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16. Abstract

This project searched available moisture-measurement technologies using gravimetric, dielectric, electrical conductivity, and suction-based methods, as potential replacements for the nuclear gauge to provide rapid moisture measurement on field construction projects. Such testing is critical for acceptance of field compaction, and could become more critical as states look toward mechanistic-based acceptance. The first phase of this project, presented in this report, carried out test method development, pilot testing, and then initial deployment of the most promising devices. These activities confirmed the utility of existing direct heat and microwave oven tests, revealed promising results with an electrical-impedance based field test, and resulted in draft test procedure development with a portable dielectric-based device and a moisture analyzer. Several procedures evaluated only test the passing No. 4 fraction; reliably predicting the moisture content on the full gradation from the passing No. 4 measurement remains a topic needing further investigation. Future work on this project will deploy the most promising devices on a number of construction projects representing a spectrum of materials, where the devices will be evaluated for bias, precision, and sensitivity. Additionally, this project identified and pilot tested a microwave resonance-based device that may enable rapid field moisture measurement with a high level of testing coverage. Future work on this project will continue development work with applying this device to windrows and processed construction materials.

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Moisture Content, Moisture Measurement, Water Content, Rapid, Soil Density Gauge, Electrical Density Gauge, Nuclear Gauge, DOT 600, SDG, EDG, Microwave, Direct Heat, Moisture Analyzer

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear here solely because these are considered essential to the object of this report.

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CHAPTER 1
LITERATURE REVIEW

OVERVIEW

To begin this project, the research team conducted extensive literature searches to review available moisture measurement technologies. Numerous technologies and devices exist for measuring water content in soil media. By the principle of operation and typical output, these technologies can be broadly categorized into gravimetric, dielectric, electrical conductivity, and suction-based methods.

For implementation into TxDOT operations, the gravimetric and dielectric-based devices offer the greatest potential, because use of the suction-based devices requires concurrent knowledge of the soil-water-characteristic curve of the material being tested, and electrical conductivity devices are subject to several interferences. The review of other agency specifications and procedures reveals almost no use of dielectric or suction-based devices, while about one third of the agencies reviewed do allow the microwave or direct heat methods.

Tables 1.1–1.4 present the list of candidate devices within the broad categories of gravimetric, dielectric, electrical conductivity, and suction-based methods. The remainder of this chapter then presents discussions of each of the major categories of technologies, a review of how other agencies measure water content, and recommendations for which devices to further evaluate in this project.

Table 1.1. Summary of Potential Test Devices for Moisture Measurement Based on Gravimetric Method.

Device List	Applicability		Benefits	Limitations	Test turnaround time	Cost ($)	Standard method applicable to the device
	Base	Soil					
Oven-dry	√	√	- Most routine - Regarded as a ground truth	- Not suitable for field QC/QA application & - Time-consuming	Half day	-	ASTM D2216
Microwave Oven	√	√	- Reduce test time compared to oven-dry method	- Suitable for minus No. 4 soils - Not recommended for high accuracy results	~ 30 minutes	-	ASTM 4643
Moisture Analyzer (Website Link)	?	√	- Reduce test time - Different heating sources than microwave	- Calibration required along with oven-dry	Minutes	1,839	N/A
Nuclear Gauge	√	√	- Rapid, standard test method in construction	- Interference from non-water sources of hydrogen	Minutes	12,000	Tex-115-E ASTM D6938
Sartorius LMA300P Microwave resonance technology based	?	√	- Very quick measuring - Non-destructive	- Calibration required along with oven-dry	~ Few seconds	TBD	N/A
Sartorius LMA500 Spectroscopy (optic) based	?	√	- Very quick measuring - Non-destructive	- Calibration required along with oven-dry	~ Few seconds	TBD	N/A

Table 1.1. Summary of Potential Test Devices for Moisture Measurement Based on Gravimetric Method (continued).

Device List	Applicability		Benefits	Limitations	Test turnaround time	Cost ($)	Standard method applicable to the device
Speedy Moisture Tester (Calcium Carbide)	√	√	- Relatively simple - Available standard method	- Soils containing chemicals may give erroneous results - Highly plastic soil may give erroneous results due to its clods or clumps	5 minutes	2,000	ASTM D4944 AASHTO T217 Tex-425-A
Hydronix Hydro-Probe Microwave moisture sensor (Website Link)	√	√	- Measuring stabilized materials during in-place mixing	- Not suitable for measuring moisture profile in depth	-	5,000	N/A

Table 1.2. Summary of Potential Test Devices for Moisture Measurement Based on Dielectric Permittivity.

Device List	**Applicability**		**Benefits**	**Limitations**	**Test turnaround time**	**Cost ($)**	**Standard method applicable to the device**
	Base	**Soil**					
Humboldt Electrical Density Gauge (EDG) (Website Link)	√	√	- Easy to operate and transport (non-nuclear) - Accurate and repeatable results - Gravimetric moisture	- Laboratory calibration procedure not available	5–10 minutes	8,800	ASTM D7698
Transtech SDG 200 (Website Link)	√	√	- Non-nuclear based - Wide operating temperature - Gravimetric moisture	- Not technically ready to be used on all soils	~5 minutes	-	N/A
DOT 600 (Website Link)	√	√	- Portable, accurate and integrated data logger - Suitable for construction process - Gravimetric moisture	- Calibration required	~5 minutes	2,995	N/A
Sentek EnviroSCAN (Website Link) FDR based		√	- From oven-dry to saturation condition covered - Multi-depth measuring	- Very sensitive to external factors - Need to convert Gravi. water content - Volumetric water content	~5 minutes	~3,000	N/A
Dynamax TR-100 (Website Link) TDR based (Time Domain)		√	- Rugged for field study - Multi-probe	- Volumetric water content	~5 minutes	386	N/A

Table 1.2. Summary of Potential Test Devices for Moisture Measurement Based on Dielectric Permittivity (continued).

Device List	Applicability		Benefits	Limitations	Test turnaround time	Cost ($)	Standard method applicable to the device
	Base	Soil					
Rapid Soil Characterization System	√	√	- Characterizing unbound layers up to 3 feet - Measuring moisture content along with soil strength and classification	- Mainly tested on coarse grained materials	10 minutes	-	N/A
Campbell Scientific TDR (Website Link)	√	√	Relatively simple and fast multiple depth measurements available	- Need to be calibrated - Vol. water content - Limited probe length (maximum 30 cm)	10 minutes	8,000	ASTM D6565
Access Tube Type FDR based		√	Rapid measurements at the same locations and depths over time	- Calibration	-	4,000	N/A
Hand Push Probe FDR based		√	Rapid and easy for surface reading	- Difficulty in probing for drier soil or crushed base	-	500	N/A
WATERSCOUT Soil Moisture Meter (Website Link) TDR based		√	- Relatively simple - Inexpensive	- Need to maintain good contact to soil	-	1,065	N/A

Table 1.2. Summary of Potential Test Devices for Moisture Measurement Based on Dielectric Permittivity (continued).

Device List	Applicability		Benefits	Limitations	Test turnaround time	Cost ($)	Standard method applicable to the device
	Base	Soil					
AQUAFLEX soil moisture meters (Website Link) TDT based*	√	√	- Easy to install due to flexibility of sensor - Moisture and temperature in a sensor - High influence zone: 6 liters	- Limited to coarse grained material due to higher air void - Need to be calibrated - Shipping (out of U.S.)	-	2,000	N/A
Adek Down Hole Dielectric Probe	√	√	- Relatively simple and fast - Available in TxDOT	- Need to be calibrated to the soils - Depend on installation of probe in a material	10 minutes	10,000	N/A
AquaPro Moisture Probe	√	√	- Relatively accurate - Inexpensive	- Impractical for construction-control operations	-	1,000	N/A
Delta-T PR2 Probe (Website Link)	√	√	- Measuring moisture profile	- Require periodical recalibration		5,290	N/A

*Time Domain Transmission (TDT)

Table 1.2. Summary of Potential Test Devices for Moisture Measurement Based on Dielectric Permittivity (continued).

Device List	Applicability		Benefits	Limitations	Test turnaround time	Cost ($)	Standard method applicable to the device
	Base	Soil					
Decagon 5TE* (Website Link)		√	- Portable - Easy to install - Accurate - Long-term measuring	- Needs to be calibrated - Sensitive to soil mineralogy	-	220	N/A
Vertek SMR Probe* (Website Link) FDR based (Frequency Domain)	√	√	- Simple and fast - Long-term monitoring available	- Uncertain durability of sensor - Requiring dynamic pounding of the probe with DCP or CPT	~ 10 minutes	7,500	N/A

*While these devices measure electrical conductivity, the water content is determined independently using dielectric permittivity.

Table 1.3. Summary of Potential Test Devices for Moisture Measurement Based on Electrical Conductivity.*

Device List	Applicability		Benefits	Limitations	Test turnaround time	Cost ($)	Standard method applicable to the device
	Base	Soil					
Geonics EM38 (Website link)		√	- Useful to highlight zones of differing mineralogy and salt content - Useful for measuring soil magnetic susceptibility	- Interferences problems	-	61/day (rental)	N/A
Veris Technologies mapping system (Website link)		√	- Useful to highlight zones of differing mineralogy and salt content	- Interferences problems	-	Over 10k	N/A

*While in a simple system, electrical conductivity could potentially measure water content; in practice, too many interferences exist, so electrical conductivity generally is not used as a measure of water content.

Table 1.4. Summary of Potential Test Devices for Moisture Measurement Based on Suction.

Device List	Applicability		Benefits	Limitations	Test turnaround time	Cost ($)	Standard method applicable to the device
	Base	Soil					
Decagon WP4C		√	- Easy calibration - Easy to use in the field (high suction)	- Suction range : 1 to ≈ 3,000 kPa - Limit in sample size	5–10 minutes	6,400	N/A
Tensiometer		√	- Low price	- Suction range: 1 to ≈ 100 kPa - Cavitations problems around 90kPa	5 minutes	50–75	ASTM D971
Mini tensiometer Delta-T SWT (Website Link)	√	√	- Excellent accuracy in wet and irrigated soils	- Suction range: 1 to ≈ 80 kPa - Need to maintaining good contact to soil - Cavitations problems around 70kPa	10 minutes	4,105	N/A
High Capacity Tensiometer (HCT)			- Measure high suction -	- Suction range: 1 to ≈ 1,500 kPa - Cavitations problems around 1,500kPa	-		
Campbell 229-L		√	- Measurements not affected by salts in soil - Long-lasting	- Need to be calibrated	30 seconds	350	N/A

Table 1.4. Summary of Potential Test Devices for Moisture Measurement Based on Suction (continued).

Device List	**Applicability**		**Benefits**	**Limitations**	**Test turnaround time**	**Cost ($)**	**Standard method applicable to the device**
	Base	**Soil**					
Fredlund Thermal Conductivity Sensor (FTC-100)		√	- Easy calibration	- Suction range: 1 to ≈ 1,000 kPa	-		
Capacitive Hygrometer (Vaissala)	√	√	- Measuring suction and temperature	- Suction range: 0 to 10,000 kPa	days		
Equitensiometer (Dielectric constant)		√	- Total suction	- Suction range: 10,000 to 400,000 kPa			
GDS Mid-Plane Probe (Website Link)		√	- Measuring suction and pore pressure	- Suction range: 1 to ≈ 400 kPa - More suitable to lab application	-	-	N/A

GRAVIMETRIC METHODS

This method has been widely used to measure the gravimetric moisture content of pavement materials. The method typically undergoes drying the in-situ material for measuring the gravimetric water content. There are several procedures available pertaining to the gravimetric method as follows.

Oven-Dry Method

The test is performed in accordance with ASTM D2216, which involves weighing a soil sample, placing it overnight in a 230°F oven to dry, and weighing the dried soil. The weight loss is assumed to be entirely water, and thus the soil gravimetric water content can be calculated using equation (1.1).

$$W(\%) = \frac{W_{cms} - W_{cds}}{W_{cds} - W_{c}} \cdot 100 \qquad (1.1)$$

Where: W = gravimetric water content.
W_{cms} = weight of the container and moist soil.
W_{cds} = weight of container and dry soil.
W_c = weight of the container.

While widely accepted as the reference procedure, the downside of this method is the time requirement to obtain the test result. The applicability of this method covers natural subgrade soils and base materials in the uncompacted or compacted state. Since the measurement is on the basis of point measurement, the moisture profile with depth can be established through multiple measurements of soil samples taken at a desired depth or location.

Microwave Oven

Hagerty et al. (1990) used microwave ovens to measure moisture content of highly plastic clays and clays mixed with peat. Comparison of microwave oven drying results with corresponding data obtained in conventional ovens revealed that careful use of a microwave oven produced moisture content values very close to those measured from a conventional oven. Currently, the standard procedure ASTM D4643 is available to measure the water content of a soil sample using microwave oven heating. The following test procedures should be taken:

1) Determine the mass of a clean, dry container and record. The mass of moist material selected shall be in accordance with Table 1.5.
2) Place the soil specimen in the container and immediately determine and record the mass.
3) Place the soil and container in a microwave oven, then turn the oven on for three minutes.
4) After the set time has elapsed, remove the container and soil from the oven and weigh the specimen immediately.
5) Mix the soil carefully with a small spatula or knife so not to lose any soil.
6) Return the container and soil to the oven and reheat for one minute.

7) Repeat steps 4–6 until the change between two consecutive mass determinations would have an insignificant effect. A change of 0.1 percent or less should be acceptable for most specimens.
8) Use the final mass determination in calculating the water content using an equation 1.1.

Table 1.5. Test Specimen Masses (after ASTM D 4643).

Sieve retaining not more than about 10% of sample	Recommended mass of moist specimen, g
2.0 mm (No. 10)	100 to 200
4.75 mm (No. 4)	300 to 500
19 mm (3/4")	500 to 1,000

This method can be used as a substitute for Test Method D2216 when more rapid results are desired and slightly less accurate results are acceptable. This method is best suited for soils with particles that pass through the #4 sieve. Larger size particles can be tested with special care taken because of the increased change of particle shattering. Microwave heating can cause differential heating within a sample, and the sample can easily become overheated (heated to over 115°C). In this project, the soil temperatures at the end point of the microwave test varied between 110 °C and 140 °C. For this reason, the microwave oven may yield higher moisture contents than the conventional oven measurements (ASTM D4643). Gilbert (1998) invented a computer-controlled microwave oven system to overcome the overheating problem. This system uses cyclic heating in order to avoid overheating the soil samples, provides soil temperature measurements, and is consistent with conventional oven measurements.

Gaspard (2002) conducted comparative laboratory evaluations to measure moisture content on soils with and without additives. The soils were tested with a conventional oven (CO), computer-controlled microwave oven (CMWO), standard microwave oven (SMWO), and stove. Based on the statistical analysis on test results, cost, and duration of time, the standard microwave oven was found to be the most feasible device to use. While the estimated cost of a SMWO is $1,050 (including accessories and scale), the cost of a CMWO is $4,600 (excluding the laptop computer).

Freeman et al. (2008) recommended a microwave test procedure in accordance with ASTM D4643 for measuring the moisture content of soil as a part of quality assurance procedures for contingency airfield construction based on laboratory evaluation, as shown in Figure 1.1. They eliminated the computer-controlled microwave oven from the candidate list for the Joint Rapid Airfield Construction (JRAC) program due to its delicacy. The direct heating method in accordance with ASTM D4959 was selected as a backup procedure.

The researchers believe that the microwave oven system might be implementable since it is easy to operate, has a standard test procedure, is relatively inexpensive to set up, and is portable to the field site based on previous studies conducted. However, further investigations of interferences and accuracy of measurement on various soil types that will be encountered from pavement sections still remain.

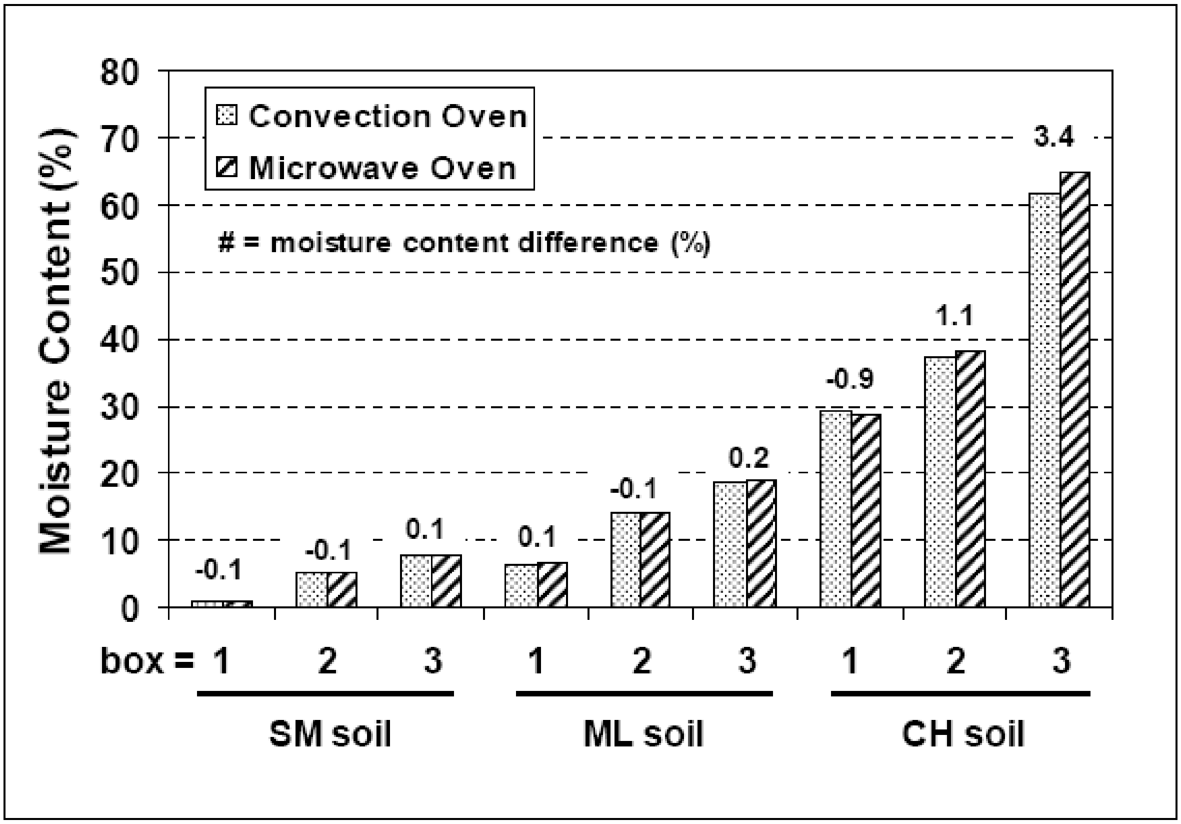


Figure 1.1. Average Measured Moisture Contents (after Freeman et al., 2008).

Direct Heating Method

This test method is designated to determine the moisture content of soils by drying with direct heat, such as using a hot plate, stove, blowtorch, etc. (ASTM D4959-07). The direct heating is defined as follows:

> *A process by which the soil is dried by conductive heating from the direct application of heat in excess of 110°C to the specimen container, such as provided by a hot plate, gas stove, or burner, heat lamps, or other heat sources. Direct application of heat by flame to the specimen is not appropriate.*

Similar to the microwave procedure, the soil sample is repeatedly stirred, heated, and weighed until two consecutive mass determinations for the dry soil change by 0.1 percent or less. Table 1.6 shows recommended sample masses.

The researchers believe that the direct heating test can be replaced with the microwave oven test due to its similarity to and less standardization than the procedure adopted for the microwave oven test.

Table 1.6. Test Specimen Masses (after ASTM D4959).

Sieve retaining not more than about 10% of sample	Recommended mass of moist specimen, g
2.0 mm (No. 10)	200 to 300
4.75 mm (No. 4)	300 to 500
19 mm (3/4")	500 to 1000

Moisture Analyzer

The moisture analyzer (shown in Figure 1.2) is a compact device typically used to measure the moisture content from pharmaceutical and chemical products to food, textile, and wastewater with a high accuracy and rapid turnaround time. The heat source is a halogen lamp that generates temperatures ranging from 50°C to 200°C. The test must be longer than 30 seconds to be valid OHAUS® 2011). The device offers flexibility to control drying time manually and automatically. The automatic option is designated to end the drying process when detecting less than 1 mg loss in 60 seconds. However, this drying time is highly dependent on the size of the sample. The maximum sample capacity of this device is 110 grams, so that may not be a sufficient amount for measuring the moisture content of granular materials. This device is more applicable to measuring the moisture content of fine materials (clay or sand subgrade) in the field or laboratory, if applicable. The cost is around $2,500, and a rental option is not available.

Figure 1.2. Moisture Analyzer.

The researchers believe that the moisture analyzer system may warrant further evaluation due to a lack of experience or available information on measuring the moisture content of soils.

Startorius LMA500

This device uses spectroscopy. When the sample is exposed to near infrared light (NIR), a part of this light is reflected and modified characteristically on interaction with the sample (Sartorius Mechatronics Corporation 2011). It is designed for analyzing the moisture content of pourable and granulated products and viscous products such as slurry. The turnaround time is exceptionally fast, usually within a few seconds (two seconds). Information on the application of measuring the moisture content of soil is unavailable. However, the cost is too expensive ($75,000) to implement for this project. Figure 1.3 shows this device.

Figure 1.3. Startorius LMA500.

Startorius LMA300P

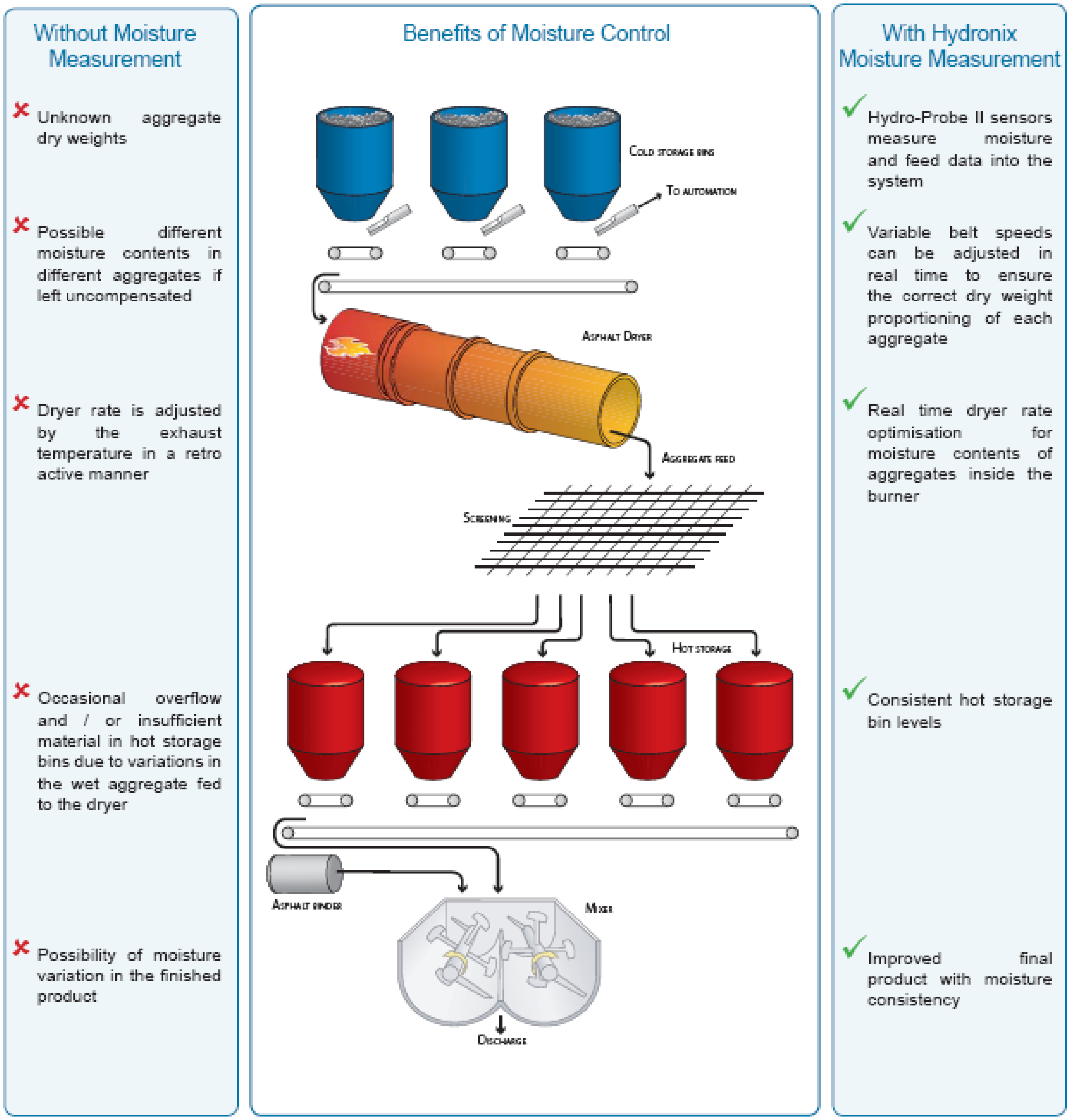
This device is based on microwave resonance technology shown in Figure 1.4. When the sample is placed in the device, the water in the sample interferes with the resonance of the microwave and changes the height and width of the resonance frequency peak accordingly (Sartorius Mechatronics Corporation 2011). The exceptionally fast turnaround time is less than one second. Due to microwave resonance technology, the sample is retained in its original condition. Unlike in infrared spectroscopy, changes in the color and surface structure of the sample do not have any influence on the measurements. Similar to the LMA500, the LMA300P can be used for nearly all pourable and granulated products as well as viscous liquids. However, the cost is too expensive ($37,000) to implement for this project.

Figure 1.4. Startorius LMA300P.

Hydro-Probe II Moisture Sensor

This device is based on the digital microwave moisture measurement technology shown in Figure 1.5. It has integral signal processing that provides a linear output, and it can feasibly be connected to any control system. Its application includes sand, cement, concrete, asphalt, and aggregate. As illustrated in Figure 1.6, this sensor system is capable of measuring in-situ moisture content during plant mixing. However, this system may not be suitable for establishing moisture profile in depth and further investigation remains to verify whether this sensor can be applicable to the materials that do not flow through bins and conveyors in a similar manner. The cost of this sensor is over $5000.

Figure 1.5. Hydro-Probe II.



Without Moisture Measurement

- ✗ Unknown aggregate dry weights
- ✗ Possible different moisture contents in different aggregates if left uncompensated
- ✗ Dryer rate is adjusted by the exhaust temperature in a retro active manner
- ✗ Occasional overflow and / or insufficient material in hot storage bins due to variations in the wet aggregate fed to the dryer
- ✗ Possibility of moisture variation in the finished product

Benefits of Moisture Control

With Hydronix Moisture Measurement

- ✓ Hydro-Probe II sensors measure moisture and feed data into the system
- ✓ Variable belt speeds can be adjusted in real time to ensure the correct dry weight proportioning of each aggregate
- ✓ Real time dryer rate optimisation for moisture contents of aggregates inside the burner
- ✓ Consistent hot storage bin levels
- ✓ Improved final product with moisture consistency

Figure 1.6. Illustration of Moisture Control in Asphalt Production (Hydronix®, 2011).

Researchers preliminarily compared the following characteristics of each device pertaining to the measurement of gravimetric moisture content described above as presented in Table 1.7. Researchers assigned numerical scores corresponding to the order of rank to come up with the overall rank as denoted in the last row. The average score is considered to be the highest rank representing the most promising means to be evaluated. Note that oven-dry was excluded for this comparison since it will be employed as a reference in this project. As shown in Table 1.7, since the direct heating method is likely to be a surrogate of the microwave oven test, researchers are of the opinion that the microwave oven and the moisture analyzer would be candidates of the gravimetric method-based devices for preliminary evaluation for Task 2.

Table 1.7. Comparison of Devices Based on Gravimetric Method.

Aspect	Microwave oven	Direct heating	Moisture analyzer	Startorius series	Hydro-Probe II
Turnaround time	4	4	2	1	3
Standard spec. & procedure	1	2	2	2	2
Applicability to soil & base	1	1	3	5	4
Zone of influence	1	1	1	1	1
Cost	2	1	3	5	4
Known inferences	2	1	2	2	2
Implementable potential	1	3	2	5	4
Avg. of scores	1.714	1.857	2.143	3.000	2.857
Overall Rank	**1**	**2**	**3**	**5**	**4**

DIELECTRIC-BASED METHODS

The dielectric constant is a measure of the capacity of a non-conducting material, such as soil mixture, to transmit electromagnetic waves. The dielectric constant of water is much greater than that of solid particles and air, as shown in Table 1.8. Consequently, the contribution of water to the overall soil mixture dominates the soil dielectric constant; that is, relatively small changes in the quantity of water have large effects on the soil dielectric constant. Using this relationship, the water content can be determined with a calibration model relating soil dielectric constant to the volumetric water content (Lee 2010).

Table 1.8. Typical Dielectric Constants in Soil Media.

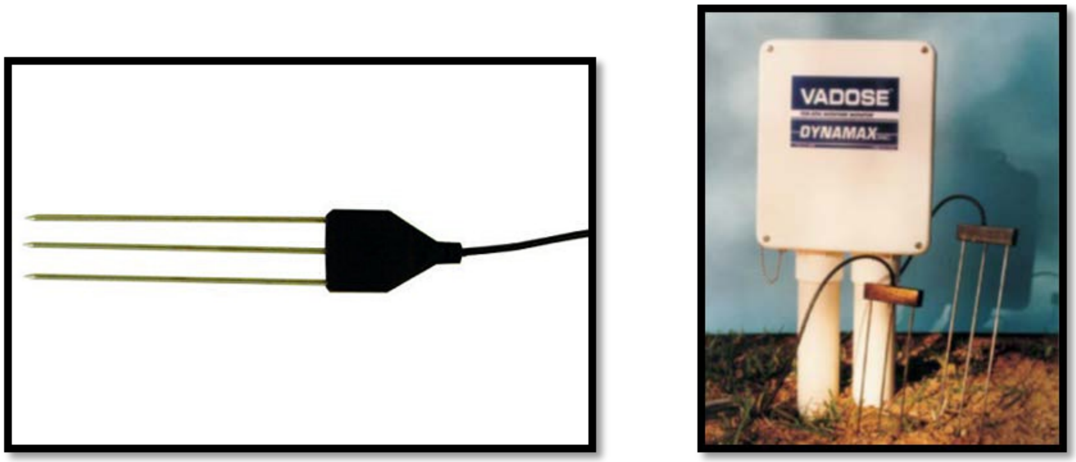
Component	Water	Soil Particle	Air
Dielectric Constant	79 ~ 81	2 ~ 6	1.0

Since the value of dielectric constant is a key parameter to estimate water content in pavement materials, the first step to estimate water content involves the measurement of the dielectric constant of each material. The approaches using the dielectric constant method provide relatively rapid measurements and accurate results with proper calibrations. Two approaches have been used to measure the dielectric constant of soil mixture and estimate the volumetric water content: time domain reflectometry and frequency domain reflectometry.

