This model is constructed in the field through readings of the material when uncompacted and dry, uncompacted and saturated, compacted and dry, and compacted and saturated. The Humboldt Electrical Density Gauge (EDG), shown in Figure 2.2, falls into this category.

Figure 2.2 – Humboldt EDG

2.2.1 Frequency Domain Reflectometry

Frequency domain reflectometry (FDR) devices use the electrical capacitance of a capacitor to determine moisture content. The capacitor uses soil as a dielectric and is connected to an oscillator to form an electrical circuit. Changes in soil moisture can be detected by changes in the circuit operating frequency (Munoz-Carpena 2004). The oscillator frequency is varied

within a certain frequency range to estimate a resonant frequency. This frequency is a measure of moisture content in the soil.

Devices that use FDR technology include the Sentek EnviroSCAN and Vertek SMR (shown in Figure 2.3). The Sentek EnviroSCAN allows for measurements of volumetric moisture content at multiple depths. The Vertek SMR probe is simple and fast. However, this device is disadvantageous in that its durability is questionable.

Figure 2.3 – Sentek EnviroSCAN (left) and Vertek SMR (right)

2.2.2 Time Domain Reflectometry

Time domain reflectometry involves the use of dielectric permittivity to determine moisture content. The details of this method are described in a subsequent section. Among the devices using this method is the Campbell Scientific TDR, which allows for fast and simple multi-depth measurements. This device is limited to volumetric moisture content measurements. The Waterscout Soil Moisture Meter and Dynamax TR-100 are other devices and are illustrated in Figure 2.4. The Waterscout Soil Moisture Meter requires good soil contact for operation. The Dynamax TR-100 is limited to volumetric moisture content and is built for field study. A couple other TDR devices as illustrated in Figure 2.5 are the Adek Down Hole Dielectric Probe and the AquaPro Moisture Probe. The Adek Down Hole Dielectric Probe is fast and simple, but must be

calibrated to the soil being tested. The AquaPro Moisture Probe is accurate, however not feasible in quality control circumstances.

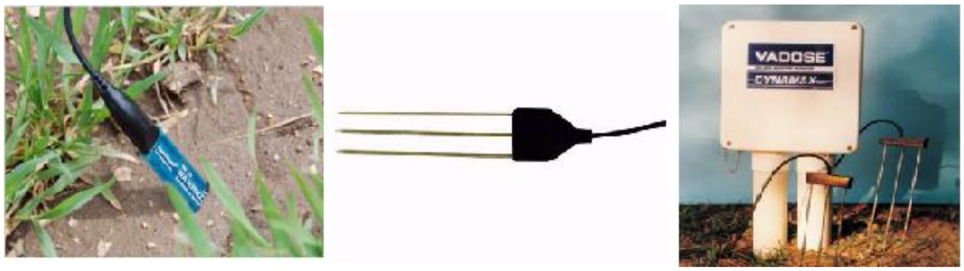

Figure 2.4 – Waterscout Soil Moisture Meter, Campbell Scientific TDR probe, and Dynamax TR-100 Probe (left to right)

Figure 2.5 – Adek Down Hole Dielectric Probe (left) and AquaPro Moisture Probe (right)

Two other devices are the Aquaflex soil moisture meter and the Decagon 5TE. The Aquaflex is able to measure temperature in addition to moisture and is confined to coarse-grained materials. The Decagon 5TE is easy to transport, simple to install, and sensitive to soil mineralogy. Both devices are shown in Figure 2.6.

Figure 2.6 – Aquaflex meter (left) and Decagon 5TE (right)

2.3 Gravimetric Devices

These devices determine moisture contents via determination of the mass of a sample and application of energy to initiate evaporation of free water. The mass of a dried sample is obtained and an equation relating the mass of water to mass of soil is used to obtain moisture content. First on this list is oven-drying, which is regarded as a ground truth and will be used as the reference moisture content in this study.

Microwave oven moisture content requires a shorter test time than oven-dry, however it works best with a constant power source (Berney et al. 2011). In this method, a sample is continuously heated and weighted at 1-min intervals until a minimal change in total mass between readings is observed. At this point, a dried sample is achieved and moisture content may be determined via comparison with the moist sample.

The Moisture Analyzer (shown in Figure 2.7) also requires a shorter test time than the oven-dry method. These types of devices utilize a ceramic heating element to heat and consequently dry a soil sample. Soil samples are enclosed in a disposable dish which is exposed to the heating element. The device will continuously record the mass of the soil during the drying process and will determine moisture content once the mass reaches a steady-state value. Calibration is normally performed with a weight of a given magnitude, and involves the

adjustment of the measured value displayed to the true weight of a sample. Additional calibration may be performed on the temperature settings of the drying unit, in order to confirm that the device heating temperature is actually meeting the set or desired temperature.

Figure 2.7 – Moisture Analyzer

2.3.1 Other Moisture Analyzer Devices

Two devices that require a matter seconds for measurements are the Sartorius LMA300P and the Sartorius LMA500. Both require calibration and are non-destructive. The Sartorius LMA500 uses spectroscopy to obtain moisture contents. This device subjects a sample to near infrared light, and changes to this light upon interaction with the sample are characterized. The change in the light is associated with the amount of water in the sample and allows for moisture content determination.

The Sartorius LMA300P incorporates microwave resonance technology to attain moisture contents. The resonance of the microwave is hindered by the water within a sample that is inserted into this device. The moisture level in the sample is related to the alteration in the characteristics of the resonance frequency peak.

Figure 2.8 – Sartorius LMA500 (top) and Sartorius LMA300P (bottom)

2.4 Chemical Devices

One of the devices in this group is the Speedy Moisture Tester. This device is fairly simple to use. This device is described in further detail later in this chapter.

2.5 Suction Devices

Suction measuring devices fall under several categories. Several devices in this group operate under the principle that the thermal conductivity of water produces heat dissipation, so that a dry material will heat up faster than a wet one (Munoz-Carpena 2004). These devices typically consist of a porous block containing a heat source and temperature sensor. The heat flow in a porous material is proportional to its moisture content. The Decagon WP4C and the Fredlund Thermal Conductivity Sensor (FTC-100) are two examples of these sensors (shown in Figure 2.9). The block temperature is obtained before and after the heat source is powered for

several seconds. This procedure allows for the block moisture to be determined via the temperature variation. Calibration of these devices involves the laboratory measurement of the temperature difference before and after heating for several suction values. This information is transferred into a calibration curve, which is then used to determine suction values in the field. The WP4C is limited to a suction range of 1–3000 kPa, while the FTC-100 has a range between 1-1000 kPa.

Figure 2.9 – Fredlund Thermal Conductivity Sensor and Decagon WP4C

Other devices which lie under this category are tensiometers, which measure moisture content through tension or pressure. A miniature tensiometer is shown in Figure 2.10. These devices behave in a manner similar to a plant root measuring the force that plants have to exert to obtain moisture from the soil (ICT 227). A tensiometer will lose water into a ceramic cup as a soil dries. This process invokes a vacuum within the tensiometer and a pressure reading is recorded. The pressure reading will increase in drier soils. Many tensiometers exist that are relatively inexpensive, but with a limited range in suction (up to 100 kPa).

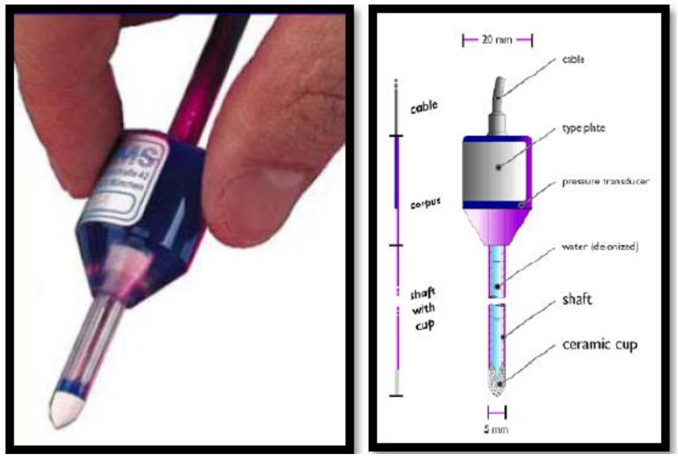

Figure 2.10 – Miniature Tensiometer

The High Capacity Tensiometer may be used for suction reading between 1-1500 kPa. The Capacitive Hygrometer (0-10,000 kPa), and Equitensiometer (10,000-400,000) provide an even greater range for suction measurements. These two devices are shown in Figure 2.11.

Figure 2.11 – Equitensiometer (left) and Capacitive Hygrometer (right)

2.6 Purdue TDR

In this study, the Purdue TDR (PMTDR, Figure 2.12) was used as the time domain reflectometry method of obtaining soil properties. This method provides a density and moisture

content through the measurement of the apparent dielectric constant of the soil being tested. A TDR device applies a stepped pulse of 0.25 volts for up to 14 microseconds to determine the dielectric constant. The TDR device is attached to a coaxial cable which is connected to a specially designed probe. This probe simulates a coaxial cable where the insulating medium is soil. The applied voltage travels through the soil at a velocity proportional to the dielectric constant of the soil. When the wave reaches the end of the probe, it reflects back through the probe and then back through the cable into the TDR instrument. The TDR converts time to distance traveled, in order to establish the relationship which determines the dielectric constant.

Figure 2.12 – Purdue TDR Device

The program accompanying the PMTDR uses soil specific calibration constants along with the dielectric constant to produce dry density and moisture content readings. These calibration constants are obtained once a user attains dielectric constant and electrical conductivity readings on soil specimens, which are then entered into an accompanying software program that generates the constants.

Diefenderfer et al. (2000) considered two time domain reflectometry (TDR) probes in a study to determine the most suitable device for obtaining moisture content. The measurements attained from the probes were compared with the measured gravimetric moisture content. The moisture contents from both probes appeared to be affected by the composition of the pavement structure.

Kestler et al. (2001) studied the ability of TDR and radio-frequency (RF) sensors to measure moisture contents in base and subgrade materials within a forest road network. They reported that both sensors were reasonably accurate, repeatable in determining moisture contents, and were durable under adverse freeze-thaw cycles. However, the field survival rate of the TDR sensors was better.

Huisman et al. (2001) examined the accuracy of the time-domain-reflectometry in comparison with ground penetrating radar (GPR) moisture content readings. Results indicated that calibration equations obtained via TDR measurements were comparable to those from GPR measurements and aggregated gravimetrical soil moisture content. They proposed that one might use available TDR calibrations for GPR measurements within a material range between sand to loam.

Yu and Drnevich (2004) developed a procedure utilizing TDR to measure moisture content in stabilized soils. The tests provided accurate measurements for moisture content and dry density of soils treated with fly ashes, lime, and a low permeability cementitious material (LPC). Additionally, the TDR measured electrical conductivity was a good indicator of the hydration process which occurs in stabilized soils.

Rao and Singh (2011) researched the determination of moisture content of soil samples on large-scale laboratory models via TDR and capacitance probe techniques. They compared the volumetric moisture contents obtained from these devices to the standard gravimetric moisture content. They concluded that both techniques are reliable and efficient methods of measuring volumetric moisture content of a soil mass.

2.7 Soil Density Gauge (SDG200)

The Transtech SDG 200 was used as the dielectric permittivity method of determining soil properties. The SDG 200 (Figure 2.13) provides a density and moisture content from the response of the device's electrical sensing field to changes in electrical impedance of the material matrix. The device provides higher soil density readings as the combined dielectric constant increases, since the percentage of air in the soil matrix is reduced. The gauge must be configured using soil index properties such as the soil gradation and Proctor test results before field application. The SDG is intended for obtaining measurements on 12 inch lifts of soil and for coarse-grained or fine-grained materials.

Figure 2.13 – Transtech SDG 200

Gamache et al. (2008) reviewed the SDG technology and determined that it possess the ability to rapidly scan large areas in a vehicle mounted configuration. They also determined that

it is advantageous in comparison with other devices, in that it produces moisture and density readings simultaneously.

Pluta and Hewitt (2009) compared soil density gauge (SDG) readings to those obtained via a nuclear density gauge. Their study revealed an increase in the accuracy of wet density measurements when using an SDG. Through the testing of materials with various gradations, they indicated that soil gradation did affect the frequency response of the SDG device. Consequently, an adjustment was developed into the algorithm utilized to obtain readings, which accounted for soil gradation.

Berney et al. (2011) compared SDG moisture content readings to those obtained by other devices using various soils. It was determined that a properly-calibrated device returned accurate values over most soil types. They deemed SDG as the most suitable device for use in the field, due to its functionality and accuracy.

2.8 Decagon 10HS Moisture Content Sensor

The Decagon 10HS (Figure 2.14) sensor determines volumetric moisture content by determining the dielectric constant of the soil using a capacitance method. Through rapid charging and discharging of a positive and ground electrode in the material, an electromagnetic field is created. The charge time is related to the capacitance of the material, which correlates to the dielectric permittivity of the material.

Figure 2.14 – Decagon 10HS

Mittelbach et al. (2011) evaluated the performance of the 10 HS sensor using laboratory and field measurements, which were compared with measurements obtained via gravimetric samples and TDR sensors. Their field measurements encompassed two different soil types, over a time frame expanding more than a year, and depths down to 1.2 m. They concluded that both sensors provide good results for laboratory and field measurements at low volumetric moisture contents. However, the measurement accuracy for the 10 HS sensor significantly decreased as volumetric moisture content increased. Furthermore, they recommended the use of the 10 HS sensor for setting up dense soil moisture networks with medium to low volumetric moisture contents and using an established site-specific calibration function.

2.9 Speedy Moisture Tester

Speedy Moisture Tester is a portable system for measuring moisture content of soils typically used in earthwork. The most common version of this device (Figure 2.15) measures the moisture content of materials passing the No. 4 sieve. Moisture measurements are made by mixing a weighed sample of the material with a calcium carbide reagent in a sealed pressure vessel. The reagent reacts chemically with water in the sample, producing acetylene gas that in turn increases the pressure within the vessel. The pressure increase in the vessel is proportional

to the amount of water in the sample, and thereby the moisture content can be read directly from the calibrated pressure gauge.

Figure 2.15 – Speedy Moisture Tester

Partridge et al. (1999) studied the use of waste foundry sand (WFS) on highway embankment by monitoring the construction process using several devices such as the Speedy Moisture Tester. They preferred the Speedy Moisture Tester for the measurement of moisture contents in the field.

Dai and Kremer (2006) and Oman (2004) worked on a project for Minnesota DOT (MnDOT) to improve DCP specification for use on aggregate base and/or granular material that accounted for gradation and moisture effects. Several moisture devices were studied. The results of the Speedy Moisture Tester were compared to the traditional oven burner method. The results showed a strong relationship between the Speedy Moisture Tester values and moisture contents from the traditional oven burner method.

Alleman et al., (1996) assessed the environmental and geotechnical performance of two highway embankments constructed using coal combustion fly ash. As part of the study they assessed several devices such as the Speedy Moisture Tester. Their results showed that water

content values measured using the Speedy Moisture Tester were overestimated by 1.25%. However, once calibrated it was considered reliable. They recommended using the Speedy Moisture Tester to check the water content of coal combustion by-products before placement, as a means of quality control in the field.

George (2001) presented a field trial initiated to investigate various methods to alleviate the shrinkage cracking problem in cement stabilized layers. Incorporated in the field trial were materials stabilized with cement, cement and fly ash, GGBF slag and lime, and lime-fly ash. The scope of the study included utilizing the Speedy Moisture Tester among other devices to monitor moisture content. The results from the Speedy Moisture Tester were comparable to the results of the sand cone and nuclear gauge.

Berney et al. (2011) also evaluated the Speedy Moisture Tester when comparing various moisture measuring devices. They concluded that the Speedy was the most precise, but the least accurate device. For all the soils tested, the Speedy overestimated the moisture content values.

2.10 DOT600 Roadbed Water Content Meter

The DOT600 Meter (Figure 2.16) measures the volumetric and gravimetric moisture content in samples of geomaterials. This method involves an indirect measurement that is sensitive to the dielectric permittivity of the material surrounding the devices' probe rods. A waveguide exist at the bottom of a 3 inch diameter sample chamber which has interlaced circuit traces that form the 'plates' of a capacitor. The oscillation frequency of the circuit is dependent on the capacitance. The amount of water in the soil determines the dielectric permittivity which is directly related to capacitance. Furthermore, the waveguide floats on precision springs. When a preset travel distance has taken place from sample compression, a limit switch is made and the

measurement is made in about 0.5 msec. A scaled oscillation frequency is measured by the device and used in an empirically derived calibration equation to provide volumetric water content. Magnetic linear sensors measure sample mass and volume to allow for the determination of gravimetric moisture content.

Figure 2.16 – DOT600 Roadbed Water Content Meter

Researchers of MnDOT studied the accuracy and effectiveness of the DOT600 for measuring soil moisture content. They compared DOT600 measurements to those taken using the standard Proctor laboratory test for 270 soil specimens from 62 different soil samples (MnDOT, Innovation Update, February 2012). Results indicated that the optimum moisture contents based on the DOT600's measurement of electrical properties were consistent with the measurements determined alongside the standard Proctor test. Additionally, it was concluded where the optimum gravimetric moisture value determined by the Proctor test varied considerably between soil types, the DOT600's optimum period appeared far less variable. Researchers recommended the DOT600 as a possible alternative to the nuclear density gauge or the sand cone and Proctor tests. However, they suggest making the device rugged enough for regular field use before it is considered as an alternative.

Chapter 3: Experimental Design and Approach

INTRODUCTION

The experimental design of this project incorporated the testing of five materials at five different moisture contents. It involved measurement recordings at two depths on a 1.5-ft-diameter by 2-ft-deep specimens, which were entirely composed of the selected geomaterials. These specimens were evaluated using the SDG 200, PMTDR, and Decagon 10 HS sensors. Several 3-ft-diameter by 2-ft-deep specimens were also constructed. These specimens were filled with 6 in. of the selected geomaterial, which was placed above a 16 in. layer of fine-grained material. Only the SDG 200 and Decagon 10 HS were evaluated with these larger specimens. The Speedy Moisture Tester and DOT600 separately evaluated samples of the selected geomaterial, since they may not be used on compacted soil specimens.

3.1 Experimental Design

Five geomaterials from Texas, Louisiana, Minnesota, and Mississippi were tested at their optimum moisture contents (OMCs), wet of OMCs, and dry of OMCs. Each material was tested at OMC±1% and OMC ±2, if its OMC was 10% or less. A material was tested at OMC± 10% OMC and OMC± 20%, if its OMC was greater than 10%. This range of moisture contents provided the best representation of material moisture contents during construction in the field. The five selected devices (consisting of the Purdue TDR, SDG 200, Decagon 10 HS, Speedy Moisture Tester, and DOT600 Roadbed Meter) were evaluated. The performance parameters that were evaluated were the precision and accuracy of each device. The precision was assessed by

repeated testing of the specimens, while the accuracy was judged by comparing the measured parameters with the oven-dried moisture contents and placement density.

3.2 Description of Materials

The grain size distributions of the five materials tested are shown in Figure 3.1. As reflected in Table 3.1, the materials covered a representative range of materials encountered in earthwork. The Atterberg limits and the classifications of the geomaterials as per Unified Soil Classification System (USCS) are included in Table 3.1. The moisture-density curves from the five materials are shown in Figure 3.2. The OMC and the maximum dry unit weight (MDUW) of each material are also summarized in Table 3.1.

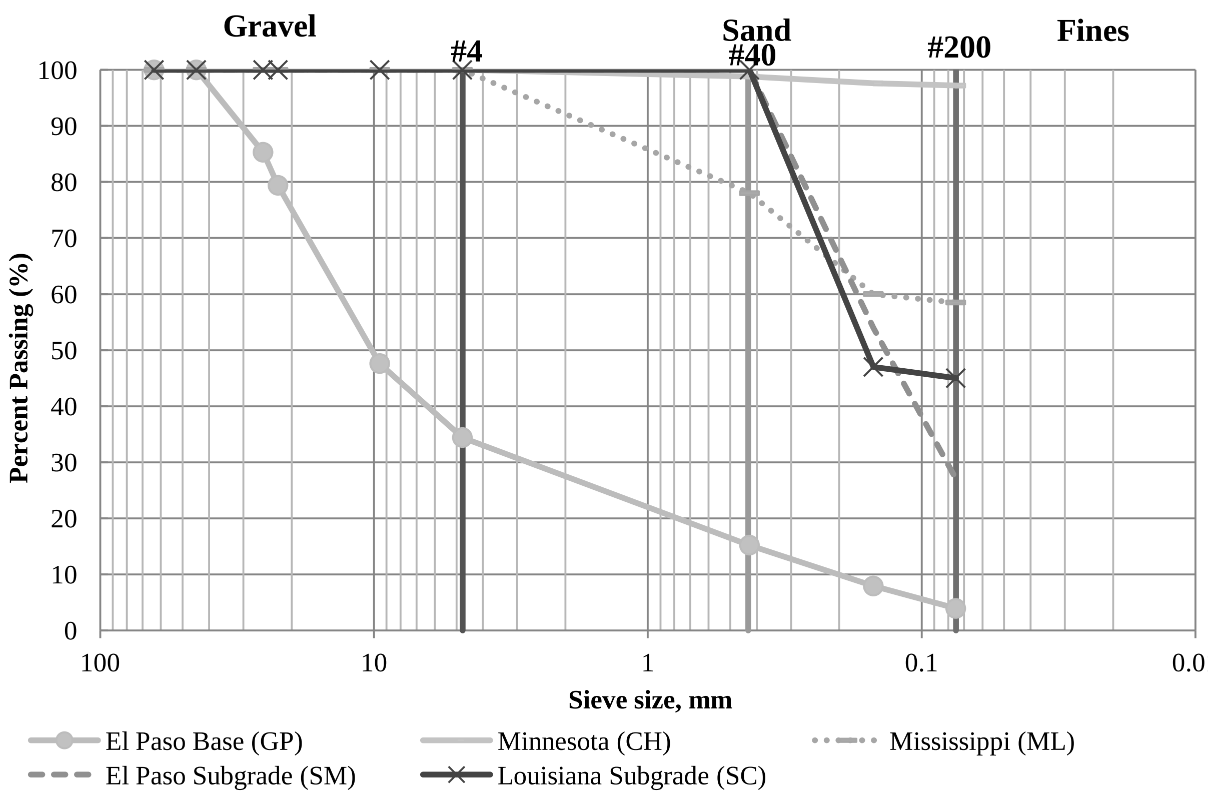

Figure 3.1 – Grain Size Distributions of Materials Tested

Table 3.1 – Soil Index Properties of Soils Used for Device Evaluation

Soil	USCS Classification	Atterberg Limits			Moisture Density Curve Summary	
		PI	LL	PL	OMC, %	MDUW, pcf
Mississippi	ML	Non Plastic			9.4	124.6
Minnesota	CH	53	86	33	25.9	95.7
Louisiana	SC	12	23	11	11.4	121.4
El Paso Subgrade	SM	Non Plastic			15.2	111.7
El Paso Base	GP	9	22	13	5.7	147.1

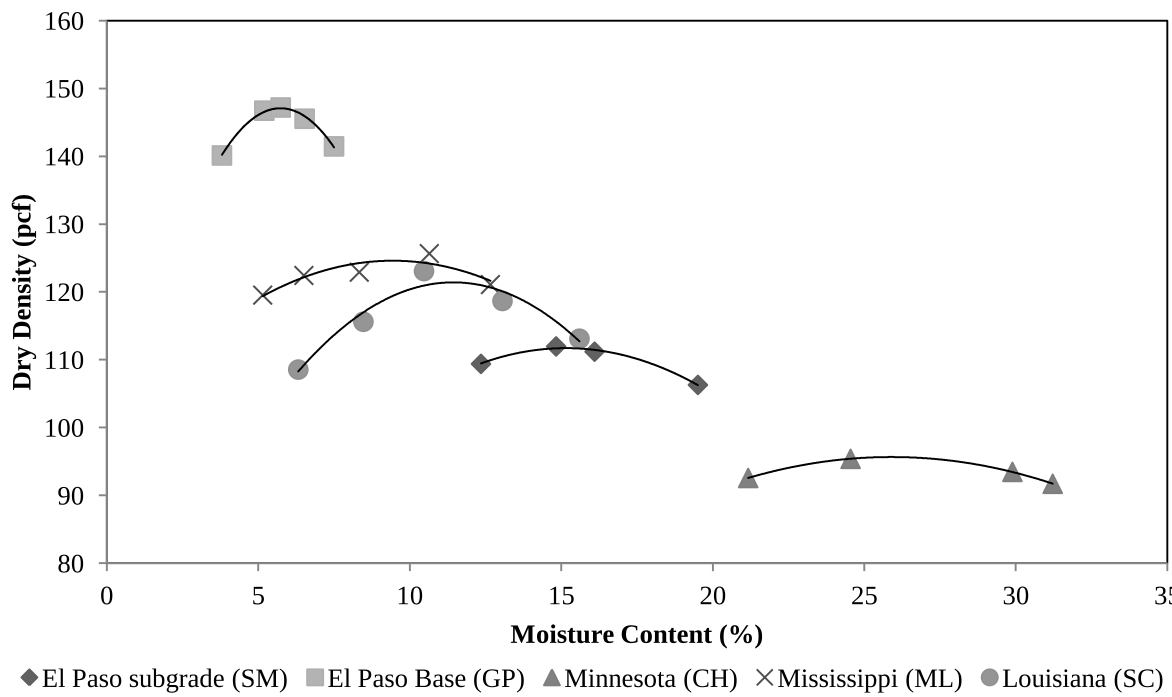

Figure 3.2 – Moisture-Density Curves of Materials Tested

3.3 Testing Procedures

As shown in Figure 3.1, the SDG 200, PMTDR, and 10 HS devices were evaluated using 18 in. by 24 in. (DxH) small-scale specimens, which were constructed within a 35 gallon barrel. A concrete mixer was used to prepare the materials to the desired moisture contents. An adequate

amount of dry geomaterial necessary to achieve a desired density for a 2-in. lift was placed in the mixer. Precise amount of water was added to the soil with a water sprayer to ensure precise moisture content. The moist material was transferred into the container and compacted to the desired density with a hand compactor. This process was repeated until a height of 12 in. was achieved. At that height, the SDG and TDR measurements for dry density and moisture content were obtained at three separate locations as discussed below. The Decagon 10 HS moisture content sensor was installed as soon as those measurements were completed.

Each specimen was then built up to its final height of 24 in. using 2-in. lifts. Once again, each specimen was evaluated for density and moisture content using both the SDG and TDR. Soil samples were extracted at every 4 in. height to obtain oven-dry moisture contents.

