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16. Abstract
Mixing and compacting soil and flexible base pavement materials at the proper moisture content is critical for obtaining adequate compaction and meeting construction specification requirements. This project sought to evaluate rapid non-nuclear techniques for measuring the moisture content on roadway base and subgrade materials. This report presents results from the final stages of testing in this project, which included 3 non-nuclear approaches, the nuclear gauge for comparison, and the oven dry gravimetric moisture as the reference value. Researchers evaluated each test for bias, precision, and sensitivity, and then scored the devices according to bias, precision, sensitivity, cost, turnaround time, suitability for uncompacted materials, and suitability for compacted materials. With these scoring parameters, the data showed the moisture analyzer most suitable for implementation. The report presents a draft test method for measuring moisture content with the moisture analyzer. The test turnaround time is typically between 15 and 30 minutes.

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RAPID FIELD DETECTION OF MOISTURE CONTENT FOR BASE AND SUBGRADE: TECHNICAL REPORT

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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.

This report is not intended for construction, bidding, or permit purposes. The researcher in charge of the project was Stephen Sebesta.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The proper application of water during compaction of roadway base and subgrade materials is important for achieving adequate compaction. Construction specifications govern the determination of this optimum water content, and field measurement historically takes place with a nuclear density gauge. However, with the regulatory requirements of using nuclear sources, and continued interest in stiffness or modulus-based compaction acceptance, a need exists to identify techniques to rapidly measure moisture content on base and subgrades without using a nuclear source.

This project began by surveying potential technologies for such rapid measurement, and Technical Report 0-6676-1 presented a host of technologies that operate on gravimetric, dielectric, and soil water tension principles. From the work described in 0-6676-1 and the input of TxDOT's project oversight team, this project narrowed its focus to three non-nuclear tests, the nuclear gauge for comparison purposes, and the oven-dry gravimetric water content for the reference value.

The new devices focused on in the last stage of this project included the Electrical Density Gauge (EDG), the DOT 600, and a moisture analyzer. After collecting data on construction projects, researchers evaluated each test for bias, precision, and sensitivity, and then scored the devices according to bias, precision, sensitivity, cost, turnaround time, suitability for uncompacted materials, and suitability for compacted materials. With these scoring parameters, the data showed the moisture analyzer most suitable for implementation. Other important considerations included:

- Driving the EDG darts into materials significantly dry of optimum proved quite difficult.
- Some equipment reliability issues occurred with the DOT 600.
- The moisture analyzer only tests the passing No. 4 size fraction. To successfully implement this device, specifications would require modification to address the moisture content of the passing No. 4 fraction for materials (such as flexible bases) that retain a significant portion on the No. 4 sieve.

This report presents a draft test procedure for measuring moisture content with a moisture analyzer. Using this method, and with the materials tested in this project, test turnaround time with the moisture analyzer was typically between 15 and 30 minutes. This test could be considered for implementation for materials that pass the No. 4 sieve, while implementation for materials retaining significant amount on the No. 4 sieve would require changes to construction specifications to include the moisture content on the passing No. 4 material.

CHAPTER 1. PERFORM EXPERIMENTAL DESIGN ON FIELD PROJECTS

Field testing of new moisture content devices under Project 0-6676 focused on the Electrical Density Gauge (EDG), the DOT 600, and the moisture analyzer (MA) test. While the EDG test is compliant with ASTM D7698, the DOT 600 and moisture analyzer are new tests in the realm of pavement materials. Technical report 0-6676-1 presented draft test methods in TxDOT format for the DOT 600 and MA tests.

To evaluate these devices, the general research plan outlined below was developed to generate data suitable for determining the bias, estimating precision, and determining the sensitivity of each device:

- Locate or purposefully create two levels of material (low and high moisture content).
- Collect 10 observations with each device at each level of material.
    - Collect at least three repeat measurements at one point of low moisture level and one point of high moisture level for use in precision estimation.
- Determine the Tex-103-E reference value for each observation point.
- Employ data processing methods in ASTM D4855 to evaluate whether bias exists.
- Use methods in ASTM D4855 to evaluate the sensitivity of each device.
- Employ data processing methods in ASTM E691 to estimate repeatability. Since data from multiple labs were not attainable in the course of the work, a reproducibility estimate is not possible.

DATA FROM PROJECTS FOR BIAS AND SENSITIVITY ANALYSIS

Flexible Base Material from IH 35 Frontage Road

The flexible base presented in Table 1 was used on the IH 35 frontage roads in the Waco District. The EDG was calibrated to the soil using 6-inch test darts, with Figure 1 presenting the calibration result in the EDG. Based on input from TxDOT, work with the DOT 600 and MA focused on the passing No. 4 size fraction. That specific focus was chosen because the DOT 600 and MA only test the passing No. 4 size, and TxDOT felt that adequate moisture control even for materials containing particles retained on the No. 4 sieve may be feasible by controlling the water content based on measurements of the passing No. 4. Table 2 and Table 3 present the results from the two different levels of moisture content sampled and tested for this flexible base material. The test depth with the nuclear gauge was 6 inches. After collecting field EDG and nuclear readings, a physical sample was excavated and split for MA, DOT 600, and Tex-103-E testing.

Table 1. Flexible Base Properties from IH 35 Frontage Road Project.

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								

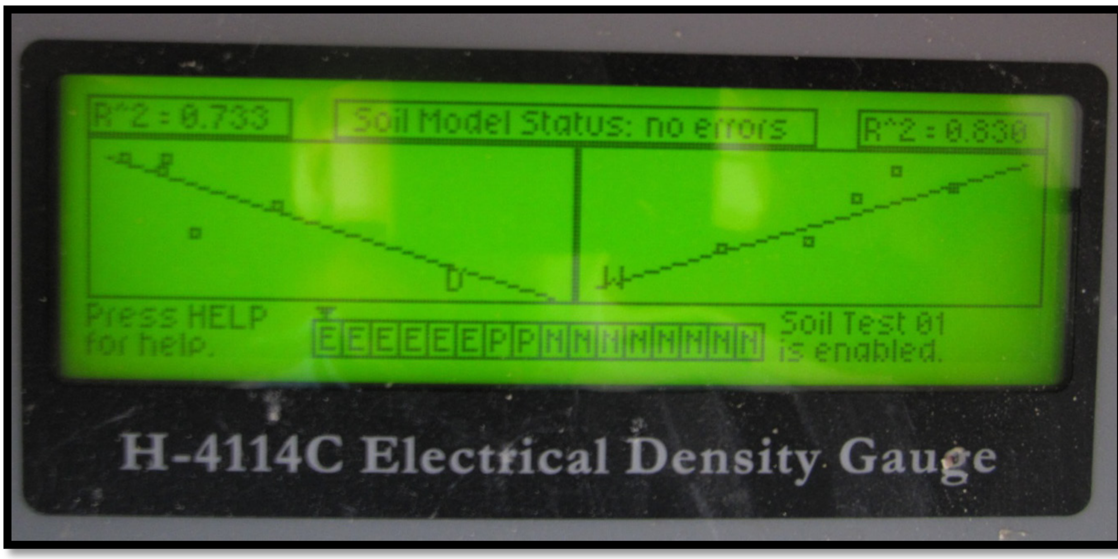

Figure 1. EDG Calibration to Flexible Base.

Table 2. Water Content from Low Moisture Zone with Flexible Base.

Location	EDG	Nuclear	DOT 600	MA	Tex-103-E Oven Dry	
					Passing No. 4	Full Gradation
1	9.4	6.4	8.05	8.30	8.95	6.24
2	10.2	5.6	8.05	7.95	8.18	5.15
3	8.6	4.9	8.13	7.25	7.73	5.00
4	9.8	6.2	8.55	8.55	8.83	5.78
5	8.4	5.3	8.25	7.30	8.31	5.46
6	9.5	6.0	9.17	8.65	9.08	6.02
7	8.2	5.4	8.00	7.35	7.22	5.70
8	10.7	6.2	8.70	8.20	8.45	5.41
9	9.2	6.3	7.85	8.35	9.00	6.32
10	10.3	6.8	8.70	9.10	8.94	7.52
11	9.6	6.6	8.80	9.25	9.08	6.62

Table 3. Water Content from High Moisture Zone with Flexible Base.