Time Domain Reflectometry (TDR)

Time Domain Reflectometry (TDR) equipment was originally developed for measuring electromagnetic wave travel times to detect breaks or shorts in electrical conductors. Subsequently, it was adapted to collect sufficient data to allow for the water content to be estimated. For use of TDR to measure soil dielectric constant, the TDR system propagates an electromagnetic wave along a coaxial metallic cable attached to parallel conducting probes that act as a waveguide inserted into the soil. The transmitted signal reflects from the end of the waveguide back to the read-out unit. The system measures the time between sending and receiving waves and computes the propagation velocity, which is influenced by the dielectric constant of material surrounding the waveguide, based on the length of the waveguide. Since the velocity inversely relates to the dielectric constant of soil, faster propagation velocity indicates a lower dielectric constant and thus lower soil water content.

The typical type of TDR waveguide inserted into soil is multiple-rod probe. The probe mainly consists of two or three stainless steel rods spaced about one inch apart. They can be installed in base and subgrade layers in horizontal, vertical, or 45 degree angle, and the dielectric constant is an average value measured along the length of the probe. The Campbell Scientific TDR probe and the Dynamax TR-100 Probe are the commercial TDR products as shown in Figure 1.7. The rod type of TDR probe may be permanently installed with coaxial cable brought to the surface for connection to a data acquisition system. This type of installation requires the excavation of a pit in a pavement layer and the insertion of the probe into the undisturbed face or ground of the pit wall for horizontal or vertical installation, respectively.



(a) Campbell Scientific TDR probe (b) Dynamax TR-100 Probe

Figure 1.7. Three-Rod TDR Probes.

Another product of TDR probe types is the Aquaflex Soil Moisture Meters. The probe is a 10-inch long flexible tape-type sensor that can be laid in a pavement layer. According to the manufacturer, the zone of influence is approximately a six-liter volume of soil surrounding the probe, so it may overcome the problems associated with measuring water content at only one point. Also, due to the flexibility of the sensor, it can stand against compaction loads applied to pavement layers during construction. However, the installation of this probe needs a narrow slit or trench in the pavement layer and in a horizontal direction. The manufacturer reports that the repeatable accuracy is plus or minus 0.25 percent using standard calibration. Figure 1.8 depicts the Aquaflex Soil Moisture Meters.

Figure 1.8. Aquaflex Soil Moisture Meters.

Both types of TDR probes are required to connect a cable tester or read-out unit to transmit an electromagnetic wave, read a reflected signal, and consequently compute dielectric constant and water content of soil. When a multiplexer is installed with several TDR probes, the water content measurements can be obtained from multiple soil depths.

An alternative probe to permanent installation of the rod type is a portable hand push waveguide probe such as the FieldScout TDR 300 Soil Moisture Meter as shown in Figure 1.9. The hand push probe allows users to rapidly and easily measure near-surface water content, which may be used for the top 1.5 to 8 inches of pavement layer by inserting lengths of rod. The portable probe, however, is difficult to use in compacted pavement layer and soil with rocks. For those cases, a separate auger is required to make a hole for inserting the probe. The manufacturer reports that the accuracy is plus or minus 3 percent for volumetric water content.

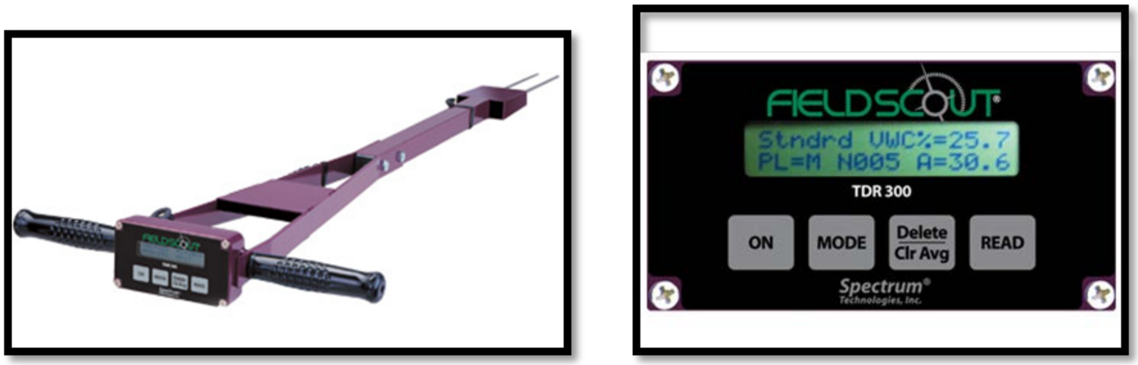


Figure 1.9. FieldScout TDR 300 Soil Moisture Meter.

All TDR probes must be carefully installed in the pavement layer with tight contact along their entire length. The air gaps around the probe may cause erroneous low soil dielectric constant since the air dielectric constant value of 1.0 is much less than those of water and soil particles. Each commercial product provides a general equation relating soil dielectric constants and volumetric water contents by its manufacturer. Nevertheless, in order to use the

TDR approach and get accurate results, it is necessary to perform a proper calibration on each device and pavement material.

Frequency Domain Reflectometry (FDR)

In order to determine the soil dielectric constant, the frequency domain reflectometry (FDR) approach basically measures soil capacitance while the TDR approach measures the velocity of electromagnetic wave. High radio frequency (RF) waves (about 150 MHz) are pulsed through a pair of electrodes (probes) inserted into the soil. The probe measures the natural resonant frequency or the frequency shift between the emitted and received frequencies, which is established due to the soil capacitance (Hanek et al. 2001). From the measurement, the soil dielectric constant can be determined because the soil capacitance is proportionally related to the dielectric constant. That is, when the amount of water increases in a soil, the FDR probe measures an increase of capacitance due to the change of soil dielectric constant that can be directly correlated with the change in water content. Three types of probes have been used for FDR electrodes: access tube type, hand push probe type, and sensor type.

Many FDR instruments using the access tube type have been developed for use in the field, such as Sentek EnviroSCAN, Adek Down Hole Dielectric Probe, AquaPro Moisture Probe, and Delta-T PR2 Probe, as presented in Figure 1.10. These probes employ an access tube similar to the neutron probe in that the electrodes are lowered into the access well and the soil water contents are measured at various depths. The FDR probes are lowered into a PVC or glass fiber access tube inserted in a pavement layer, then measure the frequency shift between the emitted and received frequencies. This probe type provides relatively accurate, rapid field measurements. Also, a moisture profile by depth can be obtained by collecting readings at different depths in the access tube. The access tube, however, should be installed with intense care to ensure a very tight fit in the auger hole since air gaps surrounding the tube outside can cause erroneous low readings. The Vertek SMR Probe is similar to the access tube type, but it uses a Dynamic Cone Penetrometer (DCP) driver instead of an access tube as shown Figure 1.11. Since the probe is inserted using a DCP driver, a smaller diameter access hole can be made into stiff pavement layers (Sebesta et al. 2006).

(a) Sentek EnviroSCAN (b) Adek Down Hole Dielectric Probe

(c) AquaPro Moisture Probe (d) Delta-T PR2 Probe

Figure 1.10. FDR Access Tube Type.

Figure 1.11. Vertek SMR Probe.

The Aquaterr M-300 Portable Soil Probe hand push probe shown in Figure 1.12 is another type of FDR that measures water contents using soil capacitance. This portable type probe allows rapid, easy measurements; however, it is difficult to insert the probe into compacted layers or soils with rocks. For use in those layers, a separate auger can be used to make a hole for the probe. The accuracy by the manufacturer is plus or minus 1.5 percent.

Figure 1.12. Aquaterr M-300 Portable Soil Probe.

The WaterScout SM100 Soil Moisture Meter and Decagon Soil Moisture Sensors, presented in Figure 1.13, are commercial products employing the sensor type of FDR probe. This probe determines the volumetric water content using the soil dielectric constant measured by soil capacitance. Similar to TDR probes, installation of the FDR sensors requires the excavation of a pit in a pavement layer and the insertion of the probe into the undisturbed face of the pit wall or ground. A read-out device should be connected to the sensors for obtaining real-time reading from each sensor. For the Decagon Soil Moisture Sensors, the zone of influence according to the manufacturer is 0.18 to 1 liter volume of soil surrounding the probe. Both manufacturers report that the accuracy is plus or minus 3 percent for volumetric water content measurement. However, it is necessary to perform calibration to obtain higher accuracy, plus or minus 1 to 2 percent.

(a) WaterScout SM100 Sensor

(b) Decagon EC-5 Moisture Sensor

Figure 1.13. FDR Sensors.

SDG 200

The Transtech SDG 200 uses electrical impedance spectroscopy to measure the dielectric constant of the test media, after which an internal soil model calculates the density and water content. The device sits atop the test layer as Figure 1.14 shows, and requires several inputs, primarily gradation information, for use in the soil model. For best results, the SDG 200 can be calibrated to reference value data from the project site.

Figure 1.14. SDG 200.

The SDG 200 can be used on both soils and bases, provided a reasonably smooth surface exists, and measures from a zone of influence to a depth of approximately the radius of the bottom plate. The device costs about $8,000; precision and accuracy are not yet clearly defined. However, a recent study by the U.S. Army Corps of Engineers ranked the SDG highest out of several moisture-measurement devices so long as a calibration to the field material was performed. The rapid test turnaround time and lack of any soil disturbance is a clear benefit to this device; however, the need to calibrate the device to the project's material could be a barrier to implementation, especially if working on projects with widely varying soils or bases. Despite these potential drawbacks, the SDG 200 is specifically marketed to the construction industry and warrants further review.

DOT 600

The Campbell Scientific DOT 600 uses FDR to measure the dielectric properties of the soil under test. This device, shown in Figure 1.15, costs about $3,000 and tests material passing the No. 4 sieve. The particle size of material tested makes the device suitable primarily to soils, although special test procedures employing scalping off larger material may enable testing flexible bases. Performing a measurement requires about five minutes and returns a local value, and the internal scale has a capacity of 1000 g. The manufacturer reports a test precision of 0.75 percent volumetric water content. The rapid turnaround time is an advantage to this device, while the small sample size may restrict the device to only certain materials.

Figure 1.15. DOT 600.

EDG

The Humboldt Electrical Density Gauge shown in Figure 1.16 uses electrical impedance spectroscopy to measure the dielectric constant of the material under test and then relates the measurement to the density and water content with a soil model. The test requires driving dart-like electrodes into the material in a fixed geometric arrangement, meaning that materials with substantial penetration resistance may prove difficult in testing. ASTM D6798 describes the test method. Electrodes from 4 to 12 inches in length are available in order to alter the zone of influence of the test. The EDG costs around $8,000, and the manufacturer reports moisture content accuracy typically within 2 percent of standard test values. The option of altering the zone of influence is the major advantage of this device, while the need to drive the darts into the material under test is the greatest drawback.

Figure 1.16. Electrical Density Gauge.

The researchers reviewed the key aspects of each of the dielectric-based devices and ranked them as shown in Table 1.9. At this time, the research team believes all the devices will need ground-truth calibration to project material to maximize test accuracy. Based on the information known at this time, the most promising dielectric-based devices appear to be the SDG and EDG. Within the remaining devices, each has its own particular strengths and drawbacks, which could influence the decision as to whether additional work should continue. For example, if TxDOT is willing to sacrifice sensors, the rod-based FDR sensors cost about $60 each and could be buried prior to compaction, possibly enabling rapid test turnaround with multiple measurement points.

Table 1.9. Comparison of Devices Based on Dielectric Method.

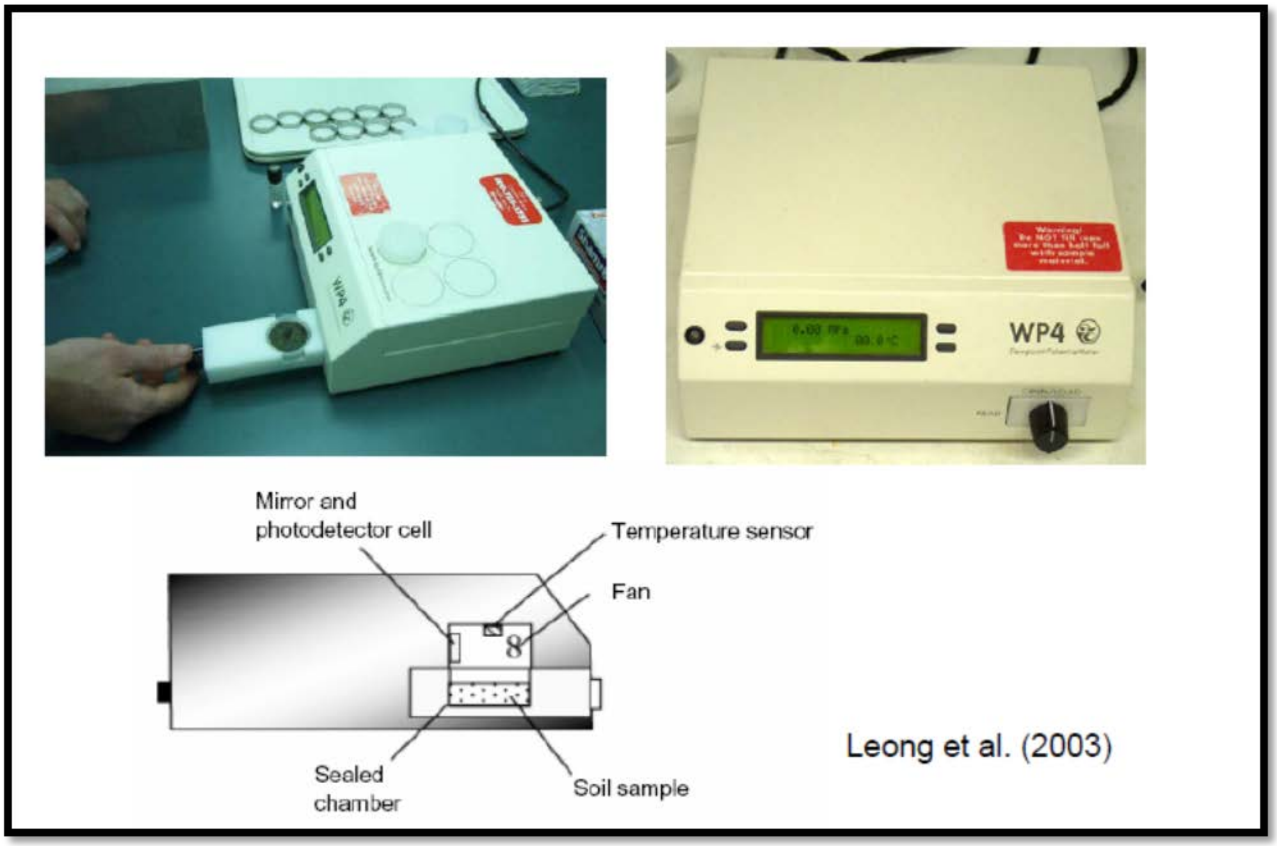
Aspect	Rod-TDR	Rod-FDR	Probe-FDR	SDG	DOT 600	EDG
Turnaround time	4*	4*	4	1	2	3
Standard spec. & procedure	1	2	2	2	2	1
Applicability to soil & base	3	3	3	1	4	2
Zone of influence	2	2	1	3	4	1
Cost	2	2	2	3	1	3
Known inferences	2	1	1	1	1	1
Implementable potential	4	4	4	1	3	2
Avg. scores	2.571	2.571	2.428	1.714	2.428	1.857
Overall Rank	**4**	**4**	**3**	**1**	**3**	**2**

*Note: Some of these sensors could be considered disposable due to their relatively low cost, resulting in a buried installation and a more rapid test turnaround time.

SUCTION-BASED METHODS

Chilled-Mirror Dew-Point Technique

The chilled-mirror dew-point psychrometer, shown in Figure 1.17, is based on measuring the relative humidity of a volume of air surrounding a soil sample in a sealed chamber (Cardoso et al. 2007). At equilibrium, the relative humidity of the surrounding air is equal to the relative humidity of the soil sample. By measuring the relative humidity, the total suction can be derived indirectly from the psychrometric law. In this device, the chamber in which the soil specimen is placed also contains a mirror, a fan, and a temperature sensor. The temperature of the mirror is precisely controlled by a thermoelectric cooler. Detection of the exact point at which condensation first appears on the mirror is observed with a photoelectric cell. A beam of light is directed onto the mirror and reflected into a photodetector cell. The photodetector senses the change in reflectance when condensation occurs on the mirror. A thermocouple attached to the mirror then records the temperature at which condensation occurs. Additionally, the chilled-mirror dew-point psychrometer uses an internal fan that circulates the air within the sample chamber to reduce the time taken to reach equilibrium. Since both dew-point and sample surface temperatures are simultaneously measured, the need for complete thermal equilibrium is eliminated, which reduces measurement times to less than five minutes (Decagon Devices 2003). Although the concept of using psychrometers to measure the relative humidity in a soil has been in use for many years (Richards and Ogata 1958), the chilled-mirror dew-point device has been a more recent development. Devices similar to that shown in Figure 1.17 below have been used by a number of different authors (Leong et al. 2003; Tang and Cui 2005; Cardoso et al. 2007; Leong et al. 2007). This technique has been found to be reliable from 1 to 60 MPa of suction (Cardoso et al. 2007).



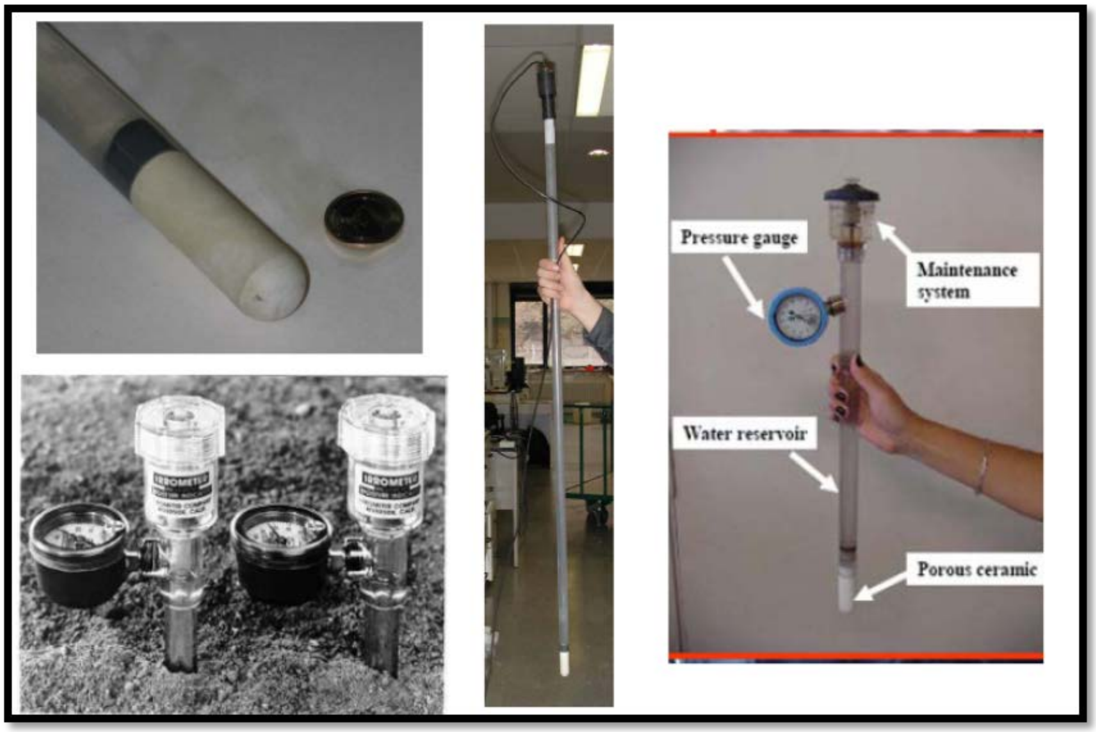
Leong et al. (2003)

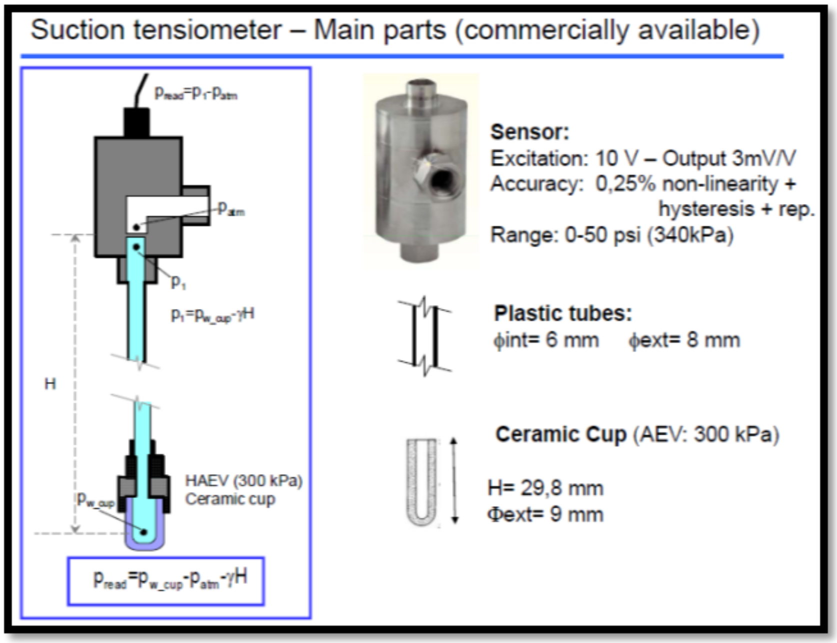
Figure 1.17. Chilled-Mirror Dew-Point Psychrometer.

The WP4 psychrometer is a bench-top instrument with a Lexan sample drawer. A reading is performed by setting a cup in the chamber and closing the latch on the drawer. Soil suction data can be stored internally or transferred to a computer or printer with the included serial RS232 interface cable. Sample cups are 4 cm in diameter and 1 cm tall with a 15 ml capacity. The chilled-mirror dew-point psychrometer can be used for uncompacted or compacted soils with test turnaround time generally around 5 minutes. The device costs about $6,400. Limitations on the sample size imply limitations on the maximum size particle of the soil to be tested. Implementation of this device would also probably require combining this device with another one suitable for a lower suction range (i.e., suction below one MPa).

Tensiometer (Low Range Tensiometer)

The low range tensiometer, also known as 'conventional tensiometer' (Stannard 1992) or simply 'tensiometer' measures the matric suction of soil directly by measuring the negative pore water pressure while pore air pressure is atmospheric (i.e., under conditions similar to the field). Low range tensiometers can measure negative water pressures only in the range from 0 to 80 kPa, which limit their application. The tensiometers can provide measurement of: (i) suction (i.e. negative pore water pressure) in unsaturated conditions; (ii) positive pore water pressure in saturated soils; (iii) and temperature. Figure 1.18 shows some typical low range tensiometers.




Suction tensiometer – Main parts (commercially available)

Sensor:
Excitation: 10 V – Output 3mV/V
Accuracy: 0,25% non-linearity + hysteresis + rep.
Range: 0-50 psi (340kPa)

Plastic tubes:
ϕint= 6 mm ϕext= 8 mm

Ceramic Cup (AEV: 300 kPa)
H= 29,8 mm
Φext= 9 mm

Figure 1.18. Low Range Tensiometers.

To use a tensiometer, the instrument is put in contact with the soil until a steady reading is achieved (generally around five minutes). Good contact between soil and tensiometer is critical for good measurements. Tensiometers can be installed in uncompacted or compacted soils and measure soil suctions from +100 to −85 kPa. A tensiometer system ranges in cost from about \$100 for a basic instrument, to around \$3500 for a system with data logging capabilities.

However, for implementation in this project, the device would probably need to be combined with another device that measures higher suction values.

Mini Tensiometer

The mini tensiometer, shown in Figure 1.19, operates on principles very similar to those already described for the tensiometer. Some advantages of the mini tensiometer include its smaller size and an extended measurement range (to −160 kPa) as compared to standard tensiometers.

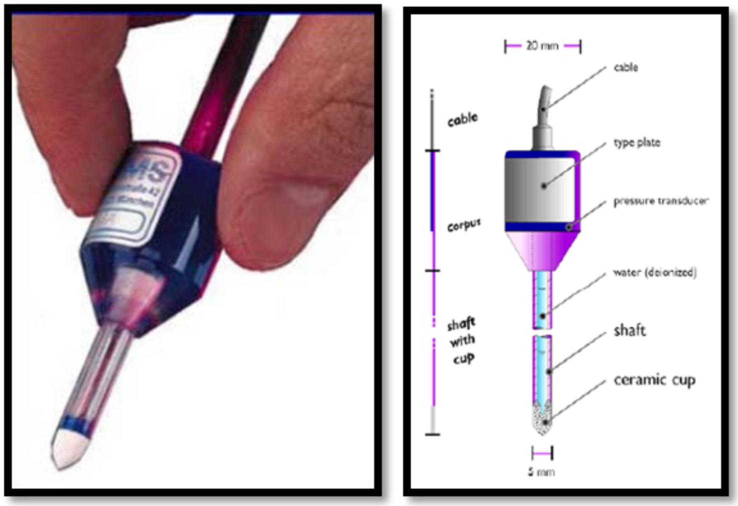


Figure 1.19. Miniature Tensiometers.

High Capacity Tensiometer (HCT)

In the early 1990s, Ridley and Burland (1993, 1995) first developed high-capacity tensiometers (HCT) capable of measuring negative water pressures down to −1500 kPa. This device is often referred to as the Imperial College tensiometer. Figure 1.20 shows an updated version of the high-capacity tensiometer presented by Ridley et al. (2003). The instrument consists of three main components: (i) a high air entry value ceramic, (ii) a water reservoir, and (iii) a pressure or strain gauge. The high air entry value ceramic is typically 15 bar (1500 kPa) in these tensiometers and separates the water and air phases as in the axis translation technique. The water reservoir must be very small in magnitude to reduce the risk of bubble formation in the reservoir. If the ceramic is in good contact with the pore water of the soil sample, water will flow between the soil and the reservoir until equilibrium is reached. An electronic transducer, typically a strain gauge attached to the water reservoir, will detect changes in movement due to the flow of water into or out of the reservoir. This enables a direct measurement of the matric suction of soil to be measured.

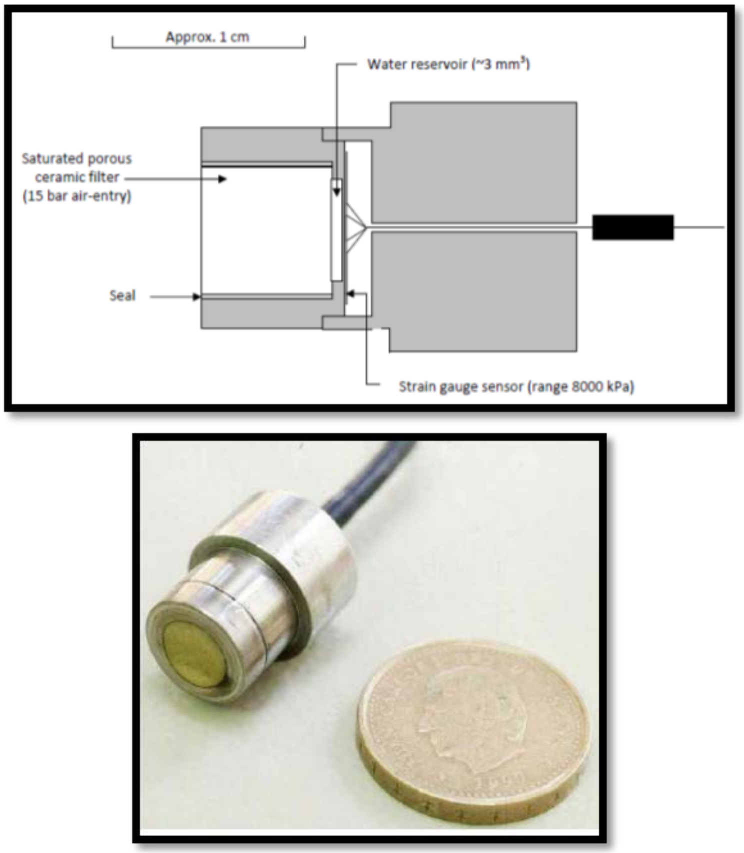


Figure 1.20. Imperial College Tensiometer (after Ridley et al., 2003).

The issue of cavitation has had an important role in the design of these instruments (i.e., use of a very small water reservoir, smooth surfaces free from roughness, etc.), but it is also responsible for the development of methodical procedures which must be followed in order to achieve reliable suction measurements. Important procedures include the initial removal of air by vacuum, initial saturation of the water reservoir and ceramic disc, and saturation prior to each measurement. Despite their limitations, the use of tensiometers in geotechnical testing campaigns has been successful but has been largely restricted to those research groups with the most knowledge and experience in the design, construction, and experimental functioning of these devices (i.e., Imperial College, Ècole Nationale des Ponts et Chausées-Paris [ENPC], and Università degli Studi di Trento). However, more recently work on high-capacity tensiometers has also been carried out at Durham University in conjunction with Wykeham Farrance (Lourenço 2008).