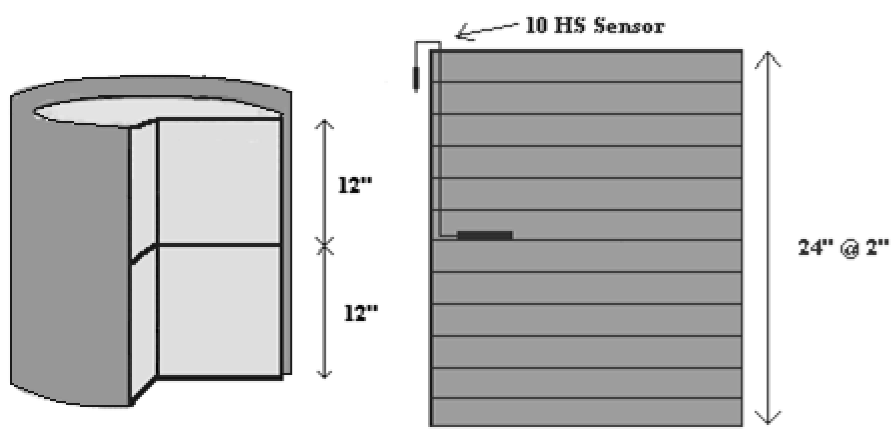

Figure 3.3- Schematic Diagram of Test Specimen Set-up

For the SDG 200 measurements, the device was placed at the center of the specimen and the proper material was selected in the device's user interface. In order for a reading to be recorded, it was required that the SDG 200 be moved in a counter clockwise direction. During this rotation, the device made five separate readings while not being moved. The internal

software then provided a measurement for moisture content and dry density. This procedure was repeated for locations to the left and right of the initial center reading as well.

As soon as the SDG measurements were completed, the PMTDR instrumentation was placed at the center of the specimen. Figure 3.2 shows how the rod guide was placed at the center of specimen and how it was removed before the placement of the probe used for the TDR reading. This procedure was then followed for measurement readings to the left and right of the initial center measurement. Volumetric moisture content readings were then obtained using the 10 HS moisture content sensor placed in the mid-height of the specimens.

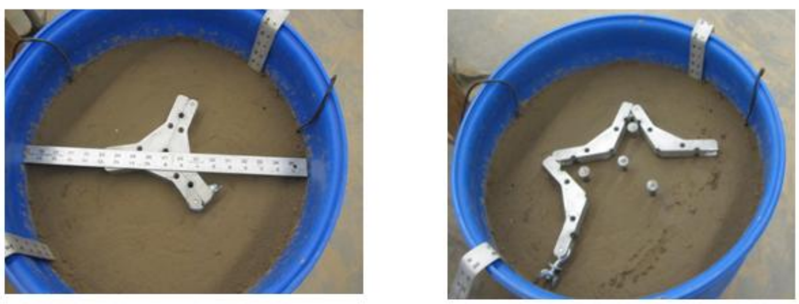

Figure 3.4 – Rod Placement for PMTDR Device

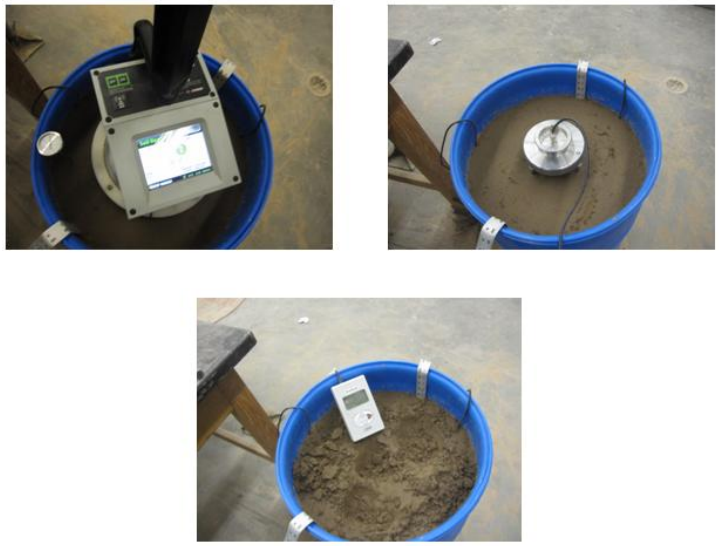

Figure 3.5 – Different Devices used for Testing of Soil Properties

The SDG 200 and Decagon 10 HS were also evaluated in 3 ft by 2 ft (DxH) specimens. An illustration of these specimens is shown in Figure 3.6. The construction of the specimens was similar to the first test specimen, but the location of measurements differed. Six measurements were obtained at the top of the specimens using the SDG 200. Additional measurements were obtained using the Decagon 10HS sensor inserted in the layer containing the geomaterial.

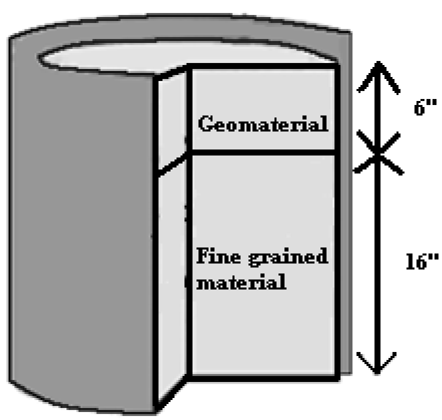

Figure 3.6 – Illustration of Second Test Specimen

Speedy Moisture Tester and DOT600 Roadbed Water Content Meter may not be used on compacted materials. Therefore, separate geomaterial was used for soil samples being tested with the Speedy and DOT600. Each device was used to evaluate the material at the five different moisture contents. Each device also evaluated six samples at each moisture content level.

The DOT600 measurements were obtained by placing soil samples in the sample chamber and weighing it using the device's accompanying scale. The samples were then compressed to a specific pressure with a compression cap and wrench. Once this pressure was attained, a volumetric moisture content value was recorded. Additionally, material was extracted from each sample to obtain reference moisture contents via the oven-dry method.

The Speedy Moisture Tester measurements were obtained by weighing and then placing a specified amount of material into the device. The specified amounts of speedy absorbent and steel balls were also inserted into the moisture tester. Then, the meter was put in motion as recommended by the standard testing procedure. Once the dial stabilized, a reading was recorded and the proper conversion chart was used to obtain a moisture content value. Sufficient amount of material was prepared at each moisture content level, in order to determine the moisture content via the oven-dry method as well.

3.4 Experimental Results

The experimental results from the above activities are presented in Appendix A. Figures 3.7 through 3.16 shows the typical data collected for material ML with different devices. The measured moisture contents with the SDG from different small-scale specimens are shown in Figures 3.7 and 3.8. These plots contain the averages of the three readings taken at the middle and top of the specimen. They show how the SDG readings increased as the oven-dry moisture content increased. However, the SDG 200 readings overestimated the oven-dry moisture content at all levels of saturation.

Figures 3.9 and 3.10 illustrate how the PMTDR moisture contents increased with an increase in the oven-dry moisture content, but slightly underestimated. Figure 3.11 illustrates how the DOT600 overestimated the moisture content and remained constant as the oven-dry moisture content increased.

The Speedy results (Figure 3.12) show slight underestimation of moisture contents. Figures 3.13 and 3.14 show how the SDG 200 mostly underestimated the dry density of the specimens. Figures 3.15 and 3.16 show how the PMTDR slightly overestimated the dry density of the specimens.

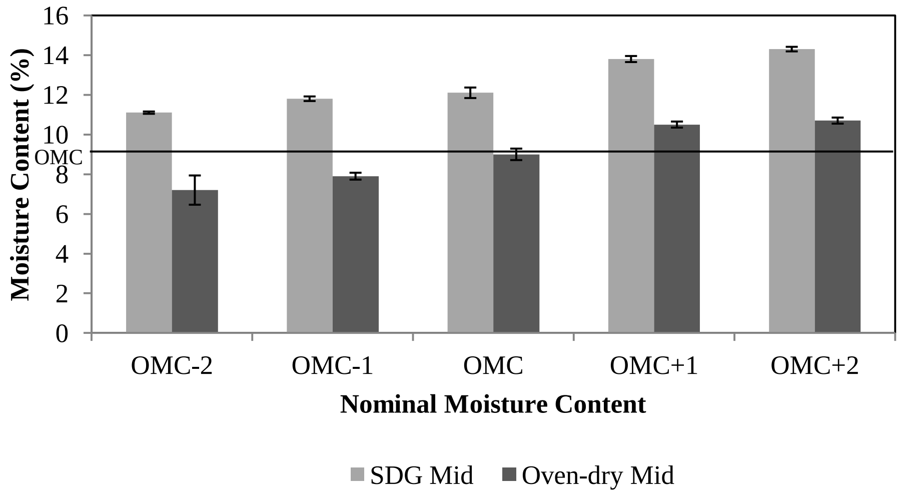

Figure 3.7 – Average SDG 200 Moisture Contents at Mid-height for Material ML

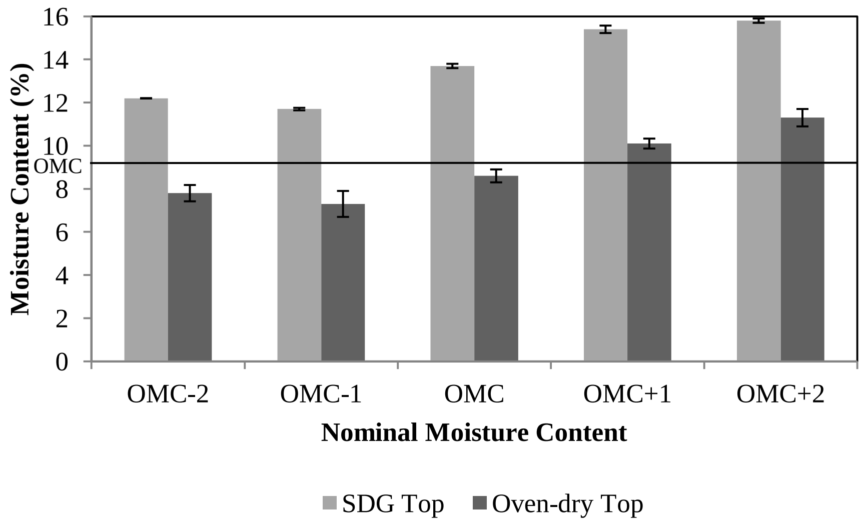

Figure 3.8 – Average SDG 200 Moisture Contents at Top for Material ML

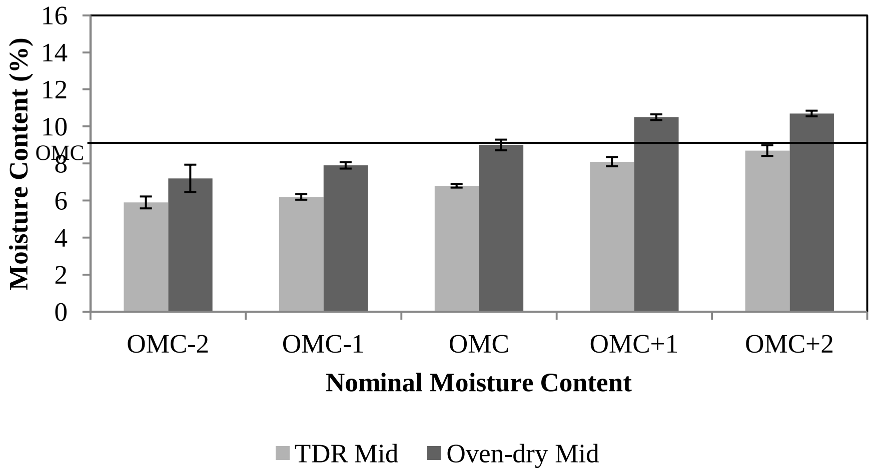

Figure 3.9 – Average PMTDR Moisture Contents at Mid-height for Material ML

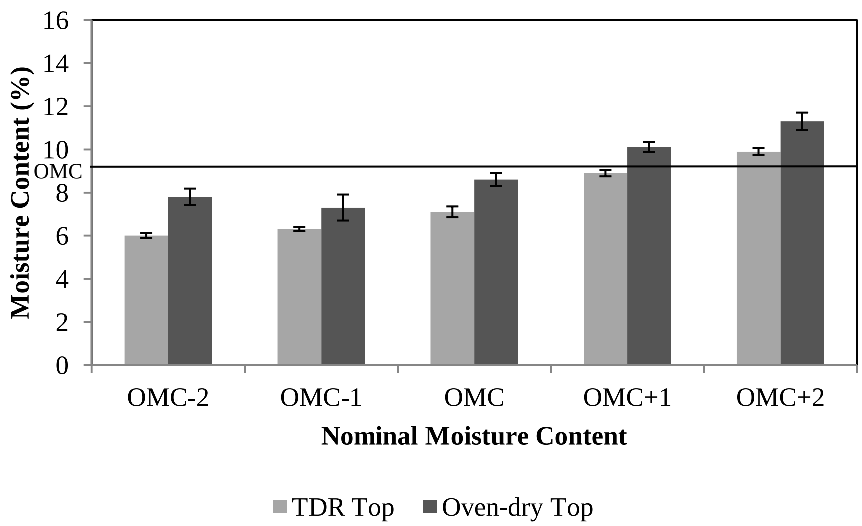

Figure 3.10 – Average PMTDR Moisture Contents at Top for Material ML

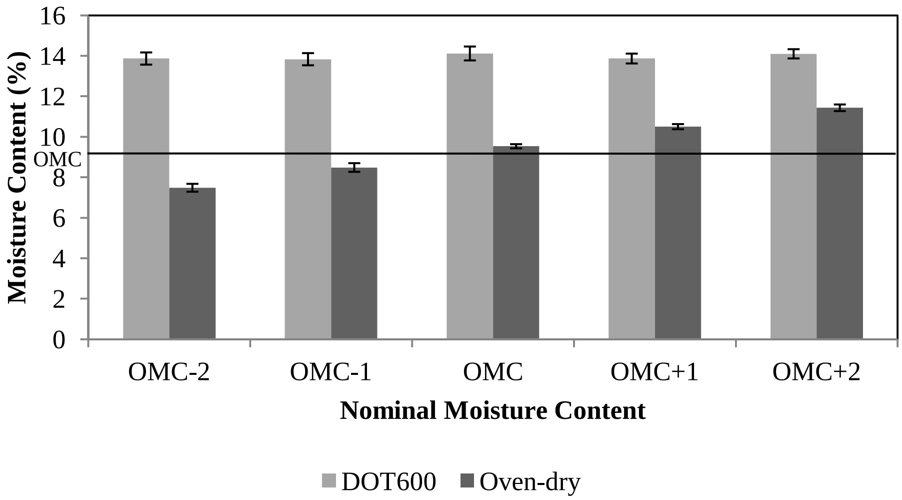

Figure 3.11 – Average DOT600 Moisture Contents for Material ML

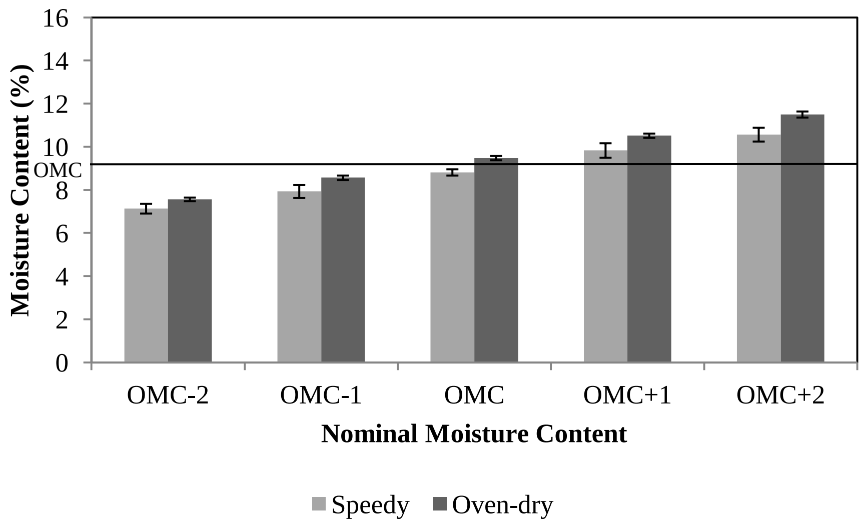

Figure 3.12 – Average Speedy Moisture Contents for Material ML

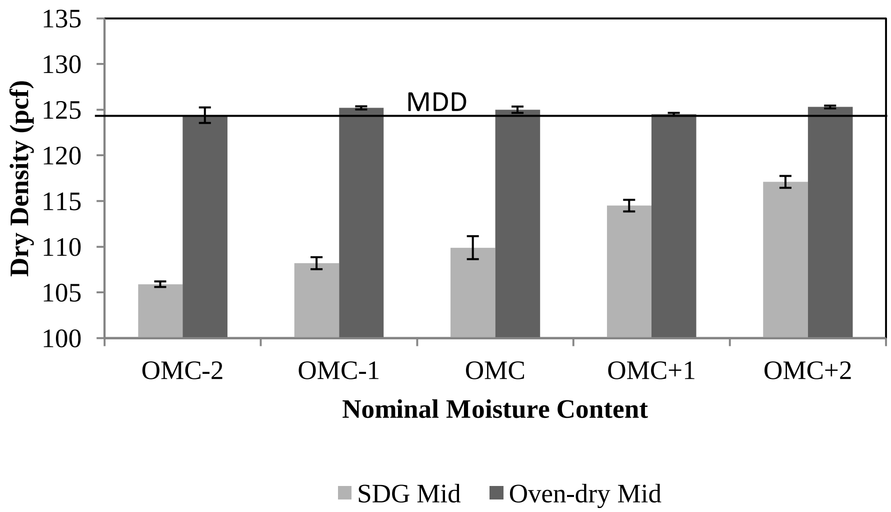

Figure 3.13 – Average SDG 200 Densities at Mid-height for Material ML

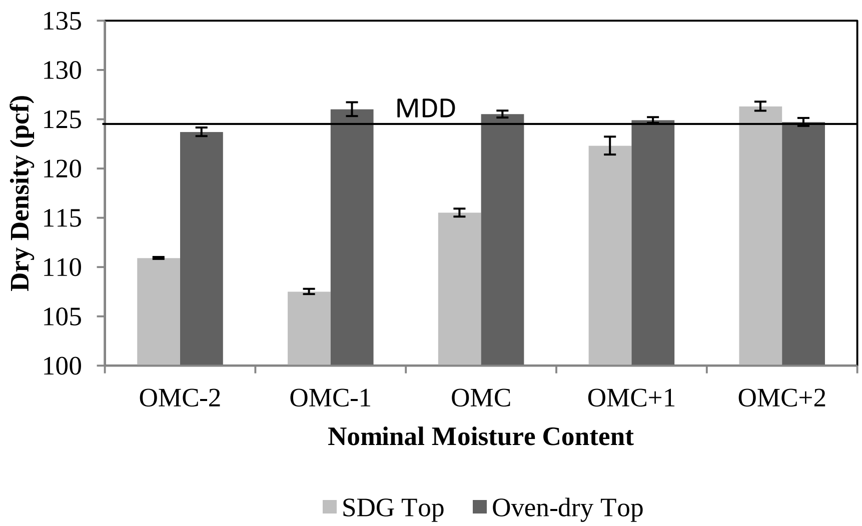

Figure 3.14 – Average SDG 200 Densities at Top for Material ML

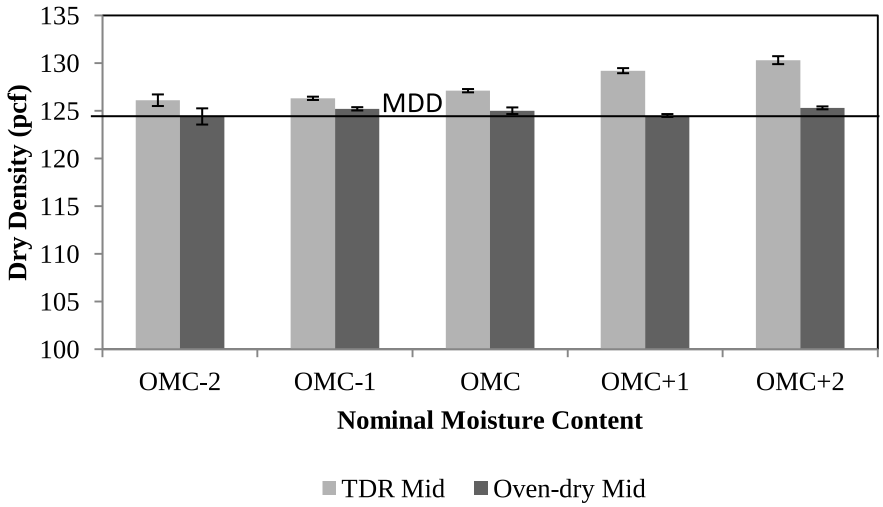

Figure 3.15 – Average PMTDR Densities at Mid-height for Material ML

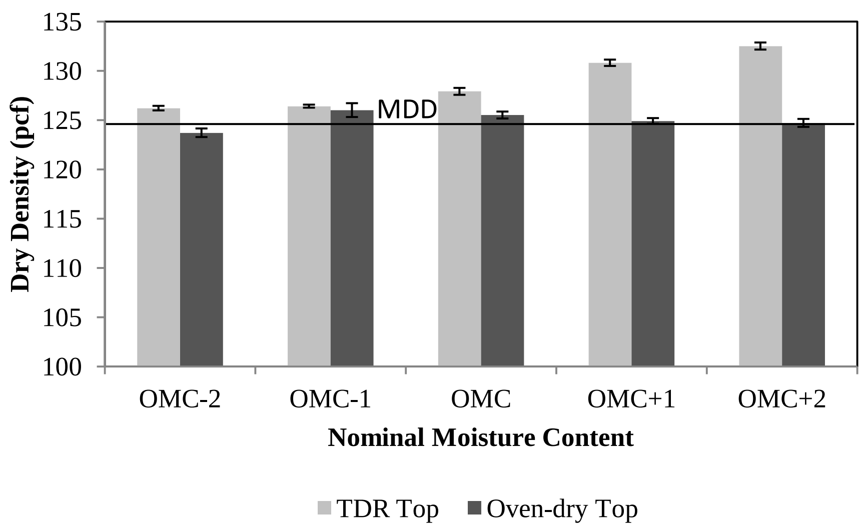

Figure 3.16 – Average PMTDR Densities at Top for Material ML

Chapter 4: Analysis of Results

4.1 Data Analysis Procedure

At the conclusion of all measurements, the data was entered into excel spreadsheets where individual plots were created for each device. The moisture content measurements for each device were plotted against oven-dry moisture content measurements. Plots were created for measurements recorded in the middle of the specimen, top of the specimen, and for both locations. These plots were created using the average value obtained from the three readings obtained using each respective device at the middle and top of the specimen. Plots were also created using all three readings obtained using each respective device at the middle and top of the specimen.

The statistical parameters obtained from these plots and sets of data were the slope, y-intercept, R^2 (coefficient of determination), and the standard error for each material. Different statistical analyses were carried out for the dry densities, since a constant density was kept for each material. The parameters determined for each method of measurement were the average, standard deviation, coefficient of variation, and f-test values.

Additionally, an overall assessment including all the materials used in this study was conducted through measurement system analysis through a so-called Gage R&R study (Minitab 2010). A Gage R&R study estimates the total variability of the devices and delineates the repeatability and reproducibility of each device. The measurement system may be divided into two variations, repeatability and reproducibility. Repeatability deals with the variation caused by the measuring device, or variation associated with the same operator measuring the same

parameter repeatedly with the same device. On the other hand, reproducibility is related to the variation caused when different operators measure the same parameter using the same device.

These analyses also provide information about the linearity and bias of the devices. The bias, which is a measure of the accuracy of a device, exhibits the difference between the observed average measurements and the reference values for specimens tested. The linearity, or the difference in bias throughout the range of moisture contents measured, is useful in determining if a device is uniformly accurate over a range of moisture contents and material types. Results of this assessment are discussed in the subsequent sections of this chapter.

4.2 SDG 200 Results

Figure 4.1 shows how the SDG 200 moisture content readings compared with the oven-dry moisture contents for all the soils tested. This plot contains all readings taken at the middle and top of the specimens. The SDG 200 readings basically remained constant as the oven-dry moisture content increased for three of the five materials. However, SDG 200 readings for ML and SM soils followed the trends of the oven-dry moisture contents with an offset. These results show that the device was responsive or sensitive to increases in moisture for some of the material types, and that a better calibration algorithm may be needed for those soils that were sensitive to moisture contents.

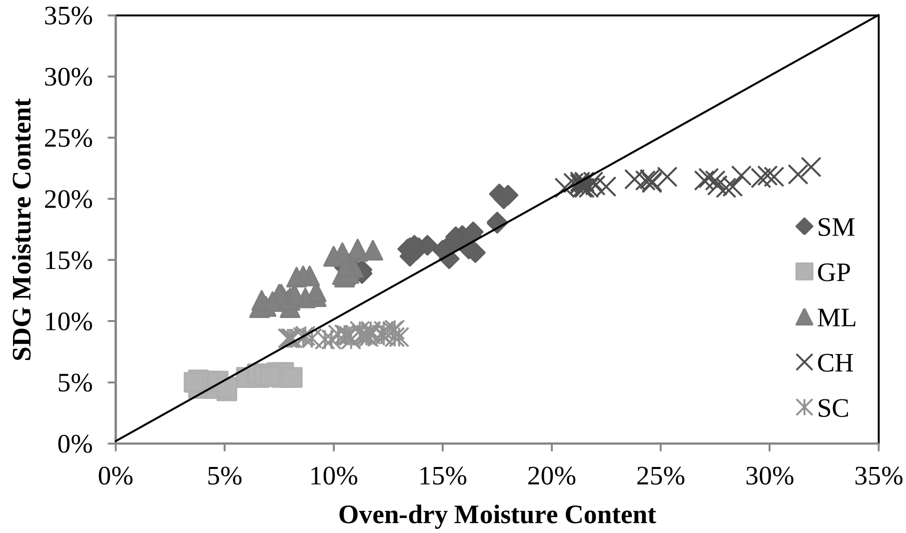

Figure 4.1 – SDG 200 Moisture Contents vs. Oven-dry Moisture Contents

Figure 4.2 illustrates the results of the linearity and bias Study conducted for the SDG 200. Based on the graph, it may be concluded that the SDG data do not represent any type of linearity. As far as the bias, although some values are near zero, most either slightly overestimated or underestimated the reference value. This is indicated from the amount of separation of the SDG 200 data (black points) from the average bias (red points). Additionally, the regression line is not truly horizontal, which would indicate moderate device accuracy.