Location	EDG	Nuclear	DOT 600	M.A. - #4	Tex-103-E Oven Dry	
					Passing No. 4	Full Gradation
1	11.4	7.2	8.33	9.20	9.25	7.19
2	11.6	8.4	9.17	9.85	10.34	7.82
3	11.3	7.8	6.53	9.45	9.59	7.28
4	11.6	7.6	7.47	9.40	9.82	7.27
5	11.5	6.6	7.00	9.55	9.11	7.06
6	12.4	7.9	8.20	10.05	10.73	7.92
7	11.3	6.9	7.43	9.20	9.60	7.20
8	11.5	7.7	7.83	10.05	10.33	7.68
9	11.3	7.5	8.13	10.30	9.97	6.75
10	11.3	7.9	7.70	10.30	11.15	7.61
11	11.6	8.0	8.13	9.65	10.80	7.73

Subgrade Soil from US 82

The subgrade soil tested from US 82 was sampled from stations 1730 to 1739. Table 4 presents the Atterberg Limits of the soil. For further testing, the samples from the stations were combined to make a representative sample, which yielded Tex-114-E optimum moisture content and maximum density of 25.1 percent and 93.1 pcf, respectively. Figure 2 shows the Tex-114-E curve.

Table 4. Atterberg Limits from US 82 Soil Samples.

Location (STA)	Atterberg Limits		
	LL	PL	PI
1730	82	25	57
1731	80	26	54
1732	79	27	52
1733	79	27	52
1734	72	27	45
1735	79	27	52
1737	74	26	48
1739	75	26	49
Average	**77.5**	**26.4**	**51.1**

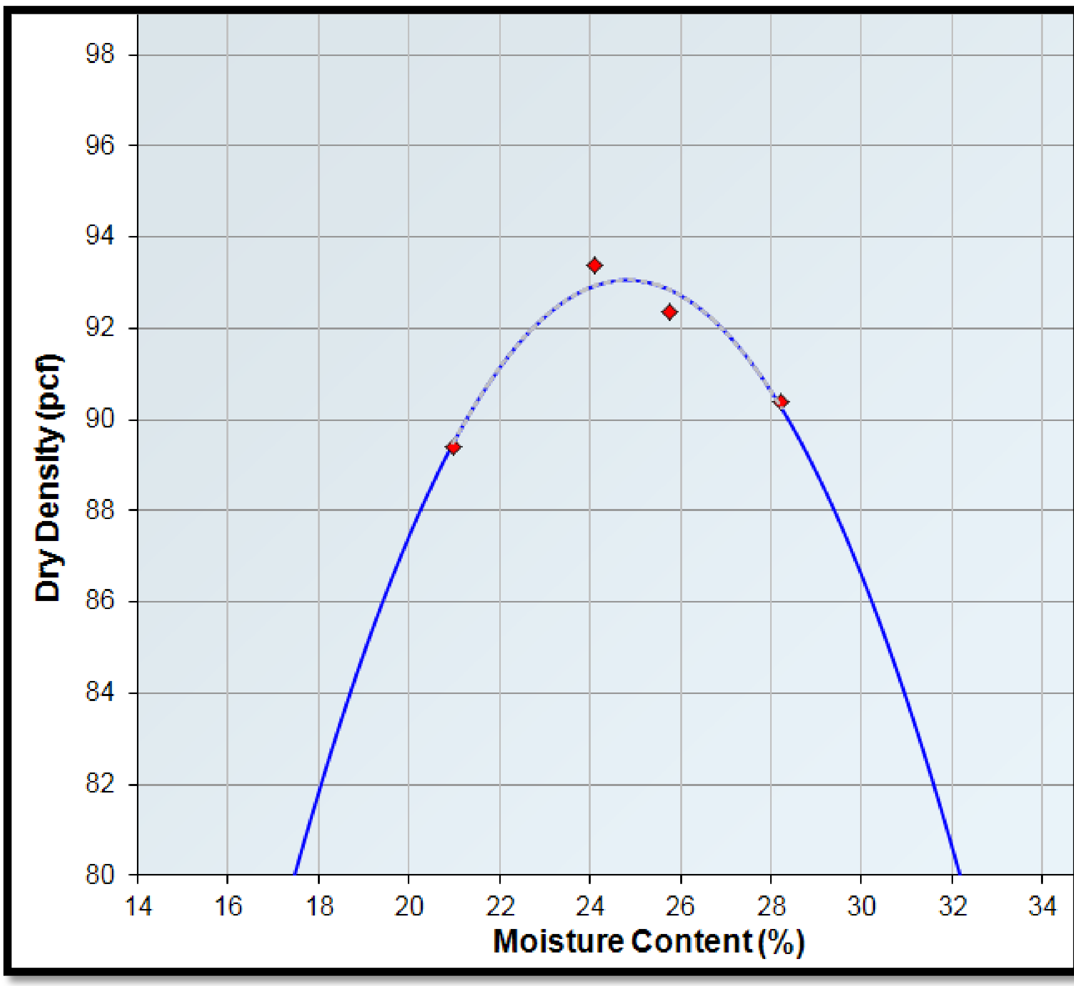

Figure 2. Tex-114-E Curve for US 82 Soil.

To perform the tests, first a calibration sequence was performed targeting moisture contents ranging from 22 to 31 percent. Both the MA and DOT 600 use passing No. 4 material. Figure 3 shows preparing and representative material prepared passing the No. 4 sieve. Figure 4 shows the calibration sequence results for the MA and DOT 600, respectively. The results indicated the MA tended to measure 3.5 percent higher than the oven dry, on average. The higher test temperature of the MA likely resulted in this occurrence, since at higher temperature clay interlayer water and even some minerals and organic matter may be burned off.

Figure 3. Preparing Passing No. 4 Material from US 82 for MA and DOT 600 Tests.

