ASSESSMENT OF THE MOISTURE DENSITY INDICATION FOR THE CONSTRUCTION QUALITY CONTROL OF COMPACTED DENSE GRADED AGGREGATE BASE LAYERS

September 2007

Prepared by Hudson Jackson, PhD, P.E

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1.0 Introduction

The objective of this study was to determine the suitability of using the Moisture Density Indication (MDI) in the construction quality control of compacted dense aggregate base layers. New Jersey Department of Transportation currently uses the nuclear density gauge to measure the dry density and moisture contents of compacted fills and base layers in its construction control program. Measurements from the MDI were therefore compared to those from the nuclear gauge.

The underlying principle of operation of the is Time Domain Reflectometry in which the apparent dielectric constant and bulk electrical conductivity are measured, and correlated to moisture content and density. The MDI used in the study was manufactured by Durham Geo Slope Indicator, and based on the University of Purdue TDR method. The test method is ASTM approved (ASTM D 6780).

Field testing was conducted on five sites that consisted of dense graded aggregates base layer as well as on some NJDOT designated I-9 porous fill materials. Limited testing was also done using an Electric Density Gauge (EDG) manufactured by EDG, LLC. The results on the field testing are presented in this report.

1.1 Basic Theory of the Time Domain Reflectometry Method

In general, TDR testing involves sending a fast-rising voltage pulse through a coaxial cable. The pulse passes through the sample and is reflected back through the coaxial cable. By measuring the electrical properties, moisture content and densities can be obtained.

The Purdue TDR setup is illustrated in Figure 1.0.

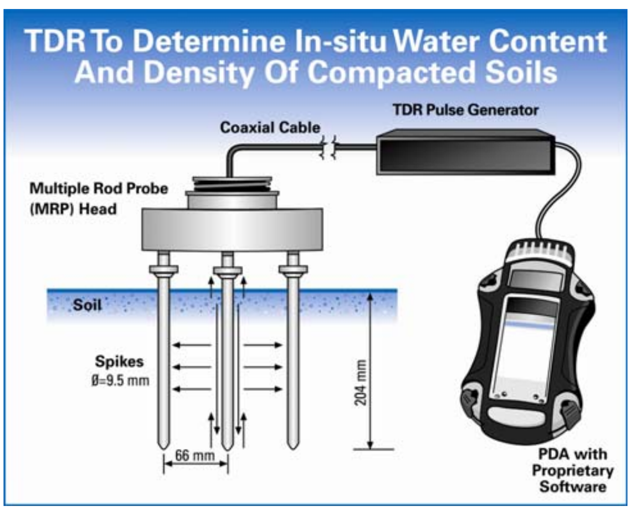


Figure 1.0: Purdue TDR Setup (MDI Manual from Durham GeoSlope)

The voltage pulse travels through the sample at a rate or velocity that is proportional to the apparent dielectric contact K_a. The surface waves that are generated propagate along the buried spikes and are attenuated in proportion to the electrical conductivity EC_b along the travel path. In the Purdue method, Drnevich developed linear relationships between these two properties and the moisture content and dry density of the sample. The straight-line relationships are presented below. More details of the theory can be found in references.

$$\sqrt{\boldsymbol{K}_a} * (*\rho_w/\rho_d) = a + bw \qquad 1.0$$

$$\sqrt{\boldsymbol{EC}_b} * (*\rho_w/\rho_d) = c + dw \qquad 2.0$$

$$\sqrt{\boldsymbol{EC}_b} = f + g\sqrt{\boldsymbol{K}_a} \qquad 3.0$$

Where K_a is the apparent dielectric constant, EC_b is the electrical conductivity, ρ_w is the density of water ρ_d is the dry density and *w* the moisture content of the sample. *a, b, c, f* and *g* are constants.

Simultaneously solving these equations, yield:

$$\rho_d = (d\sqrt{\boldsymbol{K}_a} - b\sqrt{\boldsymbol{EC}_b})/(ad - cd) \qquad 4.0$$

$$w = (c\sqrt{\boldsymbol{K}_a} - a\sqrt{\boldsymbol{EC}_b}) / (b\sqrt{\boldsymbol{EC}_b} - d\sqrt{\boldsymbol{K}_a}) \qquad 5.0$$