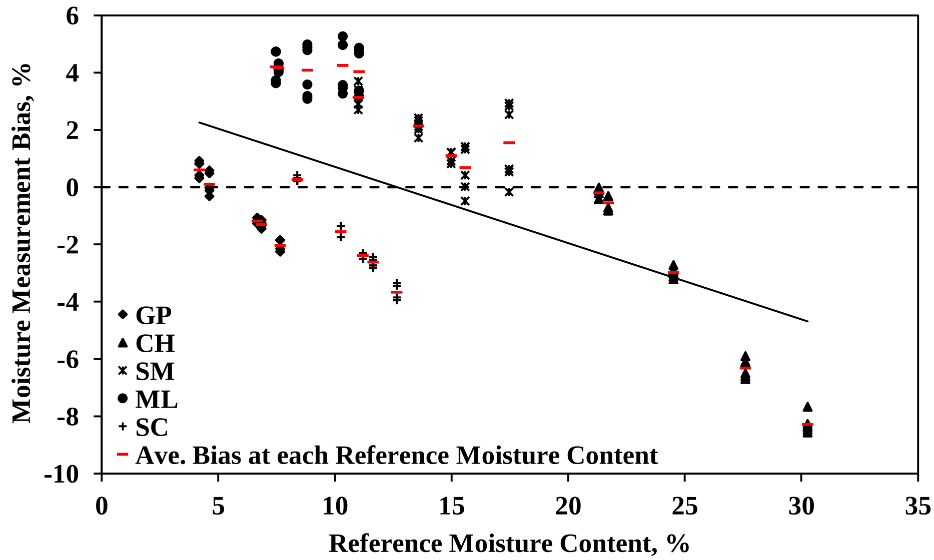

Figure 4.2 – Gage Linearity and Bias Study for SDG 200

4.3 PMTDR Results

Figure 4.3 shows how the PMTDR moisture content readings compared with the oven-dry moisture contents for all the materials tested. This plot contains all readings taken at the middle and top of the specimen. The measured moisture contents closely follow the oven-dry moisture contents except for the CH material. These results indicate that the PMTDR is sensitive to changes in moisture for most material types.

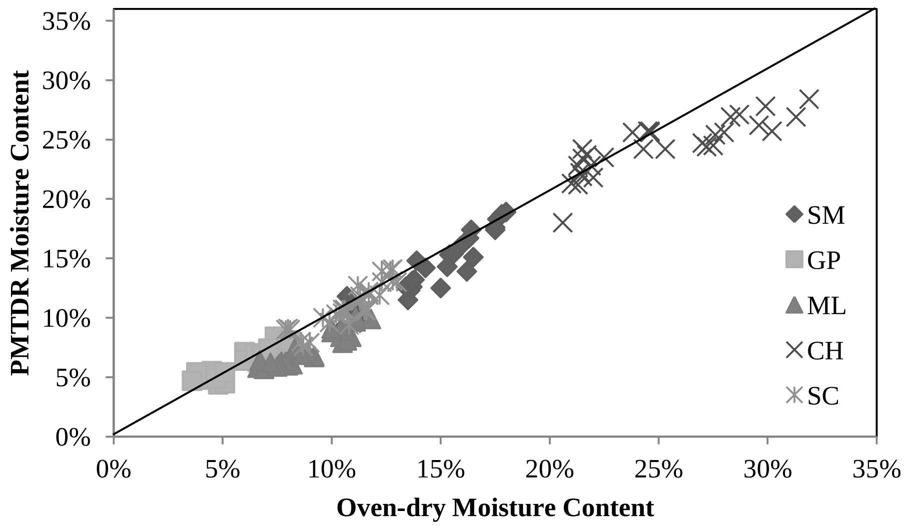

Figure 4.3 – PMTDR Moisture Contents vs. Oven-dry Moisture Contents

Figure 4.4 shows the results obtained for the PMTDR using the linearity and bias study. Similar to the SDG results, the bias values indicate that overestimation and underestimation occurs for the entire range of reference values. However, analysis of the regression line shows that it is closer to horizontal than vertical, indicating decent accuracy.

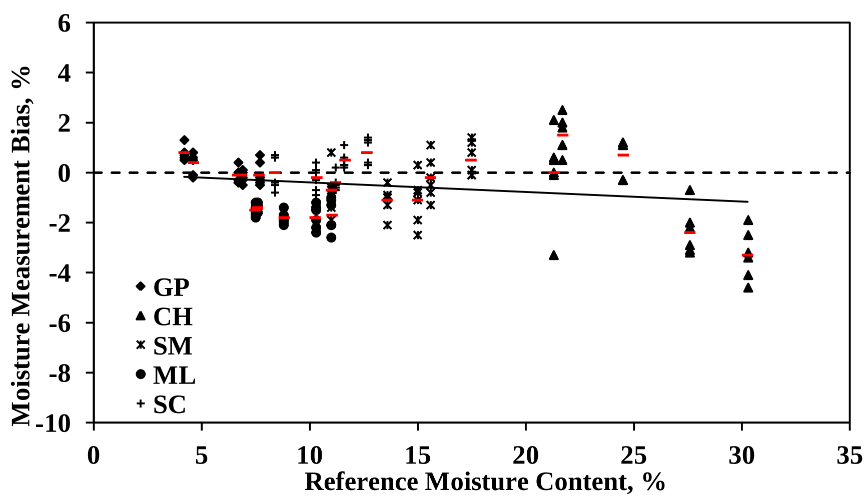

Figure 4.4 – Gage Linearity and Bias Study for PMTDR

4.4 10 HS Moisture Content Sensor Results

Figure 4.5 shows how the 10 HS sensor readings compared with the oven-dry moisture contents for all the soils tested. This plot contains the average oven-dry moisture content at the middle of specimen paired with the single reading provided by the sensor. The plot shows that for some soils the 10 HS sensor readings increased as the oven-dry moisture content increased. Conversely, there were instances where the sensor readings remained mostly constant as the oven-dry moisture content increased.

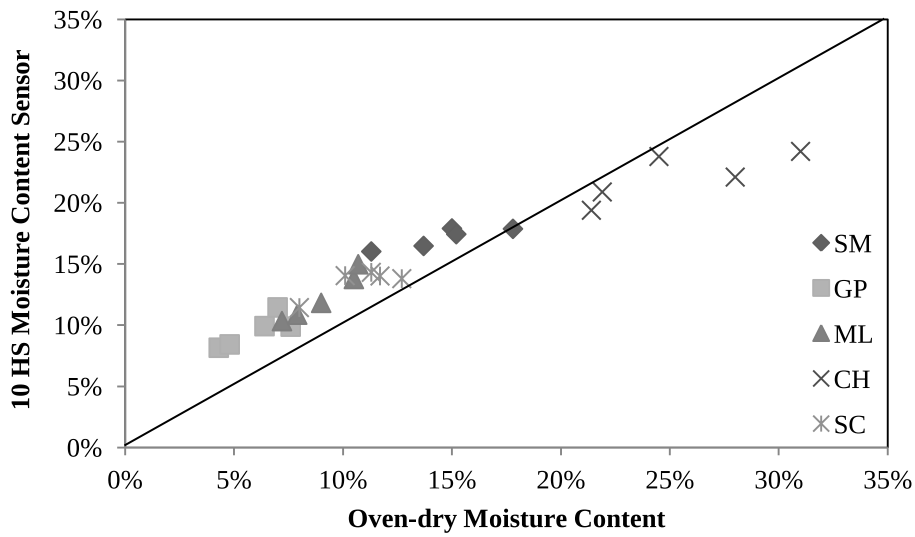

Figure 4.5 – 10 HS Moisture Content Sensor vs. Oven-dry Moisture Content

4.5 Speedy Moisture Tester Results

Figure 4.6 shows how the Speedy Moisture Tester readings compared with the oven-dry moisture content for all the soils tested. The graph illustrates how the device readings are close to the oven-dry measurements. The readings continue this trend for most of the materials with the

exception of the CH material. The Speedy Moisture Tester readings are slightly higher or below the oven-dry moisture content for this material. The Speedy responded well to moisture changes, as well as to changes in material properties.

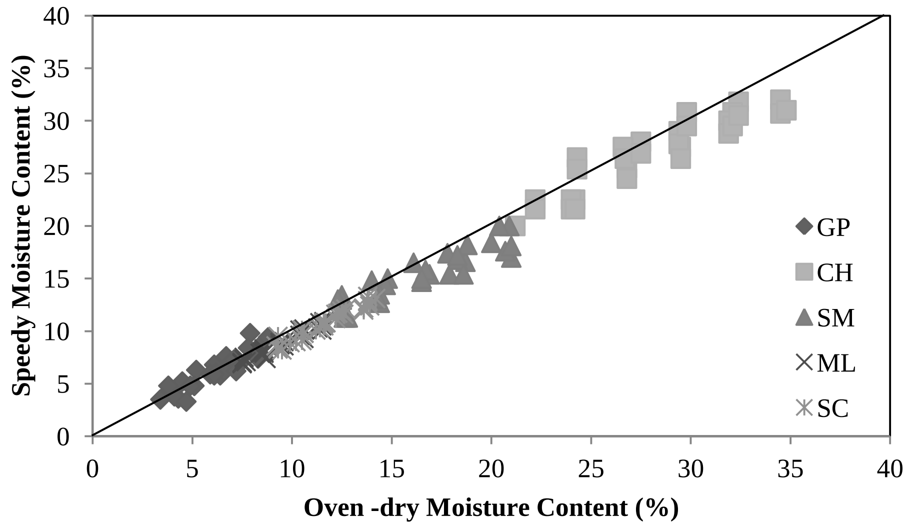

Figure 4.6 – Speedy Moisture Content vs. Oven-dry Moisture Content

Figure 4.7 illustrates the results obtained for the Speedy using the linearity and bias study. The figure shows that the Speedy underestimated the reference value based on the average bias. This is also noted by the regression line under the x-axis. The line also indicates that accuracy is decent, because it is fairly horizontal. These results show that the deviation in Speedy measurements from the actual moisture is due less to the device, and more to other factors.

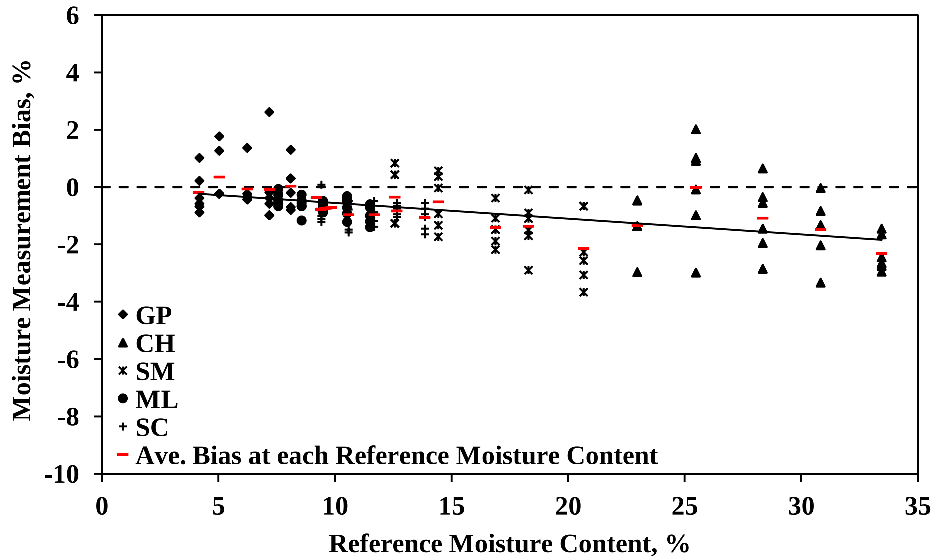

Figure 4.7 - Gage Linearity and Bias Study for Speedy

4.6 DOT600 Roadbed Water Content Meter Results

Figure 4.8 shows how the DOT600 Meter readings compared with the oven-dry moisture content for all the soils tested. The graph shows how the device readings are essentially not affected by the increase in moisture content measurements for several of the materials. Although some readings are identical to the oven-dry measurement, the DOT600 Meter readings remain constant as the moisture content is increased for each soil. This indicates that the device has poor response to moisture changes for certain material properties.

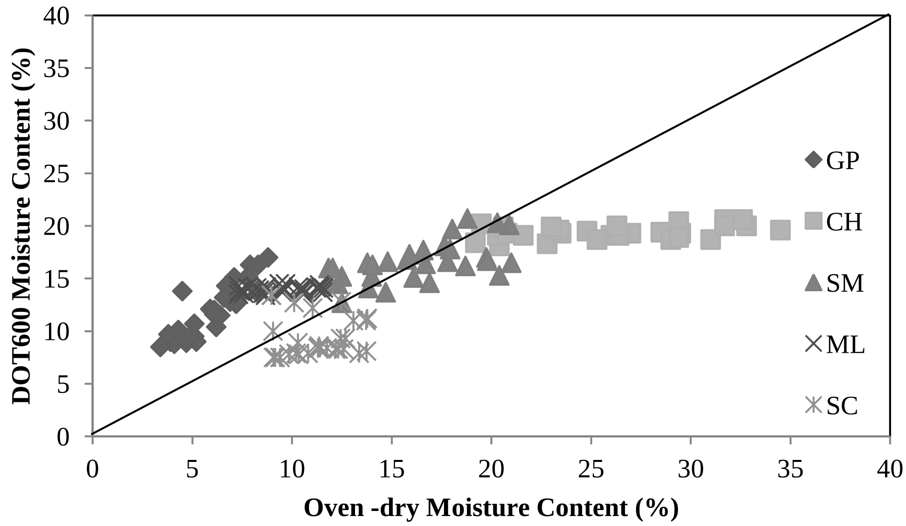

Figure 4.8 – DOT600 Meter Moisture Content vs. Oven-dry Moisture Content

Figure 4.9 illustrates the results obtained for the DOT600 using the linearity and bias study. The figure shows that the DOT600 overestimated the reference value based on the average bias. The regression line indicates a fair accuracy, because it is not entirely horizontal or vertical.

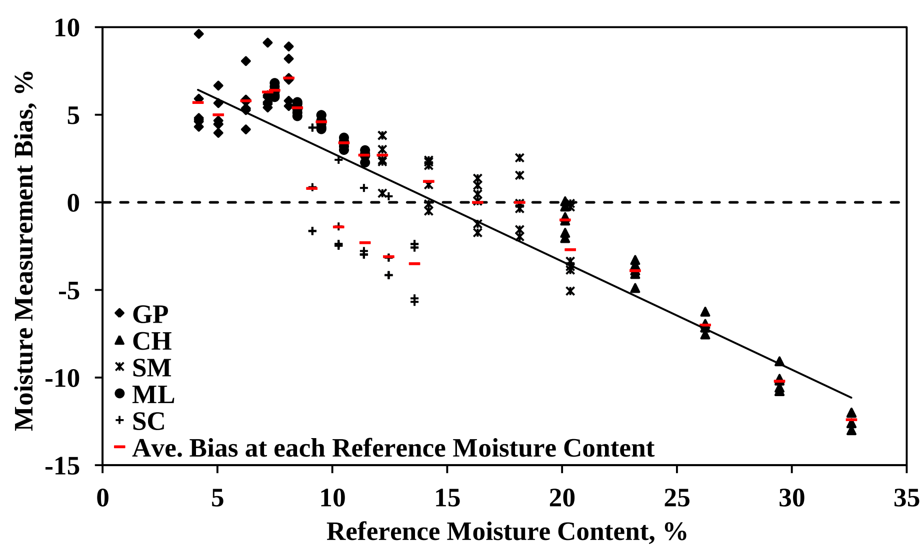

Figure 4.9 – Gage Linearity and Bias Study for DOT600

4.7 Overall Results

In addition to plotting device results on all soils, plots of device readings for each soil were created. These plots may be seen in the appendix, along with a table listing the parameters obtained from these plots. Table 4.1 shows the results determined using the ML material. When considering this material, all three devices performed in similar fashion. The SDG 200, PMTDR, and 10 HS Sensor had slopes near one, which shows that each device was fairly accurate in determining moisture content. All three had y-intercepts near zero, indicating little offset from device moisture content readings and the oven-dry moisture content. The R^2 values were mostly above 90 percent, showing that each device is well suited for predicting the moisture content of this material. Additionally, the standard errors for all devices were all below one percent, denoting minimal variability in the prediction of moisture content by each device.

When considering all materials, the PMTDR plots contained slopes near one more often than the plots for SDG 200 and the 10 HS sensor. In general, y-intercepts for all plots were near zero and standard errors were below or around one percent. R^2 values were closer to one for PMTDR plots more often than for SDG 200 or 10 HS sensor plots. Considering every material tested, the PMTDR produce slightly better results in determining the moisture content of the specimens tested.

Table 4.1 – Parameters obtained for ML Material

		Middle	Top	Both
SDG 200 Moisture Content	Slope	0.80	1.02	0.91
	Y-Intercept	0.05	.05	.05
	R^2	0.90	0.92	0.77
	SEE (%)	0.40	0.50	0.80
PMTDR Moisture Content	Slope	0.74	0.93	0.84
	Y-Intercept	0.00	-0.01	0.00
	R^2	0.90	0.91	0.86
	SEE (%)	0.40	0.50	0.50
10 HS Moisture Content Sensor	Slope	1.24		
	Y-Intercept	0.01		
	R^2	0.95		
	SEE (%)	0.50		

For every material tested, the dry density average, standard deviation, and coefficient of variation were determined. In the appendix there is a table containing this information for each material. Table 4.2 lists the dry density parameters obtained with material ML. The PMTDR produced averages closer to the measured values and its measurements had less variability than those of the SDG 200. Furthermore, f-test results indicate the probability that the variances of the data sets being analyzed are not significantly different. Both the PMTDR and SDG 200 were separately analyzed with the measured dry density values. The f-test results indicated that both devices had significantly different variances than those of the measured dry density. The results indicate that this statement is more pronounced for the SDG 200 than the PMTDR.

Considering all the materials, the PMTDR generally had averages closer to the measured dry density averages, with the exception of the CH material. Overall, both devices had around the same amount of variability in the readings they produced. F-test results generally indicated that both devices had significantly different variances than those of the measured dry density.

Table 4.2 – Dry Density Parameters obtained for ML Material

		Middle	Top	Both
Measured Dry Density	Average	124.9	125.0	124.9
	Stdev	0.5	0.9	0.7
	COV (%)	0.40	0.70	0.60
SDG 200 Dry Density	Average	111.1	116.5	113.8
	Stdev	4.3	7.2	6.4
	COV (%)	3.90	6.20	5.70
	f-test	7.18E-10	5.08E-10	1.52E-20
PMTDR Dry Density	Average	127.8	128.8	128.3
	Stdev	1.7	2.6	2.2
	COV (%)	1.40	2.00	1.70
	f-test	9.18E-05	2.57E-04	3.47E-08

Table 4.3 and 4.4 lists the results of the Crossed Gage R&R Study conducted for material ML on moisture content measurements. All other material results are included in the appendixes. The first table shows the standard deviation and variation components for repeatability, reproducibility, and R&R combined. The second table breaks down the variation from each factor by percentage. The equipment variation refers to each individual device's ability to

provide a consistent measurement, while the appraiser variation refers to the measurement system's ability to provide a consistent measurement.

The SDG 200 has the lowest standard deviation in terms of repeatability, but the Speedy and DOT600 have the smallest in terms of reproducibility. When considering the two parameters as a "Total Gage", the Speedy results are the lowest. Overall, for this material the DOT600 device contributes to the highest amount of variation. This shows that the various devices with the exception the DOT 600 are not the most significant influence in producing accurate measurements of moisture, and that other factors (such as specimen preparation) may be the main contributors.

Furthermore, as the material properties change the results of the crossed gage R&R study are generally the same. For instance, the DOT 600 contribution to device variation remained well above that shown by all other devices. Additionally, the conclusion that the various devices (excluding DOT 600) are not the most significant influence in producing accurate measurements of moisture holds true for the various materials tested.

Table 4.3 – Crossed Gage R&R Study Results for ML Material

Measurement Device	Equipment Variation (Standard Deviation due to Repeatability)	Appraiser Variation (Standard Deviation due to Reproducibility)	Combined Device Variability (Gauge R&R)	Specimen Variation (SV)	Total Variation (TV)
SDG200	0.13	0.92	0.93	1.53	1.79
PMTDR	0.20	0.44	0.48	1.44	1.52
DOT600	0.29	0.00	0.29	0.07	0.30
Speedy	0.28	0.00	0.28	1.38	1.41

Table 4.4 – Crossed Gage R&R Study Variation Percentages for ML Material

Measurement Device	Equipment Variation Proportion, %	Appraiser Variation Proportion, %	Combined R&R Proportion, %	Specimen Variation Proportion, %
SDG200	1%	26%	27%	73%
PMTDR	2%	8%	10%	90%
DOT600	94%	0%	94%	6%
Speedy	4%	0%	4%	96%

4.7.1 Large Specimen SDG200 Results

As previously mentioned, the SDG200 was evaluated using two different sized specimens. Tables 4.5 and 4.6 show the results obtained with the 3ft. diameter specimens. The different component variations reveal that the SDG 200 attributes to the greatest amount of variation around half of the time. This departs from the conclusions drawn by the studies reflecting the measurements on the smaller diameter specimen. Overall, the SDG 200 is reliable a majority of the time and provides consistent readings based on the R&R values shown below. This was demonstrated with both the large and smaller test specimens.

Table 4.5 – Crossed Gage R&R Study Results for Large Specimen

Measurement Device	Equipment Variation (Standard Deviation due to Repeatability)	Appraiser Variation (Standard Deviation due to Reproducibility)	Combined Device Variability (Gauge R&R)	Specimen Variation (SV)	Total Variation (TV)
SM	1.49	0.10	1.49	0.61	1.61
CH	0.52	0.00	0.52	0.77	0.93
ML	1.67	0.14	1.68	1.91	2.54
SC	0.57	0.05	0.57	0.32	0.65

Table 4.6 – Crossed Gage R&R Study Variation Percentages for Large Specimen

Measurement Device	Equipment Variation Proportion, %	Appraiser Variation Proportion, %	Combined R&R Proportion, %	Specimen Variation Proportion, %
SM	85.4%	0.4%	85.8%	14.2%
CH	31.3%	0.0%	31.3%	68.6%
ML	43.2%	0.3%	43.7%	56.5%
SC	76.9%	0.6%	76.9%	24.2%

4.7.2 Dry Density Results

Dry density was evaluated using both the PMTDR and SDG200 for all materials. Tables 4.7 through 4.10 separate the Crossed Gage R&R results by material tested and measuring device. The different component variations refer to the same principles stated in the explanation on the gage studies for moisture content. For every material tested using the SDG200, device variation contributed the least to the total process variation. The same may be concluded for the PMTDR device, with the exception of material GP. In other words, both devices are not the greatest influence in measurement variation for dry density. The variation may be directed to other influences such as the specimen itself.

Table 4.7 – Crossed Gage R&R Study Results for SDG200 Densities

Material	Equipment Variation (Standard Deviation due to Repeatability)	Appraiser Variation (Standard Deviation due to Reproducibility)	Combined Device Variability (Gauge R&R)	Specimen Variation (SV)	Total Variation (TV)
GP	0.40	1.46	1.51	2.75	3.14
CH	0.57	1.88	1.97	1.90	2.74
SM	1.59	6.30	6.50	9.82	11.77
ML	0.65	4.48	4.53	5.80	7.36
SC	0.17	1.22	1.23	0.31	1.27

Table 4.8 – Crossed Gage R&R Study Variation Percentages for SDG200 Densities

Material	Equipment Variation Proportion, %	Appraiser Variation Proportion, %	Combined R&R Proportion, %	Specimen Variation Proportion, %
GP	1.6%	21.7%	23.3%	76.7%
CH	4.4%	47.3%	51.7%	48.3%
SM	1.8%	28.6%	30.5%	69.5%
ML	0.8%	37.1%	37.9%	62.1%
SC	1.7%	92.3%	94.0%	6.0%

Table 4.9 – Crossed Gage R&R Study Results for PMTDR Densities

Material	Equipment Variation (Standard Deviation due to Repeatability)	Appraiser Variation (Standard Deviation due to Reproducibility)	Combined Device Variability (Gauge R&R)	Specimen Variation (SV)	Total Variation (TV)
GP	1.38	0.81	1.60	4.80	5.06
CH	1.28	2.69	2.98	0.00	2.98
SM	1.05	1.06	1.49	4.59	4.83
ML	0.33	0.89	0.95	2.27	2.46
SC	0.70	1.83	1.96	5.93	6.25

Table 4.10 – Crossed Gage R&R Study Variation Percentages for PMTDR Densities

Material	Equipment Variation Proportion, %	Appraiser Variation Proportion, %	Combined R&R Proportion, %	Specimen Variation Proportion, %
GP	7.4%	2.5%	10.0%	90.0%
CH	18.5%	81.5%	100.0%	0.0%
SM	4.7%	4.8%	9.6%	90.4%
ML	1.8%	13.0%	14.8%	85.1%
SC	1.3%	8.6%	9.9%	90.1%

Chapter 5: Evaluation of Device Performance

5.1 SDG 200

The SDG 200 predicted the moisture content of the ML and SM soils fairly accurately as opposed to the other soils. SDG average values for dry density do not compare well with the measured values, with the exception of the CH soil. However, standard deviation and coefficient of variation values are respectable, which fair well for the repeatability of the device. F-test values were minimal, indicating significant differences in the variances between the SDG 200 dry density readings and measured dry density. Overall, the SDG 200 was affected by changes in material properties. Its variation in device measurements is due less to the device itself, and more so due to other factors like specimen preparation or the offset selected on the device.

5.2 PMTDR

The PMTDR was fairly accurate in predicting moisture contents for all soils, as most soils had a coefficient of determination above .74. The average dry density readings determined via the PMTDR compare well with the measured values, with the exception of those related to the CH soil. As was the case with SDG 200 readings for dry density, f-test values indicate significant differences in the variances between the device readings those measured. The PMTDR fared well as changes in material properties occurred. This device provided moderately accurate moisture content results in comparison with the other devices. It also produced more accurate dry density results than the SDG 200 when encompassing all materials.

5.3 10 HS Moisture Content Sensor

When observing the coefficient of determination, the 10 HS moisture content sensor was accurate in predicting moisture contents for the ML soil, but was not as accurate for the other soils. Standard errors were in the same range of those obtained by the Purdue TDR plots. In general, the sensor's results for moisture content were not as accurate as other devices.

5.4 Speedy Moisture Tester

The Speedy Moisture Tester was accurate in predicting moisture content for almost all of the soils. However, it overestimated the moisture content for the CH material samples. The variation due to this device was minimal when considering the gage R&R studies. The Speedy maintained its accuracy as material properties changed and consistently provided accurate results for different levels of moisture content.

5.5 DOT600 Roadbed Water Content Meter

Overall, the DOT600 measurements were not as accurate as the other devices used to evaluate the various geomaterials. Furthermore, the DOT600 measurements did not vary from material to material. The gage R&R studies also indicated that device variation contributed significantly to the overall process variation. These conclusions demonstrate that the device itself is the main influence in the variation of and production of accurate moisture content readings.