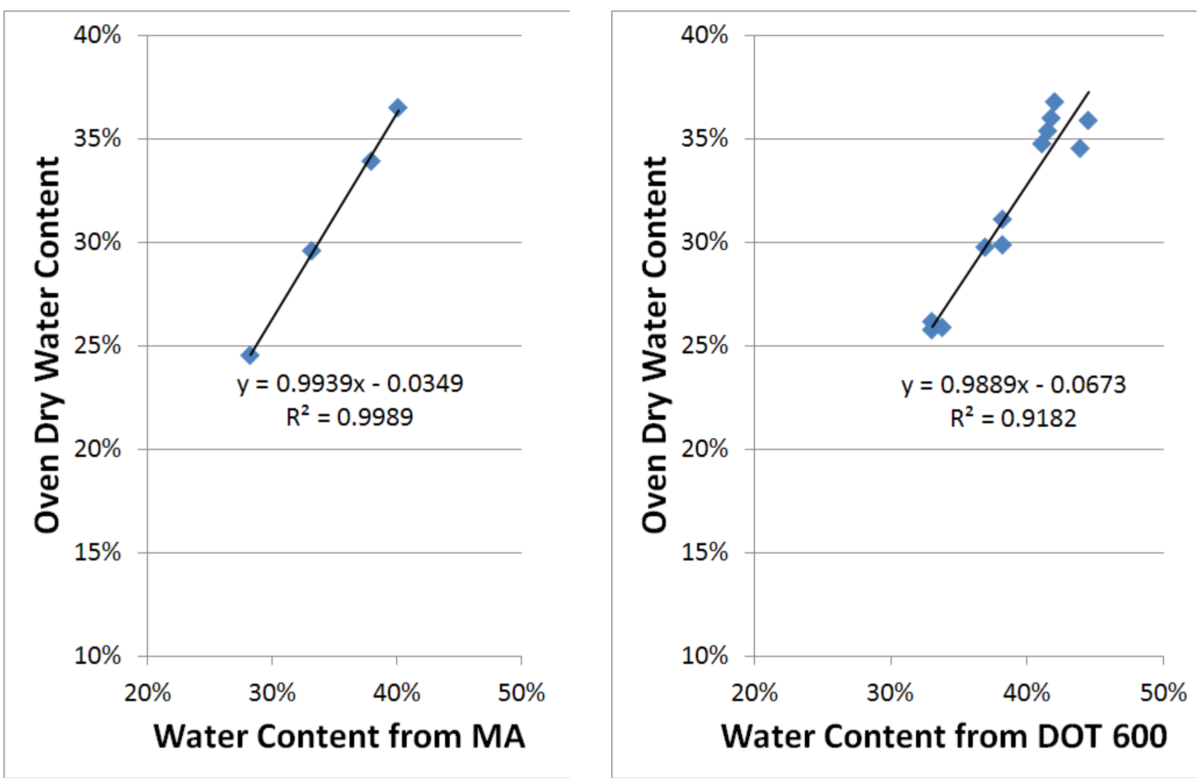

Figure 4. Calibration Results from MA and DOT 600 with US 82 Soil.

Based on the Tex-114-E results and field density control requirements for materials with PI > 35, to perform the moisture content tests the research team prepared batches of soil targeting moisture contents targeting 25 and 29 percent. Next, the batches were repetitively sampled and tested to generate the needed data for evaluation. The calibrations shown in Figure 4 were applied to the MA and DOT 600. Table 5 and Table 6 present the results from the low and high water contents, respectively.

Table 5. Water Content from Low Moisture Zone with US 82 Soil.

Test #	MA	DOT 600	Tex-103-E Oven Dry
1	24.5	27.4	25.8
2	24.4	26.1	25.4
3	24.4	26.1	25.0
4	24.8	24.8	25.6
5	24.5	24.9	26.0
6	24.6	26.8	25.8
7	24.9	27.6	25.1
8	24.4	26.4	24.3
9	24.5	30.6	24.5
10	24.3	28.3	24.7

Table 6. Water Content from High Moisture Zone with US 82 Soil.

Test #	MA	DOT 600	Tex-103-E Oven Dry
1	32.1	32.7	29.4
2	31.9	33.9	28.3
3	32.1	31.4	28.2
4	32.3	33.5	27.8
5	32.3	30.0	29.6
6	32.5	31.4	29.6
7	31.7	30.5	29.7
8	31.5	37.8	28.4
9	31.7	31.7	29.8
10	31.5	34.3	29.9

Subrage Soil from SH 21

The subgrade soil tested on SH 21 was part of a thick layer of embankment being constructed between STA 1743 and 1744. According to TxDOT, the Tex-114-E result was 95.7 pcf at 22.8 percent water. Tests for Atterberg Limits yielded the following:

- Liquid limit: 23.
- Plastic limit: 10.
- Plasticity index: 13.

To perform the tests, researchers first collected a field sample and performed a calibration sequence targeting moisture contents ranging from 19 to 28 percent. Figure 5 shows these calibration results for the MA and DOT 600, respectively. With the MA, statistical analyses show the calibration slope is not significantly different from 1.0, and the calibration intercept is not significantly different from 0. Therefore, all further test data from the MA with the SH 21 soil was used without applying any calibration factor. With the DOT 600, the calibration in Figure 4 was applied to all further test data.

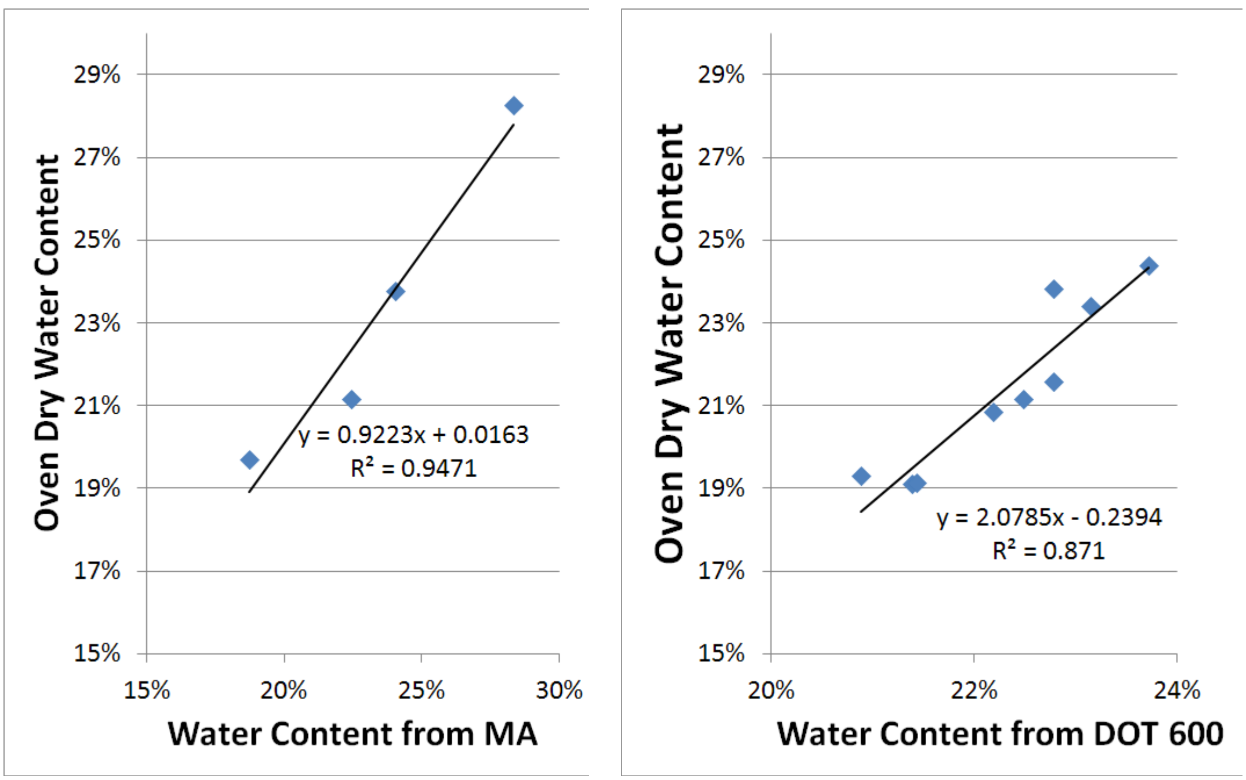

Figure 5. Calibration Results from MA and DOT 600 with SH21 Soil.

Researchers performed EDG calibration on site at 10 locations. Figure 6 shows researchers preparing the EDG test, and Table 7 presents the data used to develop the EDG soil model. The test depth was 8 inches. The EDG develops a soil model using the operator-input values of known wet density and water content for each location tested for the soil model. Figure 7 shows the result from the soil model.

Figure 6. Preparing EDG Test on SH 21.

Table 7. Data for Developing EDG Soil Model on SH 21.