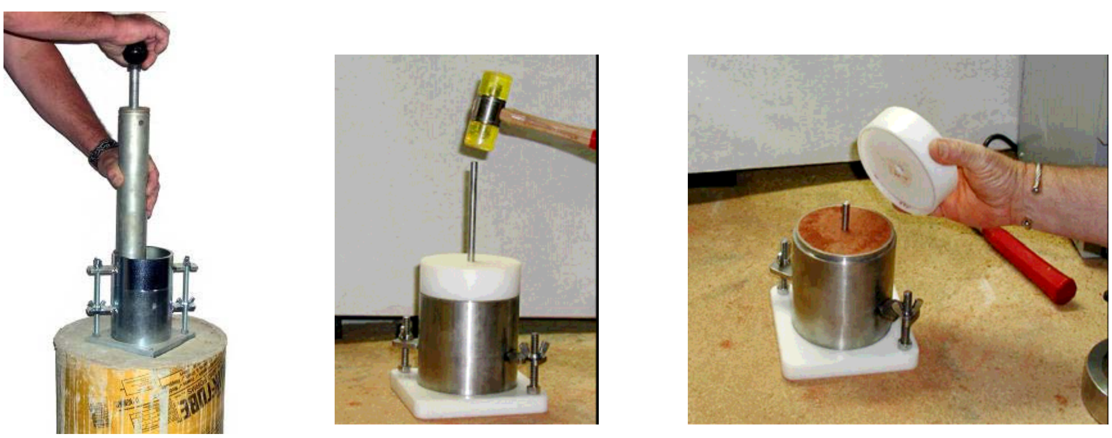
Equations 4.0 and 5.0 are the main equations used in the one- step method. It should be noted that a correction is required if the soil temperature is different from 68^{o}F; details of which are presented in reference 1 and 3. The soil constants are determined in the laboratory during the calibration procedure.

At the time of preparing this report, Rutgers did not receive any documentation on the equations and or the theory of operation from the manufacturer of the Electrical Density Gauge. However, it is understood that the EDG also operates under the TDR principle.

2.0 Laboratory Calibration-Determination of Soil Constants

In order to determine the calibration constants for the different samples, each sample was prepared as per ASTM D698. It should be noted that the maximum sizes of the DGA samples were greater than that allowed for Method A. However, the current set up for the calibration made available to Rutgers does not include a 6 inches compaction mold. The 4 inches mold provided was therefore used and sample prepared as per method A of ASTM D698. The calibration consisted of the following steps:

1. Air dry sample
2. Sieve sample through No. 4 sieve for ASTM D698 method A
3. Wet soil at different water contents to cover the range of moisture content expected in the field
4. Compact the soil in the 4-in mold mounted (Figure 2.1a) on a standard steel base as per ASTM D698 using standard compaction energy.
5. Weigh mold and soil and record as per ASTM D698.
6. Attach the mold to the non-conductive base and drive the center rod (rod must be clean) through the center of the non-conductive top template or guide (Figure 2.1b).
7. Remove guide, clean shoulder at the top of the mold, place mold collar and seat the Coaxial head on the adapter ring (Figures 2.2a). Be sure to rotate the ring and coaxial head to ensure good electrical contact.
8. Take TDR readings (Figure 2.2b) for each compaction test. A minimum of four tests is recommended.
9. After determination of the moisture content, the results of the compaction tests (dry density, TDR readings and moisture contents) can be input into the PDA software to determine the soil constants as per manufacturer's instructions. The soil constants can also be determined using the Excel template provided by the manufacturer (www.DurhamGeo.com/mdi).



(a) (b) (c)

Figure 2.1: Compaction of Sample (a), Insertion of Center Rod (b) and Removal of non-conductive top template (c)

(a) (b)

Figure 2.2: Placing of MRP Head (a) and Taking TDR Reading (b)

2.1 Calibration Results

A total of five samples from three DOT construction sites were tested. Samples were obtained from the following projects:

1. Route 206 expansion-Dense graded aggregate (DGA) samples (Southern Region)
2. Route 30 and Delilah road-NJDOT I-9 porous fill (Southern Region)
3. I-78 rehabilitation/expansion-Recycled concrete DGA sample (Northern Region)
4. I-78 rehabilitation/expansion-NJDOT I-9 porous fill (Northern Region)
5. Route 46 rehabilitation-DGA samples (Northern Region)

Photos of the samples used for the laboratory tests are shown in Figures 2.3 to 2.6.