Using the HCT is similar to using a standard tensiometer; however, the stabilization time is longer (typically around 15 minutes). Good contact between the soil and tensiometer, and having the porous stone fully saturated, is also critical. The HCT can be used for uncompacted or compacted soils and measures suction values from 0 to −1,500 kPa. This device is currently not commercially available.

Fredlund Thermal Conductivity Sensor (FTC-100)

The FTC-100, shown in Figure 1.21, measures soil suction and temperature in the field. The system consists of ceramic-tipped sensors, a datalogger, and a power supply. Typically, 16 sensors are included with 10 m (30 ft) of cable for each sensor. Each sensor's tip has a miniature heating element and a temperature sensor embedded in the center. The heating curve of the sensor is obtained by sending a controlled current to the heating element. The temperature change in the sensor after heating depends on the water content of the sensor, which is in turn a function of the surrounding soil suctions. Typically, a 160 mA current is sent over a 60-second period, and the heating curve is recorded for 1.5 minutes during a measuring cycle.

The temperature difference between before and after heating corresponding to several suction values is obtained in the laboratory and the information is provided in a calibration curve. The calibration curve is used to compute the suction corresponding to the temperature rise of the sensor in the field. A pressure cell assembly equipped with high-air entry value disks (500 kPa) is used in the calibration process. Therefore, the calibration data is available up to a maximum suction of 500 kPa. The surrounding soil temperature can slightly influence the suction measurements, because the calibration data are determined in the laboratory under a standard temperature. A temperature correction is incorporated in the computation process to reduce this influence. The soil properties such as bulk density, solute content in pore fluids, and grain size distribution do not influence the suction measurements.

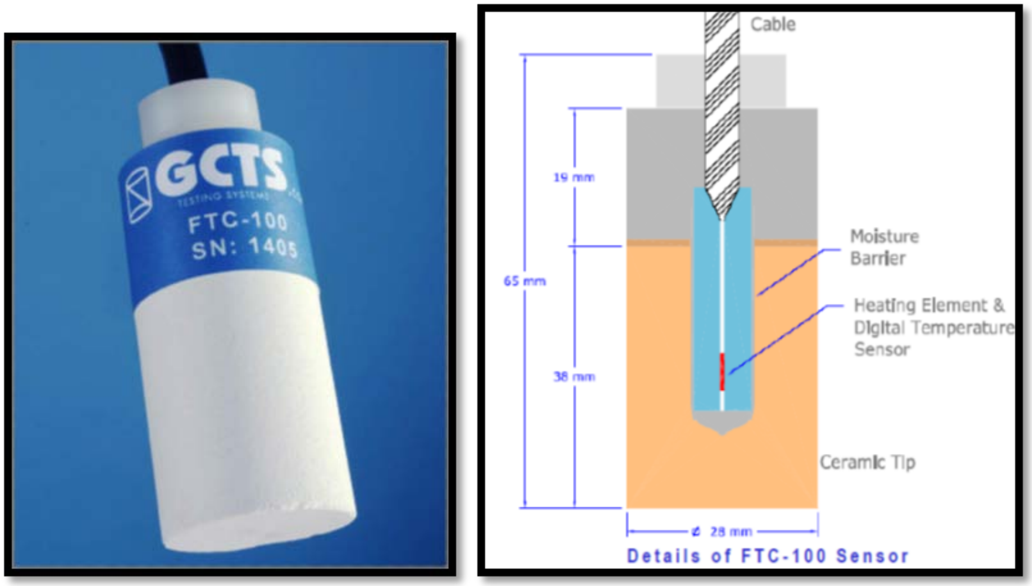


Figure 1.21. Fredlund Thermal Conductivity Sensor.

To use the FCT, the sensor is put in close contact with the soil and the measurement is taken. The duration of the thermal pulse is 180 seconds. It is a short duration test capable of measuring suction values from −10 to −2500 kPa. A complete system costs about $6500.

Water Matric Potential Sensor–Campbell 229-L

The 229 Water Matric Potential Sensor illustrated in Figure 1.22 consists of a heating element and thermocouple placed in epoxy in a hypodermic needle, which is encased in a porous ceramic matrix. To calculate soil water matric potential, a Campbell CE4 or CE8 current excitation module applies a 50 mA current to the 229's heating element, and the 229's thermocouple measures the temperature rise. The magnitude of the temperature rise varies according to the amount of water in the porous ceramic matrix, which changes as the surrounding soil wets and dries.

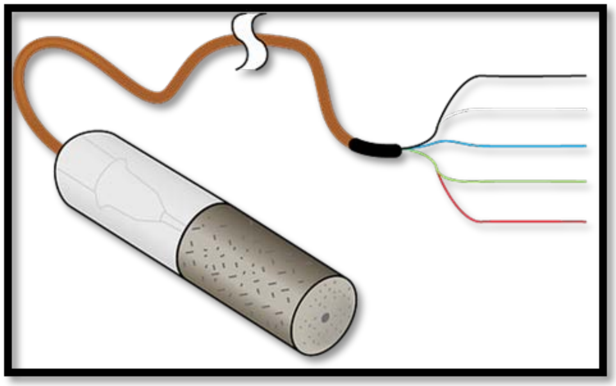


Figure 1.22. Campbell Water Matric Potential Sensor.

Soil water matric potential is determined by applying a second-order polynomial equation to the temperature rise. Users must individually calibrate each of their 229 sensors in the soil type in which the sensors will reside. A reference temperature measurement is required for the 229's thermocouple measurement. The temperature sensor built into many of the dataloggers' wiring panel typically provides this measurement.

To collect a reading, the sensor is put in close contact with the soil and the measurement is taken. Measurement time is around 30 seconds and the measurement range is from −10 to −2500 kPa. The sensor and module together cost about $500.

Capacitive Hygrometer (Vaissala)

The capacitive hygrometer measures the relative humidity (RH), which can be directly converted to water potential through the psychrometric law (Kelvin's Law). The sensor measures the capacitance of an electrode where a polymer acts as the dielectric portion of the capacitor. The properties of the polymer/dielectric change proportionately with the change in relative humidity, which results in a change of the measured capacitance.

The HMP230 Series Humidity and Temperature Transmitters shown in Figure 1.23 have been designed for use in demanding applications where humidity control is important. The sensor provides accurate and reliable measurements with excellent long-term stability over the whole measurement range. The sensor is immune to particulate contamination and most chemicals.

Figure 1.23. Capacitive Hygrometer.

To use the capacitive hygrometer, the sensor is put in close contact with the soil, and the measurement is taken. Measurement time is typically around 20 seconds. The capacitive hygrometer should be suitable for use in both uncompacted and compacted soils and can measure from 0 to 100 percent RH. The sensor costs about $2,500.

Equitensiometer (Delta-T)

Based on the ML2x ThetaProbe, the EQ2 equitensiometer shown in Figure 1.24 avoids the familiar problems of water-filled tensiometers. The ThetaProbe pins are embedded into a specially formulated porous matric material. Being maintenance free, (i.e., no refilling, degassing or topping up required) and low power, the EQ2 can be conveniently used at remote sites. Frost or long term burial also do not harm the device.

Figure 1.24. Equitensiometer.

To use the equitensiometer, the sensor is put in close contact with the soil and the measurement is taken. Measurement time can take typically several days. This device could be used for uncompacted or compacted soils. The equitensiometer can measure soil suctions from 0 to −1000 kPa, and the device costs about $1500.

Based on the review of suction-based devices, Table 1.10 presents a ranking of each device from the currently-known information. At this point, the heat dissipation sensors and capacitive hygrometer are the most promising of the suction-based devices.

Table 1.10. Comparison of Devices Based on Suction Method.

Aspect	WP4	Low Range Tensiometer	Mini Tensiometer	HCT	Fredlund Thermal Conductivity	229-L	Capacitive Hygrometer	Equitensiometer
Turnaround time	4	5	5	7	3	2	1	8
Standard spec. & procedure	2	1	1	3	2	2	2	2
Applicability to soil & base	5	4	3	2	1	1	1	8
Zone of influence	1	1	1	2	1	1	1	1
Cost	6	4	4	8	7	1	5	2
Known inferences	1	1	1	1	1	1	1	1
Implementable potential	6	5	5	8	2	1	3	7
Avg. of scores	3.571	3.000	2.857	4.428	2.428	1.286	2.000	4.143
Overall Rank	**6**	**5**	**4**	**8**	**3**	**1**	**2**	**7**

MOISTURE MEASUREMENT METHODS IN OTHER AGENCIES

A review of practices used for measuring water content among 12 other agencies showed the majority of agencies rely on nuclear testing and physical gravimetric drying for water content measurements. The calcium carbide method is the next most widely reported technique. Table 1.11 presents the results of the agencies reviewed. Highlights include:

- Most of the agencies use nuclear methods.
- While most agencies use gravimetric water content by drying, only about half of those agencies also allow use of the microwave or hot plate/direct heat method.
- About half of the agencies reviewed report use of the calcium carbide method.
- A dielectric-based method for water content was only found in use by the FHWA for the long-term pavement performance (LTPP) long-term monitoring project.
- Only one agency reported using a suction-based method.

Table 1.11. Summary of Moisture Measurement Practices in Other Agencies.

Agency	Available Test Method	Category[2]					Note
		N	G	D	S	C	
FHWA	Data Collection for Seasonal Monitoring Program (SMP) sections in Long-Term Pavement Performance (LTPP) *Time Domain Reflectometry (TDR)*			*			- Monitoring moisture content of subsurface - Placed 10 TDR sensors by depth
Washington DOT	WSDOT FOP[1] for AASHTO T 217 *Determination of moisture in soils by means of a calcium carbide gas pressure moisture tester*					*	- Used for non-granular soils (no appreciable amount retained No. 4 sieve) - Use conversion curve for moisture tester reading
	WSDOT FOP for AASHTO T 255 *Total evaporable moisture content of aggregate by drying*		*				- Using heat source at 110 ± 5°C (electric hot plate or microwave oven) - There is a guideline for minimum mass per nominal maximum size of aggregate
	WSDOT FOP for AASHTO T 265 *Laboratory determination of moisture content of soil*		*				- Oven dry method
	WSDOT FOP for AASHTO T 310 *In-place density and moisture content of soil and soil-aggregate by nuclear methods (shallow depth)*	*					N/A
	WSDOT Standard Operating Procedure SOP 615 *Determination of the % Compaction for Embankment & Untreated Surfacing Materials Using the Nuclear Moisture-Density Gauge*	*					- In-place density and moisture content of compacted soils and untreated surfacing materials

[1] Field Operating Procedures

[2] N: Nuclear density, G: Gravimetric, D: Dielectric, S: Suction, C: Chemical

Table 1.11. Summary of Moisture Measurement Practices in Other Agencies (continued).

Agency	Available Test Method	Category					Note
		N	G	D	S	C	
Florida DOT	Florida Method of Test FM 1-T238 *Density of Soils and Bituminous Concrete Mixtures in Place by the Nuclear Method*	*					- In-place density and moisture content of soil and soil-aggregate
	Florida Method of Test FM 1-T255 *Total Moisture Content of Aggregate by Drying*		*				- See AASHTO T 255
	Florida Method of Test FM 1-T265 *Laboratory Determination of Moisture Contents of Soils*		*				- See AASHTO T 265
	Florida Method of Test FM 5-507 *Determination of Moisture Content by Means of a Calcium Carbide Gas Pressure Moisture Tester*					*	- 20 or 26 grams moisture tester - Use conversion chart for moisture tester reading
	Florida Method of Test FM 5-535 *Laboratory Determination of Moisture Content of Granular Soils by Use of a Microwave Oven*		*				- See ASTM D4643
Minnesota DOT	Mn/DOT Grading & Base Manual 5-692.245.B *Burner Method*		*				- Used for any grading, subgrade, base or shoulder material - Dry sample on frying pan by a heating stove or oven
	Mn/DOT Grading & Base Manual 5-692.245.C *Calcium Carbide Gas Pressure Method using the 26 gram "Speedy" Moisture Meter*					*	- Used for non-granular soils (no appreciable amount retained No.4 sieve)
	Mn/DOT Grading & Base Manual 5-692.245.D *Calcium Carbide Gas Pressure Method using the 200 gram "Super Speedy" Moisture Meter*					*	- Used for granular soils and aggregate base with particle size not to exceed 2 inches
	Data Collection at MnROAD *Time Domain Reflectometry*			*			- Monitoring liquid volumetric soil water content at subsurface - Placed 7 sensors by depth
	Data Collection at MnROAD *Watermark Block*			*			- Monitoring soil water potential as negative pressure at subsurface - Placed 7 sensors next to the TDR sensors

Table 1.11. Summary of Moisture Measurement Practices in Other Agencies (continued).

Agency	Available Test Method	Category					Note
		N	G	D	S	C	
Oklahoma DOT	ODOT Standard Specification 202.04.A.(5) *Nuclear Density Gauge Testing*	*					- Used for in-place field density and soil moisture measurement
California DOT	California Test Methods 226 *Method of Test for Moisture Content of Soils and Aggregates by Oven Drying*		*				- Used for moisture content measurement for soils and aggregates
	California Test Methods 231 *Method of Test for Relative Compaction of Untreated and Treated Soils and Aggregates Using Nuclear Gages*	*					- Used for in-place wet density and moisture content measurement
	California Test Methods 370 *Method for Determining Moisture Content of Bituminous Mixtures or Graded Mineral Aggregates Using Microwave Ovens*		*				- Used for graded mineral aggregates used in bituminous mixtures
Indiana DOT	AASHTO T 255 *Total evaporable moisture content of aggregate by drying*		*				- Applicable to aggregate or sand.
	Indiana Test Method (ITM) 506 *Soil field moisture content determination*		*				- Applicable to cohesive soils.
	AASHTO T 217 *Determination of moisture in soils by means of a calcium carbide gas pressure moisture tester*					*	
	Nuclear gage testing	*					- Require to attend a certification class.
Australia	Australia Standard (AS) 1289 2.2.1 Methods for testing soils for engineering purposes: *Determination of soil moisture content and the total suction*		*		*		- This test involves the laboratory determination of the relative humidity using a psychrometer.
	Nuclear gage testing	*					- Mostly for density measurement.

Table 1.11. Summary of Moisture Measurement Practices in Other Agencies (continued).

Agency	Available Test Method	Category					Note
		N	G	D	S	C	
Oklahoma DOT	ODOT Standard Specification 202.04.A.(5) *Nuclear Density Gauge Testing*	*					- Used for in-place field density and soil moisture measurement
California DOT	California Test Methods 226 *Method of Test for Moisture Content of Soils and Aggregates by Oven Drying*		*				- Used for moisture content measurement for soils and aggregates
	California Test Methods 231 *Method of Test for Relative Compaction of Untreated and Treated Soils and Aggregates Using Nuclear Gages*	*					- Used for in-place wet density and moisture content measurement
	California Test Methods 370 *Method for Determining Moisture Content of Bituminous Mixtures or Graded Mineral Aggregates Using Microwave Ovens*		*				- Used for graded mineral aggregates used in bituminous mixtures
Indiana DOT	AASHTO T 255 *Total evaporable moisture content of aggregate by drying*		*				- Applicable to aggregate or sand.
	Indiana Test Method (ITM) 506 *Soil field moisture content determination*		*				- Applicable to cohesive soils.
	AASHTO T 217 *Determination of moisture in soils by means of a calcium carbide gas pressure moisture tester*					*	
	Nuclear gage testing	*					- Require to attend a certification class.
Australia	Australia Standard (AS) 1289 2.2.1 Methods for testing soils for engineering purposes: *Determination of soil moisture content and the total suction*		*		*		- This test involves the laboratory determination of the relative humidity using a psychrometer.
	Nuclear gage testing	*					- Mostly for density measurement.

Table 1.11. Summary of Moisture Measurement Practices in Other Agencies (continued).

Agency	Available Test Method	Category					Note
		N	G	D	S	C	
Canada	Standard Test Procedure (STP) 205-3 *Moisture by oven drying*		*				N/A
	STP 205-4 *Moisture by speedy tester*					*	The sample should be representative. Special care needs to be taken on the pressure gauge. A correction is needed for high moisture content soil over 20%.
	STP 205-8 *Moisture by microwave oven*		*				- Obtain a representative sample between 150 ~ 250 gram. A correction needs to be made on soil containing organic matter.
	Nuclear gage testing	*					- Require to attend a certification class.
United Kingdom	British Standard (BS) 1377:1975, Test 1(A) *Moisture by oven drying*		*				N/A
	BS 1377:1975, Test 1 (B) *Moisture sand-bath method*		*				- Applicable to granular material.
	Moisture by speed tester					*	N/A
	Nuclear gage testing	*					- Require to attend a certification class.
South Africa	South African National Standard (SANS) 3001-GR20 *Determination of moisture content by oven-drying*		*				N/A
	Nuclear gage testing	*					- Require to attend a certification class.
	Speedy moisture tester					*	N/A

RECOMMENDATIONS FROM LITERATURE REVIEW

Based on the literature review, the research team believes the potential time requirements for measurements with suction-based devices, plus the requirement for needing the companion soil water characteristic curve to translate the suction value into water content, means that suction-based approaches do not warrant further investigation in the scope of this project. Based upon the literature review, the research team concluded the following alternative moisture measurement approaches should be considered for ongoing investigation in the project:

- Gravimetric-based approaches:
  - Microwave oven (ASTM D4643).
  - Direct heat (ASTM D4959).
- Dielectric-based approaches:
  - SDG 200 (no known currently adopted test method).
  - EDG (ASTM D7698).

After presentation of the literature review information and these recommendations to TxDOT's project monitoring committee, further discussion revealed significant interest in efforts with the moisture analyzer, DOT 600, and fork-style FDR. From the literature review and feedback from TxDOT, Table 1.12 presents the devices that will undergo the next stage of evaluation in this project.

Table 1.12. Test Devices for Further Work Based on Literature Review.

Technology	Devices
Gravimetric	Microwave Oven
	Direct Heat
	Moisture Analyzer
Dielectric	Transtec SDG 200
	Humboldt EDG
	Campbell Scientific DOT 600
	Fork-Style FDR

CHAPTER 2
TEST METHOD DEVELOPMENT FOR MOISTURE MEASUREMENT DEVICES

OVERVIEW

To begin work with the moisture content devices recommended from the literature review, the research team obtained the necessary equipment and performed controlled tests in a laboratory setting with new devices. Dielectric-based approaches included the FDR, DOT 600, EDG, and SDG. Since the EDG and SDG are field-only tests, controlled lab tests with the dielectric-based devices were conducted only with the FDR and DOT 600. Gravimetric-based approaches included the microwave, direct heat, and moisture analyzer. The purpose of the initial work described in this chapter was to gather preliminary information on the fit between each test device and true oven-dry reference values, gather information about test parameters that may impact results from each device, and develop a basic test procedure. To accomplish these objectives, the research team first performed pilot testing on a soil of low plasticity index (PI), and then focused efforts on testing flexible base. Finally, a small set of experiments were performed using a lime-treated soil (LTS).

INITIAL RESULTS WITH LOW PI SOIL

Since the DOT 600 and the moisture analyzer technologies represented the technologies with the least known applications to construction materials, the research team initiated pilot work focusing on these two methods. For testing purposes, the team used a soil sample from FM 148, shown in Figure 2.1. This soil has a liquid limit of 15, a plastic limit of 8, and a plasticity index of 7.

Figure 2.1. Low PI Soil Used in Pilot Tests with DOT 600 and Moisture Analyzer.

Pilot Results from DOT 600 with Low PI Soil

The DOT 600 device tests a relatively small sample size (maximum of 200 g) and requires approximately 5 minutes per test. For pilot testing, the research team prepared soil at different water contents. For each sample tested, after collecting measurements with the DOT 600, the oven-dry water content was determined. The basic procedure employed with pilot tests using the DOT 600 follows:

1. Turn on the test device and use the built-in bubble level as a guide to adjust the device until it is level.
2. Create a project file.
3. Select the appropriate material type. For these tests, based on the Atterberg limits, the research team selected material type as sand.
4. Place the sample chamber on the scale and tare the scale.
5. Place the No. 4 sieve on top of the sample chamber and use your fingers to push the material through the sieve into the sample chamber. Fill the sample chamber until full.
6. Place the filled chamber on the scale and record the sample weight.
7. Ensure the area around the water content measurement pins is free of dust and loose soil, and then place the filled and weighed chamber on the pins by matching the alignment marks.
8. Place the compression cap on top of the sample chamber and twist the cap to lock it in place.
9. Use a wrench to turn the compression nut clockwise until the desired pressure is reached. Do not exceed 45 psi. For these tests, the pressure used was 15 ±1 psi.
10. Remove the wrench when the target pressure is reached, and then record the volumetric water content, applied pressure, sample volume, calculated soil bulk dry density, and calculated gravimetric water content by pressing the “Sample_VWC” button.
11. Press the “Rec_Sample_Data” button to store the test data.
12. Use the wrench and turn the compression nut counterclockwise to remove the applied pressure.
13. Remove the compression cap from the sample chamber.
14. Remove the sample chamber from the water content measurement pins.
15. Empty the soil from the sample chamber, and then wipe any residual soil and/or moisture off the interior of the sample chamber.
16. Start a new test by pressing the “New Sample” button

Figure 2.2 illustrates the major steps taking place in a test sequence using the DOT 600.

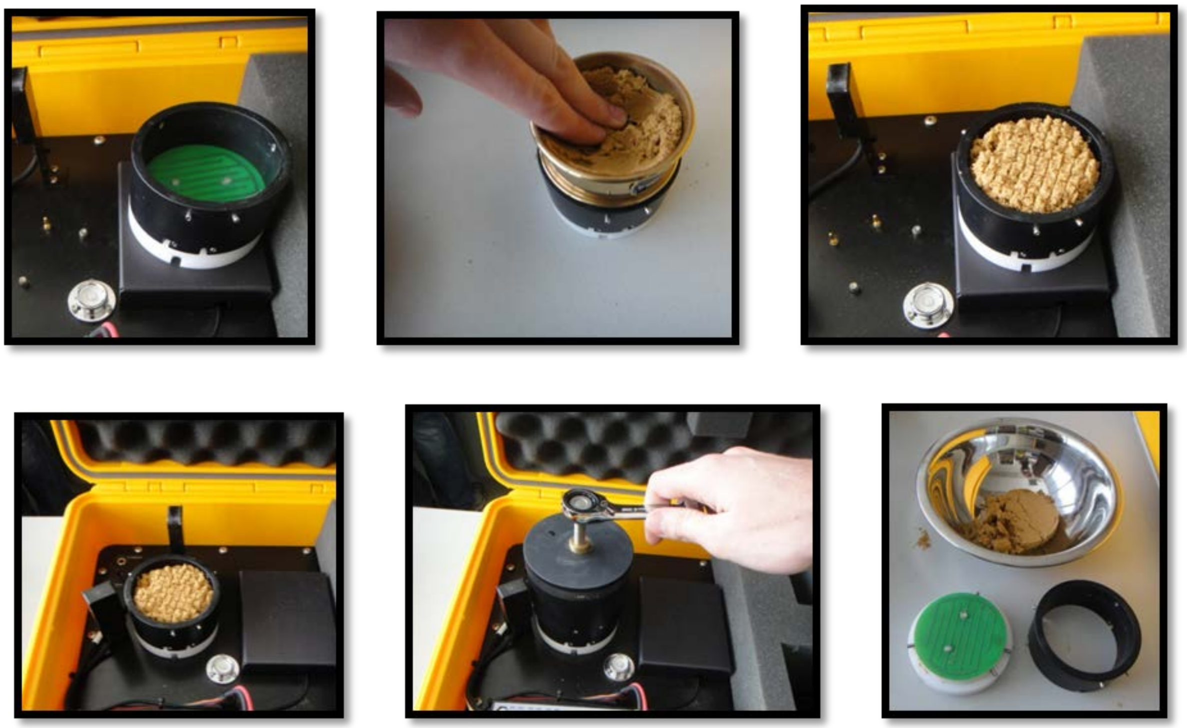


Figure 2.2. Key Steps in Performing Measurements with DOT 600.

Table 2.1 presents the results from the tests conducted. While the results do show a definite bias between the DOT 600 values and the oven-dry gravimetric values (where the DOT 600 read about 5 percent high), Figure 2.3 illustrates that an excellent correlation exists. Additionally, in Table 2.1, the fact that the gravimetric water contents determined by the DOT 600 exceed those of the volumetric water content implies that the sample had a bulk density less than 1. This implication on bulk density seemed erroneous, so the research team performed additional efforts and manually verified the DOT 600 recorded weights, sample heights, and estimated densities, and found the DOT 600 results valid.

Table 2.1. Results from Pilot Tests with DOT 600 and Low PI Soil.

	DOT 600 Result		**Oven Dry Result**				
Target Water Content (%)	**Volumetric Water Content (%)**	**Gravimetric Water Content (%)**	**Pan Weight (g)**	**Wet Weight w/ pan (g)**	**Dry Weight w/ pan (g)**	**Oven Dry Gravimetric Water Content (%)**	**Difference (DOT 600 Gravimetric – Oven Dry Gravimetric)**
3	7.60	9.00	112.0	208.4	204.6	4.10	4.90
5	9.00	10.30	107.1	198.9	194.0	5.64	4.66
7	11.50	13.60	108.1	200.1	193.3	7.98	5.62
9	12.00	13.90	113.6	221.1	212.4	8.81	5.09

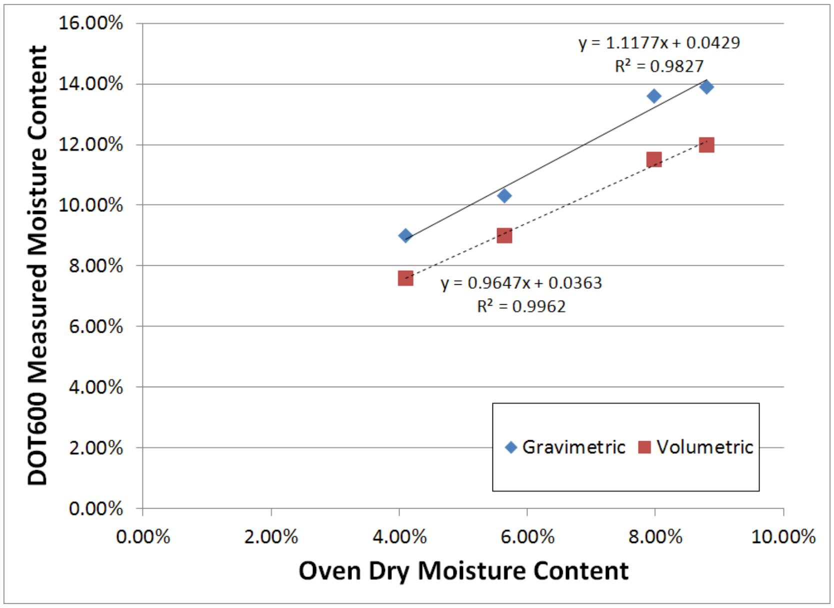


Figure 2.3. DOT 600 Results versus Oven Dry Results with Low PI Soil.

In addition to the controlled tests at different water contents conducted with the DOT 600 and low PI soil, the research team also sought to gather information on the precision of the device. For this information, the researchers used the FM 148 soil at its in-situ moisture content state and performed four tests with the DOT 600. Table 2.2 presents the results, which although limited in materials (only one material was used), imply excellent single operator precision.

Table 2.2. Single-Operator Precision from DOT 600 with Low PI Soil.

Sample	DOT 600 Gravimetric
1	9.2
2	9.3
3	9.2
4	9.2
AVG	9.2
Standard Deviation	.05
Coefficient of Variation (%)	.54

The pilot tests from the DOT 600 showed promising results as a quick moisture content method with good precision. The results also indicated calibrations to the material would be needed. Other items needing to be addressed include whether or not the pressure applied to the sample prior to testing should be changed and how to relate the water content of the passing No. 4 material to the water content of the full particle size distribution for materials that contain retained on No. 4 sizes. Further investigations discussed later in this chapter associated with testing flexible bases will address these topics.

Pilot Results from Moisture Analyzer with Low PI Soil

Similar to the DOT 600, the moisture analyzer tests a small sample (capacity 200 g). The research team performed initial experiments with the moisture analyzer using the FM 148 soil described previously and prepared purposefully at different moisture contents. After each moisture analyzer test, the research team oven-dried the sample to determine the reference value water content. The general procedure used for pilot tests with the moisture analyzer follows:

1. Turn on the device and select a moisture test where:
   % Moisture = 100*[(initial mass – dry mass)/dry mass].
   - Note: on the model procured for this project, this is called "ATRO Moisture."
2. Set the heat control to 230°F.
3. Set the measurement interval to 5 seconds.
   - Note: the measurement interval is the time at which results are computed.
4. Do not use rapid heat (if the device is so equipped).
5. Set the end point determination where a stable result is defined as the mass being stable within 0.03 g for 15 seconds.
6. Screen the material to test through a No. 4 sieve to generate sufficient quantity of material to fill the moisture analyzer pan.
7. Open the sample chamber and place a clean sample pan on the pan support.
8. Tare the sample pan.
9. Distribute passing No. 4 material evenly on the sample pan. The test sample should weigh between 100 and 175 grams or approximately fill the pan, whichever is less.
10. Close the sample chamber and start a test.
11. When the moisture analyzer determines the end-point criteria have been met, record the result, open the sample chamber, and remove the pan with sample from the chamber.
12. Remove the sample from the pan and wipe away any residual sample from the pan.

Figure 2.4 presents the major elements of the moisture analyzer test in progress.