Location	Nuke WD (pcf)	Tex-103-E Oven MC (%)	DD (pcf)
1	99.8	22.4	81.5
2	107.6	15.1	93.4
3	108.0	23.4	87.5
4	108.4	23	88.1
5	103.8	10.6	93.9
6	114.2	20.1	95.1
7	104.1	13.2	91.9
8	116.9	19.7	97.7
9	114.2	20.6	94.7
10	101.4	22.2	83.0

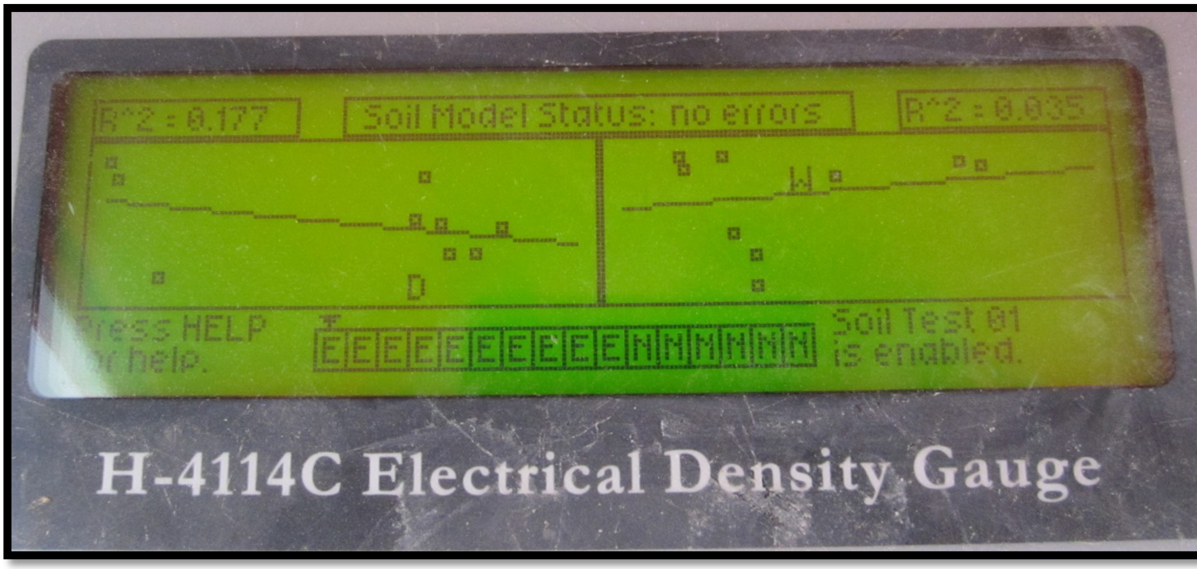

Figure 7. EDG Soil Model for SH 21.

After initial sampling and calibrations, the research team collected test data within zones of low and high water content to establish the measurements necessary for evaluating each moisture content-measuring device. Figure 8 shows the research team prepping a test area at the high water content zone. Table 8 presents the results from the low water contents, and Table 9 presents the results from the high water content. Note that even the high water content zone was below the Tex-114-E optimum.

Figure 8. Preparing Test Area at High Water Content Zone on SH 21.

Table 8. Water Content from Low Moisture Zone with SH 21 Soil.

Location	Nuke	EDG	DOT 600	Moisture Analyzer	Tex-113-E Oven Dry
1	17.4	19.4	25.1	19.4	11.8
2	19.0	18.9	26.1	20.4	11.6
3	17.9	18.6	27.3	20.1	16.2
4	17.1	18.7	24.9	19.2	14.6
5	17.1	19.2	25.4	19.0	15.4
6	17.3	19.5	24.0	18.4	15.7
7	21.4	19.4	26.6	22.0	18.1
8	19.9	19.4	27.2	22.6	17.1
9	18.7	19.1	27.6	22.3	12.6
10	19.6	18.9	26.4	21.3	11.8

Table 9. Water Content from High Moisture Zone with SH 21 Soil.

Location	Nuke	EDG	DOT 600	Moisture Analyzer	Tex-113-E Oven Dry
1	28.2	18.6	23.4	28.7	25.9
2	24.6	19.2	24.1	22.0	20.3
3	25.2	19.2	24.3	21.2	19.1
4	23.9	19.1	22.5	20.8	20.3
5	23.3	18.9	24.4	21.0	20.4
6	26.6	18.8	23.1	19.7	22.2
7	23.7	19.0	22.6	17.9	20.7
8	22.7	18.9	25.9	20.5	19.8
9	22.5	18.8	26.3	20.6	20.2
10	23.5	18.5	27.8	21.4	20.6

Subgrade Soil from US 67

The subgrade soil tested on US 67 was part of a thick layer of embankment being constructed between STA 1743 and 1744. According to TxDOT, the Tex-114-E result was 111.9 pcf at 16.6 percent water, and tests for Atterberg Limits yielded the following:

- Liquid limit: 48.
- Plastic limit: 18.
- Plasticity index: 30.

Figure 9 shows calibration test results between the MA, EDG, and oven dry values. All future test results with the MA and DOT 600 employed the calibrations shown in Figure 9.

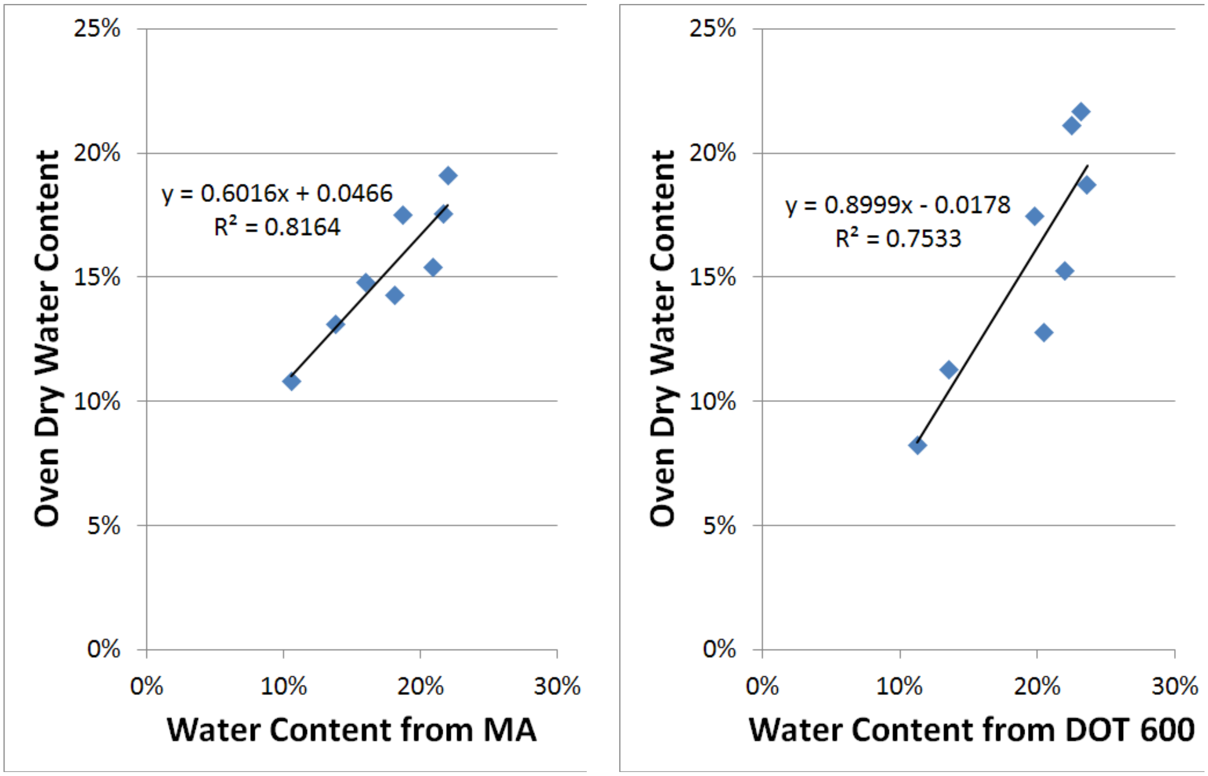

Figure 9. Calibration Results from MA and DOT 600 with US 67 Soil.

Table 10 presents the results for developing the EDG soil model on US 67. For consistency with TxDOT's field tests, nuclear tests were conducted at an 8-inch depth. However, the contractor was actually placing a 12 in. lift, so the EDG tests used 12 in. darts. Figure 10 presents the EDG soil model developed from the test data.

Table 10. Data for Developing EDG Soil Model on US 67.