Chapter 6: Conclusion and Recommendations

The Speedy Moisture Tester was overall slightly more accurate in determining the moisture content of the soils tested. The PMTDR was just behind the Speedy in accurately determining moisture content. It was also more accurate in determining the dry density of the soils, when compared to the SDG 200. The DOT600 Meter overestimated or underestimated moisture content levels for a majority of the specimens constructed, but did have measurements which were on par with the oven-dry measurements. However, the 10 HS Moisture Content Sensor provided the quickest reading for moisture content and required the least amount of time for the calibration process. Overall the study findings were as follows:

- PMTDR and Speedy had the least variability due to soil characteristics
- PMTDR, Speedy, and SDG 200 showed overall accuracy
- PMTDR, Speedy, and SDG 200 contributed the least to total process variation
- 10HS Sensor had the most time efficient measurement

The majority of the soils tested were subgrades used in pavement structures, therefore further investigation may assist in the evaluation of device performance. Future research studies may expand upon current findings by incorporating soils used in other types of infrastructure. In addition, the comparison of device performance may be enhanced with in situ readings and samples. This evaluation may then include upgraded devices and/or a greater range of devices which are capable of providing moisture content and density measurements.

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Appendix A

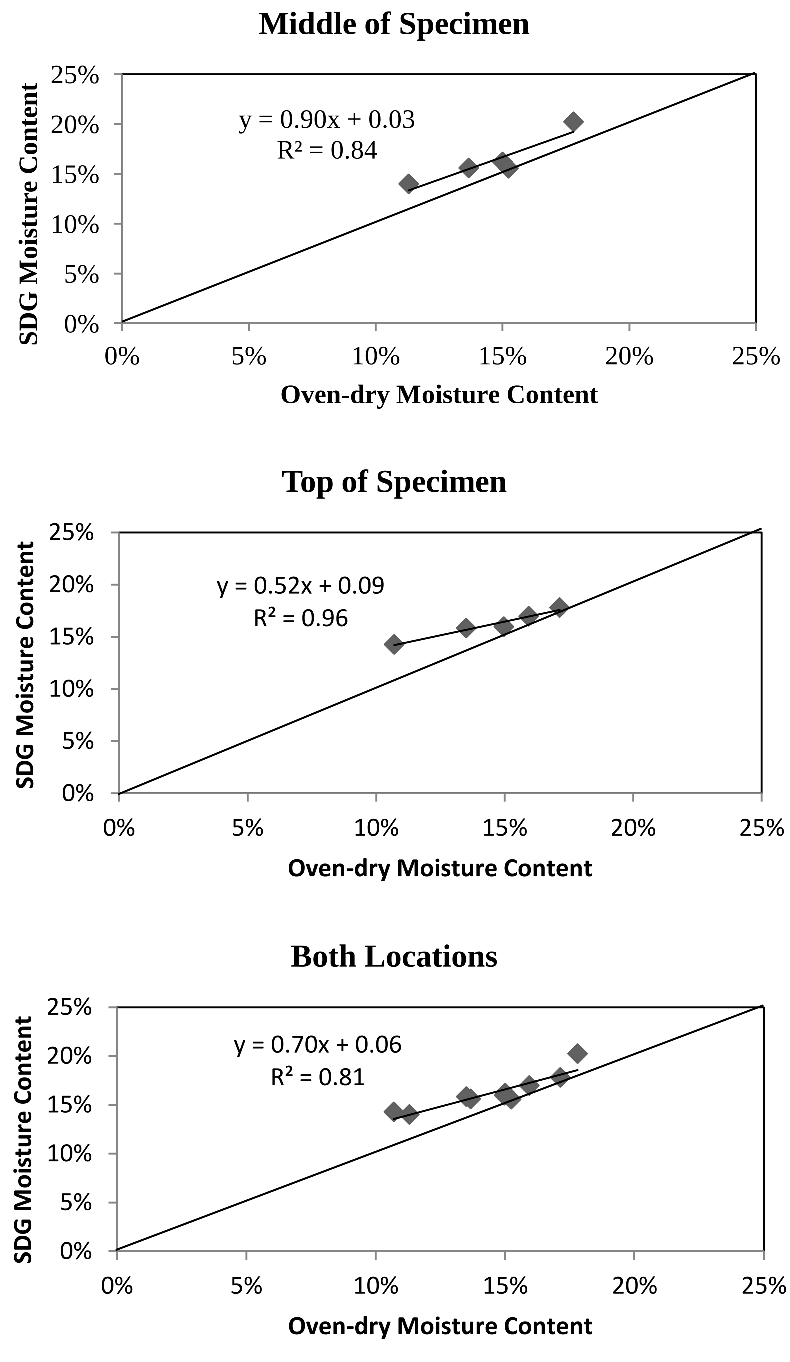


Figure A.1 – SDG 200 vs. Oven-dry Moisture Contents for SM Material

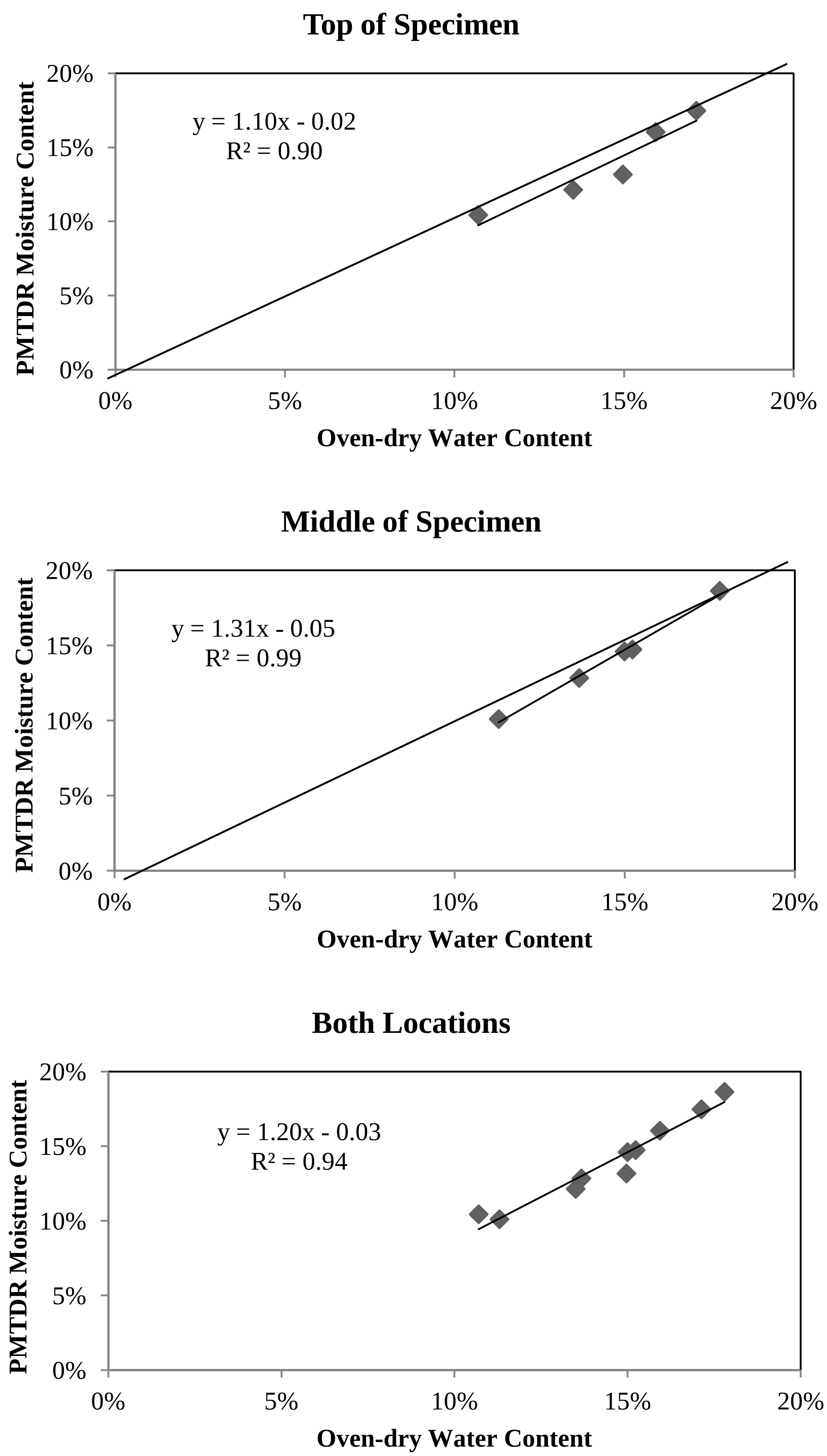


Figure A.2 – PMTDR vs. Oven-dry Moisture Contents for SM Material

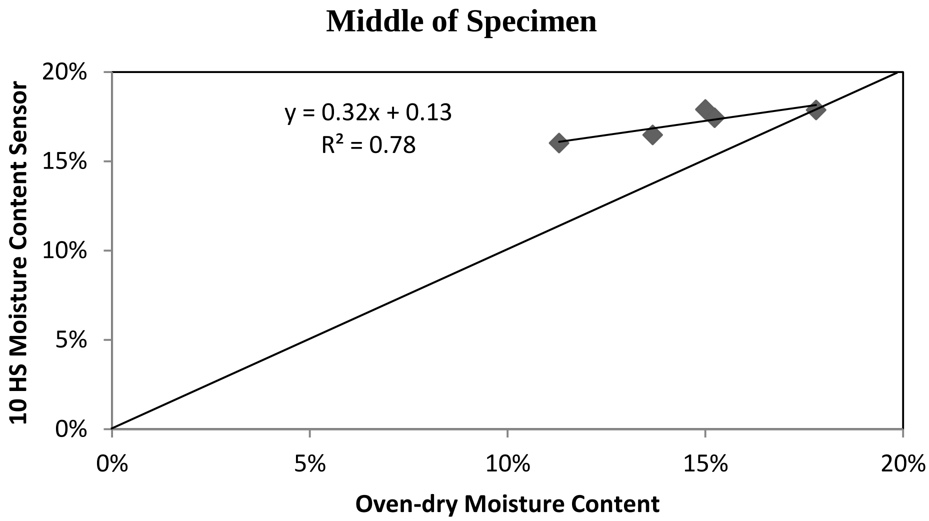
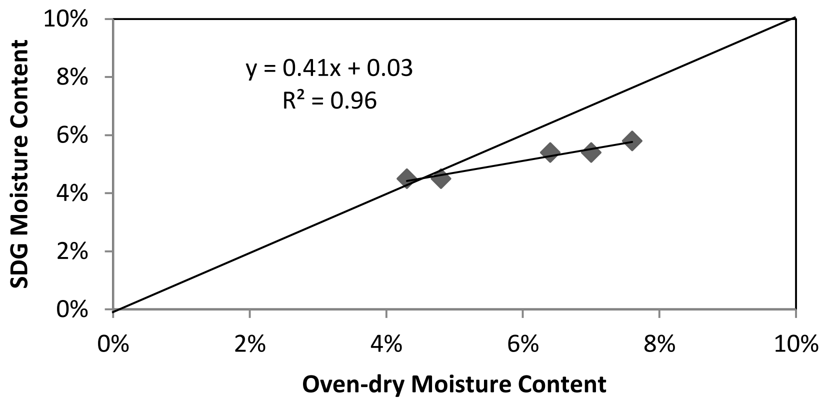
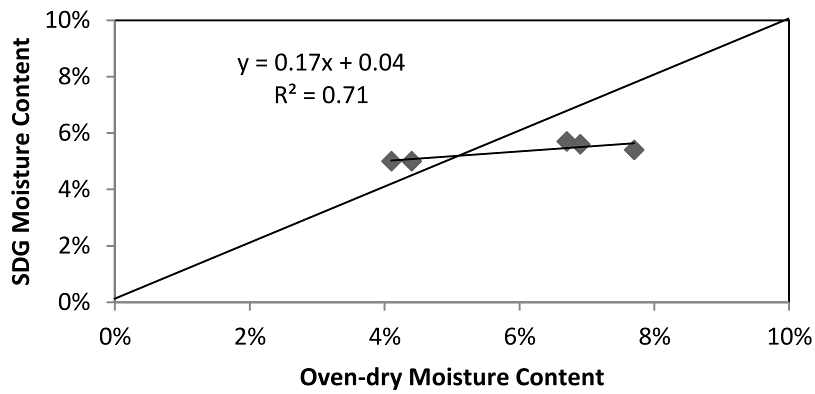


Figure A.3 – 10 HS Sensor vs. Oven-dry Moisture Contents for SM Material

Middle of Specimen



Top of Specimen



Both Locations

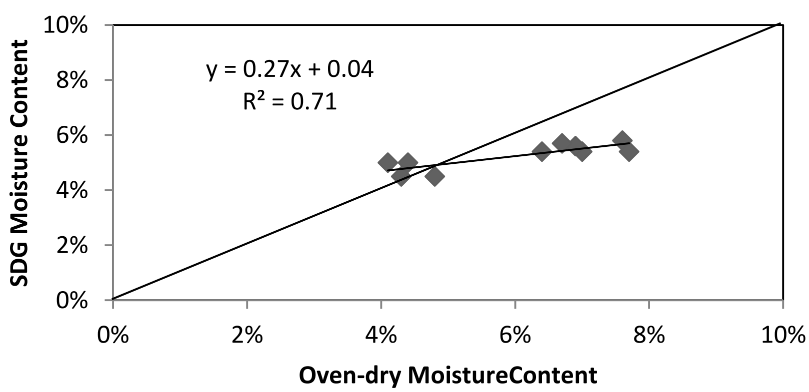
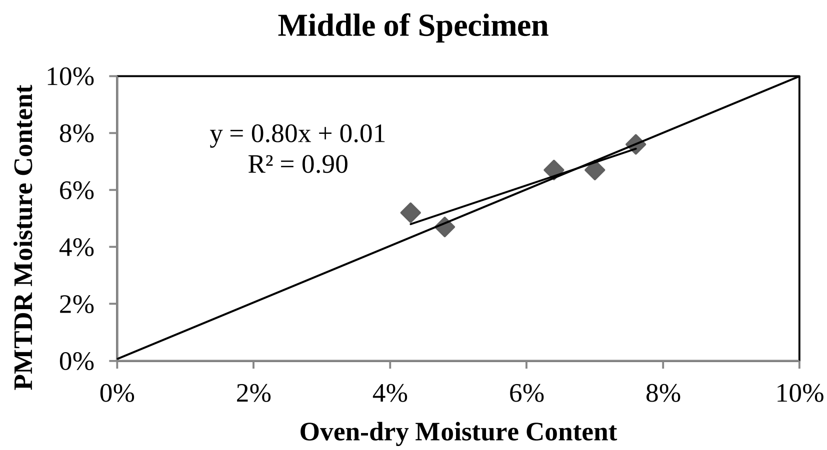
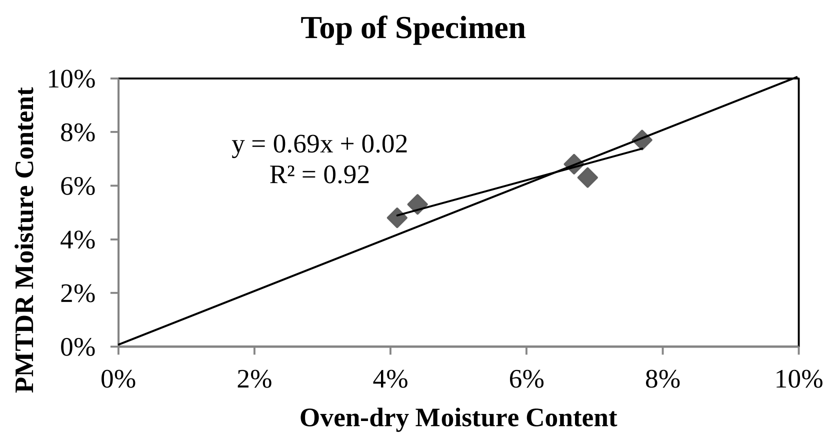


Figure A.4 – SDG 200 vs. Oven-dry Moisture Contents for GP Material





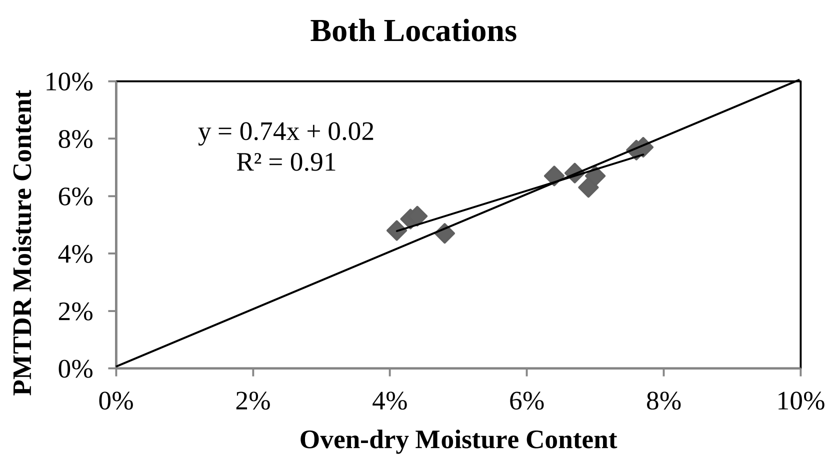


Figure A.5 – PMTDR vs. Oven-dry Moisture Contents for GP Material

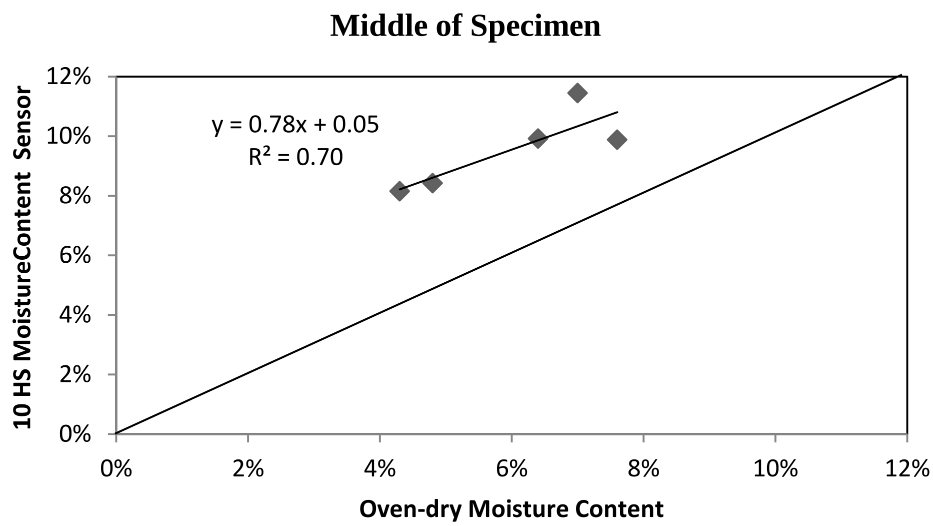


Figure A.6 – 10 HS Sensor vs. Oven-dry Moisture Contents for GP Material

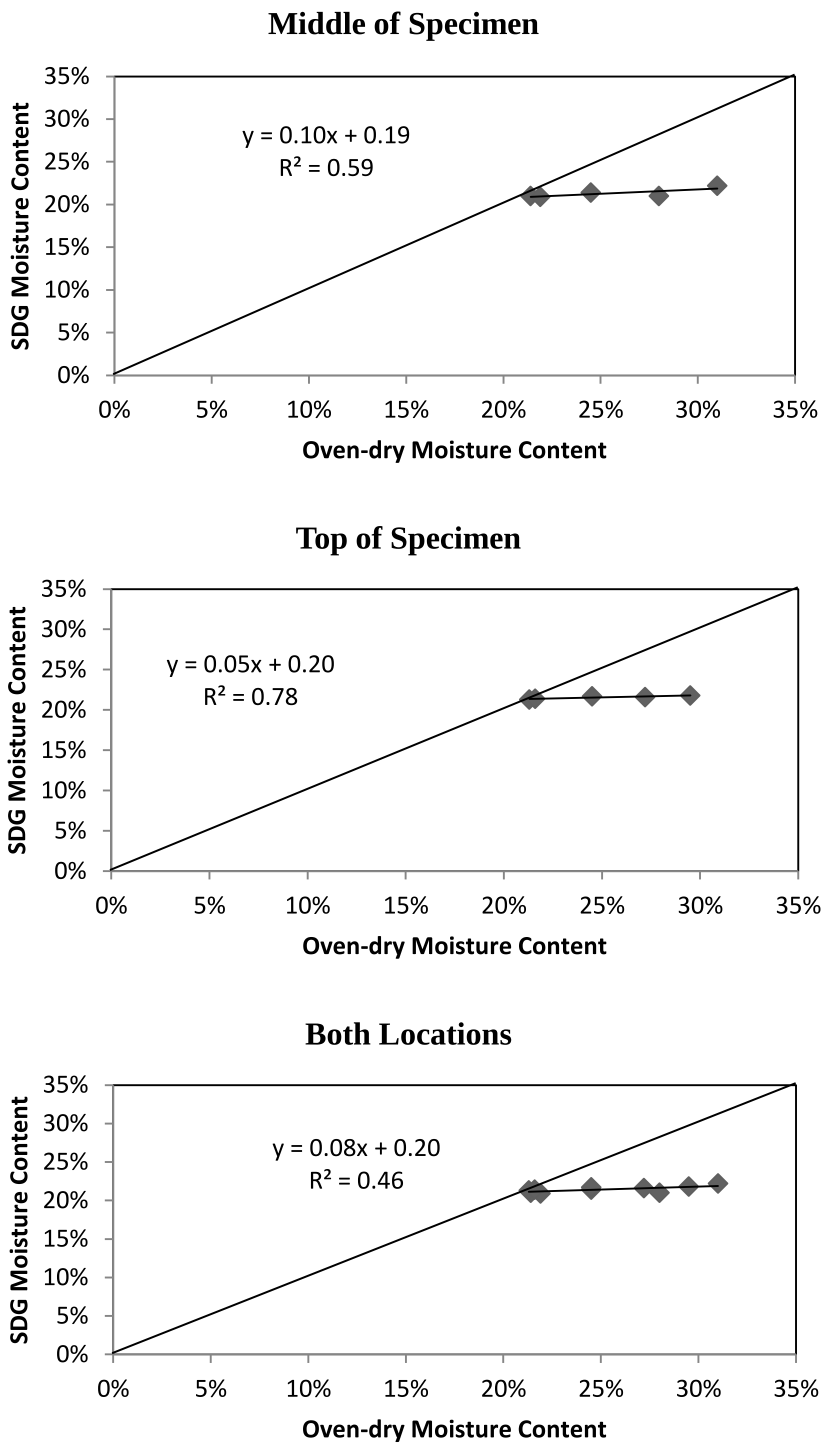


Figure A.7 – SDG 200 vs. Oven-dry Moisture Contents for CH Material

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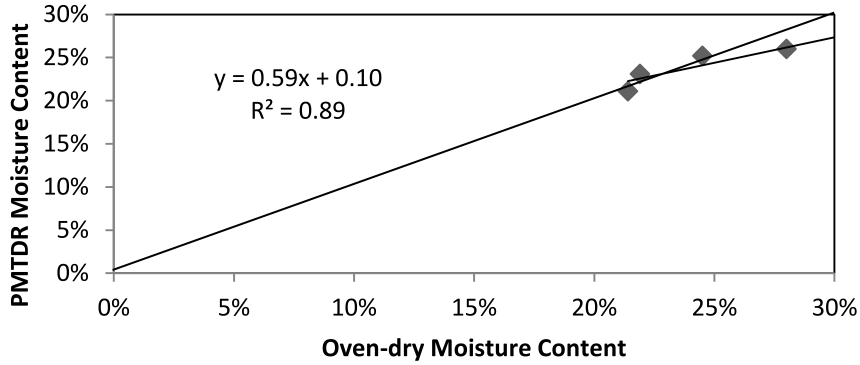

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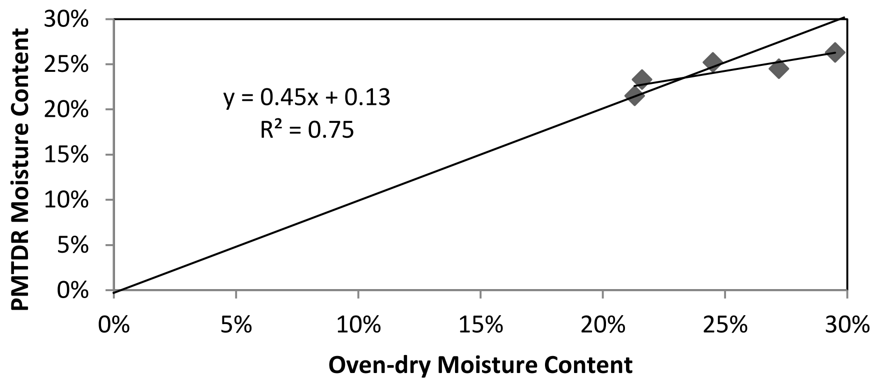