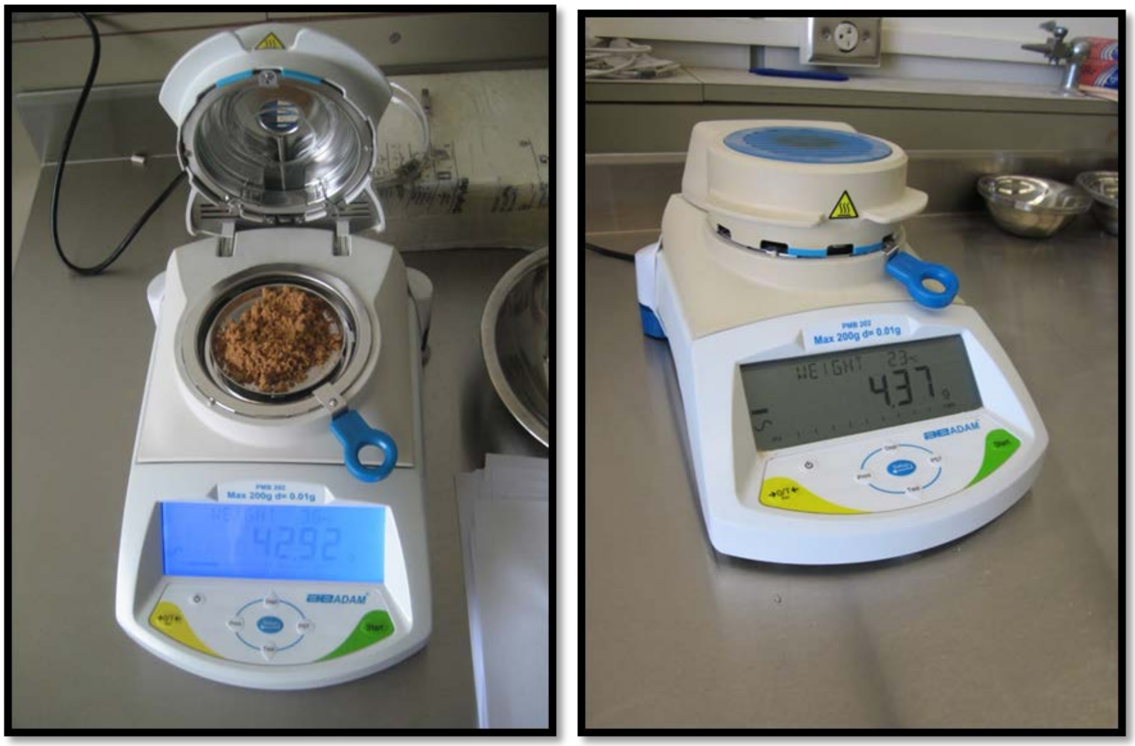


Figure 2.4. Moisture Analyzer Testing in Progress.

Table 2.3 presents the results from the initial tests. These initial tests indicate that, at least at lower water contents, the moisture analyzer test resulted in a fast turnaround time. The results also showed evidence of bias, where the moisture analyzer results were on average 3.7 percent below the oven-dry gravimetric values.

Table 2.3. Pilot Results from Moisture Analyzer with Low PI Soil.

Sample		Analyzer Test Time (Min:Sec)	% Moisture from Analyzer	Pan Weight (g)	Wet w/ Pan (g)	Dry w/ Pan (g)	% Moisture by Oven	Different (Analyzer–Oven)
As Sampled	1	3:30	1.95	230.6	268.7	267.0	4.7	−2.8
	2	3:30	0.30	187.5	304.5	301.0	3.1	−2.8
As Sampled + 5%	1	10:00	5.80	190.5	233.5	230.0	8.9	−3.1
	2	20:30	5.00	241.7	258.6	347.2	10.8	−5.8
As Sampled + Unknown	1	16:00	23.60	202.4	227.5	221.9	28.7	−5.1
	2	82:45	22.80	216.8	365.8	335.6	25.4	−2.6

Since the pilot results showed the moisture analyzer test was not fully drying the material, a second stage of pilot tests were conducted with the FM 148 soil. These tests used the same procedure previously described except that the determination of the test end point was revised where a stable result is defined as the mass being stable within 0.01 g for 15 seconds. Table 2.4 presents the results. The results still show a reasonable test turnaround time and also indicate the values from the moisture analyzer more closely match those from the oven, although those values still are low by about 1.8 percent on average.

Table 2.4. Results from Moisture Analyzer with Low PI Soil after Revising End Point Determination.

Sample		Analyzer Test Time (Min:Sec)	% Moisture from Analyzer	Pan Weight (g)	Wet w/ Pan (g)	Dry w/ Pan (g)	% Moisture by Oven	Different (Analyzer - Oven)
As Sampled	1	5:30	3.05	240.0	274.2	272.7	4.6	−1.6
	2	16:16	2.05	229.1	315.7	312.6	3.7	−1.7
As Sampled + 5%	1	8:31	9.15	189.2	211.7	209.5	10.8	−1.7
	2	46:33	7.25	211.2	306.7	297.8	10.3	−3.1
As Sampled + Unknown	1	18:46	21.05	201.1	221.0	217.2	23.6	−2.6
	2	57:03	21.95	186.0	281.2	264.0	22.1	−0.2

Figure 2.5 contrasts the results between the first two pilot experiments using the moisture analyzer with the low PI soil. This figure illustrates a good fit of data with both series of tests and also show the following:

- For both relationships, the intercept is significant at the 95 percent confidence level. This means both tests exhibit bias.
- For both relationships, the slope coefficient is significant at the 95 percent confidence level, and the 95 percent confidence interval for the slope coefficient ranges from about 0.82 to 1.15. This means the data show the slope coefficient is not significantly different from 1.0.

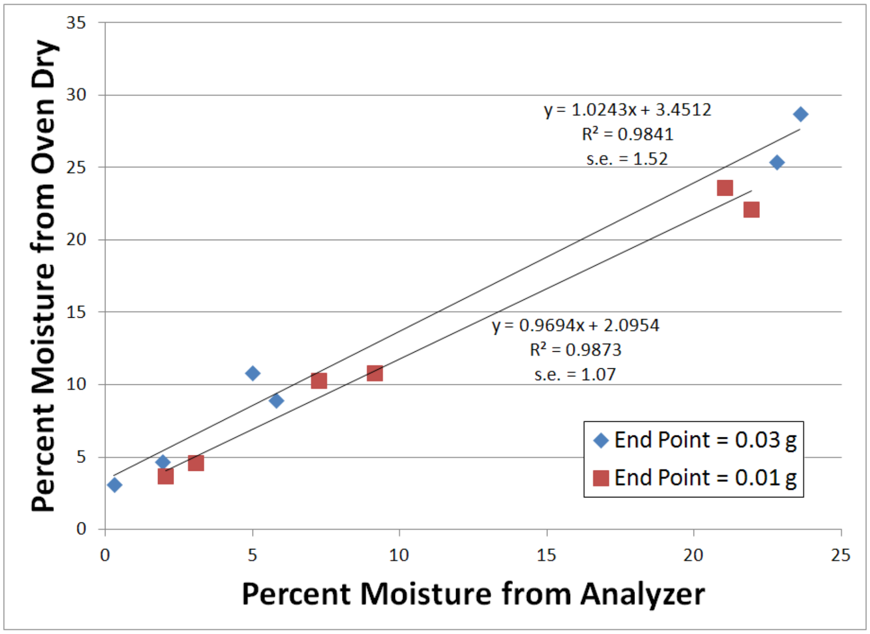


Figure 2.5. Results from Pilot Tests with Moisture Analyzer and Low PI Soil.

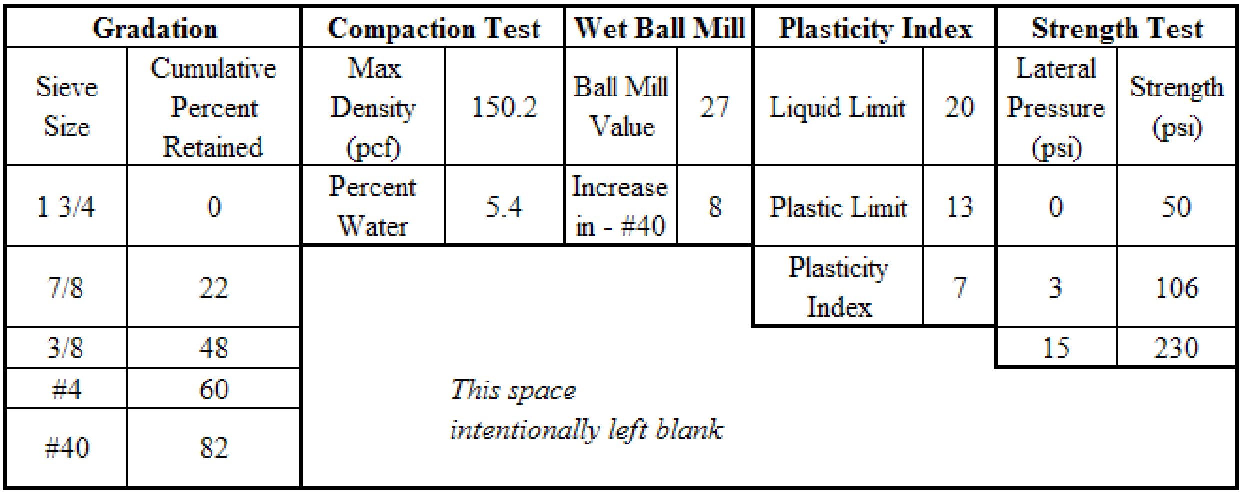
Based on the results collected and presented, the research team believes the moisture analyzer holds promise as a viable method for rapidly determining water content. Of the two variations utilized thus far, the research team believes the method using the end point stability of 0.01 g for 15 seconds should be used because that method exhibited less bias and an improved standard error of the estimate.

Additionally, relating the moisture content of passing No. 4 to that of the full particle size distribution for materials that contain retain on No. 4 sizes needs investigation. Further investigations discussed later in this chapter associated with testing flexible bases will address these topics.

RESULTS FROM TESTING FLEXIBLE BASE

After initial pilot testing with the DOT 600 and moisture analyzer on a low PI soil, the research team embarked on additional test procedure development by conducting tests using a flexible base material. Table 2.5 describes the basic properties of the Type A Grade 4 material used.

Table 2.5. Properties of Type A Grade 1 Base Used in Pilot Tests.



Gradation		Compaction Test		Wet Ball Mill		Plasticity Index		Strength Test	
Sieve Size	Cumulative Percent Retained	Max Density (pcf)	150.2	Ball Mill Value	27	Liquid Limit	20	Lateral Pressure (psi)	Strength (psi)
1 3/4	0	Percent Water	5.4	Increase in - #40	8	Plastic Limit	13	0	50
7/8	22					Plasticity Index	7	3	106
3/8	48							15	230
#4	60	*This space intentionally left blank*							
#40	82								

Using this flexible base, the research team mixed samples with target water contents of 2 percent below, at, and above optimum. The team then performed tests with the DOT 600, moisture analyzer, direct heat, and microwave oven. Oven-dry gravimetric measurements were also collected for reference purposes.

Pilot Results from DOT 600 with Flexible Base

The pilot tests with flexible base performed with the DOT 600 focused on the impact of applied test chamber pressure to the results, calibration of the DOT 600 to the reference values, and how to relate the water content of the passing No. 4 sample to the full gradation. The research team performed these tests using the same general procedures applied to the pilot testing with low PI soil, with the following exceptions:

- A large sample of several thousand grams was prepared at the desired water content.

- A representative portion of the large sample was taken and screened over a 12-inch diameter No. 4 sieve, and then three representative samples from the passing No. 4 portion tested in the DOT 600.
- DOT 600 measurements were performed at chamber pressures of approximately 10, 20, 30, and 40 psi.
- A representative portion of the original sample meeting the minimum mass requirements of Test Method Tex-103-E was taken and oven dried to obtain a reference value water content of the full gradation of material.

Table 2.6 presents the results from these tests with the DOT 600.

Table 2.6. Pilot Results from DOT 600 with Flexible Base.

Target Water Content on Bulk (percent)	Sample	Pressure	DOT 600 Volumetric Percent Moisture	DOT 600 Gravimetric Percent Moisture	Oven Percent Moisture	Bulk Gradation Sample Percent Moisture
3.4	1	9.9	10.0	5.8	5.7	3.2
		19.6	10.7	6.1		
		29.3	11.8	6.4		
		39.2	12.2	6.6		
	2	10.0	11.8	6.8	6.0	
		19.8	12.4	6.8		
		29.5	13.1	7		
		39.4	13.4	7.1		
	3	10.4	12.8	7.3	5.9	
		19.4	13.4	7.5		
		30.0	14.1	7.7		
		39.8	14.4	7.7		
5.4	4	10.2	16.9	9.6	8.0	4.7
		19.2	17.2	9.5		
		30.2	17.5	9.5		
		39.2	17.7	9.5		
	5	10.1	17.5	9.8	7.6	
		18.9	17.8	9.7		
		29.4	18.0	9.6		
		39.4	18.2	9.6		
	6	9.7	16.4	9.2	7.8	
		19.5	16.9	9.3		
		29.3	17.3	9.3		
		39.6	17.7	9.4		
7.4	7	10.1	33.0	17.1	10.9	7.4
		19.7	33.7	17.1		
		29.6	34.3	17.2		
		39.5	34.8	17.4		
	8	9.9	31.0	15.9	10.4	
		19.6	31.3	15.5		
		29.4	31.4	15.3		
		39.5	31.4	15.1		
	9	9.8	26.6	15.1	9.7	
		22.9	27.4	15.2		
		29.8	27.8	15.3		
		41.3	28.1	15.4		

From the results in Table 2.6, Figure 2.6 presents the gravimetric water content measured with different applied pressures. The results indicate a small influence of the pressure on the device output. For this reason, the research team recommends standardizing the applied sample chamber pressure at 30 ±1 psi.

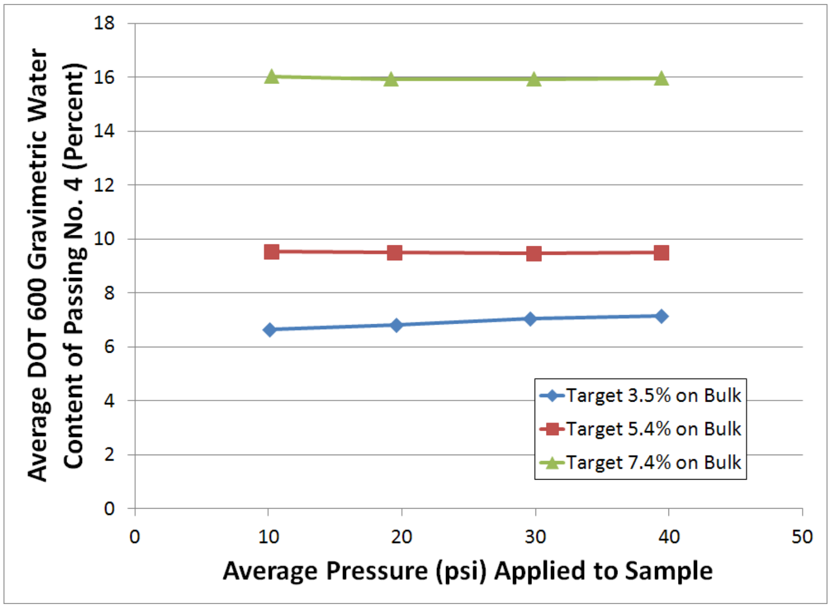


Figure 2.6. DOT 600 Measurements with Varying Sample Chamber Pressure.

Using the selected standard sample chamber pressure of 30 psi, Figure 2.7 presents the oven dry reference value results versus the results from the DOT 600. These results show:

- A good fit of the data between the DOT 600 and oven dry results exists for both the passing No. 4 and full gradation.
- The water content of the passing No. 4 was on average 2.8 percent greater than the water content on the full gradation.

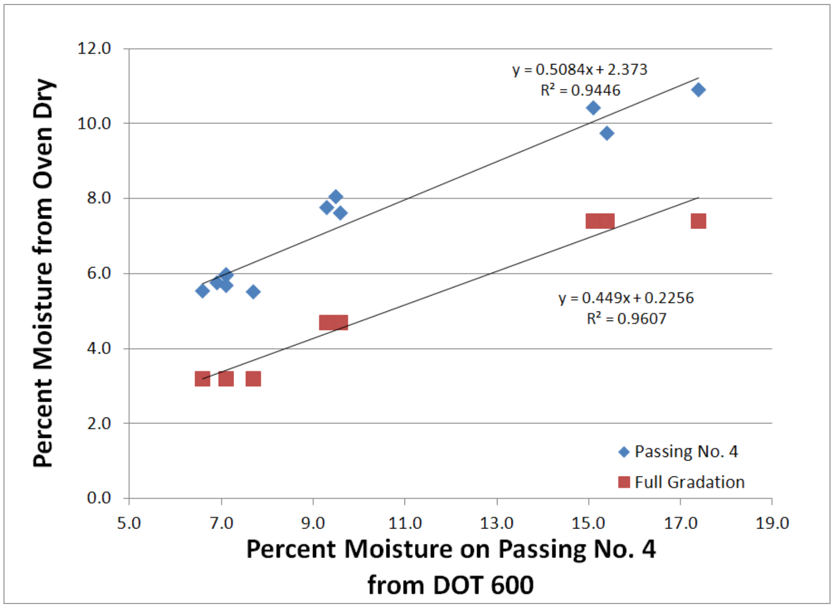


Figure 2.7. Oven Dry versus DOT 600 Results for Pilot Tests with Flexible Base.

Pilot Results from Moisture Analyzer with Flexible Base

The pilot tests on flexible base using the moisture analyzer were performed similarly to the methods employed when pilot testing with the low PI soil with the following exceptions:

- A large sample of several thousand grams was prepared at the desired water content.
- A representative portion of the large sample was taken and screened over a 12-inch diameter No. 4 sieve and then three representative samples from the passing No. 4 portion tested in the moisture analyzer.
- The endpoint determination was changed to be a stable reading within 0.01 g for 15 seconds.
- A representative portion of the original sample meeting the minimum mass requirements of Test Method Tex-103-E was taken and oven-dried to obtain a reference value water content of the full gradation of material.

Table 2.7 presents the results from the pilot tests with the flexible base.

Table 2.7. Pilot Results from Moisture Analyzer with Flexible Base.

Target Water Content on Bulk (percent)	Moisture Analyzer Percent Moisture	Moisture Analyzer Test Time (min:sec)	Oven Percent Moisture	Bulk Gradation Sample Percent Moisture
3.4	5	38:39	6.1	N/A due to insufficient sample size
	4.9	40:09	6.0	
	4.65	35:53	5.6	
3.4	4.5	35:25	5.5	3.2
	4.6	39:40	5.8	
	3.9	41:00	5.3	
5.4	7.4	50:16	7.9	4.7
	7.0	41:55	7.9	
	7.1	51:06	8.3	
7.4	10.1	48:39	11.1	7.4
	8.8	42:59	9.4	

From the results in Table 2.6, Figure 2.8 presents the results of the moisture analyzer with the oven-dry reference values. These results show:

- A good fit of the data between the moisture analyzer and oven dry results exists for both the passing No. 4 and full gradation.
- The moisture analyzer was biased on testing the passing No. 4 and typically read 1 percent below the true oven-dry value.
- The water content of the passing No. 4 was on average 2.8 percent greater than the water content on the full gradation. This observation is consistent with that observed during tests with the DOT 600.

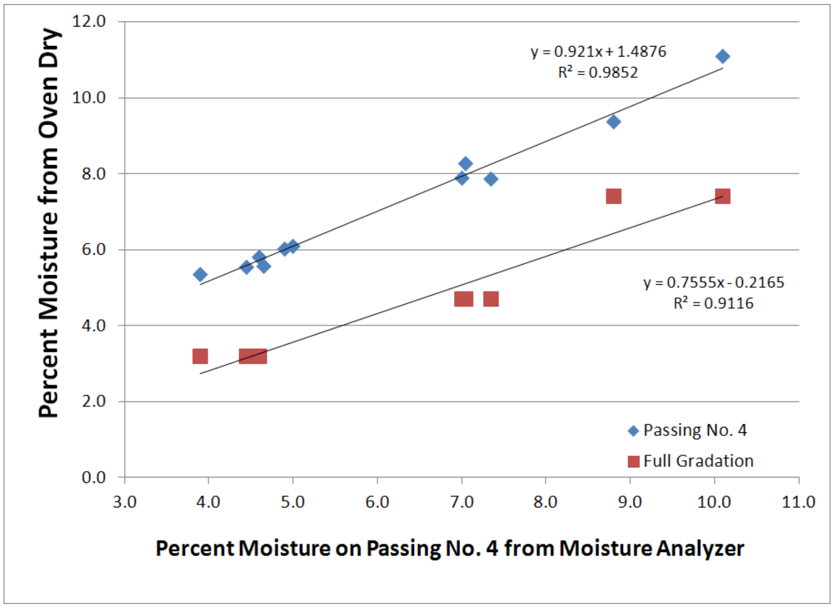


Figure 2.8. Oven Dry versus Moisture Analyzer Results for Flexible Base.

After obtaining these promising pilot results with the moisture analyzer test for flexible base, the following questions existed:

- Should the test temperature be increased?
- Should the end point determination be made even more stringent?
- Should a defined sample size be used?

To investigate these topics, the research team prepared a second series of tests where the test parameters were varied as outlined in Table 2.8. Three measurements were performed for each combination of parameters. Table 2.9 presents the summary results.

Table 2.8. Parameters Investigating Influence of Temperature, End Point Criteria, and Sample Size, on Moisture Analyzer Test.

Test Temperatures (°F)	Test End Point Determinations		Sample Size (g)
	Stability (g)	Duration (sec)	
248°F 284°F 320°F	0.01	15 30	10 50 100

Table 2.9. Results from Influence of Temperature, End Point Criteria, and Sample Size on Error and Test Time with Moisture Analyzer.

	End point = stable within 0.01 g for 15 sec						**End point = stable within 0.01 g for 30 sec**					
	Size = 100 g		**Size = 50 g**		**Size = 10 g**		**Size = 100 g**		**Size = 50 g**		**Size = 10 g**	
Temp (°F)	Error	Time (min.)	Error	Time (min.)	Error	Time (min.)	Error	Time (min.)	Error	Time (min.)	Error	Time (min.)
248	2.79	24.67	2.91	10.62	4.44	3.00	0.32	44.20	0.40	19.12	0.11	4.77
	2.94	21.15	3.13	12.18	5.69	3.00	0.14	45.83	0.20	17.55	0.01	4.15
	3.65	19.63	0.88	12.18	3.01	3.00	0.25	41.08	0.24	17.70	0.12	4.15
284	8.49	3.00	1.43	10.77	4.11	2.25	0.33	38.85	0.19	14.12	0.04	3.72
	8.65	3.00	2.10	10.77	3.98	2.75	0.21	37.48	0.13	14.77	0.46	3.72
	8.01	3.00	1.30	10.77	2.06	2.75	0.24	35.85	0.13	14.77	1.06	2.48
320	7.45	18.72	1.49	10.88	2.56	2.25	0.38	33.00	0.01	11.00	0.36	3.00
	7.85	20.23	1.77	9.32	5.32	2.25	0.27	31.00	0.13	11.50	0.12	3.00
	2.94	18.72	0.24	10.88	0.51	2.25	0.28	29.50	0.20	13.00	0.24	3.00

The results in Table 2.9 were evaluated according to the error and test time requirement to select parameters for use in the moisture analyzer test procedure. The 100-gram sample size was eliminated from consideration due to the large error that sometimes occurred with the more lenient end point and the relatively long (greater than 30 minutes) test time required with the more stringent end point. The next parameter defined was the end point determination. The more stringent end point was selected because, regardless of other parameters, that end point resulted in significantly less measurement error. Additionally, for sample sizes of 10 and 50 g, the end point duration of 30 seconds still resulted in test durations less than 20 minutes, which the research team considered reasonably rapid turnaround times.

With the only undefined parameters being test temperature and choosing between the sample size of 10 or 50 g, the research team selected the 50-gram sample size because that larger size should better represent the material under test. With the sample size set at 50 g, the team selected the highest temperature because that temperature produced the most rapid turnaround time.

Based on the results, the research team recommends setting the sample size at 50 ± 1 g, using a test temperature of 320°F, and determining the end point as a stable reading within 0.01 g for 30 seconds for the moisture analyzer test.

Pilot Results from Direct Heat with Flexible Base

The pilot results from the direct heat test followed ASTM D 4959. The research team performed initial tests using the Type A Grade 1 base presented in Table 2.5 and used a hot plate for the heating source. After preparing a several-thousand gram sample at the target water content, the research team generated representative samples of both the full gradation and the passing No. 4 fraction for the tests. The team tested the No. 4 fraction to investigate if the test turnaround time could be reduced as compared to the full gradation. Representative samples of the full gradation ranged between 500 and 1,000 g, while the sample size of the passing No. 4 ranged between 300 and 500 g. Finally, a representative sample of both the full gradation and passing No. 4 was oven dried for a reference value. Table 2.10 presents the results. Figure 2.9 illustrates the progression of drying in the direct heat test.

Table 2.10. Direct Heat Results from Pilot Tests with Flexible Base.

Target Percent Moisture on Bulk Gradation	Direct Heat Results				Oven Dry Results			
	Passing No. 4		Bulk Gradation		Passing No. 4		Bulk Gradation	
	Time (min)	Percent Moisture	Time (min)	Percent Moisture	Time (min)	Percent Moisture	Time (min)	Percent Moisture
3.4	25	5.4	50	3.1	120	5.4	1080	3.1
5.4	50	8.1	40	5.9	190	8.4	190	5.3
7.4	30	9.7	60	7.5	1170	9.7	1170	7.2

Figure 2.9. Direct Heat Test.

The results indicate excellent agreement between the direct heat and oven dry tests. The results also indicate that testing only the passing No. 4 fraction does reduce the test turnaround time for the direct heat test. Additionally, Figures 2.10 through 2.12 illustrate drying curves from both the direct heat and oven dry procedures with this material. The graphs not only illustrate the similarity of final result among the procedures but also indicate that the time frame for the oven dry test could possibly be reduced. In this case, the results suggest drying was completed in 150 to 200 minutes. Based on these promising results, the research team conducted additional tests using a different flexible base material, this time also including the microwave oven as an additional procedure.

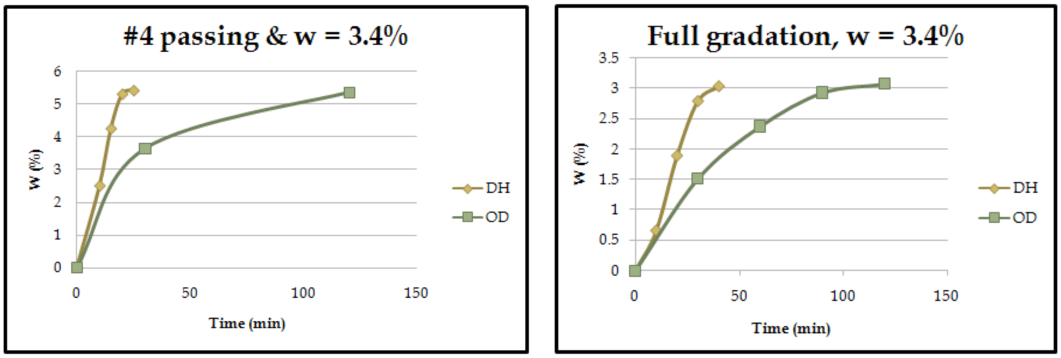


Figure 2.10. Drying Curves of Direct Heat and Oven below Optimum.

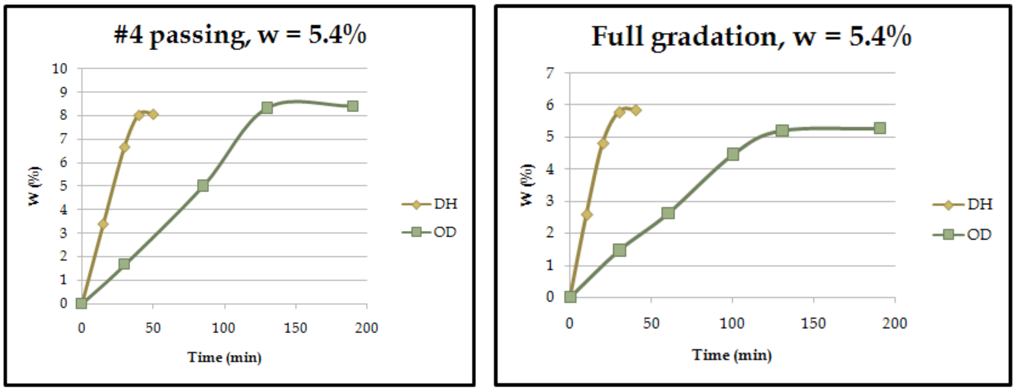


Figure 2.11. Drying Curves of Direct Heat and Oven at Optimum.

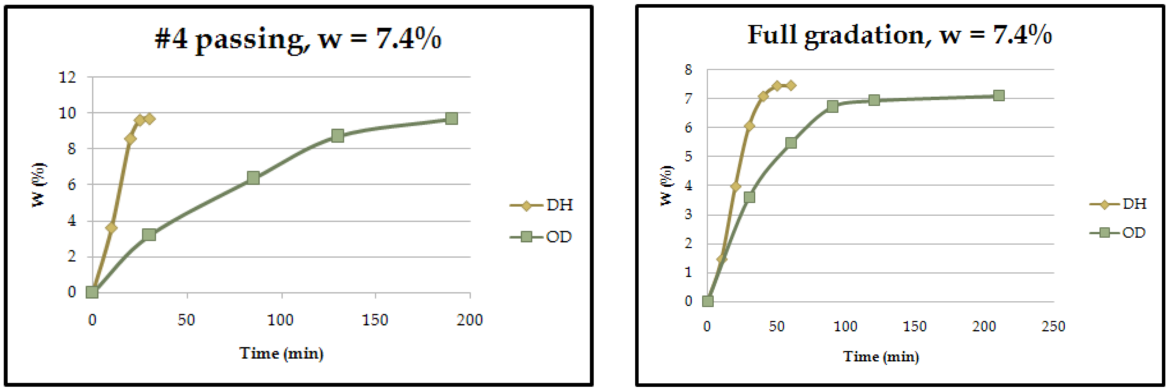


Figure 2.12. Drying Curves of Direct Heat and Oven above Optimum.

Comparison of Direct Heat, Microwave, and Oven Results with Flexible Base

For additional evaluations with the direct heat test, the research team performed parallel tests using the direct heat (ASTM D 4959), microwave (Tex-103-E, ASTM D 4643), and oven dry using the Type A Grade 1 flexible base described in Table 2.11.

Table 2.11. Flexible Base Used with Direct Heat, Microwave, and Oven Tests.