Test	Nuke WD (pcf)	Tex-103-E Oven MC (%)	DD (pcf)
SM1	126.4	14.8	110.1
SM2	115.9	13.1	102.5
SM3&4	133.1	14.3	116.4
SM5	124	10.8	111.9
SM6	126.8	17.8	107.6
SM7	132.3	17.5	112.6
SM8	132.4	15.4	114.7
SM9	127.3	19.1	106.9

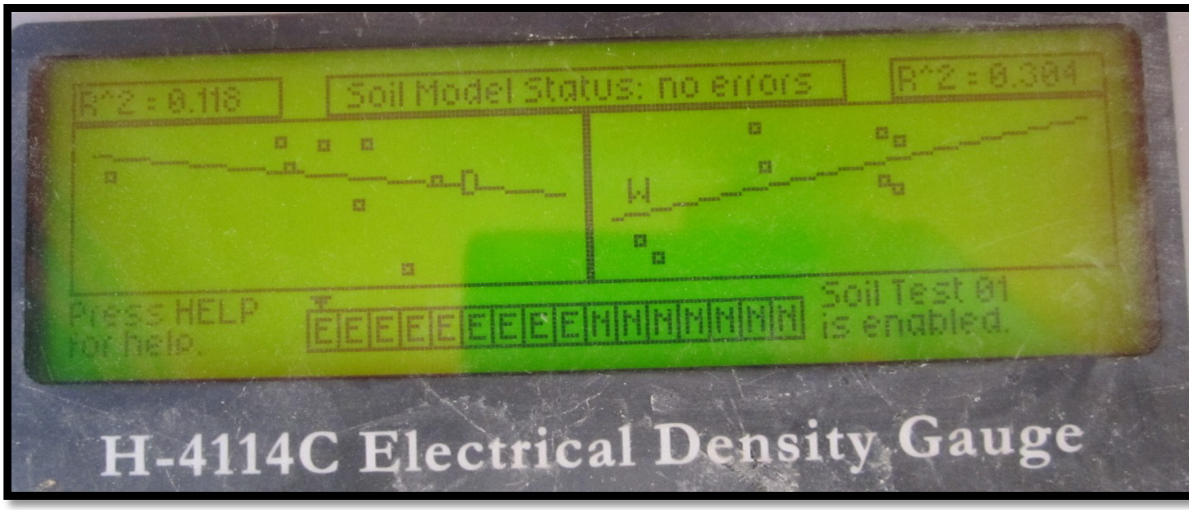

Figure 10. EDG Soil Model for US 67.

After initial sampling and calibrations, the research team collected test data within zones of low and high water content. Figure 11 shows the research team preparing for EDG testing and collecting physical samples. The research team found that, especially at the low water content areas, the EDG darts were extremely difficult to drive into the soil media.

Figure 11. Preparing for EDG Tests and Collecting Soil Samples on US 67.

Table 11 presents the results from the low water content areas, and Table 12 presents the results from the high water content areas. Even at the higher water content state, the actual oven dry values did not exceed the Tex-114-E optimum and the values were almost always within the range of water contents used for device calibrations.

Table 11. Water Content from Low Moisture Zone with US 67 Soil.

Location	Nuke	EDG	DOT 600	Moisture Analyzer	Oven
A12	12.5	13.6	9.3	12.4	12.9
A13	14.5	14.5	8.7	11.1	12.3
A14	16.4	13.9	14.6	14.8	16.1
B12	12.4	15	15.7	14.4	11.7
B13	10.4	13.2	9.5	11.1	10.4
B14	12.7	15.1	12.3	12.7	11.8
B15	10.3	12.6	7.6	10.6	9.4
C13	9.9	12.7	7.8	10.7	8.9
C14	15.3	15	15.7	13.5	12.2
C15	11.1	12.2	10.7	12.0	10.5

Table 12. Water Content from High Moisture Zone with US 67 Soil.

Location	Nuke	EDG	DOT 600	Moisture Analyzer	Oven
A22	14.94	14.4	19.5	15.6	13.5
A23	13.54	13.8	16.8	15.3	14.2
A24	14.47	15.3	20.8	16.3	16.5
B22	17.12	15.1	18.6	16.6	14.8
B23	15.43	14.6	15.9	14.5	14.7
B24	17.4	14.3	20.7	15.8	15.2
B25	16.75	16.7	22.1	17.0	15.7
C23	14.13	15.2	17.5	16.2	15.9
C24	16.4	14.1	19.8	16.4	13.9
C25	14.9	14.3	15.8	14.8	12.1

DATA FROM PROJECTS FOR PRECISION ANALYSIS

To develop inputs for precision analysis, select locations from each material were replicate tested with each device. For purposes of precision analysis, researchers clarified that a different level of treatment from a given source constitutes a new "material;" i.e., two different moisture contents from a given source is considered two separate materials for purposes of precision investigations.

Table 13 through Table 17 present the data generated for estimating precision. Since multiple lab results are not available, the precision analysis will not fully comply with ASTM E691. However, the results will be useful for estimating the repeatability of each test when replicate tests are performed within a given lab.

Table 13. Replicate Measurements from Materials Tested with Nuclear Gauge.

	Materials						
	I 35 Flexible Base			SH 21		US 67	
	Low	Medium	High	Low	High	Low	High
Replicate Test Results	5.6	7.8	10.7	19.4	23.5	No Replicate Tests Available	17.1
	5.2	8	10.9	18.5	22.6		16.4
	5.5	8.3	10.8	17.9	23		17.3

Table 14. Replicate Measurements from Materials Tested with EDG.

	Materials						
	I 35 Flexible Base			SH 21		US 67	
	Low	Medium	High	Low	High	Low	High
Replicate Test Results	6.7	7.9	9.2	18.6	18.5	13.6	15.1
	6.7	7.9	9.3	18.4	18.5	13.9	15.8
	6.7	7.9	9.4	18.4	18.5	14	16.1

Table 15. Replicate Measurements from Materials Tested with MA.

	Materials								
	I 35 Flexible Base			US 82		SH 21		US 67	
	Low	Medium	High	Low	High	Low	High	Low	High
Replicate Test Results	Not Applicable: used older test method	10.5	12.5	24.5	32.1	20.1	21.4	12.3	16.6
		10.6	12.6	24.4	31.9	20.2	21.3	12.6	16.3
		10.6	12.2	24.4	32.1	20	21.2	12.6	16.1
		This space intentionally left blank		24.8	32.3	This space intentionally left blank			
				24.5	32.3				
				24.6	32.5				
				24.9	31.7				
				24.4	31.5				
				24.5	31.7				
				24.3	31.5				

Table 16. Replicate Measurements from Materials Tested with DOT 600.

<table>
<tr><td></td><th colspan="9">Materials</th></tr>
<tr><td></td><th colspan="3">I 35 Flexible Base</th><th colspan="2">US 82</th><th colspan="2">SH 21</th><th colspan="2">US 67</th></tr>
<tr><td></td><th>Low</th><th>Medium</th><th>High</th><th>Low</th><th>High</th><th>Low</th><th>High</th><th>Low</th><th>High</th></tr>
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<tr><td colspan="3" rowspan="7">This space intentionally left blank</td><td>24.8</td><td>33.5</td><td colspan="4" rowspan="7">This space intentionally left blank</td></tr>
<tr><td>24.9</td><td>30.0</td></tr>
<tr><td>26.8</td><td>31.4</td></tr>
<tr><td>27.6</td><td>30.5</td></tr>
<tr><td>26.4</td><td>37.8</td></tr>
<tr><td>30.6</td><td>31.7</td></tr>
<tr><td>28.3</td><td>34.3</td></tr>
</table>

Table 17. Replicate Measurements from Materials Tested with Oven Drying.