(a) (b)

Figure 2.3: Route 206 DGA Sample (a) Passing Sieve No.4 and (b) Retained on Sieve No.4

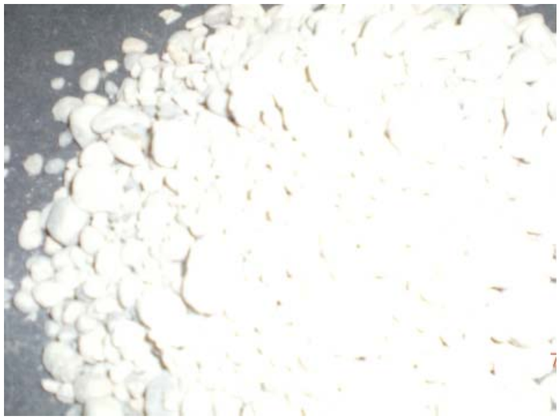


Figure 2.4: Route 30 and Delilah Road Porous I-9 Sample

(a) (b)

Figure 2.5: I-78 Samples (a) Recycled Concrete DGA and (b) Porous I-9 Fill

Figure 2.6: Route 46 DGA Sample

As previously mentioned, the purpose of the laboratory calibration is to determine the soil constants a, b, c, d, f and g required for the One-step method. These constants were determined based on the straight-line relationships discussed in section 1.1. Very good fits were obtained with R^2 ranging from 0.92 to 0.99. Table 2.1 is a summary of the soil constants. Sample plots for Route 206 are presented in Figures 2.7 to 2.9.

Table 2.1. Summary of Soil Constants

Sample	a	b	c	d	f	g
Rt. 206 DGA	0.9135	9.397	0.0156	0.3351	-0.0324	0.0347
Rt. 30/Delilah Road	0.8924	9.1568	0.0254	0.1417	0.0208	0.0155
I-78 DGA	0.1779	15.542	-0.0061	0.7543	0.0163	0.0466
I-78 I-9 Porous Fill	1.0817	8.9411	0.0786	0.9067	-0.05	0.0997
Rt. 46 DGA	0.7415	10.636	0.0032	0.0989	-0.0669	0.0623

The PDA software has the capability to automatically determine these constants and the user has to link them to the appropriate calibration file for field testing.