Gradation		Compaction Test		Wet Ball Mill		Plasticity Index		Strength Test	
Sieve Size	Cumulative Percent Retained	Max Density (pcf)	133.8	Ball Mill Value	29	Liquid Limit	19	Lateral Pressure (psi)	Strength (psi)
1 3/4	0	Percent Water	8	Increase in - #40	13	Plastic Limit	15	0	55
7/8	24					Plasticity Index	4	3	118
3/8	53							15	215
#4	64	*This space intentionally left blank*							
#40	81								
#200	87								

Table 2.12 presents the results from the tests. The results show reasonable agreement between the direct heat, microwave, and oven dry results for particle sizes tested. The results also show the microwave oven resulted in the fasted turnaround times with typical results available in less than 10 minutes.

Table 2.12. Direct Heat, Microwave, and Oven Dry Results Compared from Pilot Tests.

Target Percent Moisture on Bulk Gradation	Particle Size Tested	Direct Heat Results		Microwave Results		Oven Dry Results	
		Time (min.)	Percent Moisture	Time (min.)	Percent Moisture	Time (min.)	Percent Moisture
6.0	Full Gradation	60	5.9	7	6.8	150	6.4
	Passing No. 4	35	9.7	6	8.9	150	9.3
8.0	Full Gradation	40	7.4	7	7.7	200	8.2
	Passing No. 4	30	12.3	6	12.6	200	11.7
10.0	Full Gradation	70	9.9	11	10.4	200	10.8
	Passing No. 4	N/A due to lack of sufficient material		5	13.8	200	14.3

Figures 2.13 through 2.15 present the drying curves from this experiment. The results suggest:

- The microwave oven yields the shortest turnaround time
- The direct heat may be sped up by testing only the passing No. 4 fraction, but correction to the water content of the full gradation would be needed.
- Oven-drying may be completed sooner than typical drying times specified in test procedures. However, the times observed in these tests to obtain a stable reading (typically 100–200 minutes) still may be too long to be considered rapid for purposes of this project.

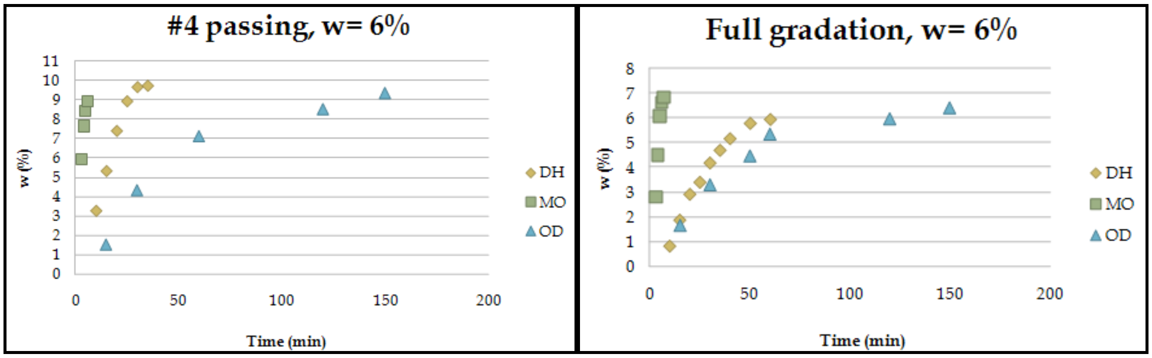


Figure 2.13. Drying Curves of Direct Heat, Microwave, and Oven below Optimum.

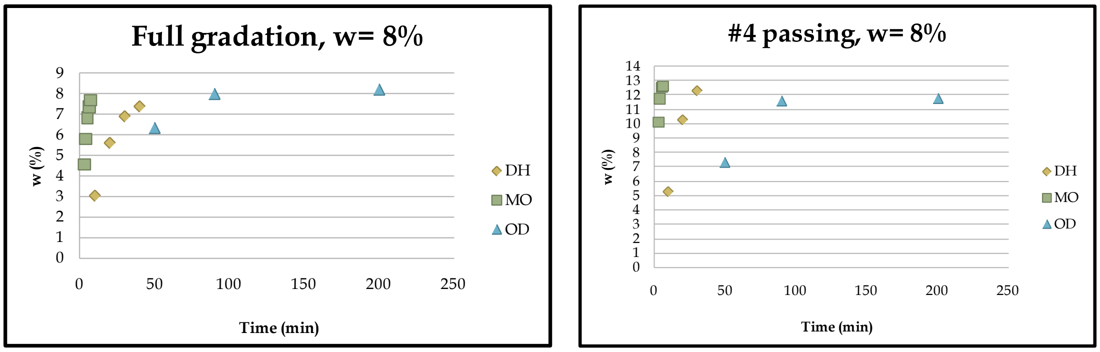


Figure 2.14. Drying Curves of Direct Heat, Microwave, and Oven at Optimum.

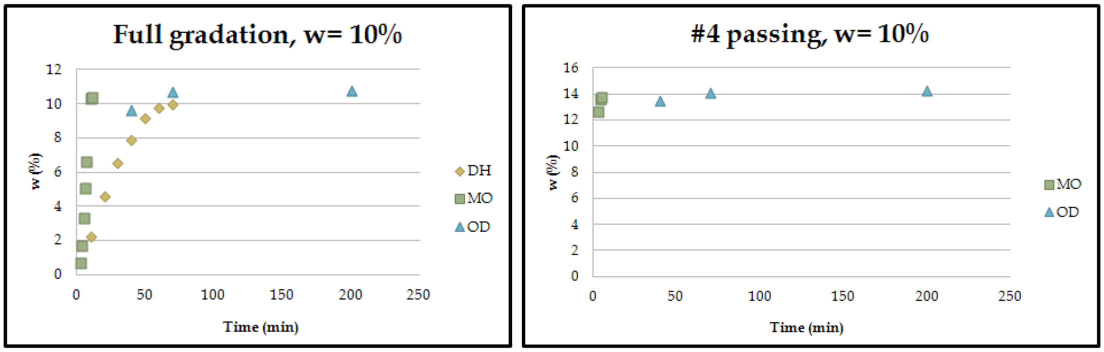


Figure 2.15. Drying Curves of Direct Heat, Microwave, and Oven above Optimum.

Pilot Results from FDR with Flexible Base

The pilot results with the FDR device employed two probes shown in Figure 2.16. The smaller probe has a 0.3 liter volume influence (EC-5 probe), while the larger probe has a 1.0 liter volume influence (EC-10 probe). The FDR test is essentially the same as ASTM D6565, except rather than using Topp's equation to determine the volumetric water content, the FDR approach included a custom calibration per the manufacturer's recommendation. The research team used the same Type A Grade 1 flexible base presented in Table 2.5 for the pilot tests. To perform these tests, the research team prepared material at different moisture contents relative to optimum, placed a known mass of material into a plastic container of known volume with the sensor placed horizontally in the middle of the base material, and then measured the raw sensor output. Finally, the oven-dry moisture content values were measured on the material for reference. Unlike the prior techniques discussed in pilot testing, the FDR generates volumetric water content. Therefore, the research team performed these tests both with uncompacted and compacted material. Figure 2.16 shows the FDR equipment, and Figure 2.17 illustrates the sequence of testing performed.

Figure 2.16. FDR Equipment for Pilot Testing with Flexible Base.

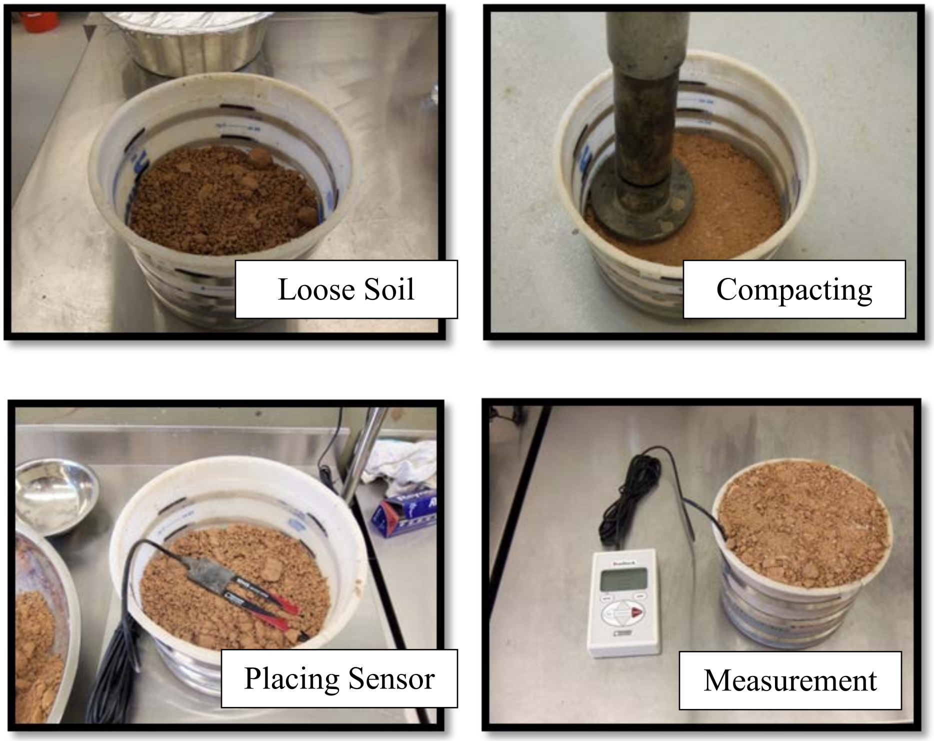
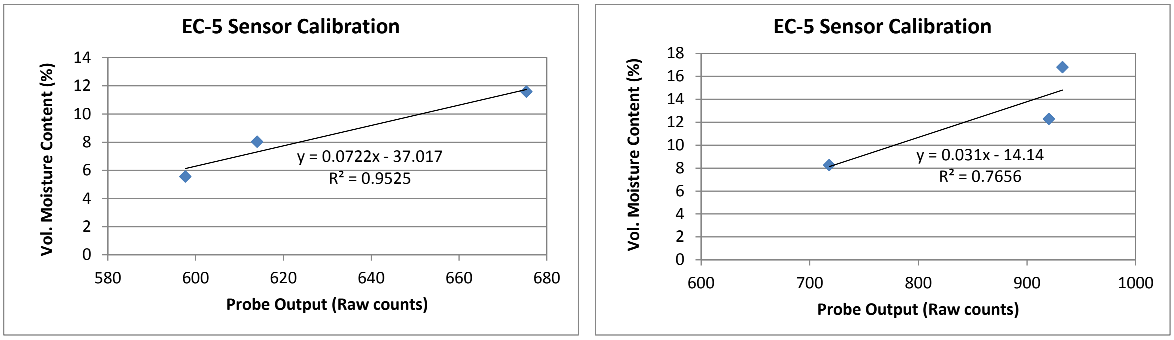


Figure 2.17. Pilot Testing FDR System with Flexible Base.

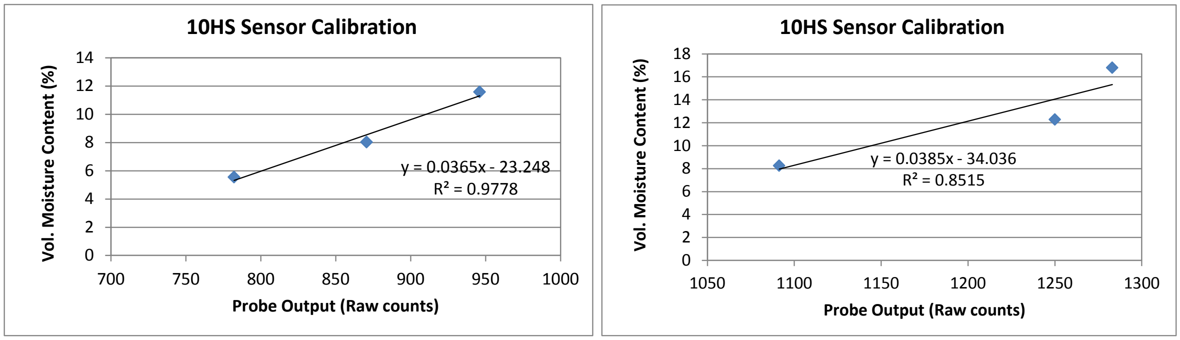
Upon collecting the raw sensor measurement and oven dry data, the research team calibrated the probes to the soil using a linear best fit model (although the vendor's software will support up to a 5th degree polynomial). Table 2.13 presents the raw sensor measurement and oven dry results, Figure 2.18 illustrates the results of the measured volumetric water content against the raw sensor counts, and Table 2.14 presents the calibration coefficients determined for the flexible base tested.

Table 2.13. Raw Sensor and Oven Dry Data from Pilot Tests with FDR.

Condition	Gravimetric Water Content		Mass Soil (lb)	Density (pcf)		Volumetric Water Content	Raw Sensor Output	
	Target	Actual		Wet	Dry		EC-5	EC-10
Loose	3.4	3.54	16.97	101.45	97.98	5.56	598	782
	5.4	5.10	17.28	103.28	98.27	8.03	614	871
	7.4	7.26	17.87	106.81	99.57	11.58	675	946
Compacted	3.4	3.54	25.24	150.79	145.63	8.26	718	1091
	5.4	5.10	26.44	157.97	150.30	12.28	920	1250
	7.4	7.26	25.93	154.92	144.43	16.80	933	1283



(a) EC-5 Calibration for loose sample (b) EC-5 Calibration for compacted sample



(a) 10HS Calibration for loose sample (b) 10HS Calibration for compacted sample

Figure 2.18. Volumetric Water Content versus Raw Sensor Data from Pilot Tests with FDR.

Table 2.14. Calibration Constants from Pilot Tests with FDR.

Condition	Sensor	Calibration Coefficients		R^2
		a	*b*	
Loose	EC-5	−37.0	0.0722	0.95
	10HS	−23.2	0.0365	0.98
Compact	EC-5	−14.1	0.0310	0.76
	10HS	−34.0	0.0385	0.85

The results from the FDR probe illustrate a better data fit exists with the material in the loose condition. The research team believes this occurs because the density of the compacted material is more variable than the loose state. For example, in Table 2.13 the compacted material dry density spanned 6 pcf from lowest to highest, while the loose material dry density only spanned about 1.6 pcf. Since the FDR measurement is based on volumetric air and water contents, the higher density variation in the compacted samples resulted in a poorer fit of the calibration. For purposes of any further testing, calibration of the probe at density states similar to those expected in the field is critical.

RESULTS FROM TESTING LIME-TREATED SOIL

In addition to a low PI soil and flexible base, the research team desired to perform pilot tests with a higher plasticity soil. Since plastic soils present workability problems for small-scale lab tests, based on feedback from the TxDOT project monitoring committee, the research team instead performed a laboratory test sequence on lime-treated soil. Table 2.15 presents the Atterberg limits of the soil. The Tex-113-E result on the LTS produced a maximum dry density of 100.0 pcf at 18.6 percent water.

Table 2.15. Atterberg Limits of Untreated and Treated High Plasticity Soil for Pilot Tests.

Soil	Liquid Limit	Plastic Limit	Plasticity Index
Untreated	47	16	31
Treated	39	30	9

To perform the pilot tests with the LTS, researchers first collected samples of the field-mixed material. Figure 2.19 illustrates the soil's appearance as sampled from the field. Next, researchers selected representative subsamples and added approximately 2 and 4 percent water above the field moisture state, resulting in samples of LTS at water contents representative of "as sampled" field moisture content, and 2 and 4 percent above the "as sampled" water content.

Figure 2.19. Representative LTS for Pilot Tests.

Pilot Results from DOT 600 with Lime Treated Soil

Table 2.16 and Figure 2.20 present the results from the DOT 600 with the LTS. As with prior tests, the DOT600 tested the passing No. 4 fraction, and then that fraction was oven dried for a reference value measurement. The results show a good relationship between the DOT600 results with the LTS and the oven dry results. The results also show the DOT600 results were biased. In the regression equation shown in Figure 2.20, the slope is significantly different from 1.0, and the intercept is significantly different from zero. Although this bias exists, the results still indicate that with proper calibration the device should be suitable for use with the LTS.

Table 2.16. Results from DOT600 with LTS.

Moisture State	Sample	Measured Moisture Content–Passing No. 4			Oven-Dry Water Content	
		DOT 600	Oven Dry	Error	Full Gradation	Passing No. 4
As Sampled	1	20.8	26.6	−5.8	26.5	27.7
	2	21.8	26.3	−4.5		
	3	21.6	27.1	−5.5		
+2%	1	28.0	30.5	−2.5	29.6	31.1
	2	29.6	30.9	−1.3		
	3	27.7	31.1	−3.4		
+4%	1	32.0	36.1	−4.1	33.2	36.8
	2	32.7	36.2	−3.5		
	3	34.7	37.0	−2.3		

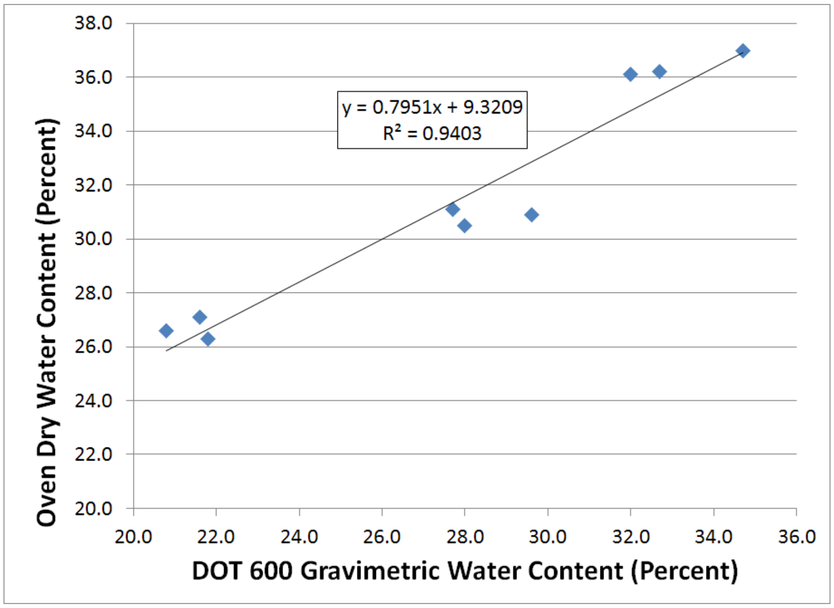


Figure 2.20. Results from DOT 600 with LTS.

Pilot Results from Moisture Analyzer with Lime Treated Soil

Table 2.17 presents and Figure 2.21 illustrates the results from the moisture analyzer with the LTS. The moisture analyzer generated results with the 50-gram sample sizes in about 30 minutes, and the results show an excellent relationship between the moisture analyzer and over dry results. The moisture analyzer results with the LTS were not biased. The slope of the regression equation in Figure 2.21 does not significantly differ from 1.0, and the intercept in the equation in Figure 2.21 does not significantly differ from zero.

Table 2.17. Results from Moisture Analyzer with LTS.

Moisture State	Sample	Moisture Content – Passing No. 4				Oven-Dry Water Content	
		Moisture Analyzer	Test Time (min.)	Oven	Error	Full Gradation	Passing No. 4
As Sampled	1	29.0	29.5	28.2	0.8	26.5	27.7
	2	29.0	29.0	28.8	0.2		
	3	29.0	30.0	28.4	0.6		
+2%	1	32.8	31.5	31.9	0.9	29.6	31.1
	2	32.4	31.0	31.6	0.8		
	3	32.8	31.5	30.1	2.7		
+4%	1	37.6	28.5	37.1	0.5	33.2	36.8
	2	37.6	29.5	36.9	0.7		
	3	37.5	35.5	36.5	1.0		

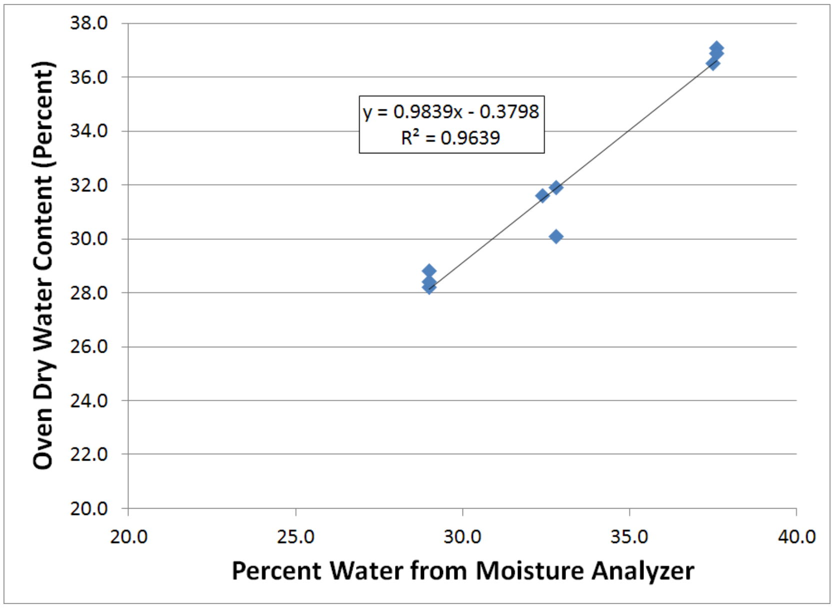


Figure 2.21. Results from Moisture Analyzer with LTS.

Pilot Results from Direct Heat with Lime Treated Soil

Table 2.18 presents and Figure 2.22 illustrates the results from the direct heat test with the LTS. The results show the test required a long time to complete (between 1 and 2 hours), and the results from the direct heat were biased. Despite the apparent bias of the direct heat measuring low, the regression equation in Figure 2.22 does not have an intercept that significantly differs from zero. The research team believes more replicate samples would enable statistical detection of bias.

Table 2.18. Results from Direct Heat with LTS.

Sample	Passing No. 4 Results				Oven-Dry Water Content (%)	
	Direct Heat		Oven-Dry Water Content	Error	Full Gradation	Passing No. 4
	Water content	Test time (min.)				
As sampled	26	75	28.2	−2.2	26.5	27.7
2%	28.6	115	31.7	−3.1	29.6	31.1
4%	34.4	120	37	−2.6	33.2	36.8

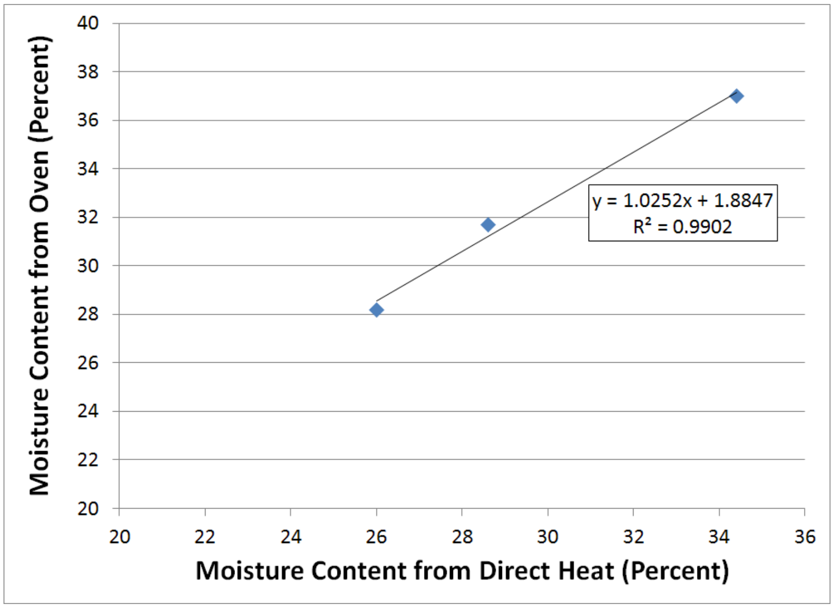


Figure 2.22. Results from Direct Heat with LTS.

To conclude the pilot testing with the LTS, the research team measured the drying curve presented in Figure 2.23 to investigate the time required to reach a stable reading with conventional oven drying. Unlike the data from flexible bases in Figures 2.10 through 2.15 (which showed relatively rapid drying times typically between 60 and 150 minutes), the LTS data in Figure 2.23 shows the LTS required over 12 hours before the reading began to stabilize. These results illustrate that the ability to accelerate traditional oven drying is material-specific.

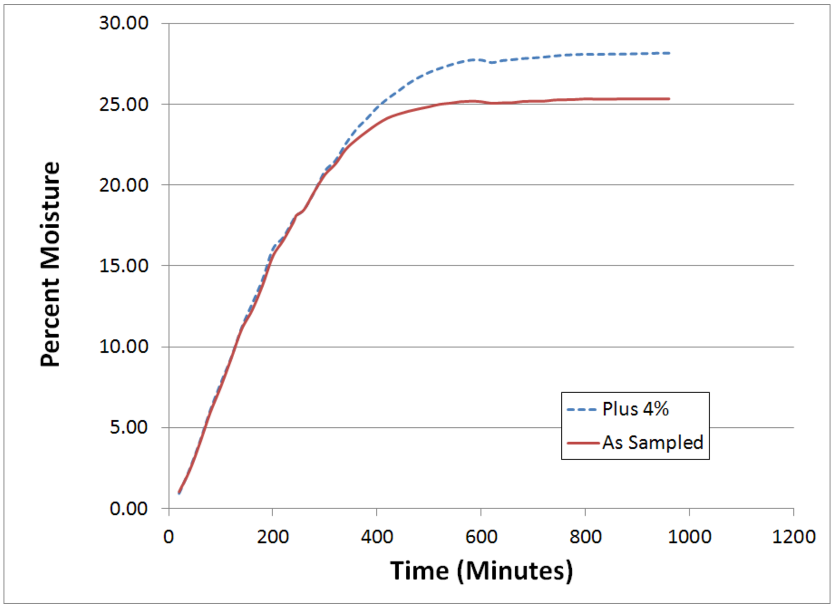


Figure 2.23. Drying Curve for LTS with Oven Drying.

CONCLUSIONS AND RECOMMENDATIONS FROM PILOT TESTING

Based on the pilot tests:

- The DOT600 exhibits promise for rapidly testing low plasticity soils, flexible bases, and lime-treated plastic soils. Testing should be conducted on the passing No. 4 fraction and the sample chamber pressure standardized at 30 ±1 psi. Although calibration to the material likely will be required, the test turnaround time is typically less than 5 minutes. Appendix A presents a draft test procedure for using the DOT 600.
- The moisture analyzer exhibits promise for rapidly testing low plasticity soils, flexible bases, and lime-treated plastic soils. Testing should be conducted on the passing No. 4 fraction and the sample size standardized at 50 ±1 g. Appendix B presents a draft test procedure for using the moisture analyzer. The last round of pilot experiments with the moisture analyzer suggests that, for testing particle sizes passing the No. 4 sieve, the test is unbiased. The pilot data suggest the test turnaround time will range between about 20 and 40 minutes.
- The direct heat method is already an approved test, and results appeared promising for all materials tested. The direct heat test result can be accelerated by testing only the passing No. 4 fraction; however, that approach requires subsequent adjustment of the result for the moisture content of the entire particle size distribution. Using the direct heat method on low plasticity soils and flexible bases typically required about 30 to 60 minutes, while testing the LTS required as much as 2 hours. The direct heat test should be performed in accordance with ASTM D 4959.
- The microwave oven test is already an approved test and provided good results for the flexible base tested. The microwave oven produced a rapid turnaround time of about

10 minutes even when testing a sample representing the full gradation of flexible base. The microwave test should be conducted in accordance with ASTM D 4643. Despite its fast turnaround time and ability to rapidly measure samples containing coarse aggregate, known interferences exist with the microwave test, making it unsuitable for some materials.

- The FDR procedure shows reasonable promise; however, the sensitivity to material density could be an issue. It requires calibration to each material and should be conducted on material at densities representative of those expected in the field. The FDR procedure should be conducted by following the guidelines of ASTM D 6565, except the manufacturer’s provided calibration module should be used.
- With some materials, the stability of mass during oven drying occurs within 150–200 minutes, which is much shorter than routine practice (typically at least 16 hours). Consideration should be given to allowing shorter drying times in the test procedure, provided a stable reading is reached.

CHAPTER 3
EVALUATIONS OF MOISTURE MEASUREMENT DEVICES WITH CONSTRUCTION PROJECT FLEXIBLE BASE MATERIAL

OVERVIEW

With pilot testing complete in the laboratory and procedures developed as appropriate for the new devices, the research team initiated a phase of controlled evaluations on a flexible base material. These evaluations used the FDR, SDG, EDG, and DOT 600 dielectric-based devices, the direct heat, microwave, and moisture analyzer gravimetric-based devices, the nuclear method for comparison, and the oven-dry method for reference values. The primary efforts focused on testing using the flexible base material presented in Table 2.11. Testing this material included:

- Perform calibrations of the devices to the material as required. The material used was the flexible base presented in Table 2.11. When possible, these calibrations were performed in the laboratory. However, the FDR, SDG, and EDG were calibrated using a large scale 3 ft × 3 ft × 8 inches deep sample compacted in two lifts.
- Perform validation tests with all devices again using 3 ft × 3 ft × 8 inches test boxes.
- Visit a construction project using the flexible base presented in Table 2.11 and collect multiple measurements with each device at dry and wet locations, and then use these results to evaluate bias of each device.

RESULTS FROM FLEXIBLE BASE TESTS

Calibration Tests

The SDG and EDG cannot be conveniently calibrated to a material in the lab. To perform these calibrations, the research team prepared flexible base at moisture contents of approximately 6, 8, and 10 percent in 3 ft × 3 ft × 8 inches test boxes. The team placed and manually tamped one half of the material and then inserted FDR probes as Figure 3.1 illustrates. Next, the team placed the remainder of the material and manually tamped the surface smooth. After collecting FDR, SDG, EDG, and nuclear data on the material, the team collected a physical sample to split for oven drying. Next, the team reworked the material and mechanically tamped the base as illustrated in Figure 3.2. After mechanical compaction, the research team smoothed the surface and again performed the sequence of non-destructive tests followed by physical sampling for reference oven-dry determination. In this manner, data was collected with each device at two different states of compaction and three different moisture contents. Figure 3.3 illustrates the final smoothing and testing sequence of SDG, EDG, and nuclear gauge. Figure 3.4 shows the research team collecting physical samples for the remaining tests.

