EVALUATION OF NON-NUCLEAR DENSITY GAUGES FOR DETERMINING IN-PLACE DENSITY OF UNBOUND MATERIALS

By

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Abstract

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Proper compaction of soils, bases, and other unbound materials is highly important in road construction and critical to the performance of pavements. Hence the ability to quickly and accurately measure density and moisture content is important; nuclear density gauges (NDGs) have long been used to perform this task. With increasing regulations and cost associated with using nuclear source material, significant effort has been made to develop non-nuclear density gauges (NNDGs). Three non-nuclear compaction measuring devices, the Humboldt Electrical Density Gauge (EDG), the Trans Tech Soil Density Gauge (SDG), and the Humboldt GeoGauge were reviewed in this study to determine if they are viable replacements for the NDG. Measurements were taken with the EDG, SDG and GeoGauge at 21 project sites in Idaho. NNDG outputs were compared to density collected from NDGs and sand cones on site, and moisture of soil samples determined from the laboratory oven. It was found that the EDG density and moisture content based on the NDG soil model correlate well with the NDG measured density and moisture content. Uncorrected SDG density correlated very poorly with traditional devices. When project specific correction factors were applied to the SDG, both EDG and SDG provided a good estimation of dry density and moisture content. However, increased scatter was

observed when data from only smaller material subsets (base, sands, and fine material) were analyzed. Stiffness and modulus measurements obtained with the GeoGauge did not correlate to density and moisture content obtained with the NDG and oven, respectively. The results indicate that NNDGs can not provide precise measurements of the soil density and moisture content for quality control and quality assurance purposes.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Dedication

To Lindsay, for putting up with my many late nights in Sloan Hall over the years.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND AND PROBLEM STATEMENT

Proper density in the pavement, base, and subgrade layers is a key factor in ensuring a long lasting road that meets performance expectations. It's very important for transportation agencies and contractors to have reliable devices and methods to determine in-situ density. Traditionally, volume replacement devices such as the sand cone and rubber balloon methods have been employed to determine the in-place density of soils, bases, and other "unbound" materials. These methods, however, are time consuming, destructive, and costly.

Many transportation agencies and contractors use nuclear density gauges (NDG) to determine the in-situ density of soils. Although reasonably accurate and much more rapid in producing results compared to volume replacement methods, NDGs have their own set of drawbacks. NDGs operate by measuring scatter of gamma radiation. Nuclear material is heavily regulated and the use of such devices requires extensive operator training and permits. Storage and transportation are also inconvenient and expensive. Furthermore, nuclear gauge possession on federal and/or military property may be restricted.

In the past 15 years, extensive research and development into non-nuclear density gauges (NNDG) has been performed. NNDGs can offer all of the benefits of the NDG while eliminating the need for licenses, hassles, and general costs of NDG ownership. However, there is considerable debate as to whether or not these devices are accurate and precise in comparison to the NDG. If non-nuclear devices are found to provide an acceptable level of accuracy while being user friendly and cost effective, their implementation into agency quality assurance (QA) and contractor quality control (QC) programs should be strongly considered.

This study evaluated three non-nuclear devices for possible replacement of nuclear gauges for soil and base applications:

- The Electrical Density Gauge (EDG) from Humboldt Manufacturing
- The Soil Density Gauge (SDG) from Trans Tech Systems, Inc.
- The GeoGauge from Humboldt Manufacturing

The EDG and SDG measure multiple material electrical parameters and relate the electrical measurement to density and moisture content. The GeoGauge measures soil stiffness, based on applied load and resulting deflection. Additional devices and technologies are discussed in the literature review section of the report, however only the above devices were tested and further evaluated in the study.

1.2 OBJECTIVE

The objective of this study is to compare the accuracy and reproducibility of non-nuclear compaction measuring devices to traditional moisture and density measuring devices, including the NDG, sand cone, and laboratory oven, based on field tests and data analysis.