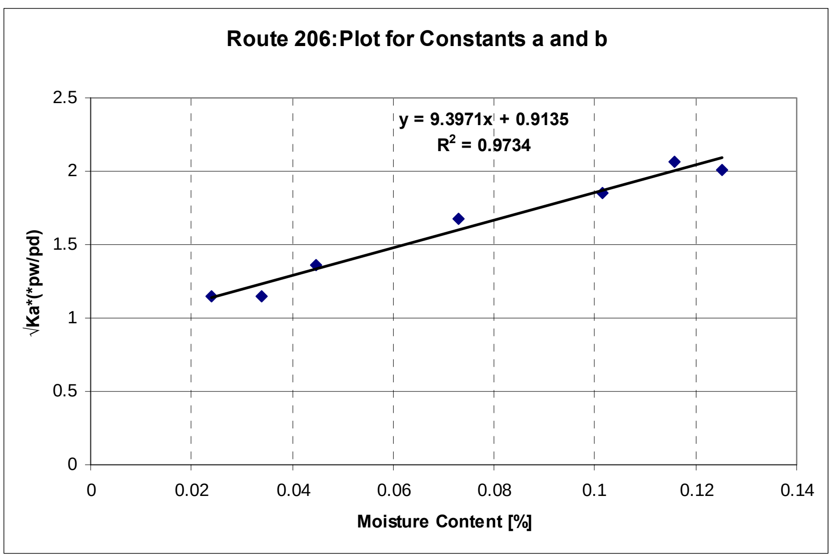


Figure 2.7: Route 206 Determination for constants a and b

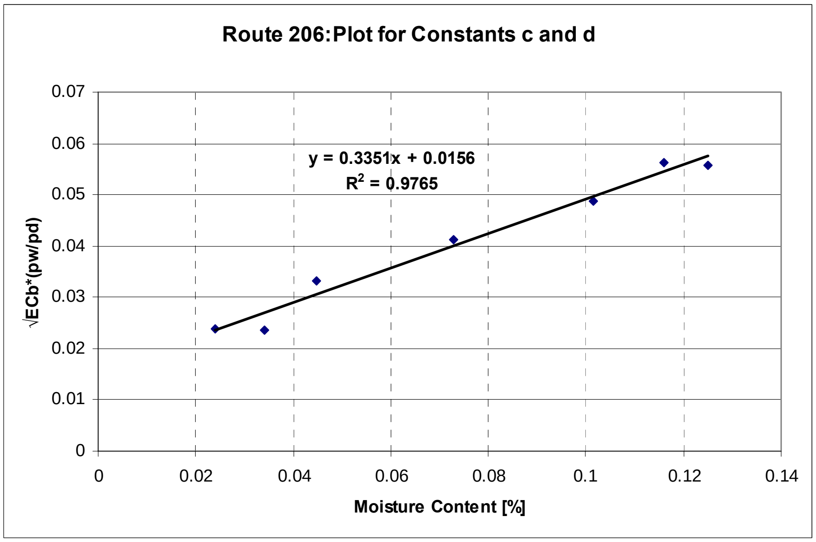


Figure 2.8: Route 206 Determination for constants c and d

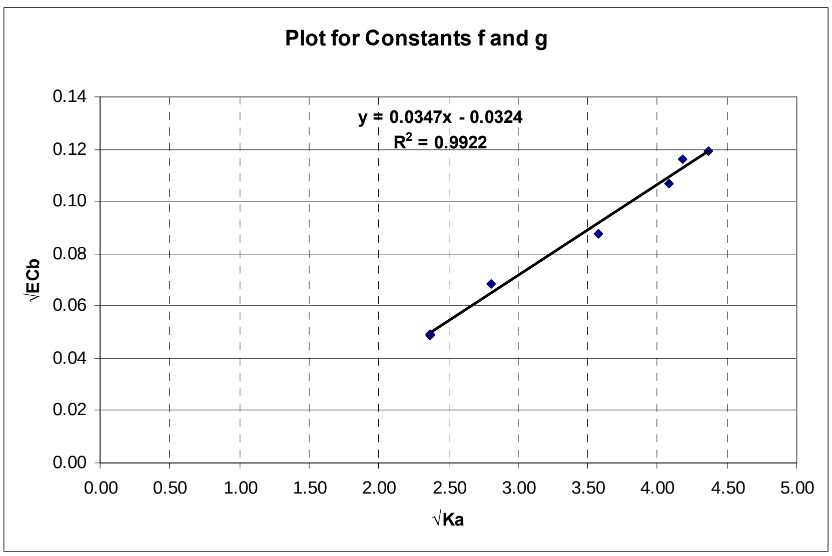


Figure 2.9: Route 206 Determination for constants f and g

3.0 Field Testing

After the calibration constants were determined configuration files were setup for the various projects. Field testing was conducted using the One-Step method because of the ease in the field. The field operations included testing using a Nuclear Density Gauge, Geo Slope MDI-2000 and the Humboldt Electrical Density Gauge (EDG). Photos of the setup for each device are shown in Figures 3.1 to 3.3.

Figure 3.1: Nuclear Gauge Setup

Figure 3.2: Moisture Density Indicator-MDI 2000 Setup

Figure 3.3: Electric Density Gauge Setup

Only limited testing was done using the EDG because the current setup does not include a procedure to determine the soil models in the laboratory. A simple field calibration procedure was used for the EDG in which sections of the field were soaked with different amounts of water and the calibration done using the nuclear gauge. Due to the fact that the purpose of this study is to compare the results of the non-nuclear devices with the nuclear gauge, it was felt that this calibration procedure produced biased results. Hence much confidence should not be placed in the results. This is not to imply that the EDG is not a viable method for compaction quality control, but that the current setup needs to be improved to ease its application. The results are therefore not discussed further.

The one-step method was conducted at project site as per manufacturer's procedure and the results from the nuclear gauge at the same locations recorded for comparison. Nuclear gauge readings were taken at a depth of approximately 9 inches equal to the length of the field spikes. The one-step field testing with the MDI included the following steps:

- Prepare soil surface
- Place template and drive in spikes
- Remove template
- Position the multiple rod probe (MRP) head on top of spikes
- Connect MRP to MDI and PDA
- Open configuration file and take TDR reading. Record temperature and apply correction
- Observe waveform to ensure good signal and save file

3.1 Field Results and Comparison

The results of the field tests (dry density and moisture content) are summarized in Table 3.1. The difference between the results of the nuclear gauge and the MDI are shown in Table 3.2.