Figure 3.1. Placing Test Box Material in Lifts and Inserting FDR Probes.

Figure 3.2. Mechanical Compaction of Test Box.

Figure 3.3. Smoothing and Testing with SDG, EDG, and Nuclear Gauge on Test Box.

Figure 3.4. Collecting Sample from Test Box.

Table 3.1 presents the results from the calibration tests for the SDG (with nuclear gauge readings presented for comparison). The EDG does not display any results during collection of calibration data. As outlined in the SDG instructions from the manufacturer, on average the SDG readings for wet density were 4.3 pcf low, and on average the SDG readings for moisture were 2.3 percent high. These values provide the offsets for later use in the gauge when testing this material. Figure 3.5 illustrates that, even though the average error for the SDG was determined, the measurements did not change linearly with the true values. Figure 3.5 also illustrates that the nuclear data correlates linearly with the oven dry values; however, the slope is significantly different from 1. These results illustrate the somewhat sporadic nature of results from test devices, even those with a long history of use with accepted methods.

Table 3.1. Calibration Test Results with Flex Base Test Boxes.

Target MC (%)	State of Compaction	SDG Result				Nuke Result					Oven Dry (%)
		Temp (F)	%M	WD (pcf)	DD (pcf)	%M	WD (pcf)	DD (pcf)	M Count	Corrected DD (pcf)*	
6	Loose	84	8.1	115.3	106.7	4.6	115.3	110.2	5.1	108.9	5.9
	Compacted	82	9.7	127.9	116.5	5.9	133.8	126.3	7.5	125.8	6.4
8	Loose	93	10.2	132.6	120.3	7.5	126.4	117.6	8.8	117.8	7.3
	Compacted	96	10.2	135.9	123.4	8.4	145.0	133.8	11.2	134.1	8.1
	Compacted-Cured	77	10.2	131.0	118.9	8.4	140.7	129.8	10.9	131.4	7.1
10	Loose	93	10.0	137.8	125.2	10.4	141.8	128.5	13.4	129.3	9.7
	Compacted	N/A - Gauge error suspected				9.6	144.2	131.5	12.7	132.5	8.8
	Compacted-Cured	77	10.9	138.6	125.0	9.2	146.2	133.9	12.3	134.9	8.4

*Based on nuclear WD and oven dry percent water

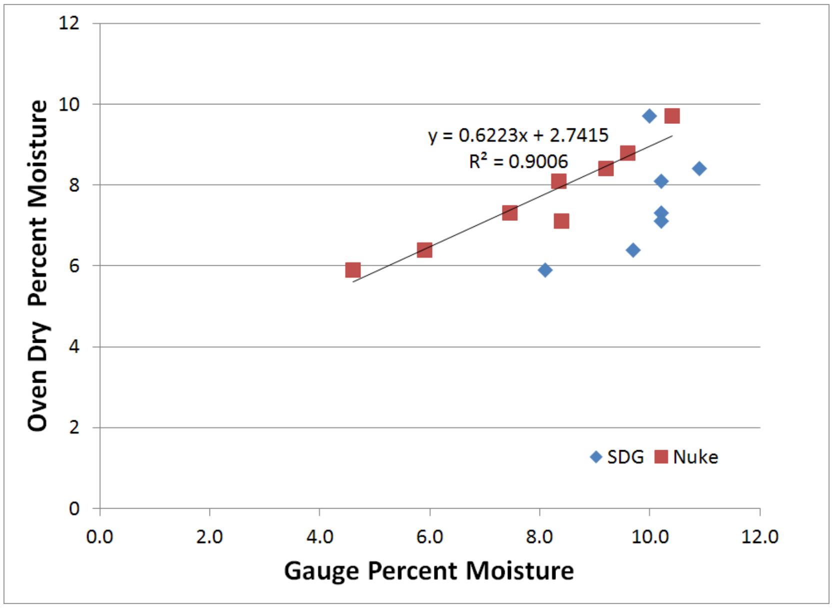


Figure 3.5. Illustrated SDG and Nuclear Results from Flex Base Test Boxes.

To calibrate the EDG, the corrected dry density readings and oven dry percent moisture from Table 3.1 were input into the EDG soil model module after the fact per the manufacturer's instructions. The photograph in Figure 3.6 illustrates the results, which show a density model with $R^2 = 0.73$ and a moisture model with an $R^2 = 0.83$.

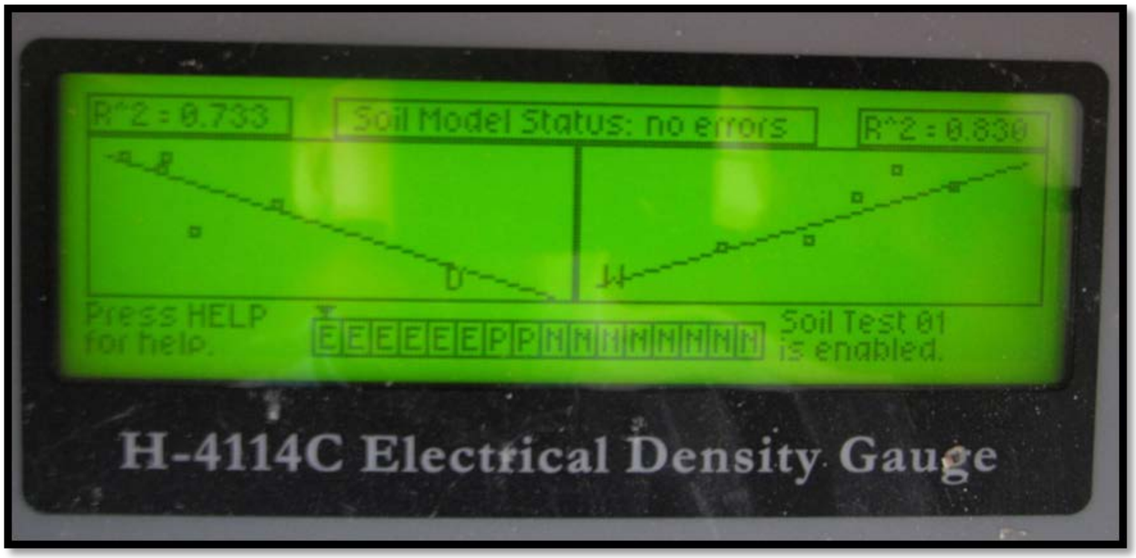


Figure 3.6. EDG Soil Model Status from Flex Base Test Boxes.

With the SDG offsets and EDG soil model developed, the research team turned its attention to the FDR calibration. Figures 3.7 and 3.8 present the calibrations for the loose and compacted material, respectively. The calibrations show an excellent fit.

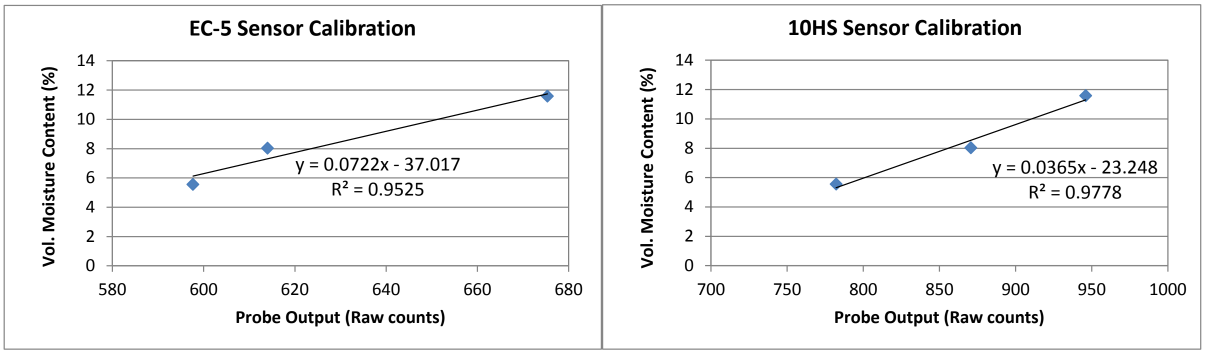


Figure 3.7. Calibration of FDR Probes with Flex Base Test Boxes at Low Density.

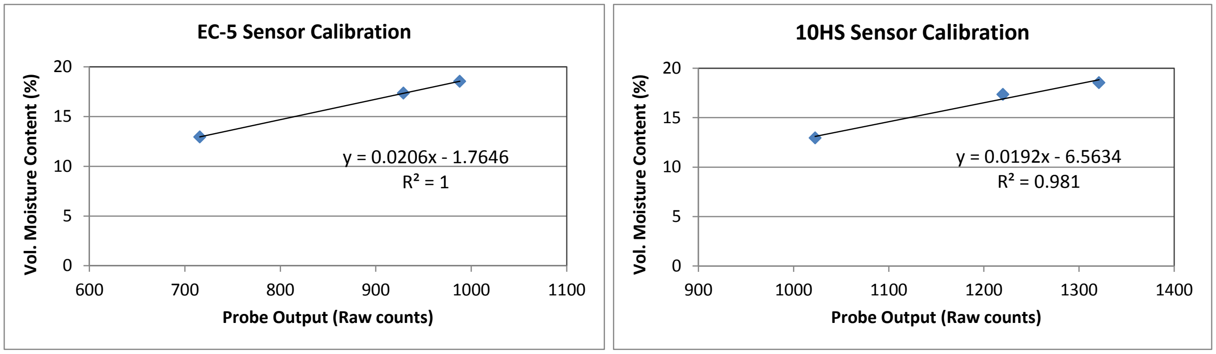


Figure 3.8. Calibration of FDR Probes with Flex Base Test Boxes at High Density.

Verification Tests

With the calibrations for the SDG, EDG, and FDR performed using the flexible base, the research team undertook verification tests. The sequence used produced test results with the material at two different density states and three moisture contents as outlined before, and the material preparation, testing, and sampling process followed those illustrated in Figures 3.1–3.4. The main difference was, for the verification tests, the team collected a larger physical sample to split into representative portions for conducting DOT 600, moisture analyzer, microwave, direct heat, and oven dry tests.

Results from SDG, EDG, and Nuclear Gauge

Table 3.2 presents the results from the SDG, EDG, and nuclear gauge, with oven dry values for reference. Figure 3.9 illustrates the correlation between the SDG, EDG, and nuclear gauge with the true oven dry values. Table 3.3 summarizes a statistical evaluation of the relationships observed. For estimating accuracy, Table 3.3 presents the error and error statistics for each device. For evaluating bias, the procedures in ASTM D 4855 were employed, which evaluate whether the mean test result at each level statistically equals the oven dry value or not. All devices exhibited bias at almost every level of material. The accuracy (assuming the devices were unbiased) can be evaluated using analysis of variance on the error terms and comparing the *F*-ratio (determined by dividing the largest variance by the smallest) to the *F*-critical value of 5.79. The results show that, if each device were unbiased, no device would provide superior accuracy in comparison with the other devices.

Table 3.2. SDG, EDG, and Nuclear Gauge Results from Flex Base Verification Test Boxes.

Target MC (%)	State of Compaction	SDG Result					EDG Result					Nuke Result							Oven Dry %
		WD (pcf)	DD (pcf)	%M	AVG DD (pcf)	AVG %M	WD (pcf)	DD (pcf)	%M	AVG DD (pcf)	AVG %M	WD (pcf)	DD (pcf)	%M	AVG DD (pcf)	Corrected DD (pcf)*	AVG %M		
6	Loose	124.6	117.1	6.4	117.0	6.4	121.9	114.8	6.2	115.3	6.1	120.9	114.9	5.5	115.1	115.1	5.5		5.4
		123.9	116.6	6.3			122.5	115.4	6.1			121.4	115.3	5.6					
		124.7	117.2	6.4			122.8	115.7	6.1			121.4	115.1	5.5					
	Compacted	117.2	111.3	5.3	110.6	5.2	131.9	123.6	6.7	124.0	6.7	136.7	129.5	5.6	129.7	130.0	5.4		5.2
		115.4	109.9	5.0			132.4	124.1	6.7			136.9	130.0	5.2					
		116.3	110.6	5.2			132.5	124.2	6.7			136.8	129.7	5.5					
8	Loose	143.9	132.4	8.7	131.1	8.6	143.2	133.5	7.3	134.1	7.4	136.9	126.6	8.2	127.1	128.0	8.1		7.3
		141.8	130.6	8.6			144.4	134.4	7.5			137.1	126.6	8.3					
		141.5	130.4	8.5			144.6	134.5	7.5			138.1	128.0	7.9					
	Compacted	143.3	132.1	8.5	132.6	8.5	145.5	134.9	7.9	135.1	7.9	144.5	134.0	7.8	133.8	134.7	8.0		7.4
		143.7	132.6	8.4			145.8	135.1	7.9			144.8	134.0	8					
		144.6	133.3	8.5			146	135.3	7.9			144.4	133.4	8.3					
10	Loose	143.4	133.1	7.7	131.6	7.4	146.6	134.1	9.3	134.5	9.3	141.5	128.0	10.5	128.2	130.9	10.6		8.3
		139.9	130.5	7.2			147.2	134.6	9.3			141.8	128.0	10.8					
		140.6	131.0	7.3			147.5	134.8	9.4			141.9	128.6	10.4					
	Compacted	Not available; gauge or test error (gauge bottom may have touched material)					147.7	135.3	9.2	135.7	9.3	144.4	130.4	10.7	130.4	132.2	10.8		9.4
							148.5	135.9	9.3			144.5	130.3	10.9					
							148.7	136	9.4			144.8	130.6	10.8					

*Based on Nuke WD and Oven Dry Percent Moisture

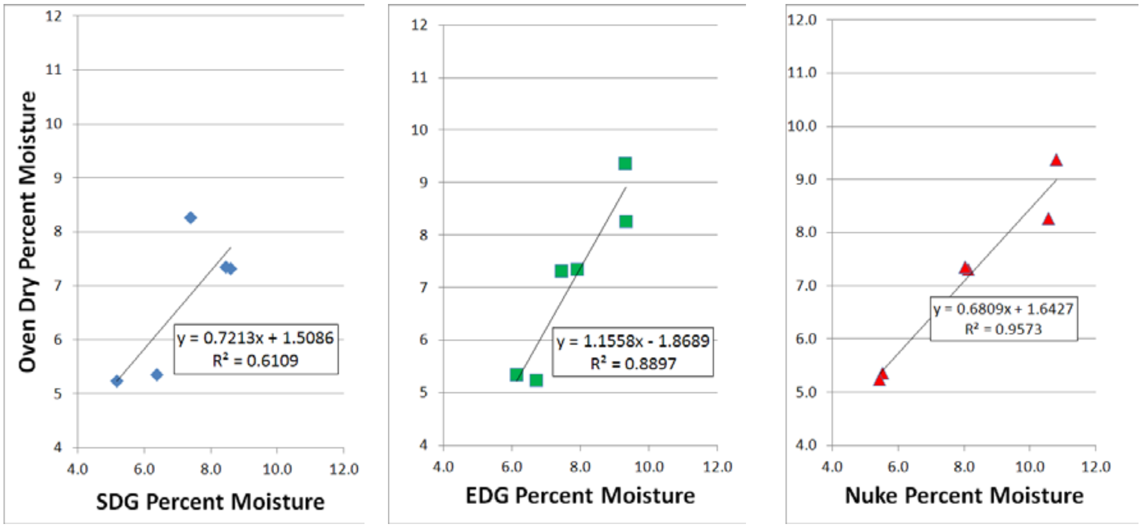


Figure 3.9. Oven Dry Moisture Content versus SDG, EDG, and Nuclear Results for Flex Base Verification Test Boxes.

Table 3.3. Accuracy and Bias Results for SDG, EDG, and Nuclear Gauges from Flex Base Verification Test Boxes.

Target Moisture (%)	**State of Compaction**	**SDG**		**EDG**		**Nuclear**	
		Error	**Biased***	**Error**	**Biased***	**Error**	**Biased***
6	loose	1.0	**0.00**	0.8	**0.00**	0.2	**0.03**
	compacted	-0.1	0.49	1.5	**0.00**	0.2	0.25
8	loose	1.3	**0.00**	0.1	0.21	0.8	**0.02**
	compacted	1.1	**0.00**	0.6	**0.00**	0.7	**0.04**
10	loose	-0.9	**0.03**	1.1	**0.00**	2.3	**0.00**
	compacted	**		-0.1	0.35	1.4	**0.00**
Error Statistics	**AVG**	0.5		0.7		0.9	
	St. Dev.	0.93		0.58		0.81	
	T-stat	1.20		2.78		2.82	
	Prot(t)	0.30		0.04		0.04	

*presents prob(t) testing whether the mean test value equals the reference oven dry value or not. Values less than 0.05 in bold indicate the mean test value differs from the oven dry value with 95 percent confidence, indicating bias existed at that level of material.

**N/A - guage error

Since the devices all exhibited bias, researchers used procedures in ASTM D 4855 to investigate whether the bias at the lowest level of material differed from the bias at the highest level of material. This procedure essentially is testing whether the difference between the bias at the low and high level is zero or not. The tabulated p-values for the differences of the bias between the low and high moisture contents are:

- SDG: p-value = 0.03; conclude Ha: the amount of bias varies by material level.
- EDG: p-value = 0.09; conclude Ho: the amount of bias does not vary by material level.
- Nuclear: p-value = 0.00; conclude Ha: the amount of bias varies by material level.

These results show the EDG to be the only device in the verification tests where the bias did not vary by material level. The implication from these results is that a slope problem exists with the SDG and nuclear gauge, i.e., simply an offset will not eliminate the bias.

Another important property obtained for each device from the test box verification experiment was an estimate of the single operator standard deviation for each device. Table 3.4 presents the pooled standard deviation for each device using the three measurements collected with each device at each moisture content/density state.. While the results suggest the single operator standard deviation from the EDG may be superior to the other devices, no statistically significant differences in variance were found using Hartley's test. From a practical perspective, all of the standard deviations are low; the research team believes the single operator precision for each of the devices is more than acceptable. In fact, the good repeatability of the devices plays a large part in the reason their results were determined to be biased, even though the absolute magnitude of the errors were low in many cases.

Table 3.4. Estimated Single Operator Variability of Moisture Content for SDG, EDG, and Nuclear Gauge.

Device	Pooled Variance	Pooled Standard Deviation
SDG	0.022	0.15
EDG	0.0050	0.071
Nuclear	0.034	0.18

Results from FDR

Using the FDR calibrations previously determined in Figures 3.7 and 3.8 for uncompacted and compacted material, respectively, the researchers measured the moisture content using the FDR systems. The research team used the corrected dry density readings in Table 3.2 to convert the FDR-generated volumetric readings into gravimetric readings. Table 3.5 presents the results, while Figure 3.10 illustrates the results. The FDR results exhibit a poorer fit and poorer standard error when contrasted with the SDG, EDG, and nuclear gauge results in Figure 3.9.

Table 3.5 FDR Results from Flex Base Verification Test Boxes.

Target MC (%)	State of Compaction	EC-5 Results				EC-10HS Results				Oven Dry %
		Probe Output	Volumetric MC (%)	Gravimetric MC (%)	AVG Gravimetric (%)	Probe Output	Volumetric MC (%)	Gravimetric MC (%)	AVG Gravimetric (%)	
6	Loose	673	12.3	6.7	6.7	983	12.4	6.7	6.7	5.4
		673	12.3	6.7		983	12.4	6.7		
		673	12.3	6.7		983	12.4	6.7		
	Compacted	773	14.2	6.8	6.8	1084	14.2	6.8	6.8	5.2
		773	14.2	6.8		1086	14.3	6.9		
		776	14.2	6.8		1082	14.2	6.8		
8	Loose	687	12.7	6.2	6.2	1011	13.0	6.4	6.3	7.3
		688	12.7	6.2		1014	13.1	6.4		
		688	12.7	6.2		1000	12.8	6.2		
	Compacted	777	14.2	6.6	6.6	1240	17.2	8.0	8.0	7.4
		777	14.2	6.6		1240	17.2	8.0		
		777	14.2	6.6		1239	17.2	8.0		
10	Loose	981	20.2	9.6	9.6	1327	20.4	9.7	9.7	8.3
		981	20.2	9.6		1327	20.4	9.7		
		980	20.2	9.6		1327	20.4	9.7		
	Compacted	988	18.6	8.8	8.8	1334	19.0	9.0	9.0	9.4
		989	18.6	8.8		1333	19.0	9.0		
		989	18.6	8.8		1334	19.0	9.0		

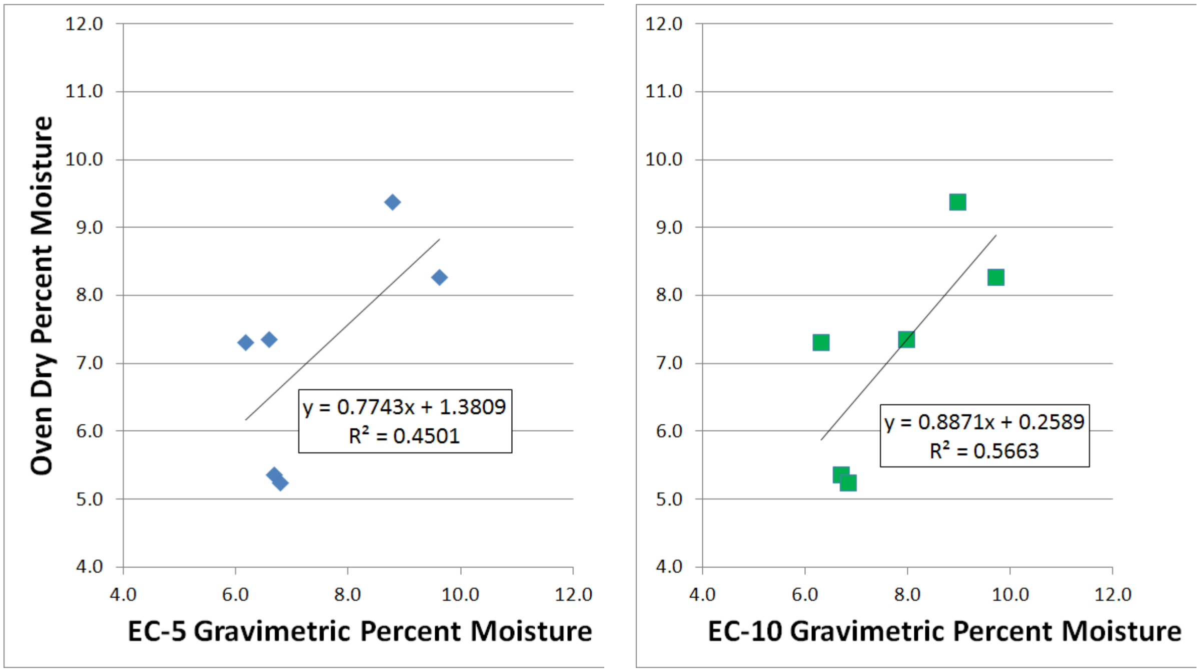


Figure 3.10. FDR Results from Flex Base Verification Test Boxes.

Table 3.6 presents a summary of the regression statistics from the FDR results. With the amount of data used to determine the regression coefficients, none of the coefficients were statistically different from zero.

Table 3.6. Summary of Relations between FDR and Oven Dry Percent Moisture from Flex Base Verification Test Boxes.

Device	Intercept*	Slope*			R^2	Standard Error
		Estimated Value	Lower 95%	Upper 95%		
EC-5	1.38	0.77	−7.59	10.35	0.45	1.34
EC-10HS	0.26	0.89	−0.19	1.96	0.57	1.19

*None of the estimated coefficients were significantly different from zero.

Table 3.7 presents the single operator indicators of test variability for the FDR probes. Since the probes are embedded in the material, the measurements were extremely precise.

Table 3.7. Estimated Single Operator Variability of Moisture Content for SDG, EDG, and Nuclear Gauge.

Device	Pooled Variance	Pooled Standard Deviation
EC5	0.000070	0.008
EC10HS	0.0012	0.04

Despite the excellent single operator repeatability, the research team's experience with the process of embedding the probes in the material, combined with the dependence of the results on knowing the density of the material under test, resulted in the team abandoning any further testing of this technology for this project. In the appropriate application (where probes are permanently or semi-permanently embedded in material), density fluctuations are of minimal concern and the technology likely works very well. However, for this project where the goal is to achieve an accurate, rapid measurement at test locations that may have a notable density variation, the research team believes the FDR technology presents too many limitations and uncertainties.

Results from DOT 600, Moisture Analyzer, Microwave, and Direct Heat

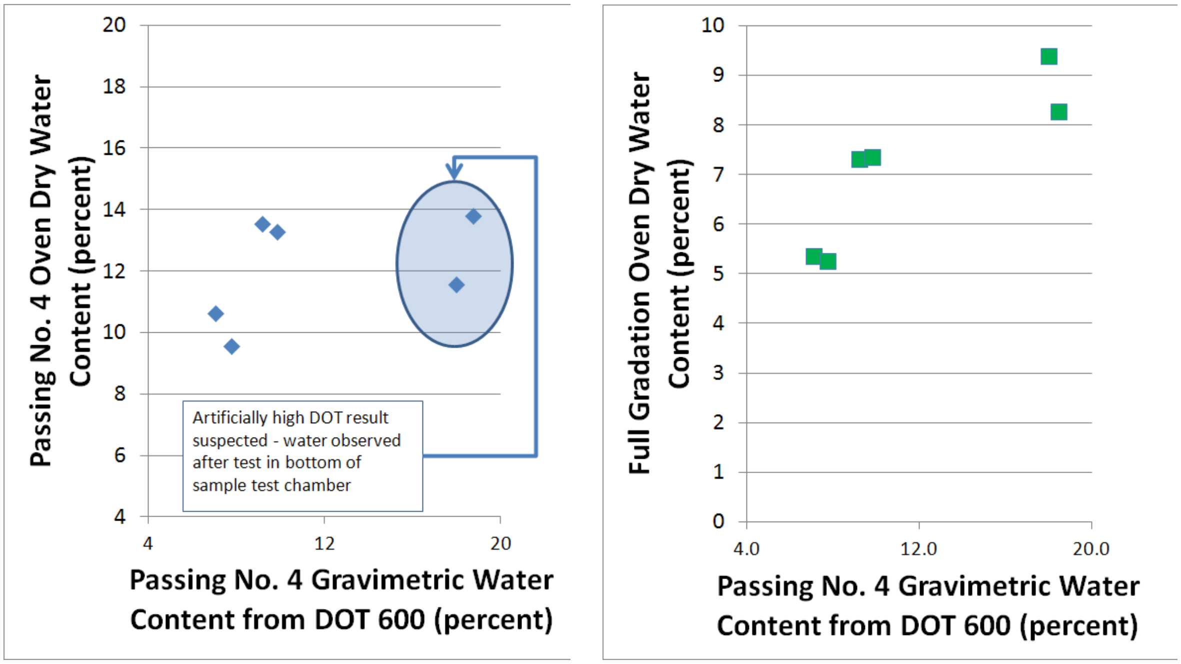
The DOT 600 and moisture analyzer procedures test only the passing No. 4 fraction, while in this phase of work the research team performed the microwave and direct heat tests on representative samples of passing No. 4 and the full material gradation. Table 3.8 presents the results.

Table 3.8. DOT 600, Moisture Analyzer, Direct Heat, and Microwave Results from Flex Base Validation Test Boxes.

Target MC (%)	State of Compaction	DOT 600			Moisture Analyzer			Direct Heat				Microwave				Oven Dry full Gradation Gravimetric (%)
		Passing No. 4 Gravimetric (%)	Oven Dry on DOT Sample (%)	DOT 600 AVG (%)	Passing No. 4 Gravimetric (%)	Test Time (minutes)	Oven dry on MA Sample (%)	Pass No. 4 (%)		Full Grad (%)		Pass No. 4 (%)		Full Grad (%)		
								Results	AVG	Results	AVG	Results	AVG	Results	AVG	
6	Loose	7.1	10.8	7.1	2.7	11.9	8.4	8	8.0	5.83	5.5	8.5	7.9	5.8	5.4	5.35
		7.0	10.4		4.2	23.9	9.0	8.13		5.14		7.74		5.2		
		7.3	10.6		5.0	30.0	7.4	8.01		5.47		7.51		5.2		
	Compacted	8.2	9.6	7.8	2.4	14.8	8.3	7.58	7.7	4.93	5.4	7.69	7.9	5.5	5.3	5.24
		8.1	9.5		3.8	28.4	8.2	8.06		5.19		7.61		4.78		
		7.1	9.5		2.8	14.8	6.0	7.57		5.96		8.42		5.51		
8	Loose	9.4	13.9	9.2	10.5	10.0	10.5	10.9	10.7	7.1	7.3	10.4	10.5	7.6	7.7	7.31
		9.6	13.6		10.6	11.0	10.7	10.6		7.1		10.3		7.7		
		8.7	13.1		10.6	9.5	10.7	10.6		7.7		10.8		7.9		
	Compacted	10.2	13.3	9.9	6.5	16.4	11.1	10.6	10.6	7.6	6.9	10.5	10.6	6.9	7.0	7.35
		9.6	12.9		6.3	19.4	11.0	10.5		6.2		10.9		6.7		
		9.8	13.6		7.7	12.1	11.5	10.6		7.0		10.5		7.3		
10	Loose	18.1	14.1	18.5	12.0	9.0	12.0	12.0	12.0	8.6	8.6	11.8	11.9	9.2	8.6	8.26
		19.2	13.8		12.2	9.0	12.2	12.1		8.7		12.1		8.4		
		18.2	13.4		12.1	10.5	12.1	11.9		8.4		11.8		8.3		
	Compacted	18.2	11.8	18.0	12.5	10.0	12.5	12.3	12.3	8.5	9.3	12.1	12.0	8.7	9.1	9.37
		18.5	11.5		12.6	10.0	12.6	12.4		9.6		11.9		9.9		
		17.4	11.4		12.2	10.0	12.2	12.3		9.7		12.1		8.6		

▨ Used old method w/lower temp and less stringent end point determination

Figure 3.11 shows the results from the DOT 600. At the lower and intermediate moisture contents, the results appear as expected. However, the results at the highest water content do not follow the expected pattern; those results show excessively high DOT 600 values and seemingly low oven dry results. During the performance of the DOT 600 tests with the highest moisture content, the research team noticed free water at the bottom of the DOT 600 test chamber at the conclusion of the test. For this reason, the team believes the water content was so high that the pressure applied to the sample in the test chamber during the DOT 600 procedure squeezed out water. This resulted in the high DOT 600 reading (since the electronics are at the bottom of the test chamber) and subsequent erroneously low oven-dry water content on the DOT 600 sample.