1.3 THESIS ORGANIZATION

This thesis is divided into five chapters. Chapter 1 introduces the background and objectives. Chapter 2 presents a review of non-nuclear density gauge literature and results from a state department of transportation survey on NNDGs. Chapter 3 introduces the field testing program performed by this study. Chapter 4 presents the results and analysis of field data. Finally, significant conclusions and recommendations are presented in Chapter 5.

CHAPTER 2: LITERATURE REVIEW AND SURVEY

2.1 INTRODUCTION

Many devices are currently commercially available that offer some potential to replace NDGs in measuring compaction of unbound materials. Due to limited scope, time and resources, only three non-nuclear devices, EDG, SDG, and GeoGauge, were selected for full evaluation in this study. Studies concerning the three devices and many additional devices for unbound materials were reviewed. Non-nuclear density gauges designed exclusively for pavement layer applications, such as the Trans Tech Pavement Quality Indicator and the Troxler PaveTracker, were not reviewed in this study. In addition to a review of device research and literature, a survey was developed and sent to state departments of transportation to gauge overall opinions and experience with NNDGs nationwide.

2.2 NON-NUCLEAR ELECTROMAGNETIC BASED DEVICES

A few devices have been developed to relate the electrical properties of soil and water to dry density and moisture content. The three most common devices include the Humboldt Electrical Density Gauge (EDG), the Trans Tech Systems Soil Density Gauge (SDG) and the Moisture + Density Indicator (MDI) from Durham Geo Slope Indicator. Most of the remaining devices measure material stiffness and modulus rather than moisture and density.

2.2.1 Electrical Density Gauge

The EDG, shown in Figure 2.1, measures the electrical properties of soils through the use of high-frequency radio waves traveling between metal darts driven into the soil (Brown, 2007). The EDG measures impedance, capacitance, and resistance between the darts. The EDG relates impedance to wet density and the ratio of capacitance and resistance to moisture content (ASTM, 2011). The EDG requires a programmed soil specific model to construct algorithms to determine the dry density of the soil (Brown, 2007). Typically, the development of a soil model consists of taking measurements with the EDG and another “true” density and moisture measuring device (i.e. NDG, sand cone and oven, etc.) at a minimum of three spots. The “true” density and moisture values are input into the EDG to relate the measured electrical parameters to moisture/density parameters for each soil. It is recommended that the soil model for the EDG be created in the field, requiring the use of either a nuclear density gauge, sand cone, or another density measuring method to assist in creating the soil model. Other researchers have developed, discussed, and analyzed the implementation of a laboratory calibration procedure (Bennert and Maher, 2008; Nazarian et al., 2011; Meehan and Hertz, 2013) but no laboratory calibration method has been formally standardized or recommended by Humboldt.

Figure 2.1. Field Testing with the Electrical Density Gauge C Model

Rathje et al. (2006) noted that the EDG would not operate on highly plastic clays. Due to this and other field restraints, remaining EDG testing only took place in a laboratory testing program. The EDG was tested on poorly graded sand samples. The device consistently reported the same dry unit weight for each specimen, although these results were different from values obtained with a sand cone and values obtained with an MDI. The authors noted that the spikes were sometimes difficult to hammer into the soil.

Brown (2007) compared the EDG and MDI with the NDG on a variety of soils including gravel sub-base, sand borrow, and granular backfill. Brown concluded that EDG results for dry density compared well with NDG readings, especially in fine grained and sandy material. Moisture content values from the EDG showed a weak linear relationship to NDG results.

Bennert and Maher (2008) found the EDG had better correlation to NDG readings than the MDI. The authors, however, expected this because they created the EDG soil model in the field using an NDG.

Cho et al. (2011) tested the EDG, NDG, and LWD against the drive cylinder method (referred to in the study as the "standard measurement") on two soil test sites. The NDG correlated better to the standard measurement for density and moisture content. The EDG did have similar results to the nuclear gauge before correction factors were used to improve NDG results. The authors speculated that if similar correction factors were developed for the EDG, the EDG would produce overall results comparable to the NDG.