Table 3.1 Field Dry Densities and Moisture Contents from Various Devices

	Test	Nuclear Gauge		MDI		EDG	
		Dry Density [pcf]	Moisture content [%]	Dry Density [pcf]	Moisture content [%]	Dry Density [pcf]	Moisture content [%]
Route 206 (DGA)	1	130.0	2.1	126.8	2.3	Not tested	Not tested
	2	138.0	3.0	127.6	3.4	Not tested	Not tested
	3	131.1	2.4	127.1	2.6	Not tested	Not tested
	4	140.0	3.2	127.4	3.1	Not tested	Not tested
Rt.30/Delilah Road (I-9 Porous Fill)	1	114.3	3.8	111.9	2.5	111.5	3.7
	2	114.2	3.5	111.9	3.2	111.0	3.6
	3	115.9	3.3	111.9	3.1	110.9	3.6
	4	110.8	4.0	111.9	3.3	111.4	3.6
	5	111.8	4.1	111.9	2.8	111.2	4.2
I-78 (DGA)	1	117.8	9.8	105.9	9.9	Not tested	Not tested
	2	116.1	9.3	105.9	9.8	Not tested	Not tested
	3	120.2	9.9	106.1	10.1	Not tested	Not tested
I-78 (I-9 Porous Fill)	1	131.9	3.8	109.3	4.8	137.3	4.3
	2	137.0	3.8	109.7	5.4	137.8	4.4
	3	133.0	3.7	108.5	3.4	134.0	4.3
Rt. 46 (DGA)	1	117.5	7.9	104.0	7.9	123.4	8.5
	2	116.5	8.7	103.3	7.1	123.4	9.0
	3	119.2	6.1	101.6	5.1	123.4	9.1

Table 3.2 Summary Percent Differences between Nuclear Gauge and MDI

	Test	Nuke –MDI		Nuke-MDI	
		Difference Dry Density [pcf]	Difference Moisture content [%]	Percent Difference Dry Density [%]	Percent Moisture content [%]
Route 206 (DGA)	1	3.2	-0.2	2.5	-9.5
	2	10.4	-0.4	7.5	-13.3
	3	4.0	-0.2	3.1	-8.3
	4	12.6	0.1	9.0	3.1
	AVG	7.6	-0.2	5.5	-7.0
Rt.30/Delilah Road (I-9 Porous Fill)	1	2.4	1.30	2.10	34.21
	2	2.3	0.30	2.01	8.57
	3	4	0.20	3.45	6.06
	4	1.1	0.70	-0.99	17.50
	5	0.1	1.30	-0.09	31.71
	AVG	1.98	0.76	1.30	19.61
I-78 (DGA)	1	11.90	-0.10	10.10	-1.02
	2	10.20	-0.50	8.79	-5.38
	3	14.10	-0.20	11.73	-2.02
	AVG	12.07	-0.27	10.21	-2.81
I-78 (I-9 Porous Fill)	1	22.60	-1.00	17.13	-26.32
	2	27.30	-1.60	19.93	-42.11
	3	24.50	0.30	18.42	8.11
	AVG	24.80	-0.77	18.49	-20.10
Rt. 46 (DGA)	1	13.50	0.00	11.49	0.00
	2	13.20	1.60	11.33	18.39
	3	17.60	1.00	14.77	16.39
	AVG	14.77	0.87	12.53	11.59

3.2 Discussion of Test Results

In general, the moisture content results of the MDI and the nuclear gauge are close but average differences in the dry density results varies from 1.98 to 14.77 pcf or 1.3% to 12.53%. Results from Route 30/Delilah road show the closest agreement in the dry density and Route 206 the closest agreement in moisture content. The MDI seems to be insensitive to the changes in the dry density measured at different locations along the site compared to those recorded by the nuclear gauge. In order words, the MDI records consistent (or the same) dry density throughout the site while those for the nuke gauge show a wider spread or more variation.

The aggregate gradations for the I-9 porous fill samples are within the range application of the MDI. The results for Delilah road show better agreement with the nuclear gauge than those from I-78. These samples were very porous and some problems were encounter in the lab during the compaction tests. The aggregate particles seem to absorb the water and release them into the mold during compaction. There were instances in which water oozed out of the sample after compaction and a drop in the weight was difficult to achieve ever after repeated attempts.

As previously mentioned, the 4" mold used in the lab to determine the constants and the constants were developed with samples finer than the No.4 sieve (4.75mm). The differences may be related to the (passing # No.4) samples not being representative of the true electrical conductivity and dielectric properties of the insitu compacted DGA aggregate base layers. The continuity and quality of the electrical response would also be affected by the amount of void within the aggregate layer (s) due to the larger size of the particles. Although the method seems to be applicable to some aggregate samples, the maximum aggregate size should be limited to ¾'' as indicated by Drnevich (1) to allow use of the 4" compaction mold.