Both Locations

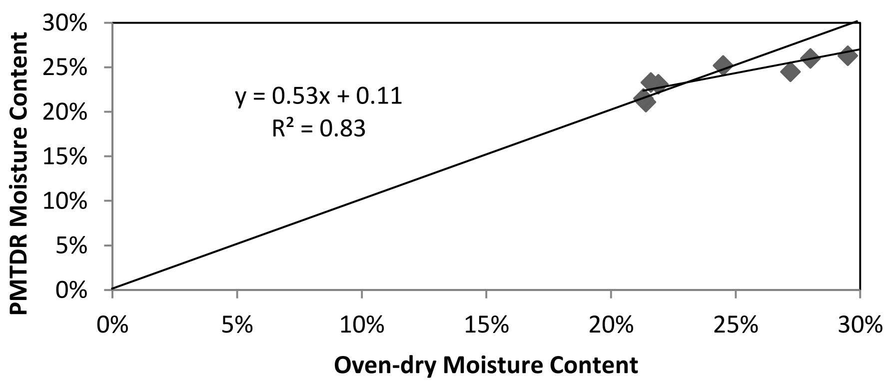


Figure A.8 – PMTDR vs. Oven-dry Moisture Contents for CH Material

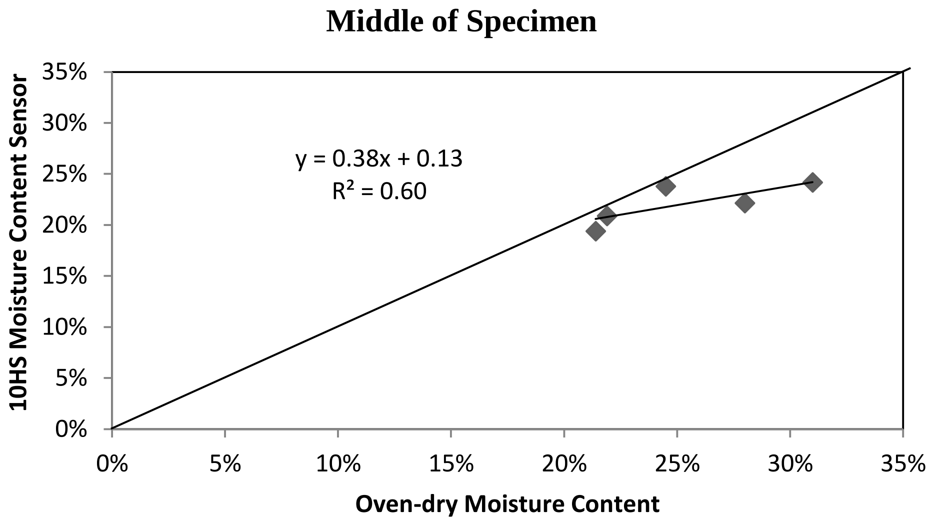
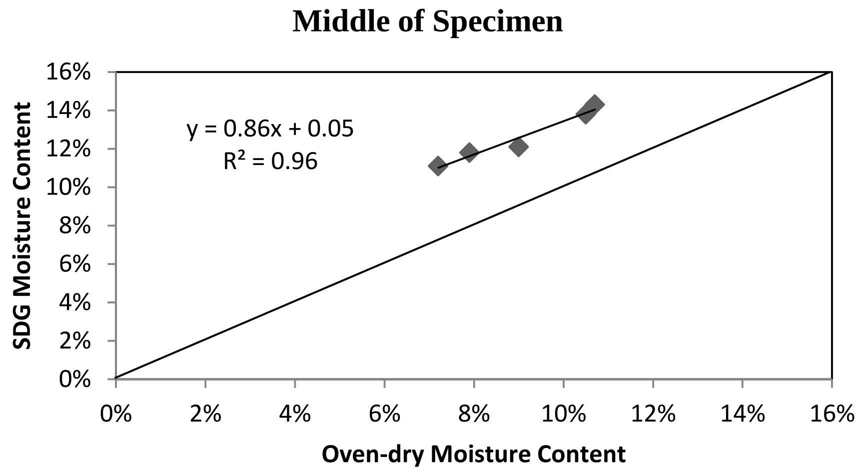
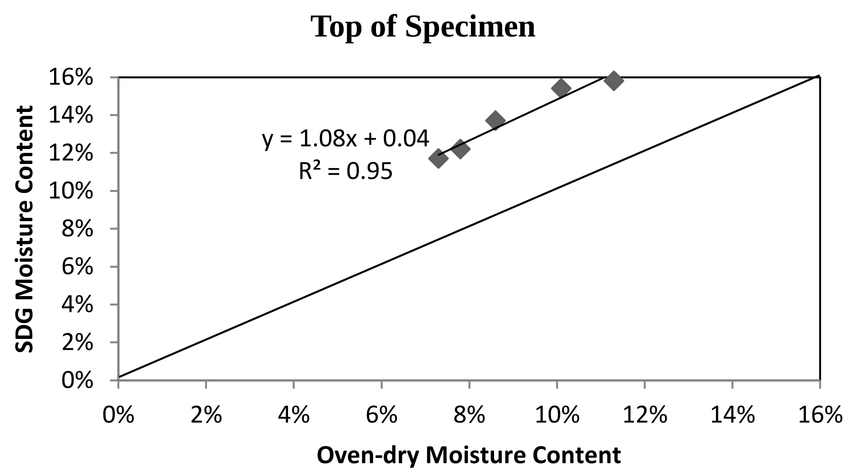


Figure A.9 – 10 HS Sensor vs. Oven-dry Moisture Contents for CH Material





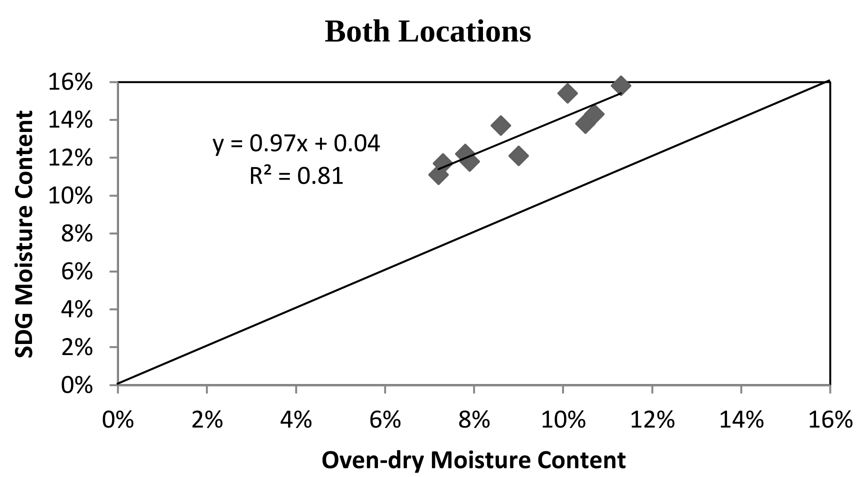
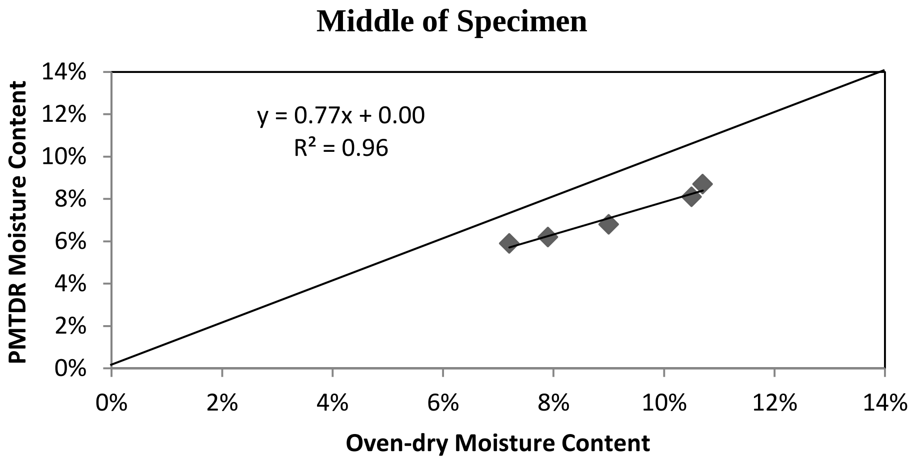
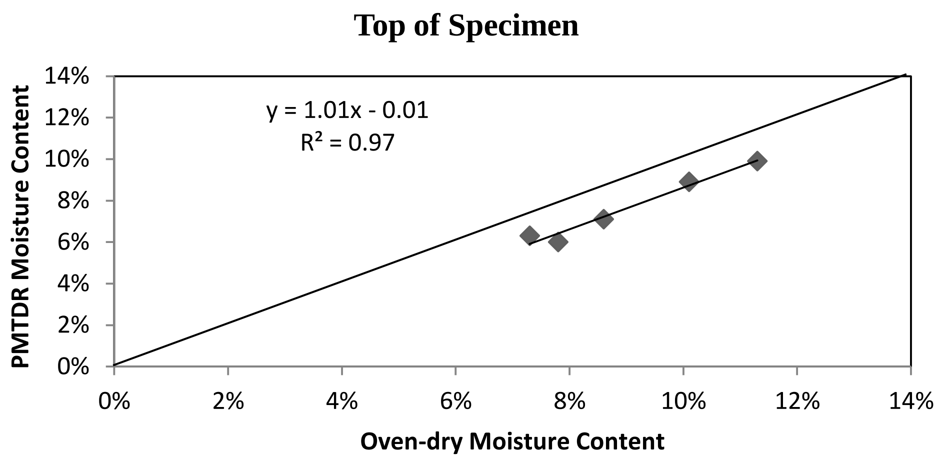


Figure A.10 – SDG 200 vs. Oven-dry Moisture Contents for ML Material





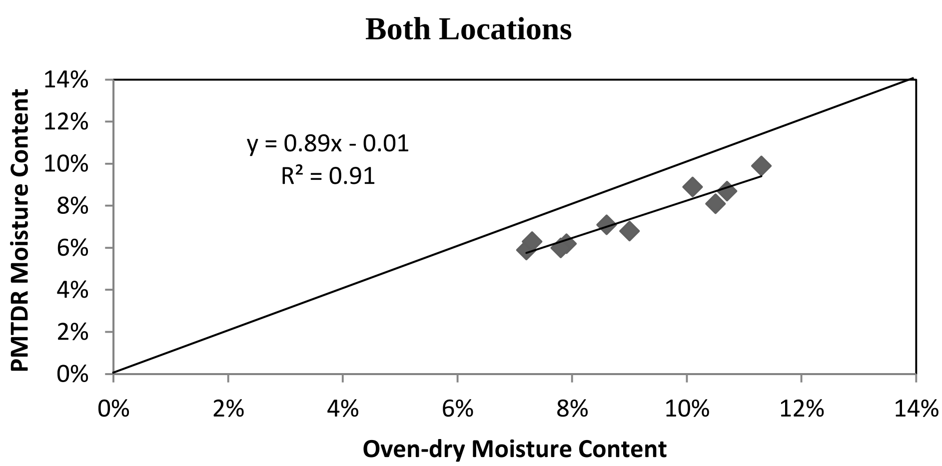


Figure A.11 – PMTDR vs. Oven-dry Moisture Contents for ML Material

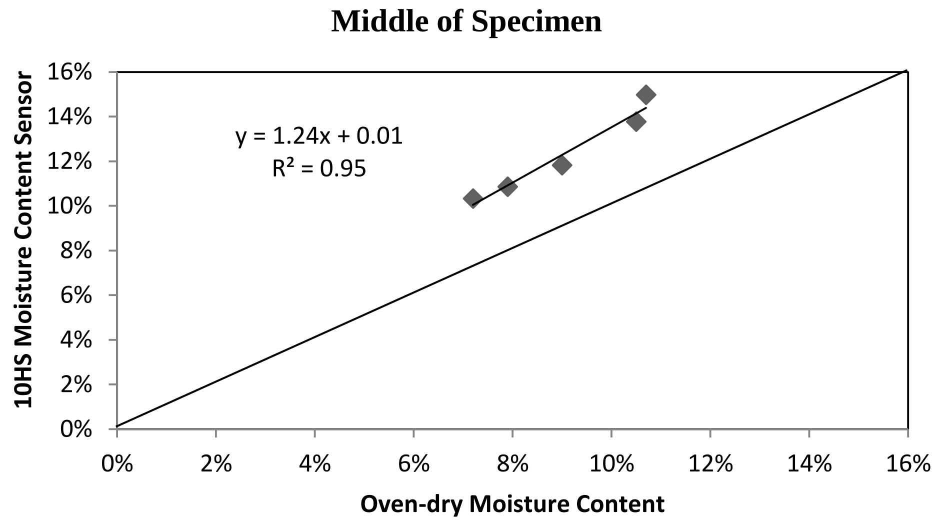


Figure A.12 – 10 HS Sensor vs. Oven-dry Moisture Contents for ML Material

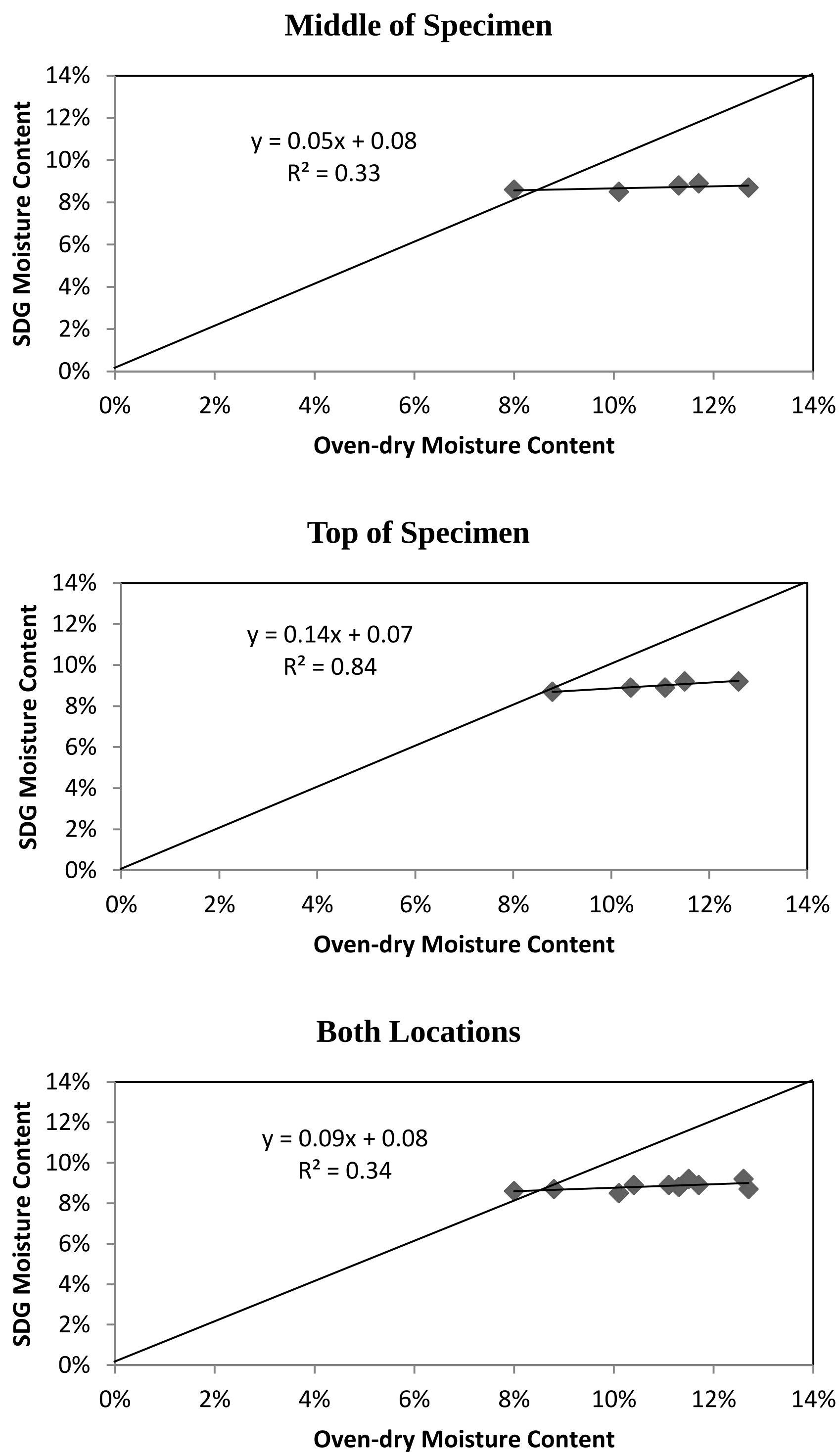
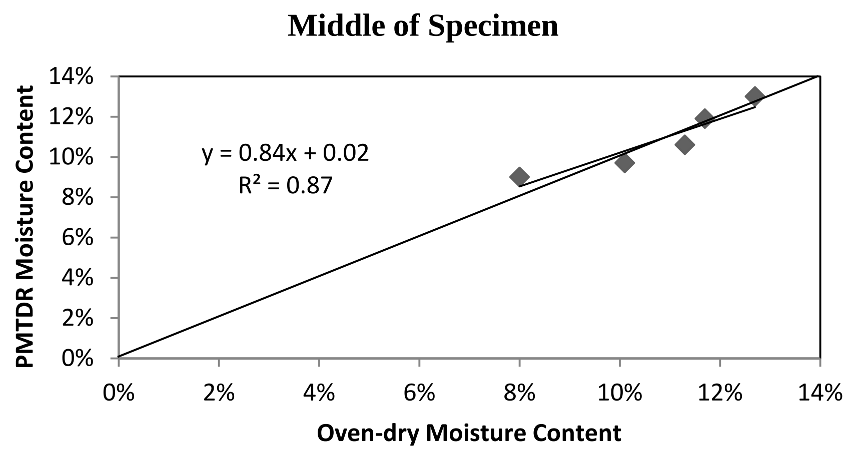
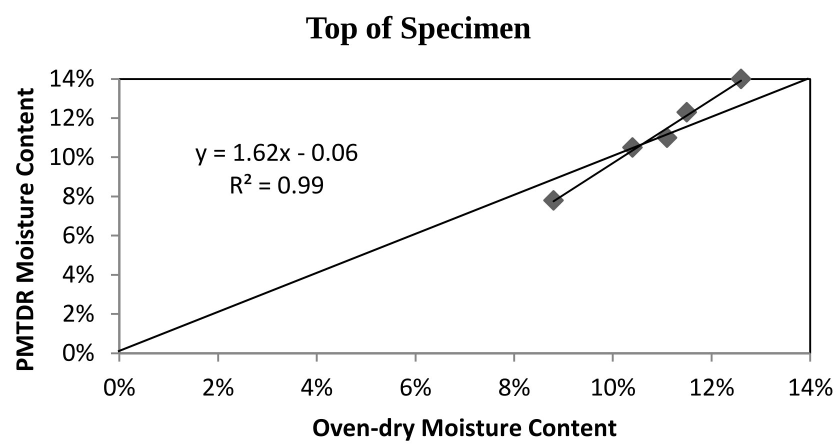


Figure A.13 – SDG vs. Oven-dry Moisture Contents for SC Material





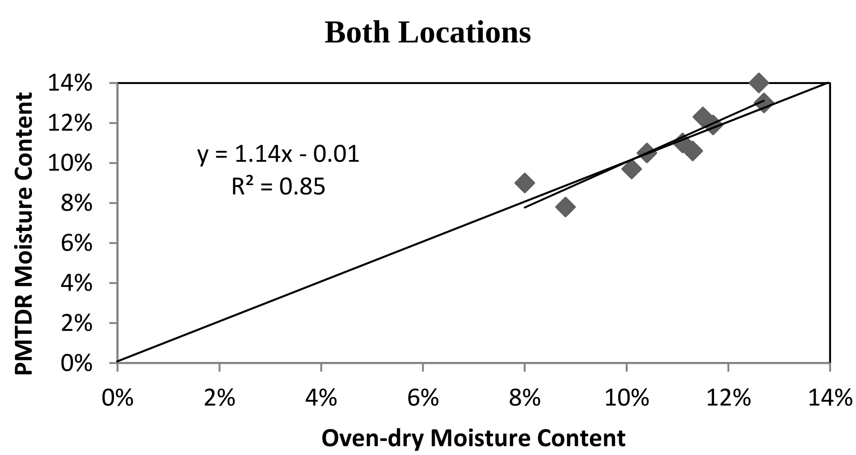


Figure A.14 – PMTDR vs. Oven-dry Moisture Contents for SC Material

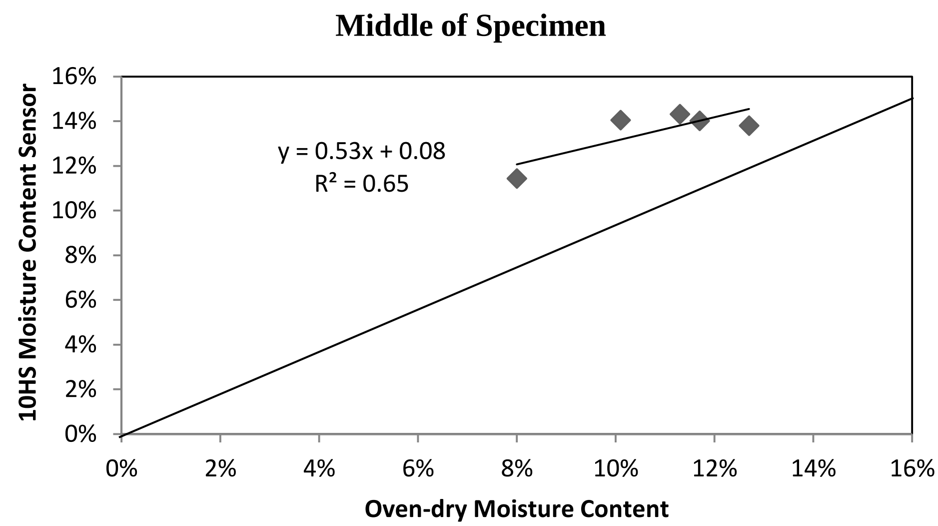


Figure A.15 – 10 HS Sensor vs. Oven-dry Moisture Contents for SC Material

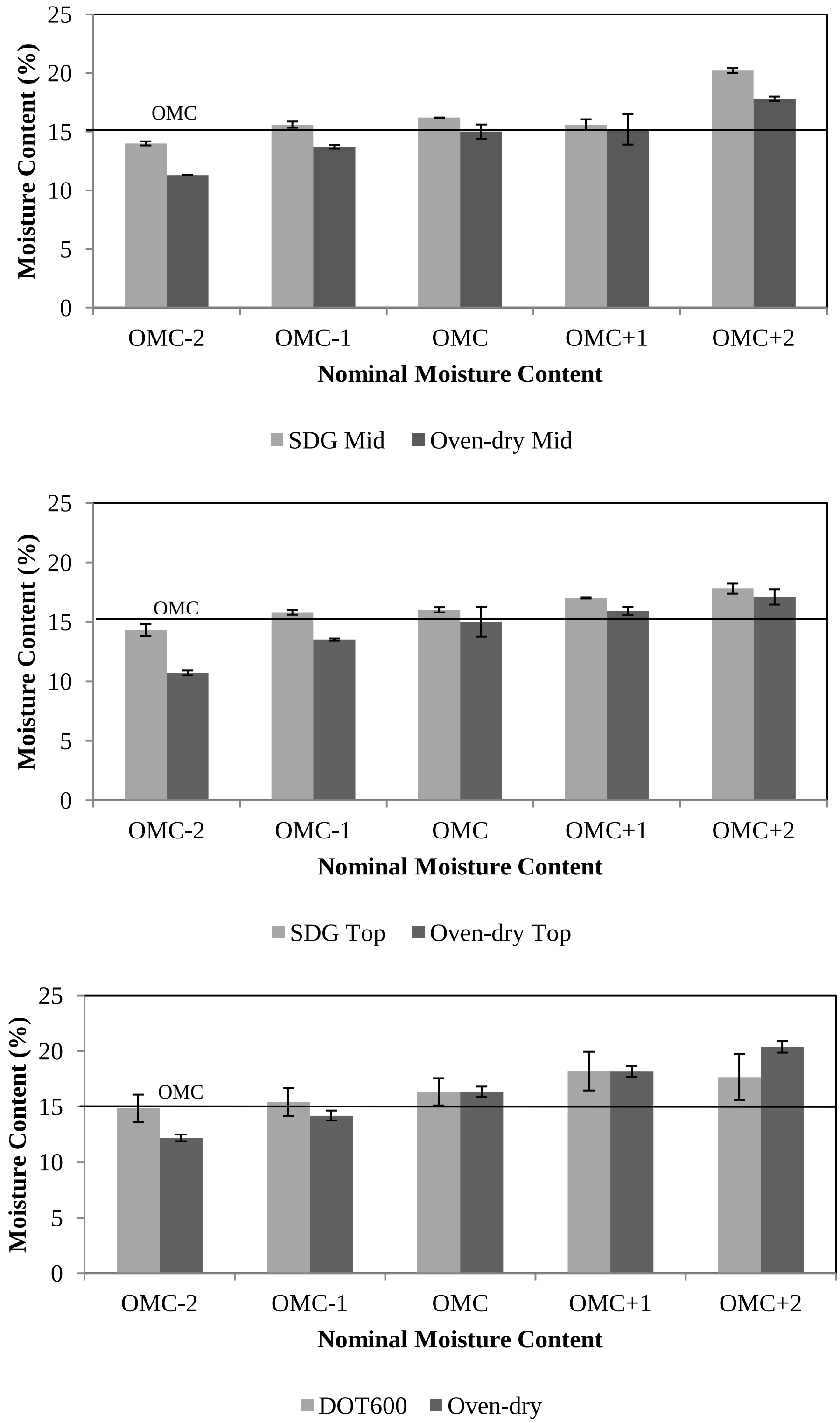


Figure A.16 – Average SDG 200 & DOT600 Moisture Contents for SM Material

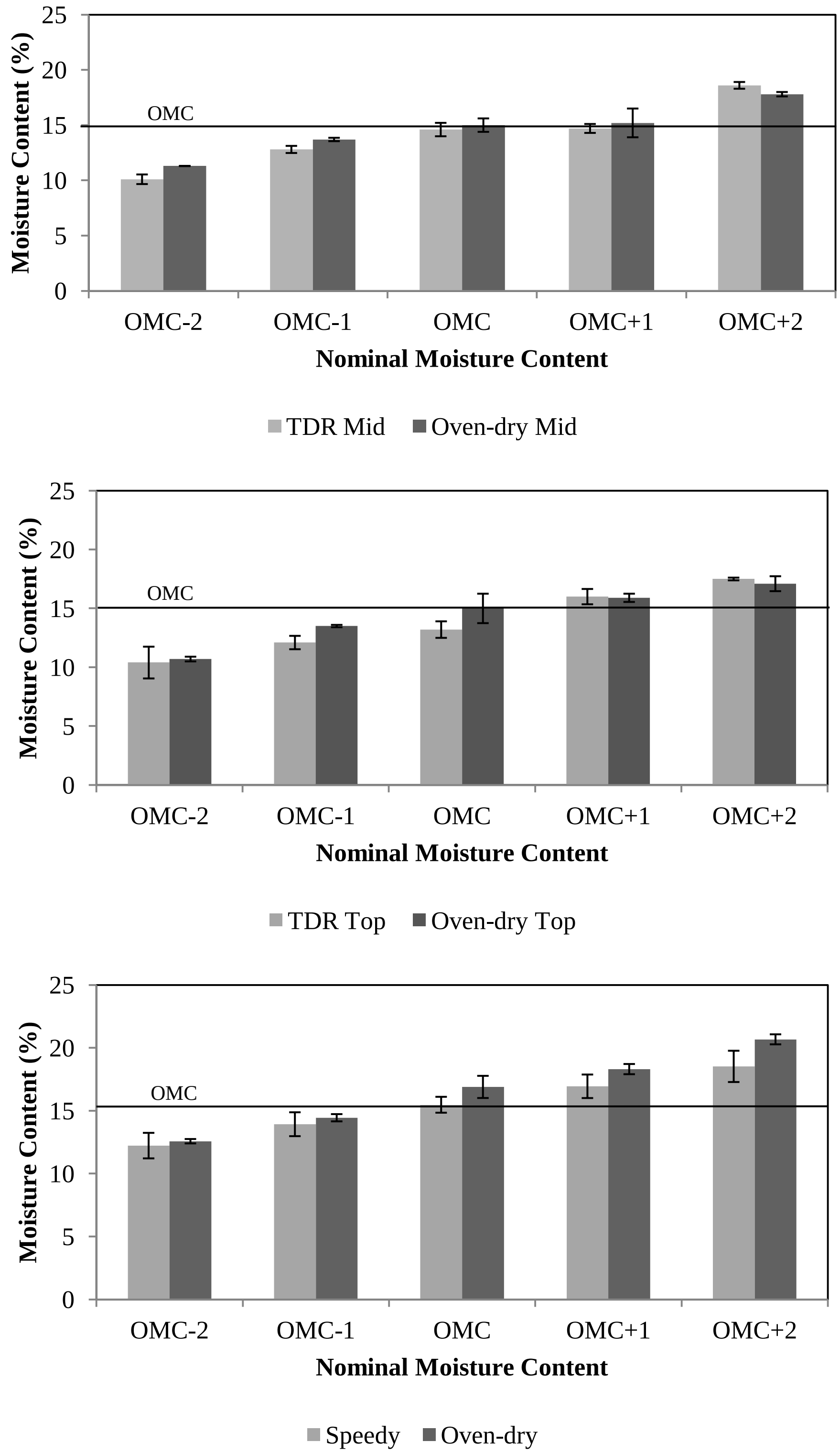
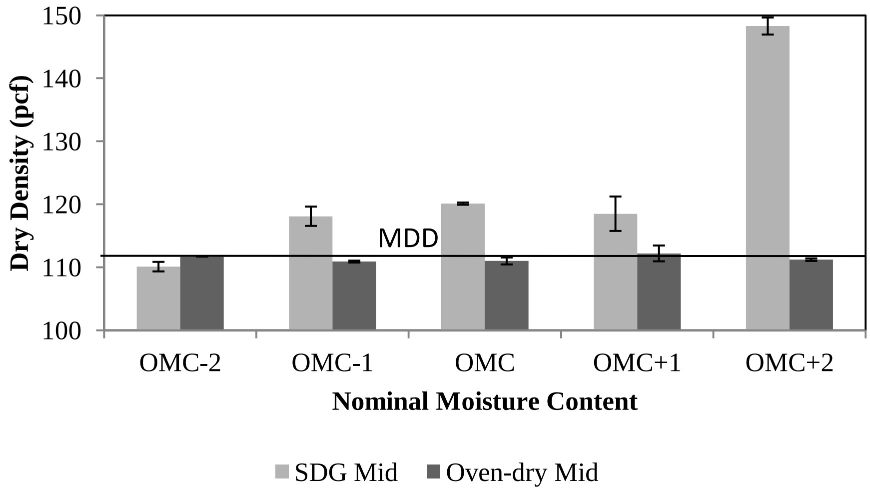