Artificially high DOT result suspected - water observed after test in bottom of sample test chamber

Figure 3.11. DOT 600 Results from Flex Base Verification Test Boxes.

Figure 3.12 presents the results from the moisture analyzer. Figure 3.12 only illustrates the results generated from the most current version of the procedure (using a sample size of 50 ± 1 g, a test temperature of 320°F, and an end point determination of a stable reading within 0.01 g for 30 seconds). The results illustrate an excellent fit between the moisture analyzer and oven dry results on the passing No. 4 fraction and a good fit between the moisture analyzer results and full gradation oven dry results.

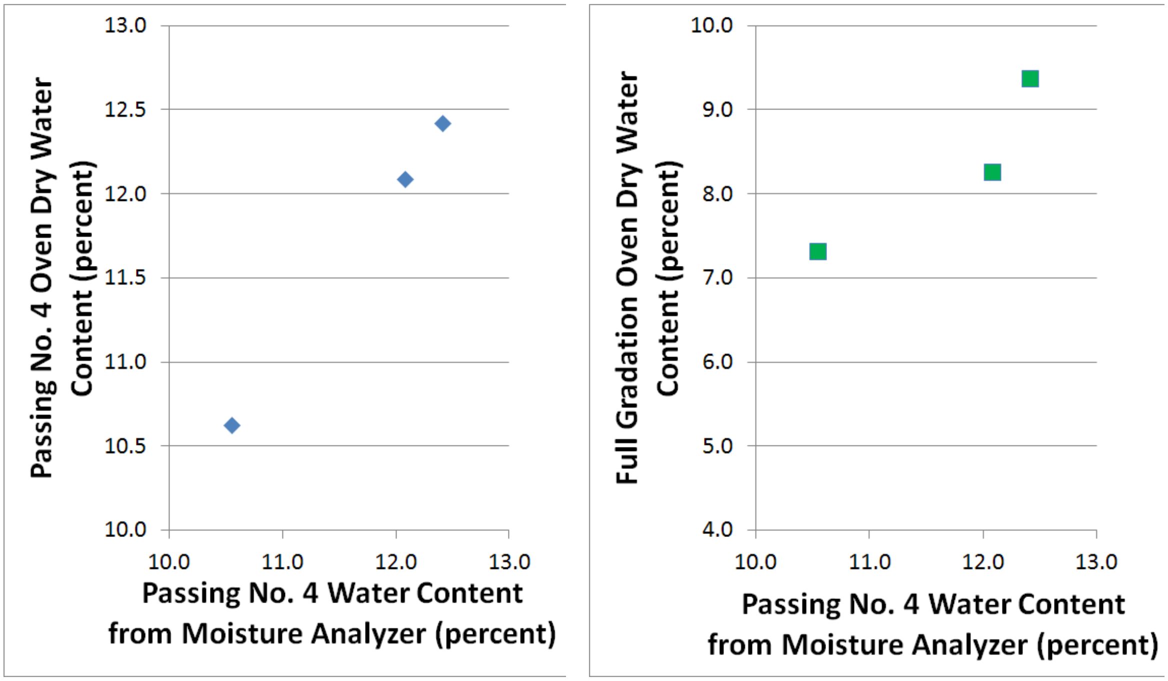


Figure 3.12. Moisture Analyzer Results from Flex Base Verification Test Boxes.

Figure 3.13 illustrates the results from the direct heat test. The direct heat test showed an excellent correlation between the test results and reference oven dry results. The direct heat results required between 20 and 35 minutes when testing the passing No. 4 and between 70 and 120 minutes when testing the full gradation.

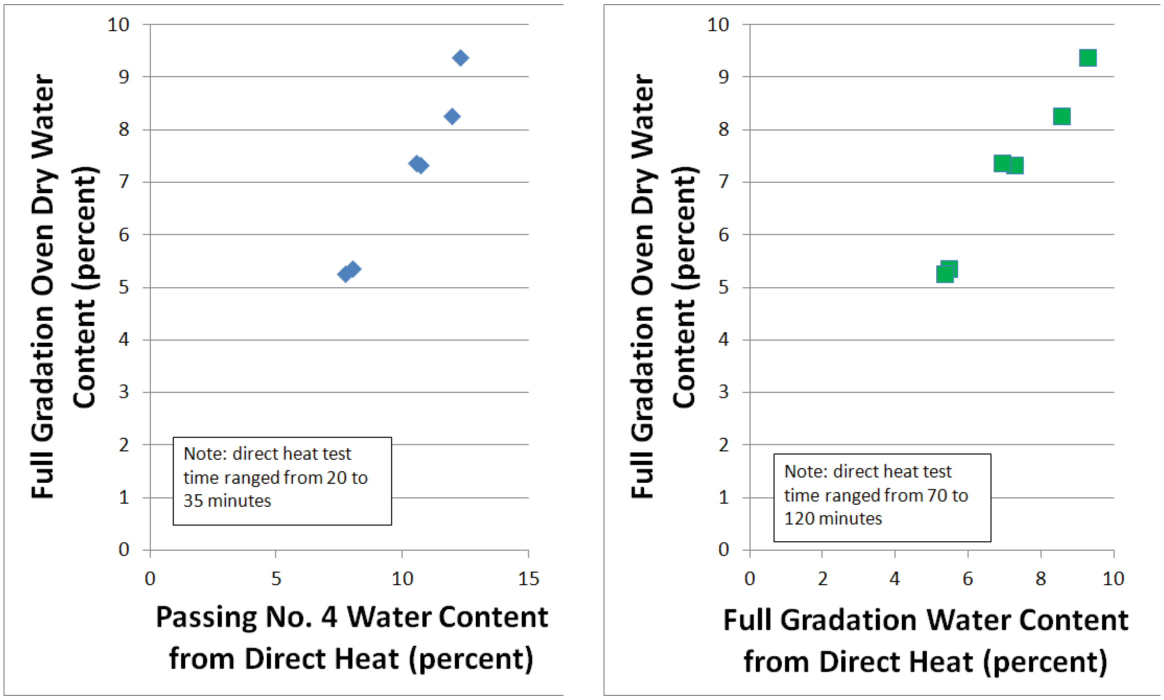


Figure 3.13. Direct Heat Results from Flex Base Verification Test Boxes.

Figure 3.14 presents the results from the microwave test. The microwave results essentially matched the results from the direct heat, and the microwave results showed an excellent correlation to the oven dry reference values. In contrast to the direct heat technique, the microwave test required less than 10 minutes to complete, regardless of which particle size distribution was tested.

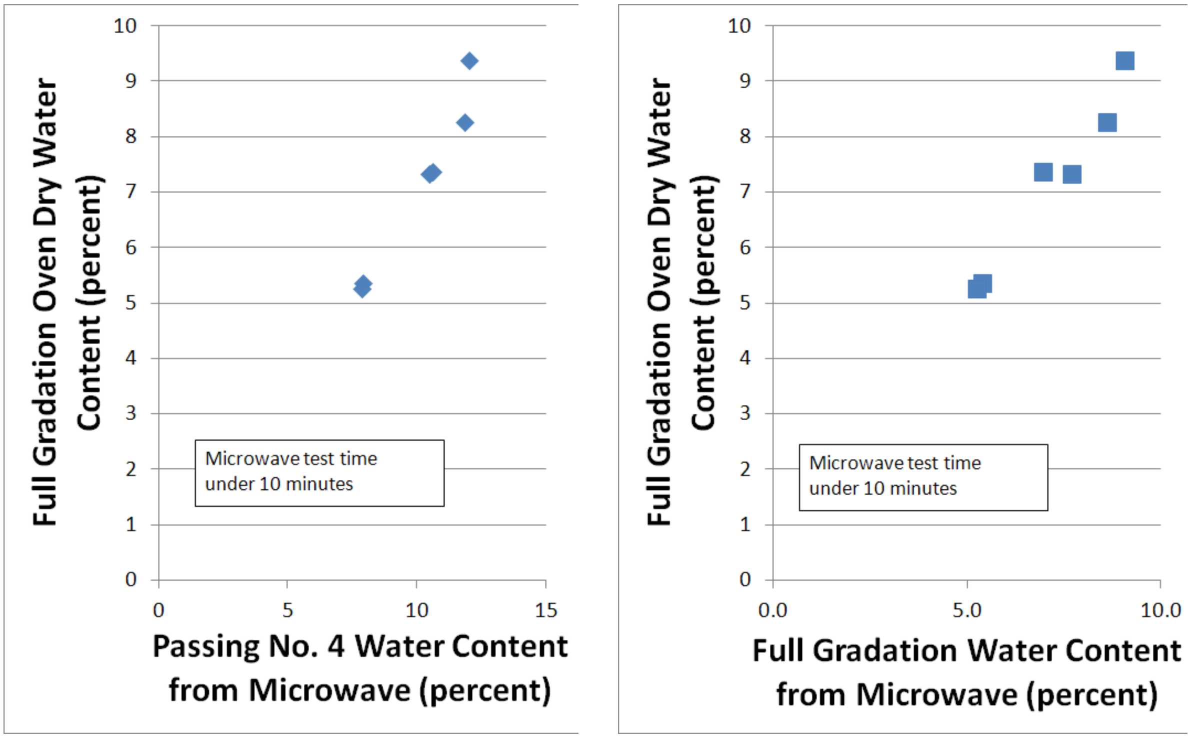


Figure 3.14. Microwave Results from Flex Base Verification Test Boxes.

Using the data in Table 3.8, the researchers evaluated each device for accuracy and bias for test sequences where appropriate oven dry reference values were available. For example, the DOT 600 and moisture analyzer cannot directly test the full gradation, so the evaluation only focused on the passing No. 4 for those devices. Table 3.9 presents the results. The data show the following:

- The DOT 600 exhibited bias at every level of material tested.
- The direct heat and microwave showed bias at one level of moisture content for material passing the No. 4 sieve.
- Overall, the bias results along with the statistical significance of the average error indicate the moisture analyzer, direct heat, and microwave tests are unbiased.
- For unbiased tests, the accuracy can be estimated by the standard deviation of the error. The devices should be accurate within ±2 standard deviations.
- Differences in accuracy among the tests can be evaluated by analysis of variance on the error terms. With the number of tests, if the *F*-ratio when dividing the larger variance by the smaller variance exceeds 5.79, a difference exists with 95 percent confidence. The data suggest (if it were unbiased) the DOT 600 with the poorest accuracy, while the moisture analyzer exhibits the best accuracy. No difference in accuracy existed among the direct heat and microwave tests.

Table 3.9. Accuracy and Bias Results from Flex Base Validation Test Boxes.

Target Moisture (%)	**State of Compaction**	**DOT 600 - Passing No. 4**		**Moisture Analyzer - Passing No. 4**		**Direct Heat**				**Microwave**			
						Passing No. 4		**Full Gradation**		**Passing No. 4**		**Full Gradation**	
		Error	Biased*	Error	Biased*	Error	Biased*	Error	Biased*	Error	Biased*	Error	Biased*
6	loose	-3.5	**0.00**	***		-0.2	0.67	0.1	0.58	-0.3	0.57	0.0	0.83
	compacted	-1.7	**0.04**	***		0.2	0.79	0.1	0.74	0.4	0.65	0.0	0.93
8	loose	-4.3	**0.00**	-0.1	0.24	0.1	0.43	0.0	0.93	-0.1	0.42	0.4	0.07
	compacted	-3.4	**0.00**	***		-0.6	**0.01**	-0.4	0.41	-0.6	**0.04**	-0.4	0.18
10	loose	**		0.0	1.00	-0.1	0.17	0.3	0.06	-0.2	0.10	0.4	0.33
	compacted	**		0.0	1.00	-0.1	0.39	-0.1	0.86	-0.4	0.04	-0.3	0.55
Error Statistics	**AVG**	-3.2		0.0		-0.1		0.0		-0.2		0.0	
	St. Dev.	1.07		0.06		0.29		0.25		0.33		0.32	
	T-stat	-6.02		-0.72		-1.04		-0.45		-1.19		0.22	
	Prob(t)	0.01		0.55		0.35		0.67		0.29		0.83	

*presents prob(t) testing whether the mean test value equals the reference oven dry value or not.
Values less than 0.05 in bold indicate the mean test value differs from the oven dry value with
95 percent confidence, indicating bias existed at that level of material.
**N/A - DOT 600 measurement error suspected due to free water in sample chamber
***N/A - used old test method

In addition to evaluating each device for accuracy and bias, the data in Table 3.8 also allows for estimating the single operator variability for the test methods. Table 3.10 presents this information. The data show each method exhibits very good precision. The variance among tests can be evaluated using Hartley's test, where (with the number of data points collected), a tabulated *F* value exceeding 9.0 indicates a significant difference in variance with 90 percent confidence.

Table 3.10. Estimated Single Operator Variability of Moisture Content for DOT 600, Moisture Analyzer, Direct Heat, and Microwave.

Device	Pooled Variance	Pooled Standard Deviation
DOT-600	0.23	0.48
Moisture Analyzer	0.015	0.12
Direct Heat – Passing No. 4	0.022	0.15
Direct Heat – Full Gradation	0.25	0.50
Microwave – Passing No. 4	0.10	0.32
Microwave – Full Gradation	0.19	0.44

Since the moisture analyzer test procedure was changed during the course of the verification test box testing, the research team proceeded to conduct another series of tests with this flexible base material using the moisture analyzer test with the hotter temperature and stringent end point determination. The team prepared flexible base material again targeting 6, 8, and 10 percent moisture, and then conducted the moisture analyzer test on the passing No. 4 fraction using the current recommended test temperature of 320°F and the end point determination of a stable reading within 0.01 g for 30 seconds. A representative split of the prepared sample with the full gradation was also oven dried. Figure 3.15 presents the results, which show an excellent fit between the moisture analyzer and the true values, and a good fit between the moisture analyzer result on the passing No. 4 and the oven dry result on the full gradation.

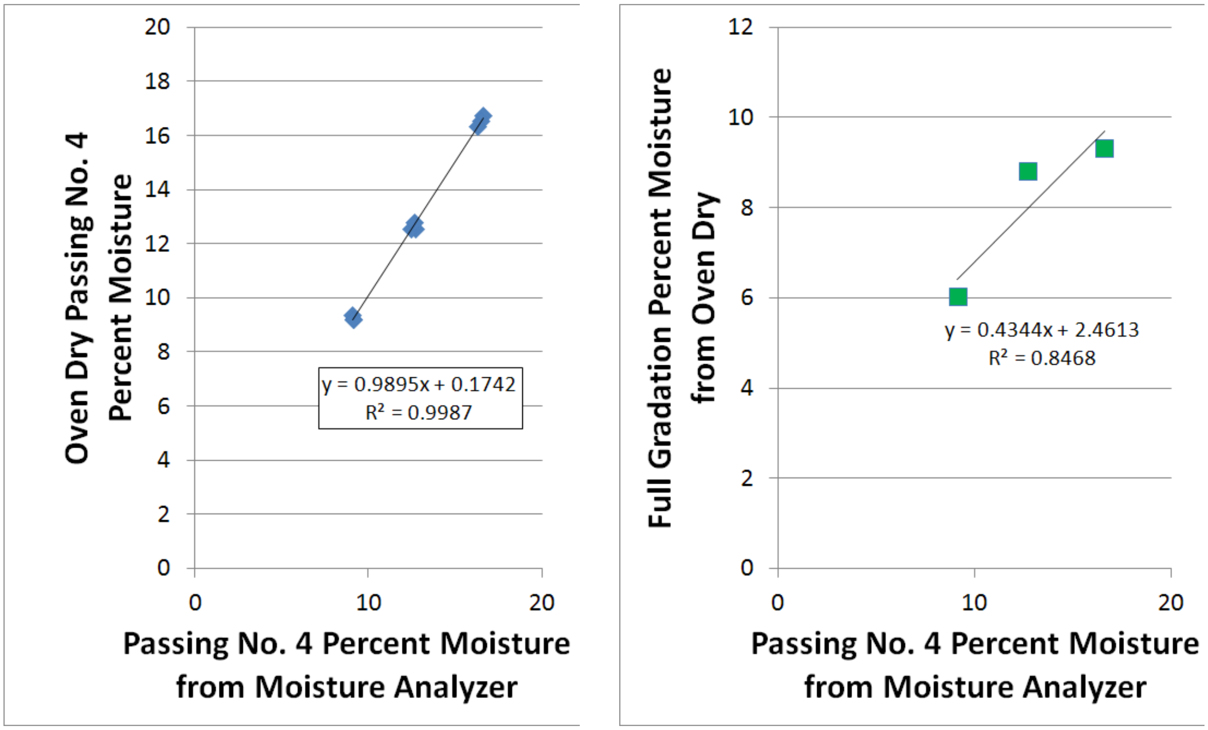


Figure 3.15. Repeat Moisture Analyzer Test Results for Material from Flexible Base Verification Test Boxes.

Correcting Passing No. 4 Moisture Content to Full Gradation Based on Verification Test Boxes

An issue with each of the devices that only test the passing No. 4 fraction is relating that moisture content to the full gradation. Based on the absorption of the plus No. 4 fraction, the material gradation, and the determined moisture content on the passing No. 4 fraction, the gravimetric water content on the full gradation can be expressed as equation 3.1:

$$M_{full} = (P_{-4})(M_{-4})/100 + (P_{+4})(A_{+4})/100 \qquad (3.1)$$

Where
M_{full} = the percent moisture content on the full gradation.
P_{-4} = the percent passing the No. 4 sieve by mass.
M_{-4} = the gravimetric percent moisture on the passing No. 4 fraction.
P_{+4} = the cumulative percent retained on the No. 4 sieve by mass.
A_{+4} = the absorption on the size fraction retained on the No. 4 sieve.

For this particular flexible base, Table 2.11 showed the percent passing the No. 4 was 36, and the percent retained on the No. 4 was 64. Researchers performed three absorption tests on the retained on the No. 4 fraction and determined the average absorption value to be 3.64 percent.

With these known values, for this particular flexible base, equation 3.2 would correct the passing No. 4 water content to the full gradation:

$$M_{full} = (0.36)(M_{-4}) + 2.33 \tag{3.2}$$

Reviewing the graphs in Figure 3.15 shows the actual test data seems to reasonably agree with this theoretical approach. However, since the moisture analyzer, direct heat, and microwave tests were all determined unbiased when testing the passing No. 4 fraction, Figure 3.16 presents all the test data from those devices showing the moisture content on the full gradation versus the test results on the passing No. 4 fraction. With many measurements spanning the region of interest for this material (optimum ± 2 percent), the empirical data do not match well with the theoretical approach.

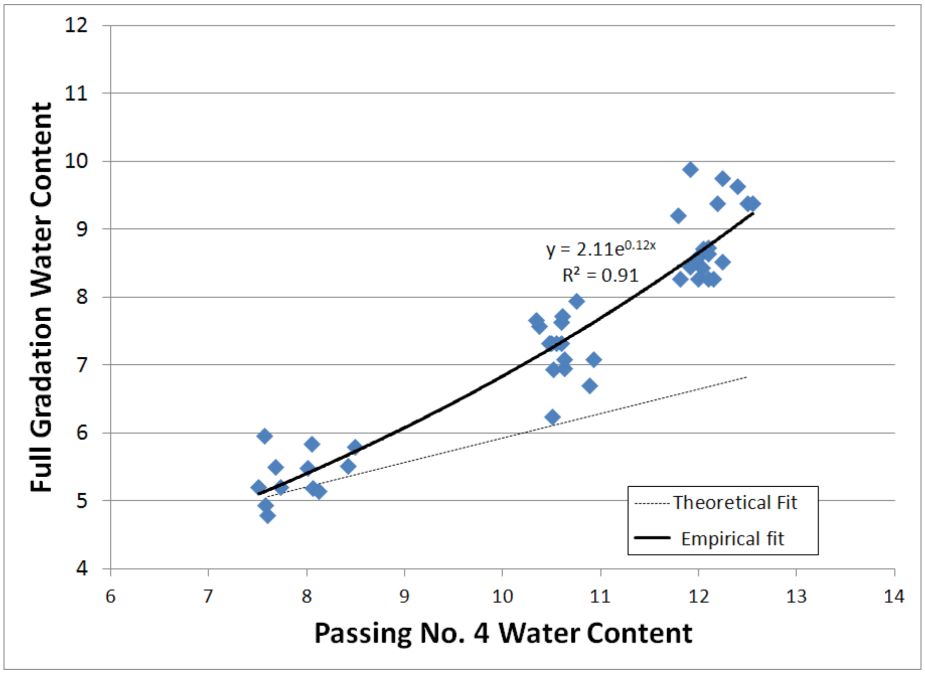


Figure 3.16. Full Gradation versus Passing No. 4 Water Content from Flex Base Verification Tests.

Conclusions from Calibration and Verification Tests

The calibration and verification tests allowed the research team to gain field experience with the test devices and obtain estimates of precision, bias, and accuracy of each device. While the results showed each device to be relatively simple to operate, concerns with the nature of installing the FDR equipment and sensitivity of the equipment's calibration led the research team to recommend removing FDR equipment from the test matrix. For the other devices, the data show:

- The single operator precision is good for all devices. Among the field-type devices (SDG, EDG, and nuclear gauge), no difference in single-operator variability existed. With the other devices, the moisture analyzer and direct heat (when testing the passing

No. 4) exhibited better single-operator repeatability, although the research team believes all devices exhibited more than acceptable results in this area.

- Bias existed with the SDG, EDG, nuclear gauge, and DOT 600. The amount of bias varied by level with the SDG and nuclear gauge, indicating a slope problem.
- The moisture analyzer, microwave oven, and direct heat were unbiased.
- Assuming each device were unbiased, some differences in accuracy exist. Figure 3.17 illustrates the findings.

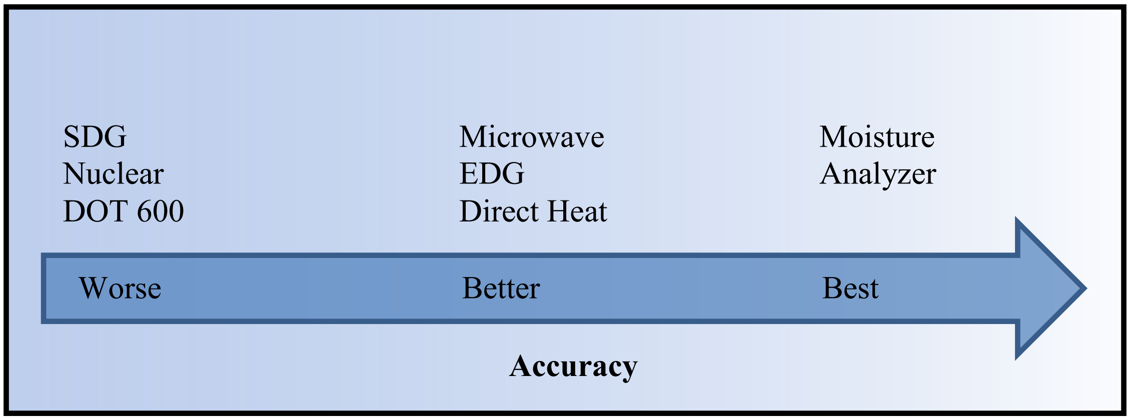


Figure 3.17. Continuum of Accuracy for Devices Based on Flex Base Verification Test Boxes.

- Relating the passing No. 4 water content to the full gradation remains an issue. A theoretical approach based on the gradation, percent moisture on the passing No. 4 sieve, and absorption of the plus No. 4 sieve fraction, did not match actual test data. For this reason, future project work will likely utilize an empirically-derived relationship for relating the passing No. 4 water content to the full gradation.
- Since the microwave test returned unbiased results in under 10 minutes for samples using the full gradation, future work with this test should only focus on testing the full gradation. Proceeding in this manner eliminates the need for a correction with this test based on the particle size tested.
- Since the direct heat test required as much as 2 hours for a result when testing the full gradation, future work with this test should focus on testing the passing No. 4 in order to maintain reasonable test turnaround times within the scope of this project’s goals. Proceeding in this manner will require a correction with this test based on the particle size tested.

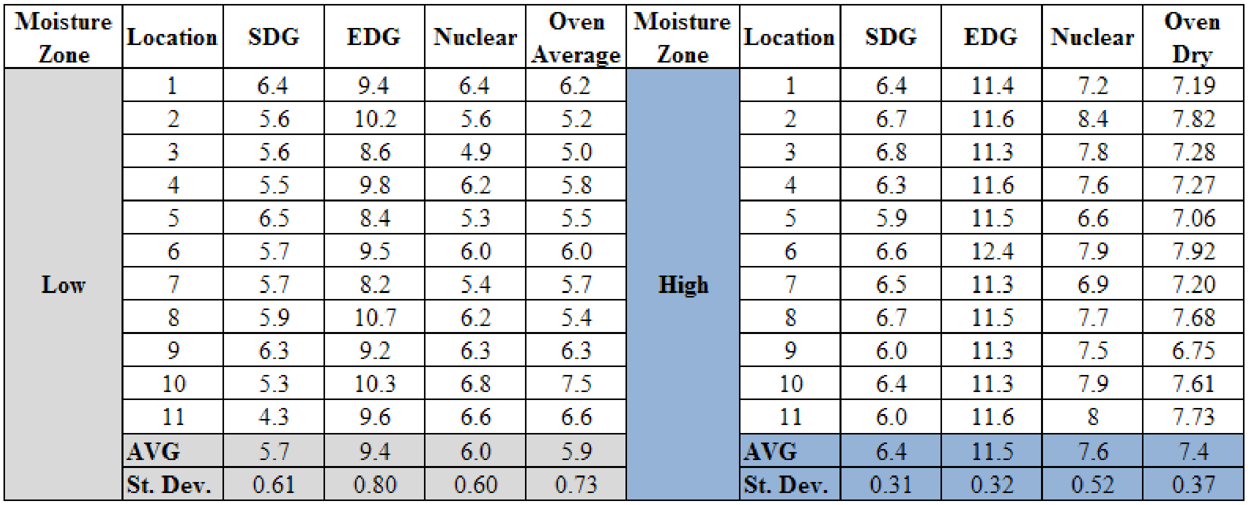
FIELD TESTS

After the calibration and verification test box sequences, the research team proceeded to test a field section of the same flexible base presented in Table 2.11. The research team tested a section of the northbound IH 35 frontage road just north of Tahuaya Drive. Figure 3.18 shows the processing of the base and the finished section.

Figure 3.18. Processing and Finished Base on Field Test Site.

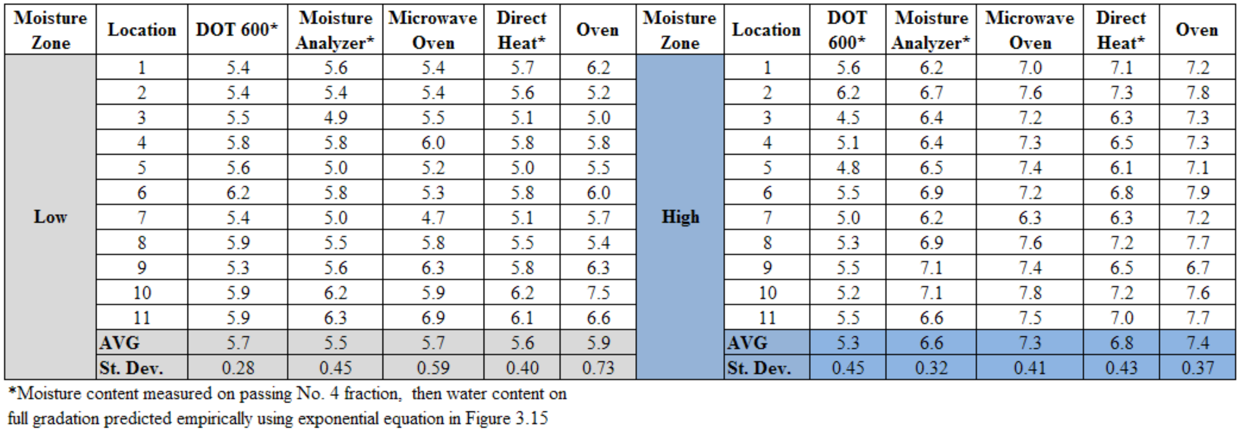
After the contractor completed the lift of base course, the research team proceeded to test 11 spot locations in zones of base that appeared dry and wet, respectively, for a total of 22 measurements. The purpose of collecting data in this manner was to evaluate each device for bias in accordance with ASTM D 4855, where the dry and wet water content zones represent low and high material levels, respectively. The research team collected data using the SDG, EDG, and nuclear gauge. Next, the research team collected a physical sample of sufficient size to split for DOT 600, moisture analyzer, microwave oven, direct heat, and reference oven dry tests. Table 3.11 presents the results from the SDG, EDG, nuclear gauge, and oven dry results. Table 3.12 presents the results from the other tests, which were performed on splits from the physical sample.

Table 3.11. Results from SDG, EDG, and Nuclear Gauges at Field Test Site.



Moisture Zone	Location	SDG	EDG	Nuclear	Oven Average	Moisture Zone	Location	SDG	EDG	Nuclear	Oven Dry
Low	1	6.4	9.4	6.4	6.2	High	1	6.4	11.4	7.2	7.19
	2	5.6	10.2	5.6	5.2		2	6.7	11.6	8.4	7.82
	3	5.6	8.6	4.9	5.0		3	6.8	11.3	7.8	7.28
	4	5.5	9.8	6.2	5.8		4	6.3	11.6	7.6	7.27
	5	6.5	8.4	5.3	5.5		5	5.9	11.5	6.6	7.06
	6	5.7	9.5	6.0	6.0		6	6.6	12.4	7.9	7.92
	7	5.7	8.2	5.4	5.7		7	6.5	11.3	6.9	7.20
	8	5.9	10.7	6.2	5.4		8	6.7	11.5	7.7	7.68
	9	6.3	9.2	6.3	6.3		9	6.0	11.3	7.5	6.75
	10	5.3	10.3	6.8	7.5		10	6.4	11.3	7.9	7.61
	11	4.3	9.6	6.6	6.6		11	6.0	11.6	8	7.73
	AVG	5.7	9.4	6.0	5.9		**AVG**	6.4	11.5	7.6	7.4
	St. Dev.	0.61	0.80	0.60	0.73		**St. Dev.**	0.31	0.32	0.52	0.37

Table 3.12. Results from DOT 600, Moisture Analyzer, Microwave, and Direct Heat.