Additionally, especially for Route I-78 and Route 46 DGA, it was observed that the samples tested in the laboratory were much cleaner than the compacted insitu materials. It would be expected that the overall electric response/properties would be much different especially if the "dirt" is of a different composition compared to that of the aggregates particles.

In reference 1, it is stated that: "The TDR method can be used with coarse-textured soils where ***30%*** by weight of the material ***has particle sizes exceeding the No. 4 sieve (4.75 mm) and the maximum particle size passes the ¾-inch sieve (19 mm).*** Most of the research and beta testing performed to date has been conducted on soils with limited gravel permitting the use of 4-inch diameter compaction molds and probe placement diameter. Equipment and procedures have not been fully developed for 6-inch diameter molds and probe placement. Nor do we have experience with problems that might be associated with driving the four probes in heavily compacted aggregates common to base course used in pavements." -Drnevich, et. al (1). These statements indicate some limitations of the current MDI setup. Due to these limitations, the results for the dense graded aggregate (DGA) samples with more than 30% retained on sieve No. 4 maybe not be reliable.

The following problems were encountered during field testing on the DGA base layers and during the laboratory calibration:

- Difficulty in driving the spikes into the aggregate base. A much larger hammer was required and it took more than 15 minutes per test to drive the spikes. Some of the spikes got slightly crooked or bent in the process.
- The size (diameter) of the spikes is too small for use in testing DGA pavement base layers. Larger spikes of a least 1" diameter would be more suitable as this would enhance driving into compacted aggregate base.
- Difficulty in removing the template after driving spikes. Release pin was hard to remove. Even after the pin was removed, getting template off was a problem due to the large aggregate sizes. Had to dig around the edges to remove.
- On several occasions, there was a problem getting a suitable signal even though the MRP head had perfect contact with the rods.
- The equipment froze on several occasions during lab and field testing and the PDA had to reset/rebooted to overcome the problem.

4.0 Conclusions and Recommendations

An evaluation of the MDI developed by the University of Purdue and manufactured by Durham GeoSlope conducted for the NJDOT to determine its suitability for use in the construction control of mostly dense graded aggregate base layers. The one-step method because of is ease and expediency in the field was favored over the two-step method.

Field evaluation involved the collection of density and moisture contents from five different project sites that consisted of either compacted dense graded aggregate base layers and or compacted porous fills. Dry densities and moisture contents measured with the MDI were compared with those from nuclear density gauges. In general, both the nuclear gauges and the MDI recorded very similar moisture contents. However, differences of up to 12.53% were observed in the dry density measurements. For the most part, the dry densities recorded by the MDI were less than those from the nuclear gauges. Better agreements were obtained for the moisture content.

The required calibration constants were determined using a 4-in mold after sieving through sieve no.4. Due to the large size of the DGA, a 6-in mold as per ASTM, would have been more suitable for the sample sizes. However, the 6-in mold laboratory calibration setup is not available when the study was conducted. The differences in the dry densities may be due to the calibration constants were not being representative of the insitu materials as the lab tests were conducted on the finer fractions that made up a small fraction of the gradation. Furthermore, Drnevich stated that the current method is limited to samples with more than 30% passing sieve number 4 and particle size not greater than ¾ inch.

Measurements from the EDG were not discussed further because of the bias introduced by using the nuclear gauge for the field calibration. The results from the EDG could therefore not be compared those from the nuclear gauge.

4.1 Recommendations

The following are recommendations are proposed for the application of the MDI to compaction control:

- The manufacturer should develop a 6-in mold setup for the laboratory determination of the calibration constants. Constants from the 6-in and 4-in molds should be compared to identify any differences and to develop modification to the test if necessary.
- Manufacture spikes with larger diameter (at least 1-inch) to facilitate driving into DGA layers.
- Spikes should be of varying lengths so that measurements can be made in layers of different depths. In practice, some base layers can be as thick as 18 or more inches. The MDI should be setup such that density and moisture content can be obtained at different depth. This would imply that the software should be setup so that the user can input different length of spike.
- Additional testing to develop a database of calibration constants. This would provide the NJDOT with a range of possible calibration constants that can be used a default values depending on the source of the aggregates.

5.0 References

1. Xiong Yu and Drnevich, V., "Soil Water Content and Dry Density by Time Domain Reflectometry," *Journal of Geotechnical and Geoenvironmental Engineering*, Sept 2004.
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