Figure A.17 – Average PMTDR & Speedy Moisture Contents for SM Material



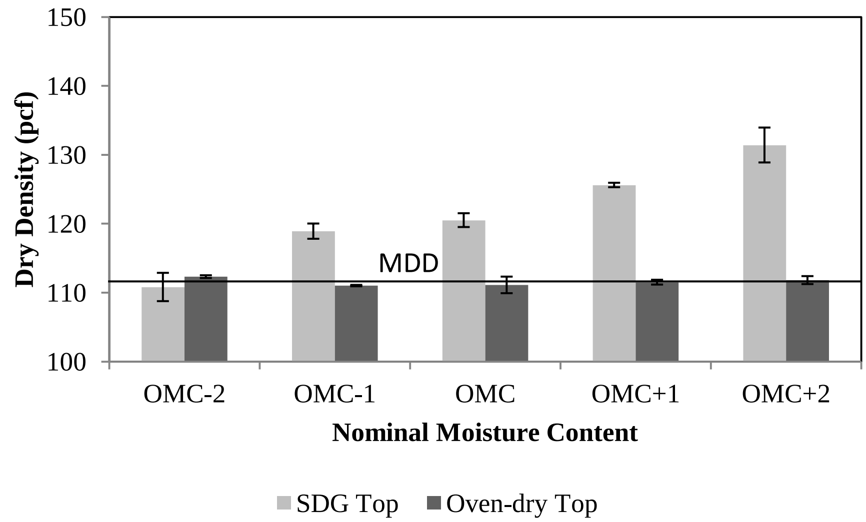


Figure A.18 – Average SDG 200 Densities for SM Material

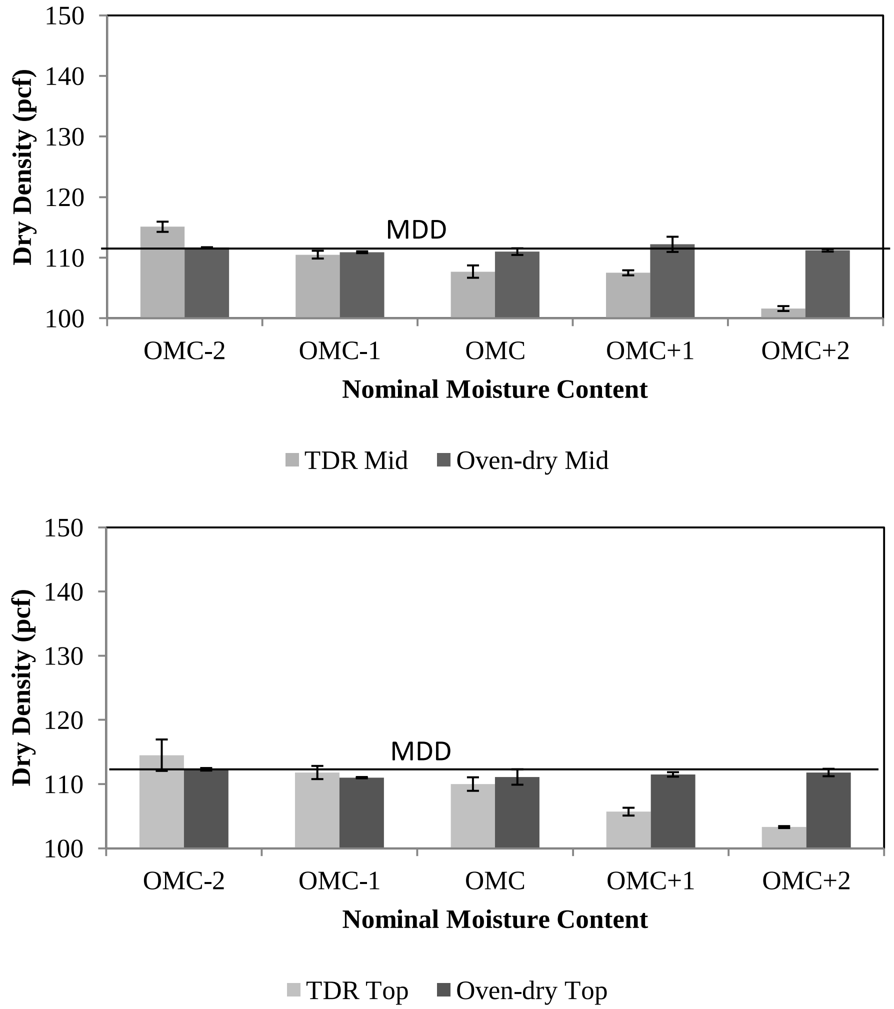


Figure A.19 – Average PMTDR Densities for SM Material

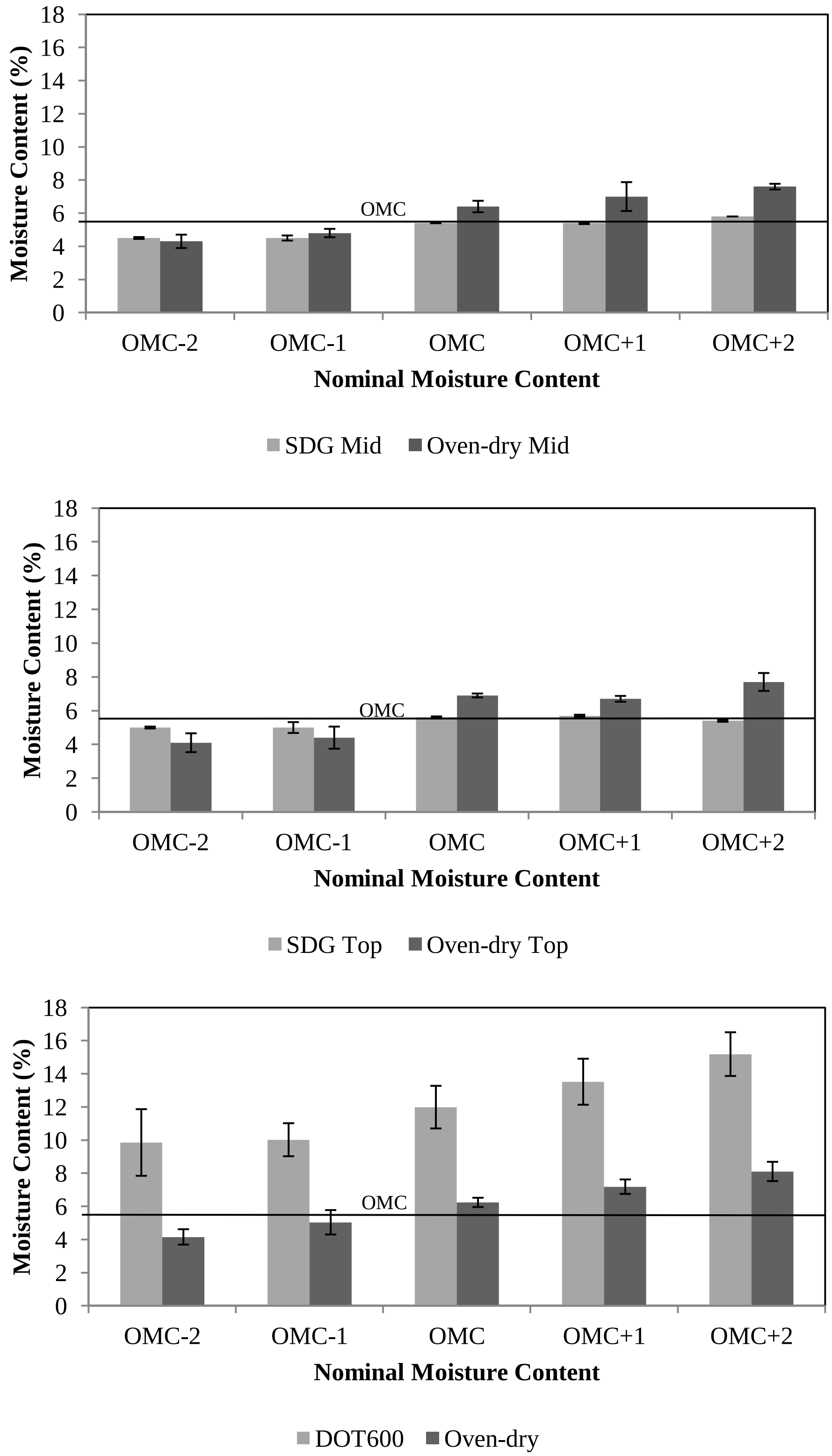


Figure A.20 – SDG 200 & DOT600 Moisture Contents for GP Material

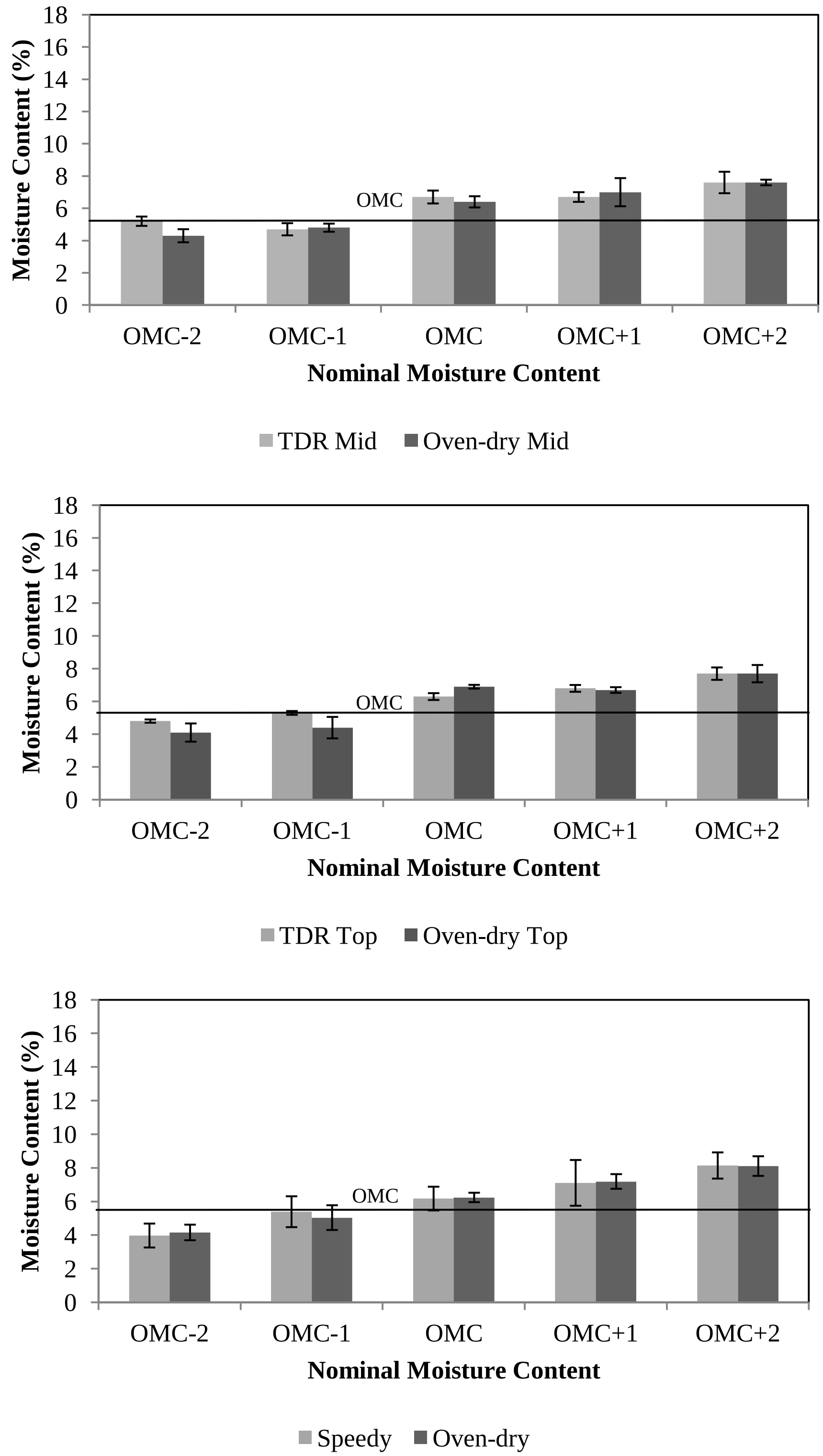


Figure A.21 – PMTDR and Speedy Moisture Contents for GP Material

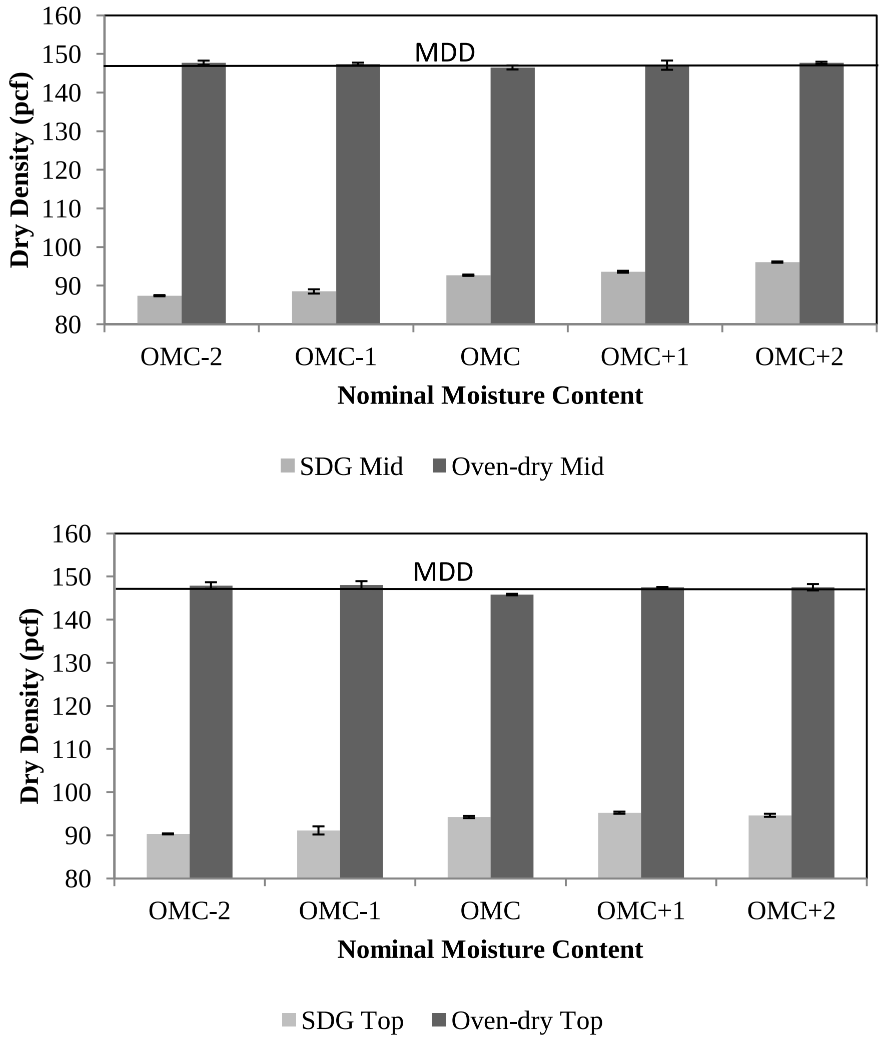
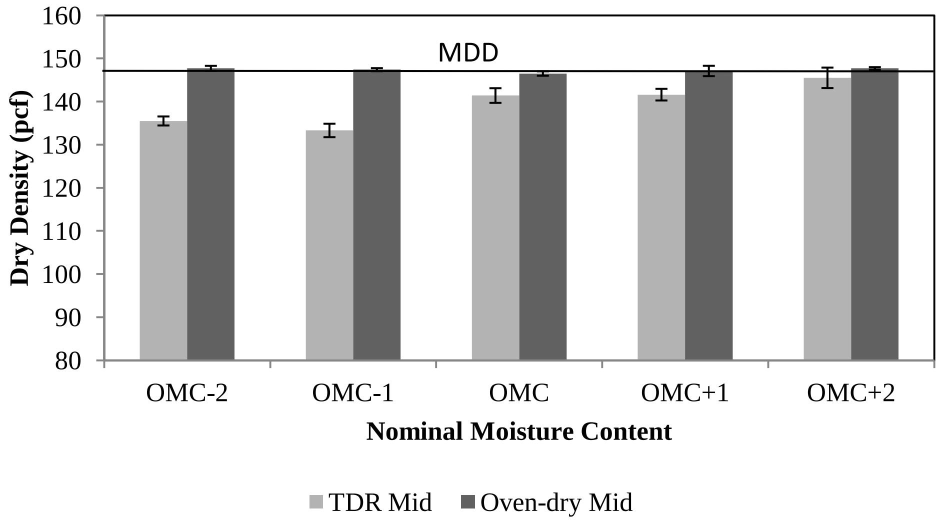


Figure A.22 – SDG 200 Densities for GP Material



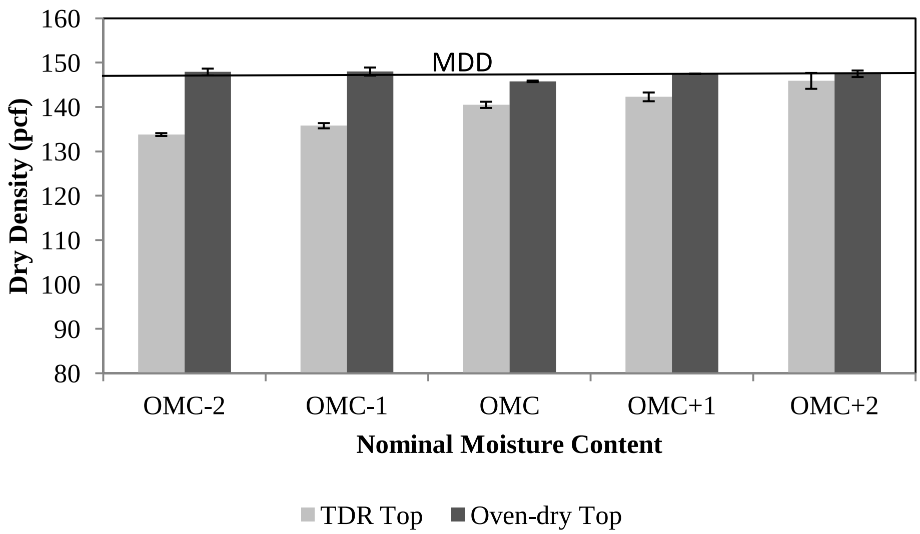


Figure A.23 – PMTDR Densities for GP Material

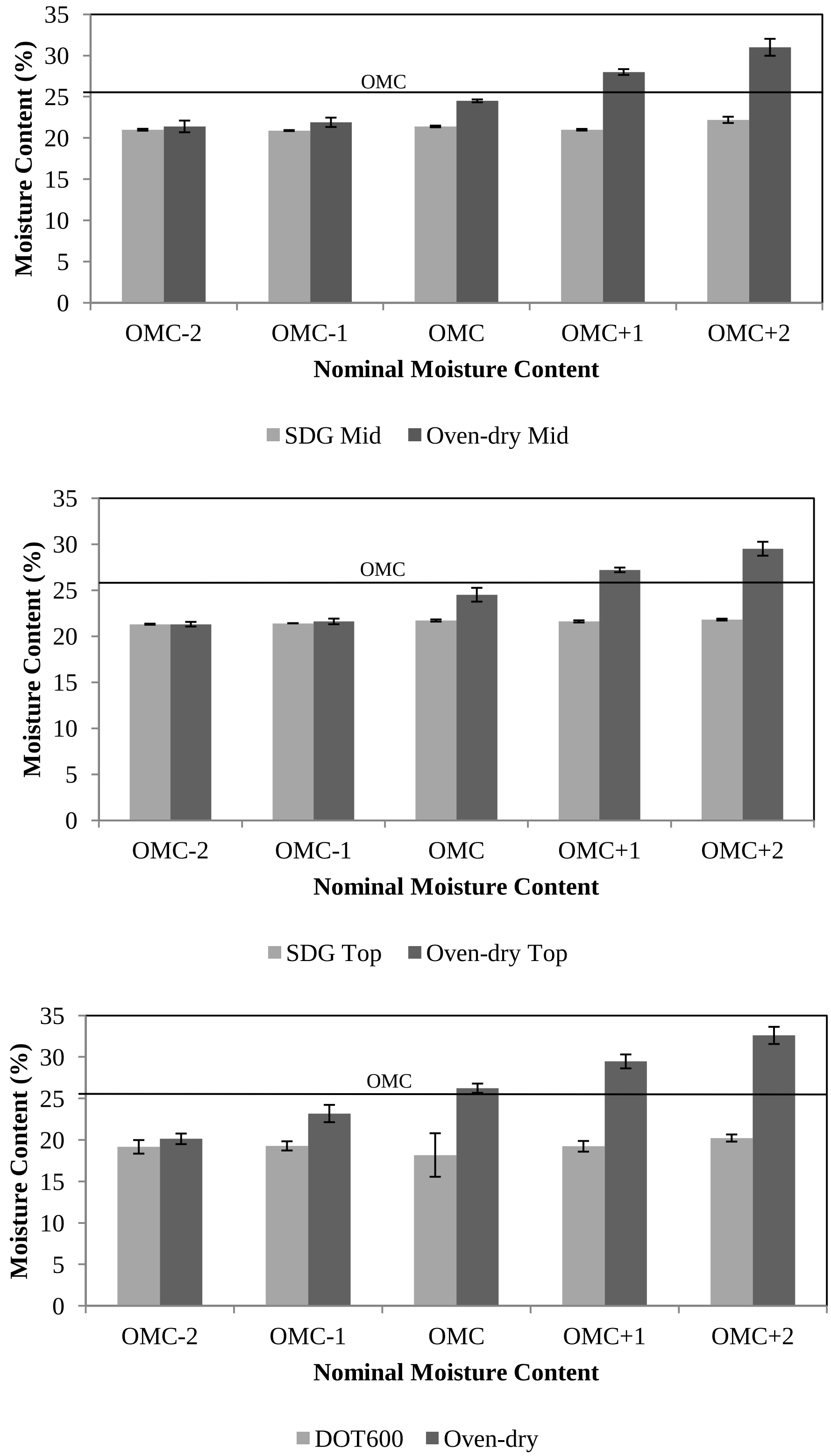
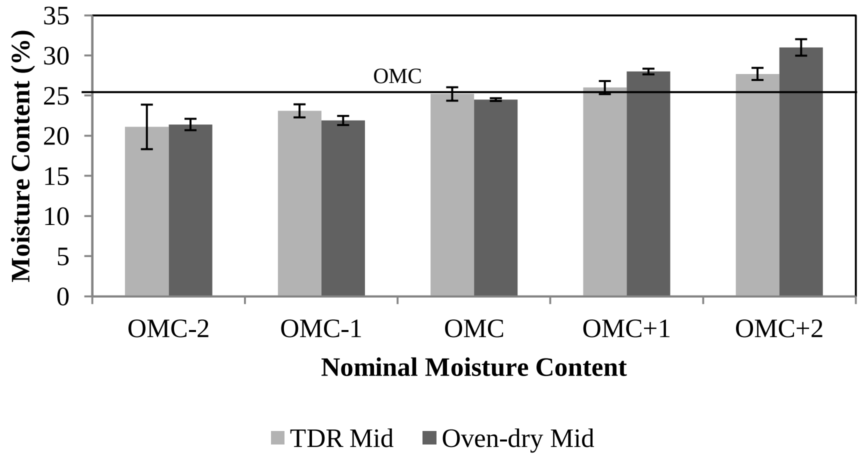
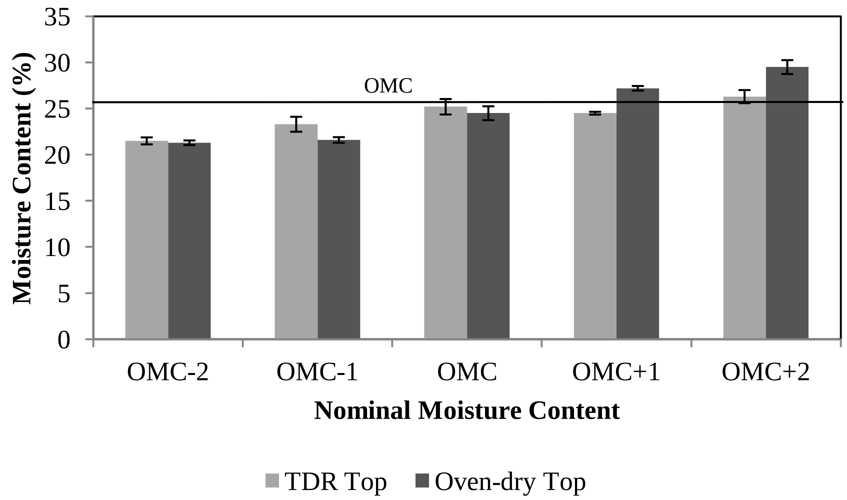