Moisture Zone	Location	DOT 600*	Moisture Analyzer*	Microwave Oven	Direct Heat*	Oven	Moisture Zone	Location	DOT 600*	Moisture Analyzer*	Microwave Oven	Direct Heat*	Oven
Low	1	5.4	5.6	5.4	5.7	6.2	High	1	5.6	6.2	7.0	7.1	7.2
	2	5.4	5.4	5.4	5.6	5.2		2	6.2	6.7	7.6	7.3	7.8
	3	5.5	4.9	5.5	5.1	5.0		3	4.5	6.4	7.2	6.3	7.3
	4	5.8	5.8	6.0	5.8	5.8		4	5.1	6.4	7.3	6.5	7.3
	5	5.6	5.0	5.2	5.0	5.5		5	4.8	6.5	7.4	6.1	7.1
	6	6.2	5.8	5.3	5.8	6.0		6	5.5	6.9	7.2	6.8	7.9
	7	5.4	5.0	4.7	5.1	5.7		7	5.0	6.2	6.3	6.3	7.2
	8	5.9	5.5	5.8	5.5	5.4		8	5.3	6.9	7.6	7.2	7.7
	9	5.3	5.6	6.3	5.8	6.3		9	5.5	7.1	7.4	6.5	6.7
	10	5.9	6.2	5.9	6.2	7.5		10	5.2	7.1	7.8	7.2	7.6
	11	5.9	6.3	6.9	6.1	6.6		11	5.5	6.6	7.5	7.0	7.7
	AVG	5.7	5.5	5.7	5.6	5.9		**AVG**	5.3	6.6	7.3	6.8	7.4
	St. Dev.	0.28	0.45	0.59	0.40	0.73		**St. Dev.**	0.45	0.32	0.41	0.43	0.37

*Moisture content measured on passing No. 4 fraction, then water content on full gradation predicted empirically using exponential equation in Figure 3.15

The first item the research team investigated was whether the oven-dry results showed the two zones tested to truly exhibit different moisture contents. The mean oven-dry moisture content at the low level was 5.9 percent, while the mean oven-dry moisture content at the high level was 7.4 percent. A statistical t-test showed these means were not equivalent, meaning the two zones tested did represent two different populations. Next, the research team evaluated whether the field measurements were biased with respect to the oven dry at each level. Table 3.13 presents the results of whether bias existed for each device at each level of moisture content.

Table 3.13. Results from Tests for Bias Based on Field Site Data.

Device	Biased	
	Low Level	**High Level**
SDG	No	Yes
EDG	Yes	Yes
Nuclear	No	No
DOT 600	No	Yes
Moisture Analyzer	No	Yes
Microwave Oven	No	No
Direct Heat	No	Yes

Discussion of Bias Results from Field Tests

Referring back to Figure 3.5, the SDG may exhibit bias at the higher level because it appears once the true moisture exceeded optimum, the SDG readings did not continue to increase. It is also possible that a simple linear offset may not adequately allow for adjusting the gauge to the material under test. Further investigation will be required to determine if this problem with bias was isolated to this material or a problem on all materials.

The EDG field test results are peculiar in that prior EDG results from the verification test boxes with this material were unbiased, yet the EDG exhibited bias on the field tests. At the low level of material in the field, the EDG bias was 3.5 percent; at the high level of material in the field, the EDG bias was 4.1 percent. Using the methods in ASTM D 4855, researchers determined the bias in the field did not vary with the level of material. Therefore, the EDG field results could be corrected with simply a linear offset. However, since the device was previously calibrated to this material, it is unknown if the test boxes did not adequately cover the zone of influence of the device, if the properties of the base material placed in the field differed substantially from the material sampled for the calibration tests, or if some other factor existed that resulted in the biased field results. In contrast to the EDG, the nuclear results were biased for the verification test boxes but unbiased at the field construction site. The reason for this occurrence is not known at this time.

Some problems existed in the field with relating the measurements on the passing No. 4 material to the full gradation. Prior work showed the moisture analyzer and direct heat provided unbiased estimates of the water content for the passing No. 4 fraction, so the researchers attribute the bias in the field to problems with the calibration or approach in correcting the water content measured on the passing No. 4 fraction to the full gradation. The field data show these devices unbiased at the low level but biased at the high level, where the approach used under-predicted the moisture content at the high level. Further investigation and development in methods for correcting the passing No. 4 moisture content to the full gradation will be required with these tests.

Of all the devices tested, the microwave oven is the only device that provided unbiased results during both small-scale verification tests and full-scale field tests. This test also provided results in about 10 minutes, regardless of which size fraction was tested.

CONCLUSIONS

The results from the flex base material lead to the following conclusions:

- No further investigation of the FDR is warranted due to installation issues and concerns of calibration consistency with changing material density.
- All of the devices exhibited good repeatability. Single operator standard deviations ranged from 0.12 to 0.5 percent moisture.
- The SDG was biased, with bias varying by level of material. This occurrence requires further investigation.
- The EDG was unbiased in initial tests after calibration, yet when moving to testing on a construction project exhibited a fixed bias, which could be corrected by a simple linear offset. Further investigation as to what may have caused the field bias to occur is needed.
- The nuclear gauge provided unbiased field performance.
- When testing the passing No. 4 material, the moisture analyzer provided the most accurate results. However, the moisture analyzer, direct heat, and microwave can all provide unbiased estimates of the moisture content of passing the No. 4 material.
- Continued development of how best to relate the moisture content of the passing No. 4 fraction to the full material gradation is needed. The empirical method employed underestimated the true moisture content at the high level from the field tests.

CHAPTER 4
CONCLUSIONS AND FUTURE RESEARCH PLAN

OVERVIEW

This project investigated available moisture-measurement technologies using gravimetric, dielectric, electrical conductivity, and suction-based methods. From numerous available technologies, this project focused on evaluation of the following:

- Gravimetric-based approaches:
    - Microwave oven (ASTM D4643).
    - Direct heat (ASTM D4959).
    - Moisture analyzer (no known current adopted method for construction materials).
    - Nuclear gauge (ASTM D6938), for comparative purposes.
    - Oven drying (ASTM D2216), for the reference value.
- Dielectric-based approaches:
    - SDG 200 (no known current adopted test method).
    - EDG (ASTM D7698).
    - DOT 600 (no known current adopted test method).
    - FDR (fork style probe; similar to ASTM D6565).

The first phase of this project focused on test method development as appropriate, pilot testing with selected construction materials and deployment of the most promising devices on a construction project. Those activities led to important results on test method development, preliminary results on device bias and accuracy, and estimates of single-operator standard deviation of repeat measurements. Through those results, the list of the most promising devices can be narrowed down and a clearer path for future research developed.

CONCLUSIONS FROM TEST METHOD DEVELOPMENT

Initial test development work focused on devices that could be used in the lab but lacked any known adopted procedures. From the approaches under investigation in this project, those usable devices were the DOT 600 and moisture analyzer, as follows.

- The DOT 600 appears promising for rapidly measuring the water content of the passing No. 4 fraction. Appendix A presents a draft test method for this device. Calibration of the device to the material may be required.
- The moisture analyzer also appears promising for rapidly measuring water content of the passing No. 4 fraction. Appendix B presents a draft test method for this device.

CONCLUSIONS FROM PILOT AND CONSTRUCTION PROJECT TESTING WITH DEVICES

The research team performed pilot tests with a low plasticity soil, a flexible base, and a lime-treated soil. The research team then performed additional small- and large-scale field tests with a second base material to evaluate bias, accuracy, and single-operator precision. These results showed:

- The FDR equipment can provide accurate, quick results. However, the probe must be buried in the material under test, meaning testing compacted layers would require either losing a probe for each test or extracting the probe from the compacted layer. This issue, combined with the influence of material density on the proper calibration, led the research team to recommend removing the FDR from the candidate devices.
- The direct heat test turnaround time exceeded 2 hours in some cases, which may not be consistent with the rapid turnaround time desired on this project. Testing only the passing No. 4 fraction expedites reaching the end point of the direct heat test. For application in this project, the research team recommended testing only the passing No. 4 fraction with the direct heat method due to the more rapid turnaround time.
- The moisture analyzer, microwave, and direct heat all provided unbiased estimates of moisture content for the passing No. 4 fraction. In testing that size fraction, the moisture analyzer exhibited the best accuracy.
- Several tests, due to physical or test time constraints, only test the passing No. 4 material. Relating the water content of this size fraction to the water content of the full gradation of material remains an area needing improvement.
- The microwave oven was the only device found unbiased in all experiments conducted and provided results generally in 10 minutes or less.
- The single-operator standard deviation for all devices was good, ranging from 0.07 to 0.5 percent.

RECOMMENDED DEVICES FOR CONTINUED WORK

Sufficient data from the pilot and construction project testing exist to form a preliminary scoring of each device. In discussion with this project's director, the devices were ranked according to the parameters in Table 4.1. The table presents the weight of each parameter and how scores were assigned. Since at this point in the project sufficient information for a repeatability or reproducibility limit does not exist for all devices, the precision scores were based on the single-operator standard deviations. Using these single operator standard deviations as point estimates for the repeatability standard deviation implies the precision scoring would encompass repeatability limits from 0.28 to almost 2 percent.

Table 4.1. Parameters for Ranking Devices.

Parameter	Scoring
Precision (15%)	6: standard deviation < 0.10 5: standard deviation >0.10 < 0.20 4: standard deviation >0.20<0.30 3: standard deviation >0.30 < 0.40 2: standard deviation >0.40 < 0.50 1: standard deviation >0.50<0.70 0: standard deviation >0.70
Bias (15%)	6: unbiased 4: biased, with bias not related to level of property 0: biased, with bias related to level of property
Existence of Accepted Test Method (5%)	2: national or state standard 1: pending standard 0: none
Suitability for Uncompacted Materials (10%)	4: yes 2: with special accommodations, which could include leveling the surface 0: no
Suitability for Compacted Materials (10%)	4: Yes 2: with special accommodations, which could include special sensor installation requirements 0: no
Turnaround Time (10%)	4: < 15 min. 3: 15–30 min. 2: 30–60 min. 1: 1–2 hr. 0: > 2 hr.
Zone of Influence (12.5%)	5: full coverage with depth 4: full coverage of surface 3: single point through depth up to ≥ 6 in. 2: single point through depth ≥2 in <6 in. 1: point value < 2 in.
Cost (10%)	4: < \$1,000 3: \$1,000–\$3,000 2: \$3,000–\$5,000 1: \$5,000–\$10,000 0: > \$10,000
Field Practicality (12.5%)	5: easily portable, self-powered 4: easily portable, externally powered by plug-in inverter or external battery 3: easily portable, externally powered by hardwire inverter or field lab power 2: somewhat portable, externally powered by plug-in inverter 1: somewhat portable, externally powered by hardwire inverter or field lab power

Table 4.2 presents the scores for each device based on the verification and field tests with the flexible base construction project. Several devices can be used to test only the passing No. 4 fraction, and therefore were scored based on their testing of that size fraction, along with a method where the moisture content on the full gradation was predicted from the measured moisture content on the passing No. 4 fraction.

Table 4.2. Scoring of Devices Based on Verification and Field Construction Project Tests.

	SDG	**EDG**	**Nuclear**	**DOT 600 - Passing No. 4**	**DOT 600 - Full Gradation***	**Moisture Analyzer - Passing No. 4**	**Moisture Analyzer - Full Gradation***	**Direct Heat - Passing No. 4**	**Direct Heat - Full Gradation**	**Direct Heat - Full Gradation***	**Microwave**
Precision**	5	6	5	2	2	5	5	5	5	5	2
Bias	0	4	6	0	0	6	0	6	6	0	6
Existence of Accepted Test Method	0	2	2	0	0	0	0	2	2	2	2
Suitability for Uncompacted Materials	2	2	2	4	4	4	4	4	4	4	4
Suitability for Compacted Materials	4	4	4	4	4	4	4	4	4	4	4
Turnaround Time	4	4	4	4	4	4	4	2	1	2	4
Zone of Influence	3	3	3	1	1	1	1	1	2	2	2
Cost	1	1	0	2	2	3	3	4	4	4	4
Field Practicality	5	5	5	5	5	3	3	3	3	3	1
Total	**24**	**31**	**31**	**22**	**22**	**30**	**24**	**31**	**31**	**26**	**29**
Total (%)	**60**	**78**	**78**	**55**	**55**	**75**	**60**	**77.5**	**77.5**	**65**	**73**

*Test performed on passing No. 4. and then full gradation moisture content predicted

**Score based on single-operator standard deviation

The implications of the scores in Table 4.2 are:

- For field tests, particularly for in-place testing, the EDG appears most promising as a replacement for the nuclear gauge.
- Despite early promising pilot tests in this project, the DOT 600 results from the verification and construction project tests are disappointing.

- Both the moisture analyzer and direct heat work well for testing the passing No. 4 fraction.
- Relating the passing No. 4 measurements to the moisture content of the full gradation still proves problematic; solving that issue would resolve the bias problem for tests that rely on a passing No. 4 measurement to predict the moisture content of the full gradation.
- The microwave oven worked well, and the scores from that test were primarily reduced due to precision and field practicality.

Based on these results, consideration should be given to removing the SDG and DOT 600 from the testing matrix. The direct heat test and microwave test, as carried out on a representative sample of material in accordance with the appropriate test procedures, work well. Since these are accepted methods already adopted within many agencies, additional work on this project may not be warranted with the direct heat and microwave tests on the full material gradation. Instead, additional work should focus on improving the reliability of relating the passing No. 4 moisture content to the moisture content of the full gradation of flexible base materials. Achieving this reliable relationship would allow expedited results from the moisture analyzer or the direct heat methods by only testing the passing No. 4 size fraction. For materials that pass the No. 4 sieve, the data show the moisture analyzer test and direct heat test as developed in this project provide rapid, unbiased results with good precision.

FUTURE RESEARCH PLAN

With the reduced list of candidate devices, additional work on projects representing a variety of construction materials needs to take place for a more thorough evaluation. Future work on this project should focus on evaluating the bias, precision, and sensitivity of the devices on a variety of construction projects. Additionally, if new devices are identified, pilot testing should take place with those devices if possible. Finally, the project should conclude by providing the most promising methods to TxDOT (including equipment), along with training workshops to assist in technology transfer.

Evaluating Bias, Precision, and Sensitivity on Construction Projects

To evaluate the devices on construction projects, the research team will work with TxDOT and this project's director to try to identify 10 projects representing different construction materials. At each project, after sampling the construction materials and performing any calibrations of equipment as required, the bias will be evaluated performing the following:

- Locate or purposefully create two levels of material (low and high moisture content) at the construction site. The range of these levels should be at least 1.5 percent and preferably should be between 2 and 2.5 percent, with the low level below optimum and the high level above optimum.

- Collect 10 observations with each device at each level of material. This number of observations was selected based on the following method from ASTM D4855:

  $E = \delta/s_p$

  where

  E = the smallest difference of practical importance expressed as a multiple of standard deviation
  δ = the smallest difference of practical importance expressed as units of measure
  s_p = the best available estimate of the average standard deviation for individual observations

  In selecting 10 observations, the research team used a value of 1 for δ, and the data in Tables 3.11 and 3.12 results in a value of s_p of just less than 0.5, resulting in a value of 2 for E. According to ASTM D4855, this would require seven observations, so planning to collect 10 observations provides a safety margin for obtaining at least the minimum required number of observations.
- Collect a physical sample from each test location to determine the oven-dry reference value.
- Employ data processing methods in ASTM D4855 to investigate if bias exists between the new methods and the oven-dry results.

Data for evaluating precision will be collected concurrently at the construction projects while collected the data for evaluating the bias. The precision will be evaluated by:

- Collecting three repeat measurements at one point of low moisture level and one point of high moisture level on each construction project.
- Using data processing techniques in ASTM E691 to provide a repeatability limit estimate for the different mean moisture contents observed during testing. If the precision of a device does not vary significantly with the level of moisture content, determine the pooled standard deviation to obtain a single repeatability limit estimate.
- Since multiple labs will not be able to participate in these efforts, a reproducibility estimate will not be possible, and the repeatability estimate will not fully comply with ASTM E691 requirements. However, the repeatability estimate will provide a reasonable basis for evaluating the precision potential among the devices under evaluation.

The sensitivity of each device will be determined using methods in ASTM D4855. The data collected for evaluation bias will provide all the information needed to evaluate the sensitivity.

New Moisture Measurement Devices

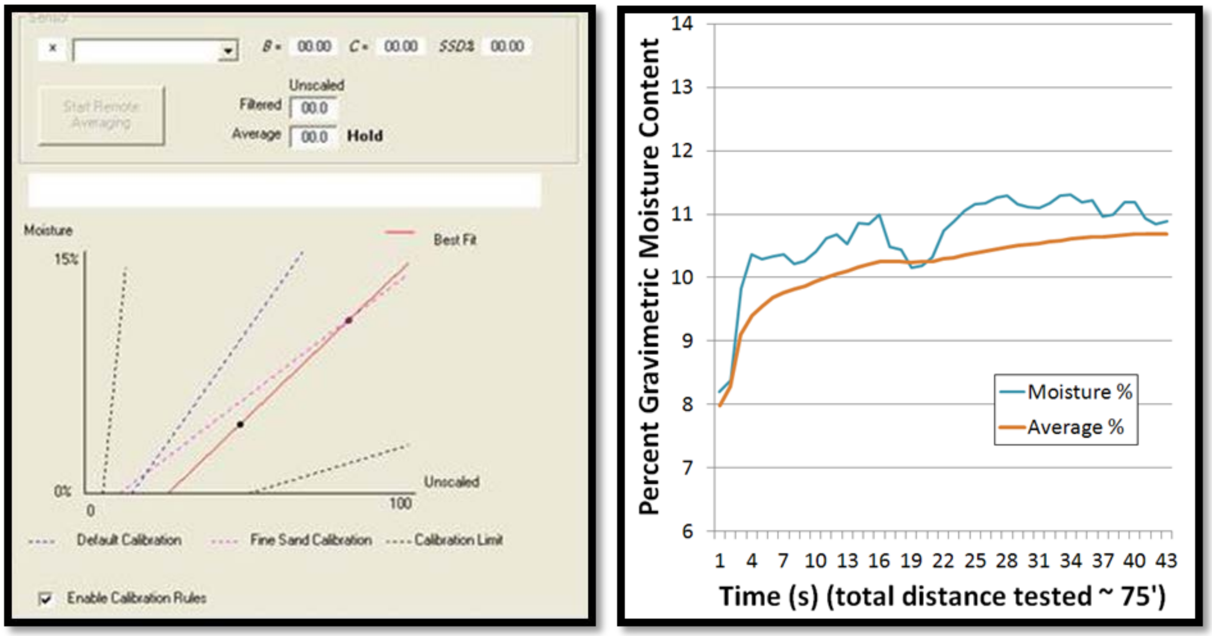
Ongoing efforts in this project may also involve pilot evaluations of new promising technologies and reporting those results to TxDOT. One such technology is the microwave-resonance based probe shown in Figure 4.1. This probe, while intended for permanent installations in flow processes of bulk materials, is marketed to the construction industry and may be adaptable for testing windrows or even processed base material on a construction project.

Figure 4.1. Microwave Probe for Measuring Moisture Content of Bulk Materials.

The research team has procured this device to test windrows of flexible base material, as Figure 4.2 illustrates. A mounting system allows coarse height adjustment and lateral telescoping of the probe's placement, while an 18-inch stroke linear actuator affixed to the probe's holder allows for fine height adjustment.

Figure 4.2. Measuring Windrow Moisture Content with Microwave Probe.

Since this probe is intended for fixed installations, the vendor's software only collects in the time mode. Figure 4.3 illustrates a calibration and example data output from testing with this system. The results appear promising, and continued work with this system should take place in ongoing efforts on this project.


B = 00.00 C = 00.00 SSD% 00.00

Filtered 00.0

Average 00.0

☑ Enable Calibration Rules

Figure 4.3. Example Calibration and Data Output from Microwave Probe.

The potential with this system has led the research team to develop a data acquisition program that will collect data using distance rather than time to define the sample interval. The new data acquisition program also collects GPS data. Ongoing efforts in this project with this system should:

- Verify the proper execution of data collection with new software by pilot testing with three materials. The moisture content of the materials should be varied from about 2 percent below to 2 percent above optimum. Currently, the research team believes work with this system should focus on windrows of flexible base materials.
- Develop and test a system for applying this technology to materials that have been processed. For example, after a contractor spreads and wets base material but prior to compaction, a modified plow arrangement may be able to generate a small windrow of sufficient height to collect data with this sensor. This sensor requires a minimum of 6 inches of material for proper data collection.

Equipment and Training

Following the collection and reduction of data, this project will select the most promising new moisture measurement technology with the intent of providing TxDOT with three systems. A draft test procedure in TxDOT format will accompany the new systems, and the TTI research staff will conduct one training workshop with TxDOT. This training should take place at TxDOT's materials and tests branch. Although the final recommended device has not yet been identified, the training workshop likely will include the learning objectives and course outline as follows:

Learning Objectives

- Understand the importance of water content on compaction and performance characteristics of materials used in pavement construction.
- Understand the methods available to measure water content and the strengths and limitations of each method.
- Develop a working knowledge of new, non-nuclear techniques for measuring water content within TxDOT.

Course Outline

- Impact of water content on compaction (10 percent).
- Influence of water content on mechanical properties (10 percent).
- Methods for measuring water content (15 percent):
  - Oven-dry gravimetric.
  - Microwave.
  - Speedy.
  - Other (to be determined during research project).
- Results from new, non-nuclear moisture measurement method(s) (15 percent).
- Test procedure for new moisture measurement method within TxDOT, including demonstration (50 percent):
  - Apparatus.
  - Equipment calibration.
  - Sample/test site preparation.
  - Collecting data.
  - Calculations and reporting.

Concurrently with the training workshops, a training video should be produced following a similar format of the workshop material. By combining new devices with appropriate test procedures and training materials, the output from the future research on this project should position TxDOT well for establishing more widespread use of non-nuclear moisture measurement techniques that can provide rapid results for field quality control.

APPENDIX A

DRAFT TEST PROCEDURE FOR GRAVIMETRIC WATER CONTENT USING A PORTABLE DIELECTRIC PERMITTIVITY AND MOISTURE CONTENT KIT

1. SCOPE

1.1 This test method determines the gravimetric water content of a sample using a portable dielectric permittivity kit. The test performs three measurements on representative samples of passing No. 4 material.

1.2 The portable dielectric permittivity kit uses a variety of different sensors to measure sample volume, mass, and dielectric permittivity and calculate the volumetric water content of a sample. The device then converts the volumetric water content into gravimetric water content using internal or custom calibrations.

1.3 The values given in parentheses (if provided) are not standard and may not be exact mathematical conversions. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

2. APPARATUS

2.1 Portable dielectric permittivity kit consisting of:

- 2.1.1 Carrying case that houses:
    - 2.1.1.1 Internal scale with capacity of 1,000 g, accuracy of ±0.032%, and repeatability of 0.02%.
    - 2.1.1.2 Measurement and control datalogger.
    - 2.1.1.3 Dielectric permittivity sensors.
    - 2.1.1.4 Magnetic linear sensors.
- 2.1.2 Sample chamber consisting of:
    - 2.1.2.1 Sample chamber base.
    - 2.1.2.2 Sample chamber cylinder.
- 2.1.3 Compression cap.
- 2.1.4 3 in. diameter Sieve, U.S. Standard No. 4 (4.75 mm).
- 2.1.5 Ratcheting wrench.
- 2.1.6 RS-232 serial cable.
- 2.1.7 External keypad (optional).
- 2.1.8 AC charger.
- 2.1.9 Software.

2.2 Sample pans and sample bags.

2.3 12-in. diameter Sieve, U.S. Standard No. 4 (4.75 mm).

2.4 Scoops, shovels, or pickaxes for field sampling.

3. TEST FORM

3.1 GWC_DPK.xlsx.

4. PROCEDURE

4.1 Sample preparation:

4.1.1 Select a representative sample according to the appropriate test method (Tex-100-E or Tex-400-A) large enough to yield at least 600 g of soil binder.

NOTE—If sample is to be tested in field,

4.1.2 Store samples prior to testing in airtight containers at a temperature between 2.8°C and 30°C and in an area that prevents direct contact with sunlight.

4.1.3 Make water content determination as soon as practical after sampling, especially if potentially corrodible containers, or sample bags are used.

4.2 When sample is to be tested, thoroughly sieve sample over a 12-in. diameter No. 4 sieve.

4.2.1 Material passing the No. 4 sieve becomes sample to be tested.

4.2.2 Material retained on the No. 4 sieve can be discarded.

4.3 Measuring moisture content:

4.3.1 Input preliminary identification information into the datalogger.

4.3.1.1 Input project and location information if applicable.

4.3.1.2 Select unit system as SI or Imperial.

4.3.1.3 Select material type based on USDA soil texture types, or input custom calibration.

4.3.2 Tare the sample chamber on the internal scale.

4.3.3 Place 3-inch diameter No. 4 sieve on sample chamber and begin to fill chamber. If material does not fall through with gentle shaking, pressing material through the sieve with fingers is a suitable option.

4.3.3.1 Fill sample chamber to top. Do not overfill and do not partially compact then re-fill.

4.3.4 Weigh sample and sample chamber on internal scale.

4.3.5 Place filled sample chamber over dielectric sensor, and affix compression cap.

4.3.6 Ratchet compression cap to a stable pressure of 30 ± 1 psi (206.8 kPa).

NOTE 1—When compressing sample, the datalogger may initially report a false compaction pressure. This happens when the mechanism inside the compression cap has not yet begun to compress the sample. Once the sample is being compacted, the datalogger will read the accurate pressure.

NOTE 2—When 30 psi compaction is reached, allow sample to sit approximately 1 minute or until the compaction pressure stabilizes. Sample may need additional compression after it is allowed to relax.

4.3.7 Sample the volumetric water content with the datalogger.

4.3.8 Record the sample data with the datalogger.

4.3.9 Record sample gravimetric water content on the form GWC_DPK.

4.3.10 Remove the sample chamber from the dielectric sensor.

4.3.11 Loosen the compression cap and then remove the compression cap from the sample chamber.

4.3.12 Remove the sample from the sample chamber and discard the sample. Wipe away any residual soil and/or moisture from the interior of the sample chamber.

4.4 Repeat section 4.3 twice, for a total of three representative measurements.

5. CALCULATIONS

5.1 Use form GWC_DPK to calculate and record the average gravimetric water content**.**

APPENDIX B
DRAFT TEST PROCEDURE FOR GRAVIMETRIC WATER CONTENT USING MOISTURE ANALYZER

1. SCOPE

1.1 This test method determines the gravimetric water content of a sample using a moisture analyzer device.

1.2 The moisture analyzer uses a heating element to heat a small sample of material placed on an internal scale. The analyzer measures the weight change until a specified end-point is reached and then displays the gravimetric water content of the sample.

1.3 The values given in parentheses (if provided) are not standard and may not be exact mathematical conversions. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

2. APPARATUS

2.1 Moisture analyzer, consisting of:

2.1.1 *Primary unit with internal scale* with capacity up to 200 g, accuracy of 0.01 g, precision of 0.05%.

2.1.2 *Heating element* with temperature range of 50°C to 160°C, with set points available in 1°C increments.

2.1.3 *Interface capable of storing and recalling saved procedures*.

2.1.4 *Pan support and lower chamber insert*.

2.1.5 *Sample pan lifter*.

2.1.6 Aluminum sample pans.

2.1.7 *AC power cable*.

2.2 *Sample pans and sample bags*.

2.3 *Sieve,* U.S. Standard No. 4 (4.75 mm).

2.4 *Scoops*, shovels, or pickaxes for field sampling.

3. TEST FORM

3.1 GWC_MA.xlsx.

4. ANALYZER PROCEDURE SETUP

4.1 Create and save a new procedure containing the following specifications:

- 4.1.1 Moisture content measurement based on dry weight.
- 4.1.2 Single heating temperature of 160°C.
- 4.1.3 Recording interval of 5 s.
- 4.1.4 Endpoint criteria of:
  - 4.1.4.1 Stable sample weight within 0.01 g.
  - 4.1.4.2 Stable sample weight for 30 s.
- 4.1.5 Manual start.

5. PROCEDURE

5.1 Sample preparation:

- 5.1.1 Select a representative sample according to the appropriate test method (Tex-100-E or Tex-400-A) large enough to yield at least 300 g of soil binder.
- 5.1.2 Store samples prior to testing in airtight containers at a temperature between 2.8°C and 30°C and in an area that prevents direct contact with sunlight.
- 5.1.3 Make water content determination as soon as practical after sampling, especially if potentially corrodible containers, or sample bags are used.

5.2 When sample is to be tested, thoroughly sieve sample over a No. 4 sieve.

- 5.2.1 Material passing No. 4 sieve becomes sample to be tested.
- 5.2.2 Material retained on No. 4 sieve can be discarded.

5.3 Measuring moisture content.

- 5.3.1 Select analyzer procedure created in section 4.
- 5.3.2 Weigh an aluminum sample pan on the moisture analyzer’s scale and record as Tare Mass Pan on form GWC_MA, then tare.
- 5.3.3 Place 50±1 g of sample as prepared in section 5.2 on the sample pan. Record the weight as Wet Sample Mass on form GWC_MA.
- 5.3.4 Press the start button to initiate the test.
- 5.3.5 When the test is finished, record the final calculated moisture, time of test, and dry sample weight on form GWC_MA.

6. REPORTING

6.1 Use form GWC_MA to report the moisture content result.