<table>
<tr><td></td><th colspan="9">Materials</th></tr>
<tr><td></td><th colspan="3">I 35 Flexible Base</th><th colspan="2">US 82</th><th colspan="2">SH 21</th><th colspan="2">US 67</th></tr>
<tr><td></td><th>Low</th><th>Medium</th><th>High</th><th>Low</th><th>High</th><th>Low</th><th>High</th><th>Low</th><th>High</th></tr>
<tr><th rowspan="10">Replicate Test Results</th><td>9.6</td><td>13.3</td><td>11.8</td><td>25.8</td><td>28.5</td><td>14.4</td><td>20.6</td><td>12.9</td><td>14.8</td></tr>
<tr><td>9.5</td><td>12.9</td><td>11.5</td><td>25.4</td><td>29.3</td><td>16.2</td><td>22</td><td>12.2</td><td>17.2</td></tr>
<tr><td>9.5</td><td>13.6</td><td>11.4</td><td>25.0</td><td>29.0</td><td>16.7</td><td>21.4</td><td>11.7</td><td>16.8</td></tr>
<tr><td colspan="3" rowspan="7">Note: the above results are from the passing No. 4 since multiple oven dry tests of full gradation were not available</td><td>25.6</td><td>29.3</td><td colspan="4" rowspan="7">This space intentionally left blank</td></tr>
<tr><td>26.0</td><td>28.9</td></tr>
<tr><td>25.8</td><td>29.2</td></tr>
<tr><td>25.1</td><td>29.2</td></tr>
<tr><td>24.3</td><td>29.2</td></tr>
<tr><td>24.5</td><td>29.4</td></tr>
<tr><td>24.7</td><td>29.6</td></tr>
</table>

CHAPTER 2. EVALUATE BIAS, PRECISION, AND SENSITIVITY OF EACH TEST DEVICE

Data collected on field projects under Project 0-6676 focusing on the Electrical Density Gauge the DOT 600, and the moisture analyzer tests for moisture measurement allow for analysis of the bias, precision, and sensitivity of each device. Researchers used data processing techniques in ASTM D4855 to evaluate each device for bias and sensitivity. For bias analysis, the oven-dry values from Tex-103-E served as the reference value. Using replicate measurements from each device, researchers used methods in ASTM E691 to estimate the repeatability of each device. Since the testing did not include results from multiple labs, the results are not fully compliant with ASTM E691; however, the results are useful for comparing the devices and obtaining an indicator of within-lab precision.

Table 18 summarizes the results for bias. Despite prior calibrations to the materials, each of the new devices often exhibited bias.

Table 18. Summary of Bias Results.

Device	Observations from Bias Evaluations
Nuke	Generally unbiased; when biased not influenced by material level
EDG	Generally biased, with bias often influenced by level
MA	Mixed results, ranging from unbiased to biased, with bias influenced by material level
DOT 600	Generally biased, with bias often influenced by level

Table 19 summarizes the results for sensitivity. The sensitivity is an indicator of the response of the device to changing material levels relative to the device's precision.

Table 19. Average Sensitivity Values for Devices.

Device	Average Sensitivity
Nuclear Gauge	2.73
EDG	1.34
MA	8.40
DOT 600	0.90
Oven Dry	3.23

Table 20 summarizes the results for precision. The results show the EDG and MA are very precise relative to other methods investigated.

Table 20. Repeatability Estimates from Devices.

Device	Repeatability Limit
Nuclear Gauge	1.2
EDG	0.6
MA	0.4
DOT 600	2.2
Oven Dry	2.0

The remainder of this chapter presents the results from which Table 18 through Table 20 were developed.

RESULTS FOR BIAS AND SENSITIVITY

IH 35 Frontage Road

Table 21 and Table 22 present the results from the IH 35 frontage road project for the low and high moisture contents, respectively. Table 23 presents the p-values from testing whether each method is biased when compared to the oven dry values. The results show:

- The EDG was biased at both levels.
- The nuclear gauge was not biased.
- The DOT 600 not biased at the low level but was biased at the high level.
- The MA was unbiased.

Table 21. Results from Low Moisture Zone on IH 35 Frontage Road.

Location	EDG	Nuclear	DOT 600	MA	Oven Dry	
					Passing No. 4	Full Gradation
1	9.4	6.4	8.05	8.30	8.95	6.24
2	10.2	5.6	8.05	7.95	8.18	5.15
3	8.6	4.9	8.13	7.25	7.73	5.00
4	9.8	6.2	8.55	8.55	8.83	5.78
5	8.4	5.3	8.25	7.30	8.31	5.46
6	9.5	6.0	9.17	8.65	9.08	6.02
7	8.2	5.4	8.00	7.35	7.22	5.70
8	10.7	6.2	8.70	8.20	8.45	5.41
9	9.2	6.3	7.85	8.35	9.00	6.32
10	10.3	6.8	8.70	9.10	8.94	7.52
11	9.6	6.6	8.80	9.25	9.08	6.62
AVG	**9.4**	**6.0**	**8.4**	**8.2**	**8.5**	**5.9**
St. Dev	**0.80**	**0.60**	**0.42**	**0.69**	**0.62**	**0.73**

Table 22. Results from High Moisture Zone on IH 35 Frontage Road.

Location	EDG	Nuclear	DOT 600	MA	Oven Dry	
					Passing No. 4	Full Gradation
1	11.4	7.2	8.33	9.20	9.25	7.19
2	11.6	8.4	9.17	9.85	10.34	7.82
3	11.3	7.8	6.53	9.45	9.59	7.28
4	11.6	7.6	7.47	9.40	9.82	7.27
5	11.5	6.6	7.00	9.55	9.11	7.06
6	12.4	7.9	8.20	10.05	10.73	7.92
7	11.3	6.9	7.43	9.20	9.60	7.20
8	11.5	7.7	7.83	10.05	10.33	7.68
9	11.3	7.5	8.13	10.30	9.97	6.75
10	11.3	7.9	7.70	10.30	11.15	7.61
11	11.6	8.0	8.13	9.65	10.80	7.73
AVG	**11.5**	**7.6**	**7.8**	**9.7**	**10.1**	**7.4**
St. Dev	**0.32**	**0.52**	**0.71**	**0.41**	**0.66**	**0.37**

Table 23. P-Values from Testing Methods against Oven Dry for Bias from IH 35.

	p-values	
Method	Low Level	High Level
EDG	0.00	0.00
Nuclear	0.88	0.36
DOT 600	0.55	0.00
MA	0.27	0.17

Table 24 presents the results from investigating if bias varies by level for the EDG and DOT 600. The results show the bias did not vary by level with the EDG, while the bias did vary by level with the DOT 600.

Table 24. Summary of Statistics for Evaluating if Bias Varies by Level for IH 35.

	EDG	DOT 600
s2 diff	0.13	0.14
s diff	0.36	0.37
t-stat	1.68	5.72
p-value	0.10	0.00

The sensitivity of each device depends on both the precision of the device and its ability to measure differences in changes of the material level. Table 25 presents the sensitivities of each device. Analyses of these ratios per ASTM D4855 show:

- All devices were more sensitive than the DOT 600.
- The EDG was more sensitive than the MA.
- The EDG was more sensitive than the oven dry.
- No other differences in sensitivity existed.

Table 25. Sensitivities of Devices from IH 35 Data.

Method	Sensitivity
EDG	3.72
Nuclear	2.91
DOT 600	-1.02
MA	2.77
Oven Passing No. 4	2.40
Oven Full Gradation	2.71

Subgrade Soil from US 82

Table 26 presents the result from US 82 for both the low and high moisture content. Table 27 presents the p-values from testing whether each method is biased when compared to the oven dry values. The results show both the MA and DOT 600 were biased at each level, despite prior calibration tests to the material.

Table 26. Results from US 82.