Figure A.24 – SDG 200 & DOT600 Moisture Contents for CH Material





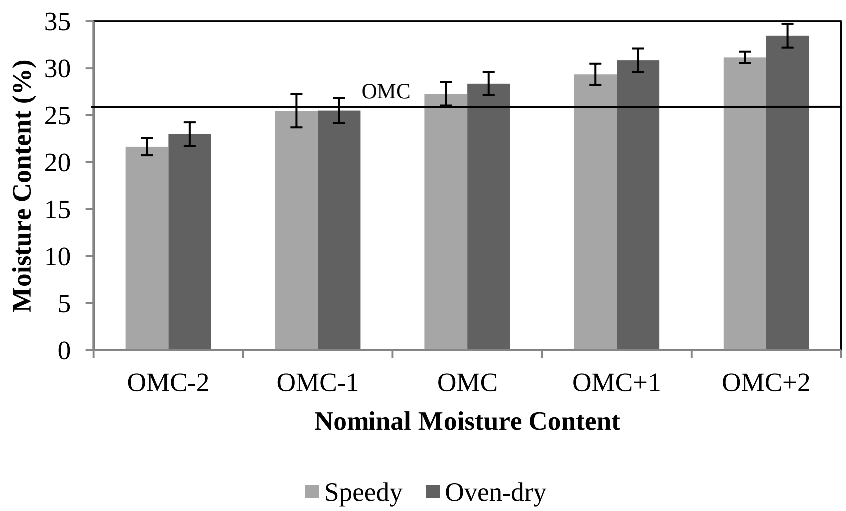
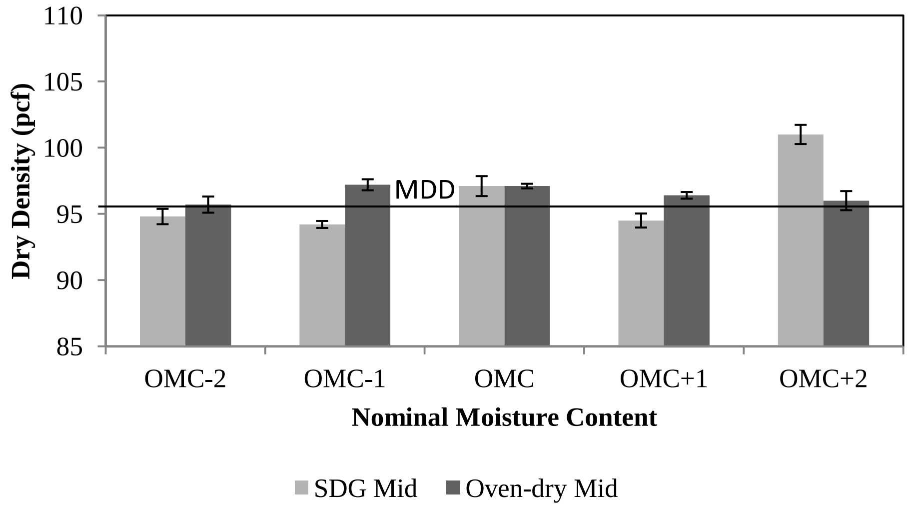


Figure A.25 – PMTDR & Speedy Moisture Contents for CH Material



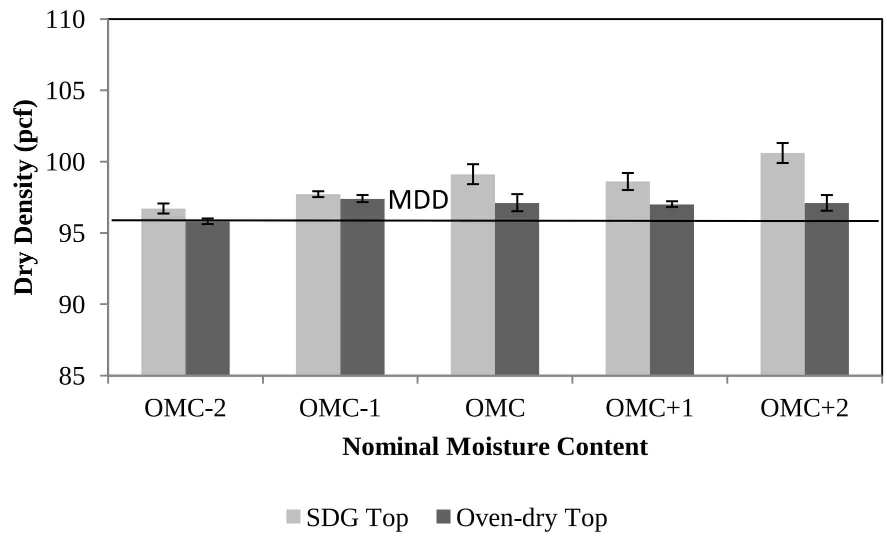


Figure A.26 – SDG 200 Densities for CH Material

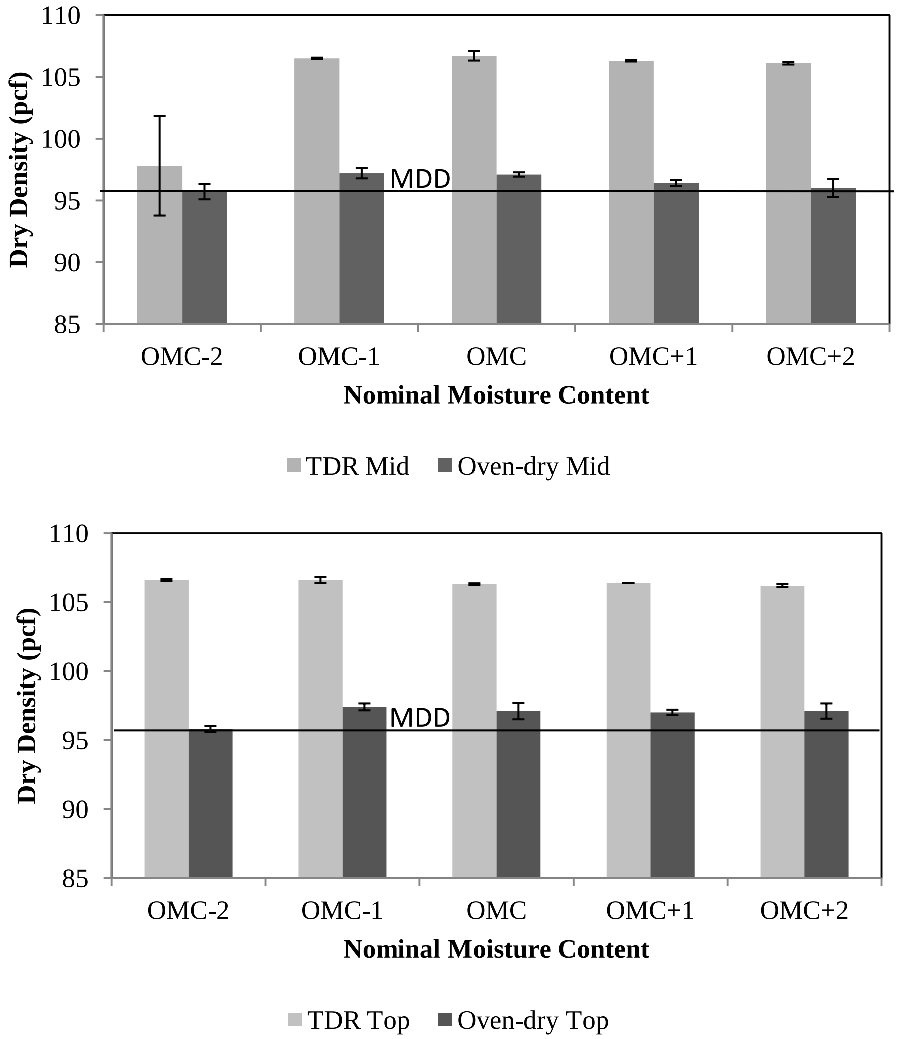


Figure A.27 – PMTDR Densities for CH Material

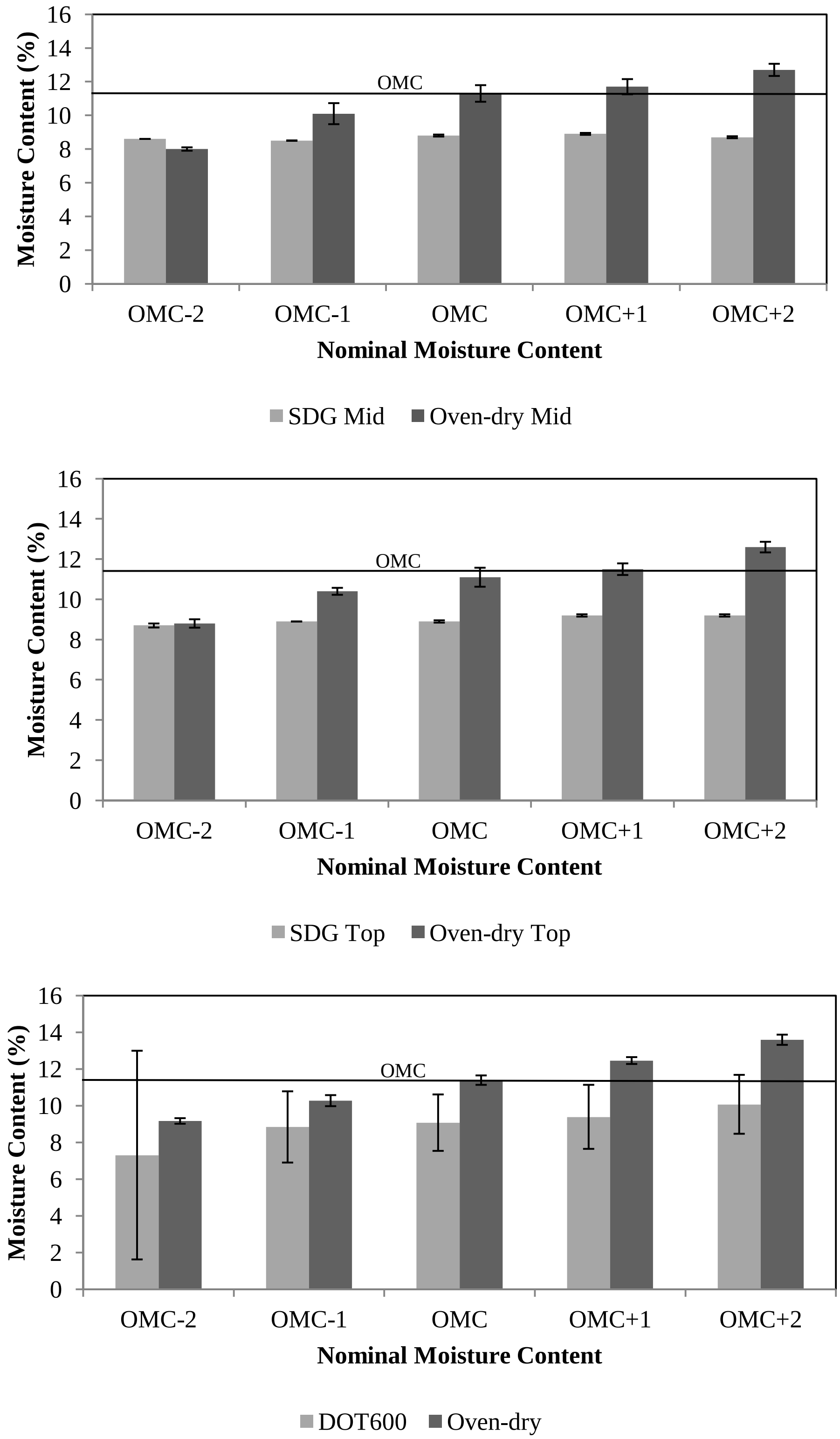


Figure A.28 – SDG 200 & DOT600 Moisture Contents for SC Material

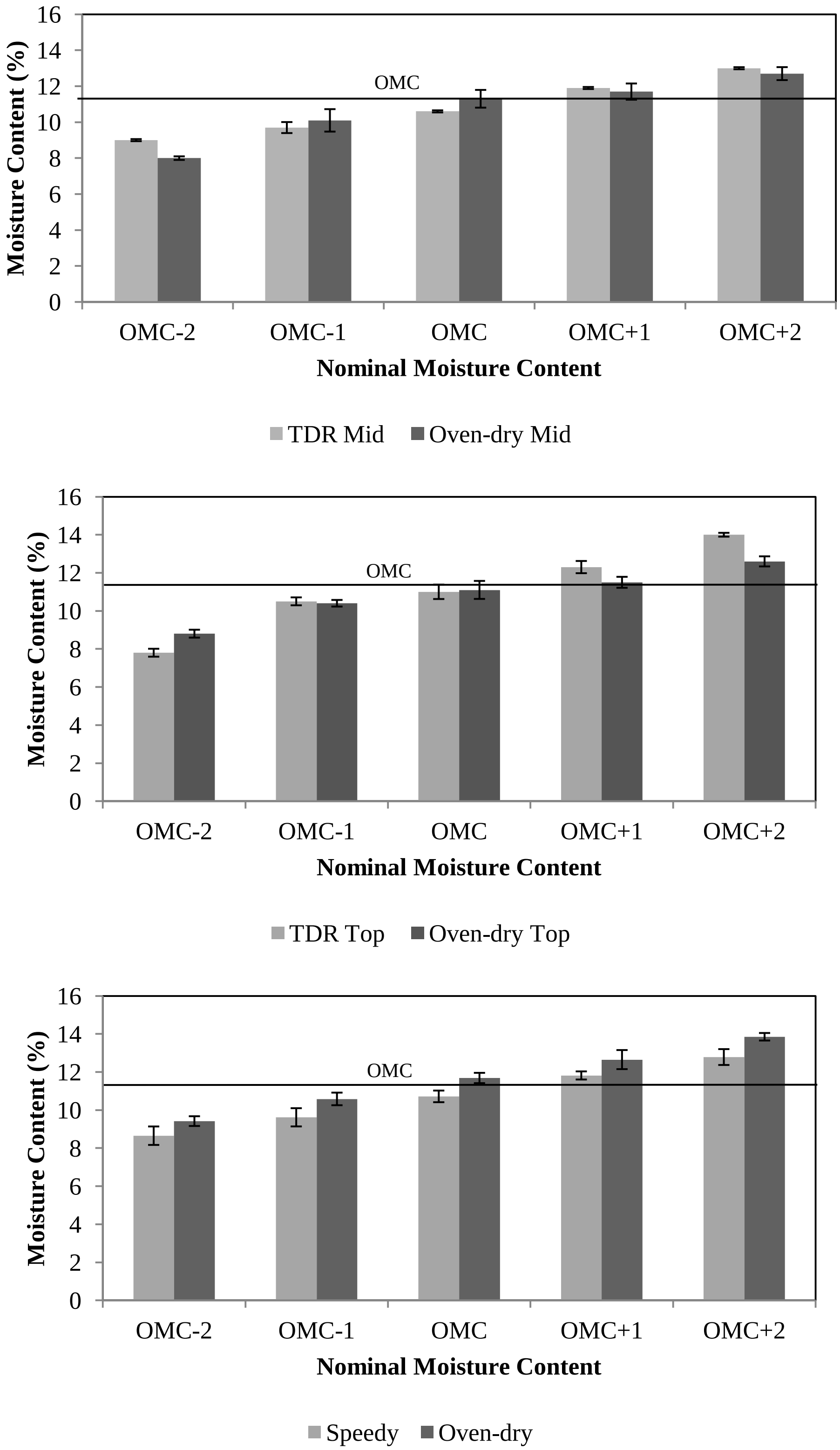
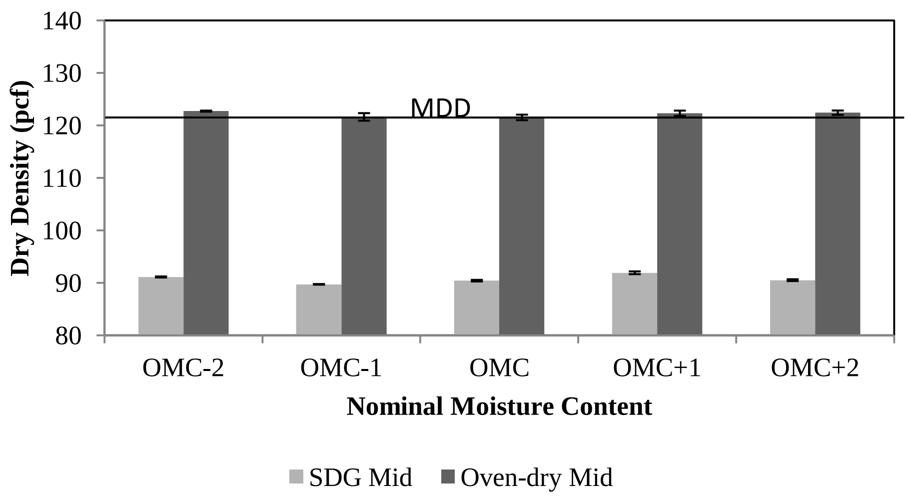


Figure A.29 – PMTDR & Speedy Moisture Contents for SC Material



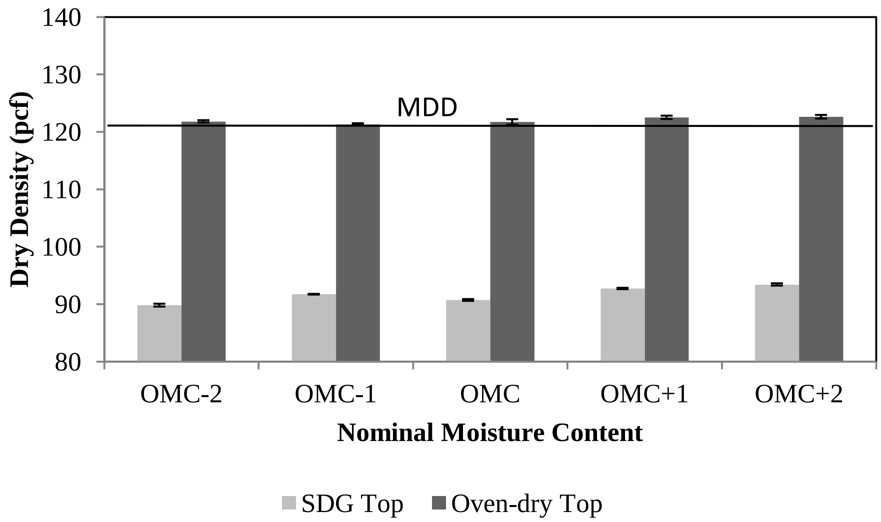


Figure A.30 – SDG 200 Densities for SC Material

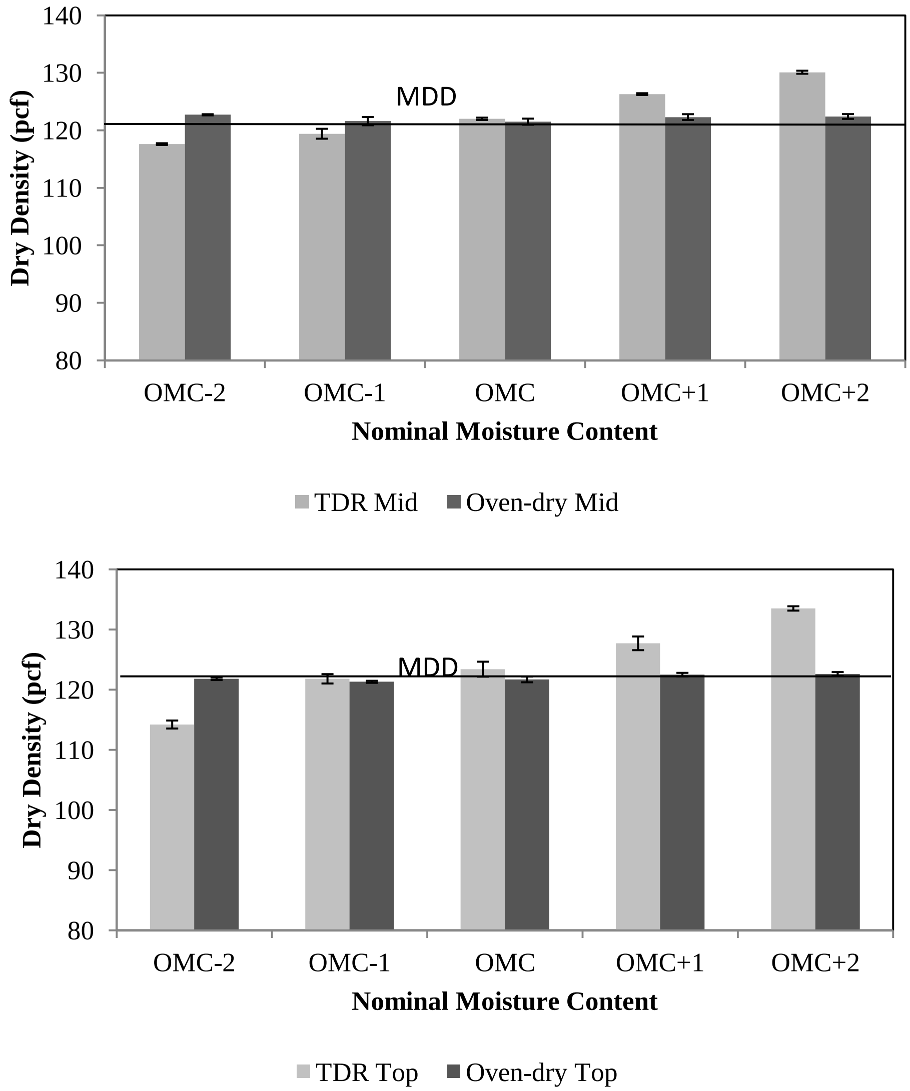


Figure A.31 – PMTDR Densities for SC Material

Table A.1 – Statistical Properties Resulting from Plotting Device Moisture Contents vs. Oven-dry Moisture Contents

Material	**Location**	**SDG 200 Moisture Content**				**PMTDR Moisture Content**				**10HS Moisture Content Sensor**			
		Slope	**Y-Intercept**	**R2**	**SEE (%)**	**Slope**	**Y-Intercept**	**R2**	**SEE (%)**	**Slope**	**Y-Intercept**	**R2**	**SEE (%)**
ML	**Middle**	0.80	0.05	0.90	0.40	0.74	0.00	0.90	0.40	1.24	0.01	0.95	0.50
	Top	1.02	0.05	0.92	0.50	0.93	-0.01	0.91	0.50				
	Both	0.91	0.05	0.77	0.80	0.84	0.00	0.86	0.50				
CH	**Middle**	0.10	0.19	0.57	0.30	0.60	0.09	0.75	1.40	0.38	0.13	0.60	1.50
	Top	0.05	0.20	0.68	0.10	0.43	0.13	0.64	1.10				
	Both	0.08	0.20	0.45	0.30	0.53	0.11	0.70	1.30				
SC	**Middle**	0.05	0.08	0.35	0.10	0.79	0.02	0.80	0.70	0.53	0.08	0.65	0.80
	Top	0.14	0.07	0.77	0.10	1.54	-0.06	0.94	0.50				
	Both	0.09	0.08	0.33	0.20	1.08	-0.01	0.80	0.80				
SM	**Middle**	0.90	0.03	0.84	1.10	1.31	-0.05	0.99	0.30	0.32	0.13	0.78	0.50
	Top	0.52	0.09	0.96	0.30	1.10	-0.02	0.90	1.00				
	Both	0.70	0.06	0.81	0.80	1.20	-0.03	0.94	0.70				
GP	**Middle**	0.37	0.03	0.86	0.20	0.74	0.02	0.74	0.60	0.78	0.05	0.70	0.80
	Top	0.15	0.04	0.50	0.20	0.66	0.02	0.88	0.40				
	Both	0.25	0.04	0.60	0.30	0.70	0.02	0.80	0.50				

SEE – Standard Error

Table A.2 – Statistical Properties Related to Dry Density Readings

Material	Location	Measured Dry Density			SDG 200 Dry Density				PMTDR Dry Density			
		Average	STDEV	COV	Average	STDEV	COV	f-Test	Average	STDEV	COV	f-Test
ML	Middle	124.9	0.5	0.40%	111.1	4.3	3.90%	7.18E-10	127.8	1.7	1.40%	9.18E-05
	Top	125.0	0.9	0.70%	116.5	7.2	6.20%	5.08E-10	128.8	2.6	2.00%	2.57E-04
	Both	124.9	0.7	0.60%	113.8	6.4	5.70%	1.52E-20	128.3	2.2	1.70%	3.47E-08
CH	Middle	96.5	0.7	0.70%	96.3	2.7	2.80%	1.45E-05	104.7	3.9	3.70%	1.20E-07
	Top	96.9	0.7	0.70%	98.5	1.4	1.50%	5.94E-03	106.4	0.2	0.20%	1.05E-05
	Both	96.7	0.7	0.70%	97.4	2.4	2.50%	3.57E-09	105.5	2.8	2.70%	4.48E-11
SC	Middle	122.1	0.6	0.50%	90.7	0.8	0.90%	4.07E-01	123.1	4.7	3.80%	1.49E-09
	Top	122.0	0.6	0.50%	91.7	1.3	1.50%	3.07E-03	124.1	6.7	5.40%	3.92E-12
	Both	122.0	0.6	0.50%	91.2	1.2	1.30%	4.02E-04	123.6	5.7	4.60%	2.13E-21
SM	Middle	111.4	0.7	0.70%	123.0	13.6	11.10%	6.38E-15	108.5	4.6	4.30%	1.84E-08
	Top	111.6	0.7	0.70%	121.4	7.3	6.00%	3.08E-11	109.1	4.4	4.00%	3.10E-08
	Both	111.5	0.7	0.60%	122.2	10.8	8.80%	7.27E-27	108.8	4.4	4.10%	6.31E-16
GP	Middle	147.3	0.7	0.50%	91.7	3.4	3.70%	7.89E-07	139.4	4.8	3.40%	7.96E-09
	Top	149.3	4.3	2.90%	93.1	2.1	2.20%	1.08E-02	139.7	4.6	3.30%	7.72E-01
	Both	148.3	3.2	2.20%	92.4	2.8	3.10%	5.37E-01	139.6	4.6	3.30%	5.08E-02

STDEV – Standard deviation, COV – Coefficient of Variation

Table A.3 – Crossed Gage R&R Study Results for SM Material

Measurement Device	Equipment Variation (Standard Deviation due to Repeatability)	Appraiser Variation (Standard Deviation due to Reproducibility)	Combined Device Variability (Gauge R&R)	Specimen Variation (SV)	Total Variation (TV)
SDG200	0.30	0.98	1.03	1.62	1.92
PMTDR	0.63	0.71	0.95	2.88	3.04
DOT600	1.47	0.62	1.59	1.30	2.06
Speedy	0.71	0.86	1.12	2.45	2.70

Table A.4 – Crossed Gage R&R Study Variation Percentages for SM Material

Measurement Device	Equipment Variation Proportion, %	Appraiser Variation Proportion, %	Combined R&R Proportion, %	Specimen Variation Proportion, %
SDG200	2%	26%	29%	71%
PMTDR	4%	5%	10%	90%
DOT600	51%	9%	60%	40%
Speedy	7%	10%	17%	83%

Table A.5 – Crossed Gage R&R Study Results for GP Material

Measurement Device	Equipment Variation (Standard Deviation due to Repeatability)	Appraiser Variation (Standard Deviation due to Reproducibility)	Combined Device Variability (Gauge R&R)	Specimen Variation (SV)	Total Variation (TV)
SDG200	0.12	0.26	0.29	0.40	0.49
PMTDR	0.34	0.20	0.40	1.15	1.22
DOT600	1.35	0.65	1.50	2.22	2.68
Speedy	0.76	0.69	1.03	1.57	1.87

Table A.6 – Crossed Gage R&R Study Variation Percentages for GP Material

Measurement Device	Equipment Variation Proportion, %	Appraiser Variation Proportion, %	Combined R&R Proportion, %	Specimen Variation Proportion, %
SDG200	6%	28%	35%	67%
PMTDR	8%	3%	11%	89%
DOT600	25%	6%	31%	69%
Speedy	16%	14%	30%	70%

Table A.7 – Crossed Gage R&R Study Results for CH Material

Measurement Device	Equipment Variation (Standard Deviation due to Repeatability)	Appraiser Variation (Standard Deviation due to Reproducibility)	Combined Device Variability (Gauge R&R)	Specimen Variation (SV)	Total Variation (TV)
SDG200	0.15	0.28	0.31	0.31	0.44
PMTDR	1.10	0.15	1.11	2.15	2.43
DOT600	0.59	0.11	0.60	0.38	0.71
Speedy	1.21	0.00	1.21	3.63	3.83

Table A.8 – Crossed Gage R&R Study Variation Percentages for CH Material

Measurement Device	Equipment Variation Proportion, %	Appraiser Variation Proportion, %	Combined R&R Proportion, %	Specimen Variation Proportion, %
SDG200	12%	40%	50%	50%
PMTDR	20%	0%	21%	78%
DOT600	68%	3%	71%	29%
Speedy	10%	0%	10%	90%

Table A.9 – Crossed Gage R&R Study Results for SC Material

Measurement Device	Equipment Variation (Standard Deviation due to Repeatability)	Appraiser Variation (Standard Deviation due to Reproducibility)	Combined Device Variability (Gauge R&R)	Specimen Variation (SV)	Total Variation (TV)
SDG200	0.05	0.23	0.23	0.14	0.27
PMTDR	0.21	0.60	0.63	1.89	1.99
DOT600	1.89	0.86	2.08	0.00	2.08
Speedy	0.31	0.32	0.44	1.65	1.71

Table A.10 – Crossed Gage R&R Study Variation Percentages for SC Material

Measurement Device	Equipment Variation Proportion, %	Appraiser Variation Proportion, %	Combined R&R Proportion, %	Specimen Variation Proportion, %
SDG200	3%	73%	73%	27%
PMTDR	1%	9%	10%	90%
DOT600	83%	17%	100%	0%
Speedy	3%	3%	7%	93%

Appendix B

Table B.1 – Averaged Moisture Content Measurements

Material	Middle				Top		
	Oven-dry	SDG	TDR	10HS*	Oven-dry	SDG	TDR
SM	11.3%	14.0%	10.1%	16.0%	10.7%	14.3%	10.4%
	13.7%	15.6%	12.8%	16.5%	13.5%	15.8%	12.1%
	15.0%	16.2%	14.6%	17.9%	15.0%	16.0%	13.2%
	15.2%	15.6%	14.7%	17.4%	15.9%	17.0%	16.0%
	17.8%	20.2%	18.6%	17.9%	17.1%	17.8%	17.5%
GP	4.3%	4.5%	5.2%	8.2%	4.1%	5.0%	4.8%
	4.8%	4.5%	4.7%	8.4%	4.4%	5.0%	5.3%
	6.4%	5.4%	6.7%	9.9%	6.9%	5.6%	6.3%
	7.0%	5.4%	6.7%	11.4%	6.7%	5.7%	6.8%
	7.6%	5.8%	7.6%	9.9%	7.7%	5.4%	7.7%
ML	7.2%	11.1%	5.9%	10.3%	7.8%	12.2%	6.0%
	7.9%	11.8%	6.2%	10.9%	7.3%	11.7%	6.3%
	9.0%	12.1%	6.8%	11.8%	8.6%	13.7%	7.1%
	10.5%	13.8%	8.1%	13.8%	10.1%	15.4%	8.9%
	10.7%	14.3%	8.7%	15.0%	11.3%	15.8%	9.9%
CH	21.4%	21.0%	21.1%	19.4%	21.3%	21.3%	21.5%
	21.9%	20.9%	23.1%	20.9%	21.6%	21.4%	23.3%
	24.5%	21.4%	25.2%	23.8%	24.5%	21.7%	25.2%
	28.0%	21.0%	26.0%	22.1%	27.2%	21.6%	24.5%
	31.0%	22.2%	27.7%	24.2%	29.5%	21.8%	26.3%
SC	8.0%	8.6%	9.0%	11.4%	8.8%	8.7%	7.8%
	10.1%	8.5%	9.7%	14.0%	10.4%	8.9%	10.5%
	11.3%	8.8%	10.6%	14.3%	11.1%	8.9%	11.0%
	11.7%	8.9%	11.9%	14.0%	11.5%	9.2%	12.3%
	12.7%	8.7%	13.0%	13.8%	12.6%	9.2%	14.0%

*Only one measurement was produced by the 10 HS sensor

Table B.2 – Moisture Content Measurements on the Bottom Half of the Specimen

	SM			GP			ML			CH			SC		
	Oven dry	**SDG**	**TDR**	**Oven dry**	**SDG**	**TDR**	**Oven dry**	**SDG**	**TDR**	**Oven dry**	**SDG**	**TDR**	**Oven dry**	**SDG**	**TDR**
Middle of the specimen	11.3%	14.2%	10.3%	4.5%	4.5%	5.5%	8.0%	11.1%	6.3%	21.5%	20.9%	23.4%	7.9%	8.6%	9.0%
	13.8%	15.8%	13.2%	4.8%	4.6%	4.4%	8.0%	11.9%	6.0%	22.5%	21.0%	23.5%	9.6%	8.5%	10.0%
	15.4%	16.2%	15.3%	6.0%	5.4%	7.1%	9.2%	12.0%	6.8%	24.6%	21.3%	25.7%	11.5%	8.8%	10.6%
	16.5%	15.6%	15.1%	7.6%	5.4%	7.0%	10.5%	13.6%	7.9%	28.3%	21.0%	26.9%	11.7%	8.9%	11.9%
	17.6%	20.4%	18.3%	7.4%	5.8%	8.4%	10.9%	14.4%	8.4%	31.3%	22.0%	26.9%	13.0%	8.7%	13.0%
	11.3%	13.9%	9.6%	3.8%	4.5%	5.0%	6.6%	11.1%	5.8%	20.6%	20.9%	18.0%	8.1%	8.6%	9.0%
	13.7%	15.7%	12.6%	5.1%	4.3%	4.5%	8.0%	11.7%	6.2%	21.7%	20.9%	23.7%	9.9%	8.5%	9.6%
	14.3%	16.2%	14.2%	6.6%	5.4%	6.3%	9.2%	12.4%	6.7%	24.3%	21.5%	24.2%	10.7%	8.8%	10.5%
	15.3%	15.1%	14.3%	7.4%	5.5%	6.7%	10.4%	13.8%	8.4%	28.0%	20.9%	25.6%	11.3%	8.8%	11.8%
	17.8%	20.0%	18.7%	7.7%	5.8%	7.2%	10.7%	14.2%	8.9%	31.9%	22.6%	28.4%	12.8%	8.7%	13.1%
	11.3%	13.9%	10.4%	4.5%	4.6%	5.0%	6.9%	11.2%	5.7%	22.0%	21.1%	21.8%	8.0%	8.6%	9.1%
	13.5%	15.3%	12.7%	4.6%	4.5%	5.1%	7.7%	11.9%	6.3%	21.4%	20.9%	22.2%	10.8%	8.5%	9.4%
	15.3%	16.2%	14.3%	6.6%	5.4%	6.7%	8.7%	11.9%	6.9%	24.6%	21.4%	25.6%	11.6%	8.7%	10.6%
	13.9%	16.0%	14.8%	6.0%	5.4%	6.4%	10.7%	13.9%	8.1%	27.6%	21.1%	25.4%	12.2%	8.9%	11.9%
	18.0%	20.3%	18.9%	7.7%	5.8%	7.3%	10.6%	14.4%	8.9%	29.9%	21.9%	27.8%	12.3%	8.8%	13.0%

Table B.3 – Moisture Content Measurements on the Top Half of the Specimen

	SM			**GP**			**ML**			**CH**			**SC**		
	Oven dry	**SDG**	**TDR**	**Oven dry**	**SDG**	**TDR**	**Oven dry**	**SDG**	**TDR**	**Oven dry**	**SDG**	**TDR**	**Oven dry**	**SDG**	**TDR**
Top of the specimen	10.9%	13.7%	10.4%	4.0%	5.0%	4.8%	8.2%	12.2%	6.1%	21.5%	21.3%	21.9%	9.0%	8.6%	7.9%
	13.6%	15.6%	12.3%	4.3%	5.1%	5.2%	7.9%	11.7%	6.3%	21.9%	21.4%	22.8%	10.5%	8.9%	10.7%
	16.2%	15.9%	13.9%	6.8%	5.6%	6.7%	8.9%	13.7%	7.1%	24.5%	21.6%	25.7%	11.3%	8.9%	11.4%
	15.9%	17.0%	16.0%	6.8%	5.7%	6.6%	10.4%	15.6%	8.9%	27.0%	21.5%	24.7%	11.2%	9.2%	12.7%
	17.5%	18.0%	17.4%	7.9%	5.4%	7.5%	11.8%	15.8%	9.9%	28.7%	21.9%	27.1%	12.8%	9.3%	14.1%
	10.5%	14.4%	9.1%	4.7%	5.1%	4.9%	7.6%	12.2%	6.1%	21.0%	21.3%	21.3%	8.6%	8.7%	8.0%
	13.5%	16.0%	11.5%	3.8%	5.2%	5.4%	6.7%	11.7%	6.4%	21.3%	21.4%	22.8%	10.5%	8.9%	10.4%
	15.0%	15.8%	12.5%	7.0%	5.5%	6.4%	8.6%	13.7%	6.9%	25.3%	21.8%	24.2%	11.5%	8.9%	10.8%
	15.6%	16.9%	15.4%	6.5%	5.7%	7.0%	10.0%	15.3%	8.8%	27.2%	21.7%	24.4%	11.7%	9.1%	12.1%
	16.4%	17.3%	17.4%	8.1%	5.4%	8.1%	11.1%	15.7%	9.7%	30.2%	21.8%	25.7%	12.7%	9.2%	14.0%
	10.7%	14.7%	11.8%	3.6%	5.0%	4.7%	7.5%	12.2%	5.9%	21.3%	21.2%	21.2%	8.7%	8.8%	7.6%
	13.4%	15.9%	12.6%	5.1%	4.6%	5.4%	7.2%	11.6%	6.2%	21.5%	21.4%	24.2%	10.2%	8.9%	10.3%
	13.7%	16.2%	13.1%	7.0%	5.6%	6.3%	8.3%	13.6%	7.4%	23.8%	21.6%	25.6%	10.6%	8.8%	10.7%
	16.3%	17.0%	16.7%	6.8%	5.6%	6.9%	10.0%	15.3%	9.1%	27.5%	21.5%	24.5%	11.7%	9.2%	12.2%
	17.5%	18.1%	17.6%	7.1%	5.5%	7.4%	11.1%	15.9%	10.0%	29.6%	21.7%	26.2%	12.3%	9.2%	13.9%

Table B.4 – Averaged Dry Density Measurements

	SM			GP			ML			CH			SC		
	Oven-dry	**SDG**	**TDR**	**Oven-dry**	**SDG**	**TDR**	**Oven-dry**	**SDG**	**TDR**	**Oven-dry**	**SDG**	**TDR**	**Oven-dry**	**SDG**	**TDR**
Middle of Specimen	111.7	110.1	115.1	147.7	87.4	135.5	124.4	105.9	126.1	95.7	94.8	97.8	122.7	91.1	117.6
	110.9	118.1	110.5	147.4	88.5	133.3	125.2	108.2	126.3	97.2	94.2	106.5	121.6	89.7	119.4
	111.0	120.1	107.7	146.5	92.7	141.4	125.0	109.9	127.1	97.1	97.1	106.7	121.5	90.4	122.0
	112.2	118.5	107.5	147.1	93.6	141.6	124.5	114.5	129.2	96.4	94.5	106.3	122.3	91.9	126.3
	111.2	148.3	101.6	147.7	96.1	145.5	125.3	117.1	130.3	96.0	101.0	106.1	122.4	90.5	130.1
Top of Specimen	112.3	110.8	114.5	147.9	90.3	133.8	123.7	110.9	126.2	95.8	96.7	106.6	121.8	89.8	114.2
	111.0	118.9	111.8	148.0	91.1	135.8	126.0	107.5	126.4	97.4	97.7	106.6	121.3	91.7	121.8
	111.1	120.5	110.0	145.8	94.2	140.5	125.5	115.5	127.9	97.1	99.1	106.3	121.7	90.7	123.4
	111.5	125.6	105.7	147.5	95.2	142.3	124.9	122.3	130.8	97.0	98.6	106.4	122.5	92.7	127.7
	111.8	131.4	103.3	147.5	94.6	145.9	124.7	126.3	132.5	97.1	100.6	106.2	122.6	93.4	133.5

Table B.5 – Dry Density Measurements on the Bottom Half of the Specimen

	SM			GP			ML			CH			SC		
	Oven-dry	**SDG**	**TDR**	**Oven-dry**	**SDG**	**TDR**	**Oven-dry**	**SDG**	**TDR**	**Oven-dry**	**SDG**	**TDR**	**Oven-dry**	**SDG**	**TDR**
Middle of the specimen	111.7	111.0	114.7	147.4	87.4	136.7	123.4	105.8	126.8	95.6	94.5	101.1	122.8	91.2	117.5
	110.7	118.9	109.8	147.4	88.9	132.2	125.1	108.1	126.1	96.7	94.4	106.5	122.2	89.7	120.3
	110.7	120.3	106.5	147.1	92.6	143.0	124.8	109.7	127.2	97.0	96.4	106.5	121.3	90.5	122.2
	111.0	119.0	107.2	146.3	93.6	142.9	124.5	113.8	129.0	96.2	94.3	106.2	122.3	92.0	126.3
	111.4	149.6	102.0	148.0	96.2	148.2	125.2	117.1	129.8	95.8	101.8	106.2	122.1	90.6	130.0
	111.7	109.8	116.1	148.4	87.2	134.8	125.0	106.2	125.8	96.4	94.5	93.3	122.6	91.1	117.6
	110.8	119.0	111.0	147.0	87.9	132.7	125.1	107.6	126.4	97.3	94.3	106.5	121.8	89.6	119.2
	111.7	120.0	108.4	146.2	92.9	139.6	124.8	111.2	126.9	97.3	97.9	107.1	122.1	90.4	121.8
	112.1	115.6	108.0	146.6	93.9	141.6	124.6	114.9	129.5	96.4	94.1	106.3	122.7	91.6	126.1
	111.2	146.9	101.5	147.5	96.2	144.0	125.4	116.4	130.4	95.4	100.6	106.0	122.3	90.3	130.4
	111.7	109.6	114.6	147.4	87.5	135.0	124.7	105.6	125.7	95.2	95.5	98.9	122.7	91.0	117.8
	111.0	116.3	110.8	147.7	88.8	135.1	125.4	108.9	126.4	97.5	93.9	106.6	120.8	89.7	118.6
	110.8	120.0	108.1	146.2	92.6	141.5	125.4	108.7	127.2	97.0	97.0	106.4	121.1	90.2	122.0
	113.5	121.0	107.4	148.5	93.4	140.2	124.3	114.9	129.1	96.7	95.1	106.3	121.7	92.1	126.4
	111.0	148.4	101.2	147.5	95.9	144.2	125.5	117.7	130.6	96.8	100.5	106.1	122.9	90.6	129.9

Table B.6 – Dry Density Measurements on the Top Half of the Specimen

	SM			GP			ML			CH			SC		
	Oven-dry	**SDG**	**TDR**	**Oven-dry**	**SDG**	**TDR**	**Oven-dry**	**SDG**	**TDR**	**Oven-dry**	**SDG**	**TDR**	**Oven-dry**	**SDG**	**TDR**
Top of the specimen	112.1	108.5	114.5	148.1	90.4	133.9	123.2	111.0	126.3	95.6	96.7	106.6	121.6	89.6	114.5
	110.9	117.7	111.5	148.1	91.4	135.1	125.2	107.8	126.4	97.1	97.7	106.8	121.2	91.7	122.7
	109.9	120.1	108.9	146.0	94.4	141.3	125.2	115.9	127.9	97.1	98.8	106.3	121.5	90.7	124.8
	111.6	125.8	105.4	157.4	95.4	141.2	124.6	123.3	130.7	97.2	98.0	106.4	122.8	92.8	129.0
	111.5	132.3	103.4	147.3	94.6	145.0	124.2	126.0	132.6	97.7	101.3	106.1	122.3	93.6	133.8
	112.5	111.3	117.0	147.1	90.4	134.0	123.9	110.9	126.3	96.0	97.0	106.6	122.0	89.8	114.6
	111.0	119.9	112.9	148.8	91.8	136.2	126.6	107.4	126.6	97.6	97.9	106.5	121.2	91.7	121.6
	111.0	119.7	111.0	145.7	93.9	140.2	125.5	115.6	127.5	96.5	99.9	106.4	121.3	90.8	122.7
	111.9	125.2	106.4	157.4	95.2	143.0	125.1	121.9	130.6	97.0	99.2	106.4	122.3	92.6	126.8
	112.5	128.5	103.3	147.0	94.3	148.0	124.9	126.0	132.1	96.6	100.6	106.3	122.4	93.4	133.6
	112.3	112.5	112.1	148.6	90.2	133.4	124.0	110.8	125.9	95.8	96.3	106.5	121.9	90.1	113.4
	111.1	119.0	110.9	147.0	90.0	136.0	126.0	107.3	126.3	97.4	97.5	106.4	121.5	91.8	121.2
	112.3	121.6	110.1	145.7	94.2	140.0	125.9	115.1	128.2	97.7	98.6	106.3	122.2	90.5	122.6
	111.2	125.7	105.3	157.4	94.9	142.8	125.1	121.6	131.2	96.8	98.6	106.4	122.3	92.6	127.4
	111.5	133.3	103.1	148.4	95.0	144.8	124.9	126.8	132.8	97.1	99.9	106.2	122.9	93.2	133.1

Table B.7 – Speedy Moisture Content Measurements (%)

GP		CH		SM		ML		SC	
Oven	**Speedy**	**Oven**	**Speedy**	**Oven**	**Speedy**	**Oven**	**Speedy**	**Oven**	**Speedy**
4.5	5.2	22.2	22.5	12.5	13.4	7.6	7.3	9.3	8.4
6.1	6.8	24.3	26.5	14.8	15.0	8.7	7.4	10.5	9.6
6.7	7.6	27.5	28.0	16.9	15.4	9.6	8.6	11.6	10.7
7.9	9.8	29.8	30.8	18.7	16.6	10.6	9.3	12.6	11.6
8.8	9.4	32.4	31.8	21.0	17.0	11.5	10.1	13.8	12.8
4.3	3.6	21.2	20.0	12.5	13.0	7.7	7.1	9.9	8.9
5.1	4.8	24.2	22.5	14.7	14.4	8.6	8.1	11.2	10.1
6.2	6.0	26.8	25.5	16.7	15.8	9.6	9.0	12.2	11.2
6.9	7.0	29.5	27.5	18.8	18.2	10.6	10.2	13.6	12.0
8.3	7.9	32.1	30.8	20.9	20.0	11.6	10.9	14.2	13.1
3.9	4.4	24.0	22.5	12.3	13.0	7.5	6.9	9.3	9.5
5.2	6.3	26.6	27.5	14.0	14.8	8.4	7.9	10.5	10.1
5.9	5.9	29.4	29.0	16.1	16.5	9.4	8.9	11.7	10.8
7.3	6.8	31.9	30.0	17.8	17.4	10.4	10.1	12.7	12.1
8.3	8.4	34.5	32.0	20.4	20.0	11.4	10.8	13.8	13.3
4.1	3.8	24.0	21.6	12.7	11.3	7.5	7.0	9.3	8.3
5.1	4.8	26.7	26.4	14.4	12.7	8.5	8.0	10.5	9.1
6.4	5.8	29.4	27.8	16.5	14.7	9.4	8.9	11.6	10.5
7.2	6.6	31.9	28.8	17.9	15.4	10.4	9.6	12.5	11.9
7.8	8.4	34.5	30.7	20.7	17.6	11.7	10.8	13.8	12.9
3.4	3.5	24.2	21.6	12.8	11.3	7.5	7.0	9.2	8.6
3.8	4.8	26.8	24.5	14.4	13.5	8.6	8.3	10.2	9.0
6.1	5.8	29.5	26.4	16.5	15.0	9.5	8.8	11.6	10.8
6.6	6.2	32.1	29.5	18.3	16.8	10.6	9.8	12.3	11.7
7.1	7.3	34.8	31.0	21.0	18.1	11.3	10.3	13.9	12.4
4.7	3.3	22.2	21.6	12.6	11.3	7.6	7.5	9.5	8.2
4.9	4.8	24.3	25.4	14.3	13.1	8.6	7.9	10.6	9.8
6.1	5.9	27.5	26.9	18.6	15.4	9.4	8.7	11.4	10.3
7.2	6.2	29.8	29.5	18.3	17.2	10.5	10.0	12.2	11.6
8.3	7.4	32.4	30.5	20.0	18.4	11.5	10.5	13.6	12.2

Table B.8 – DOT600 Moisture Content Measurements (%)

GP		CH		SM		ML		SC	
Oven	**DOT600**	**Oven**	**DOT600**	**Oven**	**DOT600**	**Oven**	**DOT600**	**Oven**	**DOT600**
4.5	13.8	20.4	18.1	12.5	15.2	7.3	14.3	9.2	7.5
6.1	11.7	22.8	18.3	14.8	16.6	8.2	14.1	10.3	7.8
6.7	14.3	26.0	19.1	16.9	14.6	9.4	14.5	11.4	8.4
7.9	16.3	28.5	19.4	18.7	16.2	10.3	14.2	12.6	8.3
8.8	17.0	32.3	20.6	21.0	16.5	11.2	14.1	13.7	11.0
4.3	10.1	20.3	19.1	12.5	12.7	7.4	13.8	9.1	7.5
5.1	9.5	23.5	19.3	14.7	13.7	8.6	13.6	10.2	7.9
6.2	10.4	27.0	19.3	16.7	16.4	9.5	13.8	11.3	8.4
6.9	12.8	29.0	18.7	18.8	20.7	10.5	13.9	12.4	9.3
8.3	13.9	32.8	20.0	20.9	20.1	11.5	14.2	13.8	11.2
3.9	9.0	20.6	19.9	12.3	14.5	7.5	13.9	9.1	10.0
5.2	9.0	23.4	19.6	14.0	15.2	8.4	13.9	10.3	8.9
5.9	12.1	26.4	19.1	16.1	15.1	9.6	14.0	11.4	8.6
7.3	13.3	29.5	19.3	17.8	16.6	10.6	13.5	12.3	8.3
8.3	16.3	34.5	19.6	20.4	15.3	11.3	14.1	13.7	8.1
4.1	8.8	20.8	19.3	11.9	14.6	7.3	13.5	9.0	13.4
5.1	10.7	24.8	19.5	13.8	14.1	8.3	13.8	10.1	12.7
6.4	11.5	26.4	19.1	16.6	17.7	9.5	13.7	11.0	12.2
7.2	12.6	31.0	18.7	18.0	19.7	10.4	13.9	12.5	12.8
7.8	15.2	32.6	20.6	20.3	20.3	11.4	14.4	13.4	7.9
3.4	8.5	19.5	20.2	11.8	16.0	7.8	14.1	9.0	13.4
3.8	9.7	23.0	19.9	13.8	16.5	8.7	13.4	9.9	7.8
6.1	12.0	26.3	20.0	15.8	16.8	9.7	14.5	11.4	8.4
6.6	13.2	29.4	20.4	17.7	18.1	10.6	13.7	12.2	8.3
7.1	15.1	31.7	20.6	19.8	17.0	11.6	14.1	13.1	11.0
4.7	8.9	19.2	18.4	12.0	16.0	7.6	13.6	9.4	7.5
4.9	9.5	21.6	19.1	14.0	16.3	8.7	14.2	10.8	7.9
6.1	11.6	25.3	18.7	15.9	17.3	9.5	14.2	11.8	8.4
7.2	12.9	29.4	18.9	17.9	17.8	10.6	14.0	12.7	9.3
8.3	13.6	31.7	20.0	19.8	16.7	11.6	13.7	13.8	11.2

Vita

Martin Jesus Sotelo was born on September 26, 1987 in El Paso, Texas. The second child of Rosa E. Sotelo and Martin Sotelo, he graduated from Ysleta High School in El Paso, Texas in the spring of 2006. In the fall of 2010, he graduated from The University of Texas at El Paso with a Bachelor of Science in Civil Engineering. In the spring of 2011, he entered the graduate school at The University of Texas at El Paso. While pursuing a master degree in civil engineering, he worked as a Graduate Research Assistant at the Center for Transportation Infrastructure Systems (CTIS). He was a recipient of the ExxonMobil Latinos on the Fast Track Fellowship for the academic year, (2011).

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