Low Moisture Zone				High Moisture Zone			
Test #	**MA**	**DOT 600**	**Oven Dry**	**Test #**	**MA**	**DOT 600**	**Oven Dry**
1	24.5	27.4	25.8	1	32.1	32.7	29.4
2	24.4	26.1	25.4	2	31.9	33.9	28.3
3	24.4	26.1	25.0	3	32.1	31.4	28.2
4	24.8	24.8	25.6	4	32.3	33.5	27.8
5	24.5	24.9	26.0	5	32.3	30.0	29.6
6	24.6	26.8	25.8	6	32.5	31.4	29.6
7	24.9	27.6	25.1	7	31.7	30.5	29.7
8	24.4	26.4	24.3	8	31.5	37.8	28.4
9	24.5	30.6	24.5	9	31.7	31.7	29.8
10	24.3	28.3	24.7	10	31.5	34.3	29.9
AVG	24.6	26.9	25.2	**AVG**	32.0	32.7	29.1
St. Dev	0.19	1.69	0.59	**St. Dev**	0.35	2.29	0.80

Table 27. P-Values from Testing Methods against Oven Dry for Bias from US 82.

Method	p-values	
	Low Level	High Level
MA	0.00	0.00
DOT 600	0.01	0.00

Table 28 presents the results from investigating if bias varies by level. The results show the bias did vary by level with the MA, while the bias did not vary by level with the DOT 600.

Table 28. Summary of Statistics for Evaluating if Bias Varies by Level for US 82.

	MA	DOT 600
s2 diff	0.11	0.91
s diff	0.34	0.95
test statistic	-10.46	-2.08
p-value	0.00	0.05

Table 29 presents the sensitivities of each device from US 82. Analyses of these ratios per ASTM D4855 show:

- The MA was more sensitive than both the DOT 600 and the oven dry.
- The oven dry was more sensitive than the DOT 600.

Table 29. Sensitivities of Devices from US 82 Data.

Method	Sensitivity
MA	27.40
DOT 600	2.93
Oven	5.55

Subgrade Soil from SH 21

Table 30 and Table 31 present the result from SH 21 for the low and high moisture content zones, respectively. Table 32 presents the p-values from testing whether each method is biased when compared to the oven dry values. The results show that, with the exception of the MA at the higher moisture content, all the results from each device were biased.

Table 30. Results from Low Moisture Zone on SH 21.

Location	Nuke	EDG	DOT 600	Moisture Analyzer	Oven
1	17.4	19.4	25.1	19.4	11.8
2	19.0	18.9	26.1	20.4	11.6
3	17.9	18.6	27.3	20.1	16.2
4	17.1	18.7	24.9	19.2	14.6
5	17.1	19.2	25.4	19.0	15.4
6	17.3	19.5	24.0	18.4	15.7
7	21.4	19.4	26.6	22.0	18.1
8	19.9	19.4	27.2	22.6	17.1
9	18.7	19.1	27.6	22.3	12.6
10	19.6	18.9	26.4	21.3	11.8
AVG	18.5	19.1	26.1	20.5	14.5
St. Dev.	1.44	0.32	1.18	1.50	2.39

Table 31. Results from High Moisture Zone on SH 21.

Location	Nuke	EDG	DOT 600	Moisture Analyzer	Oven
1	28.2	18.6	23.4	28.7	25.9
2	24.6	19.2	24.1	22.0	20.3
3	25.2	19.2	24.3	21.2	19.1
4	23.9	19.1	22.5	20.8	20.3
5	23.3	18.9	24.4	21.0	20.4
6	26.6	18.8	23.1	19.7	22.2
7	23.7	19.0	22.6	17.9	20.7
8	22.7	18.9	25.9	20.5	19.8
9	22.5	18.8	26.3	20.6	20.2
10	23.5	18.5	27.8	21.4	20.6
AVG	24.4	18.9	24.4	21.4	21.0
St. Dev.	1.80	0.24	1.73	2.80	1.91

Table 32. P-Values from Testing Methods against Oven Dry for Bias from SH 21.

Method	p-values Low Level	p-values High Level
Nuke	0.00	0.00
EDG	0.00	0.00
MA	0.00	0.69
DOT 600	0.00	0.00

Table 33 presents the results from investigating if bias varies by level. The results show the bias did not vary by level with the nuclear gauge, while the bias did vary by level with the EDG, DOT 600, and MA.

Table 33. Summary of Statistics for Evaluating if Bias Varies by Level for SH 21.

	Nuke	EDG	DOT 600	MA
s2 diff	1.47	0.95	1.38	1.95
s diff	1.21	0.98	1.17	1.40
test statistic	0.48	6.84	6.89	3.98
p-value	0.64	0.00	0.00	0.00

Table 34 presents the sensitivities of each device from SH 21. These ratios show:

- The EDG and DOT 600 were insensitive to changing material levels (as the material level went up, the average value from these devices actually decreased).
- The nuclear gauge was more sensitive than the MA.
- The oven dry and nuclear gauge had equivalent sensitivity.

Table 34. Sensitivities of Devices from SH 21 Data.

Method	Sensitivity
Nuke	3.62
EDG	−0.75
DOT 600	−1.11
MA	0.42
Oven	3.01

Subgrade Soil from US 67

Table 35 and Table 36 present the result from US 67 for the low and high moisture content zones, respectively.

Table 37 presents the p-values from testing whether each method is biased when compared to the oven dry values. The results show:

- The nuclear gauge was unbiased.

- The EDG was biased at the low level but not at the high level.
- The MA was not biased at the low level but was biased at the high level.
- The DOT 600 was not biased at the low level but was biased at the high level.

Table 35. Results from Low Moisture Zone on US 67.

Location	Nuke	EDG	DOT 600	Moisture Analyzer	Oven
A12	12.5	13.6	9.3	12.4	12.9
A13	14.5	14.5	8.7	11.1	12.3
A14	16.4	13.9	14.6	14.8	16.1
B12	12.4	15	15.7	14.4	11.7
B13	10.4	13.2	9.5	11.1	10.4
B14	12.7	15.1	12.3	12.7	11.8
B15	10.3	12.6	7.6	10.6	9.4
C13	9.9	12.7	7.8	10.7	8.9
C14	15.3	15	15.7	13.5	12.2
C15	11.1	12.2	10.7	12.0	10.5
AVG	12.6	13.8	11.2	12.3	11.6
St. Dev.	2.22	1.09	3.18	1.52	2.04

Table 36. Results from High Moisture Zone on US 67.

Location	Nuke	EDG	DOT 600	Moisture Analyzer	Oven
A22	14.94	14.4	19.5	15.6	13.5
A23	13.54	13.8	16.8	15.3	14.2
A24	14.47	15.3	20.8	16.3	16.5
B22	17.12	15.1	18.6	16.6	14.8
B23	15.43	14.6	15.9	14.5	14.7
B24	17.4	14.3	20.7	15.8	15.2
B25	16.75	16.7	22.1	17.0	15.7
C23	14.13	15.2	17.5	16.2	15.9
C24	16.4	14.1	19.8	16.4	13.9
C25	14.9	14.3	15.8	14.8	12.1
AVG	15.5	14.8	18.8	15.9	14.7
St. Dev.	1.34	0.84	2.19	0.80	1.29

Table 37. P-Values from Testing Methods against Oven Dry for Bias from US 67.

Method	p-values Low Level	p-values High Level
Nuke	0.34	0.16
EDG	0.01	0.79
MA	0.39	0.02
DOT 600	0.72	0.00

For the devices that exhibited bias, Table 38 presents the results from investigating if bias varies by level. The results show the bias did vary by level with the EDG and DOT 600, but did not vary by level with the MA.

Table 38. Summary of Statistics for Evaluating if Bias Varies by Level for US 67.

	EDG	DOT 600	MA
s2 diff	0.77	2.07	0.88
s diff	0.88	1.44	0.94
test statistic	2.31	3.15	0.52
p-value	0.03	0.00	0.60

Table 39 presents the sensitivities of each device from US 67. These ratios show:

- The EDG had the worst sensitivity.
- The nuclear gauge and oven had equivalent sensitivities and were more sensitive than the EDG.
- The MA and DOT 600 had equivalent sensitivities and were the most sensitive of all devices.

Table 39. Sensitivities of Devices from SH 21 Data.

Method	Sensitivity
Nuke	1.66
EDG	1.04
DOT 600	2.82
MA	3.04
Oven	1.82

RESULTS FOR PRECISION

Table 40 through Table 44 present the results for repeatability estimates for the nuclear gauge, EDG, DOT 600, MA, and oven dry, respectively. The pooled standard deviations from repeat tests were:

- Nuclear gauge: 0.43.
- EDG: 0.21.
- DOT 600: 0.78.
- MA: 0.15.
- Oven dry: 0.70.

Table 40. Repeatability Estimates for Nuclear Gauge from Test Data.

	Materials					
	I 35 Flexible Base			SH 21		US 67
	Low	Medium	High	Low	High	High
Replicate Test Results	5.6	7.8	10.7	19.4	23.5	17.1
	5.2	8	10.9	18.5	22.6	16.4
	5.5	8.3	10.8	17.9	23	17.3
AVG	5.4	8.0	10.8	18.6	23.0	16.9
St. Dev.	0.21	0.25	0.10	0.75	0.45	0.47
Repeatability Limit	0.58	0.70	0.28	2.11	1.26	1.32
Pooled St. Dev.	0.43					
Pooled Repeatability Limit	1.2					

Table 41. Repeatability Estimates for EDG from Test Data.

	Materials						
	I 35 Flexible Base			SH 21		US 67	
	Low	Medium	High	Low	High	Low	High
Replicate Test Results	6.7	7.9	9.2	18.6	18.5	13.6	15.1
	6.7	7.9	9.3	18.4	18.5	13.9	15.8
	6.7	7.9	9.4	18.4	18.5	14	16.1
AVG	6.7	7.9	9.3	18.5	18.5	13.8	15.7
St. Dev.	0.00	0.00	0.10	0.12	0.00	0.21	0.51
Repeatability Limit	0.00	0.00	0.28	0.32	0.00	0.58	1.44
Pooled St. Dev.	0.21						
Pooled Repeatability Limit	0.59						

Table 42. Repeatability Estimates for DOT 600 from Test Data.

	Materials								
	I 35 Flexible Base			US 82		SH 21		US 67	
	Low	Medium	High	Low	High	Low	High	Low	High
Replicate Test Results	8.2	10.2	18.2	27.4	32.7	27.7	27.8	9.3	18.6
	8.1	9.6	18.5	26.1	33.9	26.5	27.5	9.7	17.7
	7.1	9.6	17.4	26.1	31.4	25.8	25.6	9.4	18.0
AVG	7.8	9.8	18.0	26.5	32.7	26.7	27.0	9.5	18.1
St. Dev.	0.61	0.35	0.57	0.74	1.24	0.96	1.19	0.21	0.46
Repeatability Limit	1.70	0.97	1.59	2.08	3.46	2.69	3.34	0.58	1.28
Pooled St. Dev.	0.78								
Pooled Repeatability Limit	2.18								

Table 43. Repeatability Estimates for MA from Test Data.

	Materials							
	I 35 Flexible Base		US 82		SH 21		US 67	
	Medium	High	Low	High	Low	High	Low	High
Replicate Test Results	10.5	12.5	24.5	32.1	20.1	21.4	12.3	16.6
	10.6	12.6	24.4	31.9	20.2	21.3	12.6	16.3
	10.6	12.2	24.4	32.1	20	21.2	12.6	16.1
AVG	10.6	12.4	24.5	32.0	20.1	21.3	12.5	16.3
St. Dev.	0.06	0.21	0.06	0.11	0.10	0.10	0.17	0.25
Repeatability Limit	0.16	0.58	0.16	0.32	0.28	0.28	0.48	0.70
Pooled St. Dev.	0.15							
Pooled Repeatability Limit	0.42							

Table 44. Repeatability Estimates for Oven Drying from Test Data.

	Materials								
	I 35 Flexible Base			US 82		SH 21		US 67	
	Low	Medium	High	Low	High	Low	High	Low	High
Replicate Test Results	9.6	13.3	11.8	25.8	28.5	14.4	20.6	12.9	14.8
	9.5	12.9	11.5	25.4	29.3	16.2	22	12.2	17.2
	9.5	13.6	11.4	25.0	29.0	16.7	21.4	11.7	16.8
AVG	9.5	13.3	11.6	25.4	28.9	15.8	21.3	12.3	16.3
St. Dev.	0.06	0.35	0.21	0.40	0.40	1.21	0.70	0.60	1.29
Repeatability Limit	0.16	0.98	0.58	1.12	1.13	3.39	1.97	1.69	3.60
Pooled St. Dev.	0.70								
Pooled Repeatability Limit	1.96								

CHAPTER 3. RECOMMEND NEW TEST DEVICE(S) AND METHOD(S)

Based on the precision, bias, sensitivity, cost, turnaround time, and suitability for use on materials, the data show the moisture analyzer as the most suited device for implementation. Table 45 and Table 46 present the scoring method and scores for each of the devices, respectively. A draft test method follows in this chapter after Table 46. In addition to these scoring and test method items, other important considerations include:

- Driving the EDG darts into untreated compacted materials that were significantly dry of optimum was quite difficult in the field.
- During the course of testing, the DOT 600 scale quit working one time, and later in the course of evaluations, the threaded device in the DOT 600's test chamber used to apply appropriate pressure to the test specimen stripped out, rendering the device inoperable.
- While the moisture analyzer is the most implementable of the alternative devices tested, the moisture analyzer only tests passing number 4 materials. Therefore, for construction materials that retain a significant percentage on the number 4 sieve such as flexible bases, TxDOT's specification approach to moisture control would have to change. The most likely approach would be to use the moisture content of the passing No. 4 material when the bulk aggregate matrix is at the Tex-113-E-determined optimum.
- Results in Table 46 are not intended to imply that the oven dry test is inferior, as clearly that test is the accepted reference standard. The oven dry method is included in Table 46 for comparative purposes, and its relatively low score is due simply to its slow turnaround time in context of the speed of measurement desired in this project.

Table 45. Parameters for Ranking Devices.

Parameter	Scoring
Precision (~18%)	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 (~18%)	6: unbiased 5: generally unbiased; when biased not influenced by material level 4: biased, with bias not related to level of property 2: biased, with bias sometimes related to level of property 0: biased, with bias related to level of property
Sensitivity (~18%)	6: sensitivity > 3.5 < 4 5: sensitivity > 3 < 3.5 4: sensitivity > 2.5 < 3 3: sensitivity > 2.0 < 2.5 2 sensitivity > 1.5 < 2.0 1: sensitivity > 1.0 < 1.5 0: sensitivity < 1
Cost (~12%)	4: < $1,000 3: $1,000–$3,000 2: $3,000–$5,000 1: $5,000–$10,000 0: > $10,000
Turnaround Time (~12%)	4: < 15 min. 3: 15–30 min. 2: 30–60 min. 1: 1–2 hr. 0: > 2 hr.
Suitability for Uncompacted Materials (~12%)	4: yes 2: with special accommodations, which could include leveling the surface 0: no
Suitability for Compacted Materials (~12%)	4: yes 2: with special accommodations, which could include special sensor installation requirements 0: no

Table 46. Scoring of Devices.

Parameter	EDG	Nuclear	DOT 600	Moisture Analyzer	Oven
Precision	4	2	0	5	1
Bias	2	5	2	2	6
Sensitivity	1	4	0	3	5
Cost	1	0	2	3	1
Turnaround Time	4	4	4	3	0
Suitability for Uncompacted Materials	4	4	4	4	4
Suitability for Compacted Materials	4	4	4	4	4
Total	**20**	**23**	**16**	**24**	**21**
Total (%)	**59**	**68**	**47**	**70**	**62**

APPENDIX

Test Procedure for
GRAVIMETRIC WATER CONTENT USING MOISTURE ANALYZER

Draft

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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.

4.15 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.