Berney and Kyzar (2012) compared the EDG, SDG, steel shot replacement device, and sand cone to the NDG for density, and also compared the EDG, SDG, NDG, and a variety of other devices to a lab oven for moisture content. The authors found a higher dry density variation for the EDG compared to the corrected SDG and sand cone. To measure the precision and accuracy for moisture measurement, the authors measured the total analytical error based on device bias, standard deviation, and mean. The total analytical error was slightly higher (meaning less precise and accurate) than the corrected SDG and the NDG. The authors noted as a whole the EDG performed well but required a complex calibration.

Meehan and Hertz (2013) evaluated the EDG in field and laboratory experiments in Delaware. Testing was conducted at two field sites. Twenty locations were tested at one site and twenty nine tested at the second. The authors used all test locations at each site to build the soil model, and soil models were developed with and without an internal temperature correction applied. The calibration data was very scattered. Each location was also used to take an EDG density measurement which was then compared to the NDG measurement. No strong agreement was found between the EDG and the NDG, although the entire NDG data set was used to establish the soil model. The EDG produced greater variability at the site with more variable soils, indicating multiple soil models may be required in soils with higher variability. The authors ultimately decided to explore alternative methods for establishing the soil model due to difficulties establishing the model in the field. A laboratory calibration model was developed using a large mold. However, further laboratory tests proved to have similar scattered results. Laboratory soil models were later used in outdoor "large box" testing and EDG, NDG, drive cylinder, and sand cone results were compared. NDG and drive cylinder had the best agreement. The EDG was found to have more density scatter than the NDG, but less than the sand cone. The EDG was found to have more moisture scatter than both the NDG and sand cone. For all testing, the internal temperature correction did not significantly improve the EDG results.

2.2.2 Soil Density Gauge

Similarly to the EDG, the SDG, shown in Figure 2.2, measures the dielectric soil properties through the use of high frequency radio waves. Based on technology similar to Trans

Tech's Pavement Quality Indicator (PQI), the SDG creates an electromagnetic field using a transmitter and receiver. In order to determine the values of both moisture and density, the SDG uses an electrical impedance spectroscopy (EIS) measurement. EIS is the measurement of soil impedance at a variety of frequencies, in order to separate the effects of water and soil on the measurement. Whereas the PQI only needs a measurement at a single frequency to determine the density of hot mix asphalt pavement, the SDG takes measurements at over 80 frequencies ranging between 300 kHz and 40 MHz to measure soil density and moisture content (Plunta and Hewitt, 2009). Unlike the EDG and MDI, there are no darts or stakes to drive with the SDG, making its use completely non-destructive.

Figure 2.2. Soil Density Gauge 200

Sawangsuriya et al. (2008) tested two beta SDG models on three types of pavement materials in Thailand. The materials tested were sand embankment, soil-aggregate sub-base, and crushed rock base. The authors concluded the SDG showed good potential future use for construction phase evaluation but did not elaborate further. They also noted that with quicker measurement times, more spots could be tested therefore increasing the overall test coverage area.

Plunta and Hewitt (2009) concluded that accounting for the specific surface area of the material under test would improve the accuracy of SDG compared to the NDG. Average wet density error between the NDG and SDG was reduced by 119% when surface area adjustments were applied to the data.

Berney and Kyzar (2012) reported that among four devices evaluated (SDG, EDG, sand cone, and steel shot) in comparison to the NDG, the SDG showed the lowest density deviations from NDG density. The study also found the total analytical error for SDG moisture content to be less than all devices tested except for the NDG and the gas stove drying method. The authors did have to “correct” the SDG readings by inputting a linear offset based on a single sand cone density reading and a single oven moisture content. The uncorrected SDG readings produced higher deviations from the NDG and oven results. The authors concluded that when correction and calibration for density and moisture content was possible, the SDG was the best non-nuclear density device evaluated.

Mejias-Santiago et al. (2013) studied the performance of the SDG on sixteen fine grained soils. The authors reported better performance of SDG as more measured soil properties, instead of default values, were input into the gauge. When compared to the NDG, the SDG dry density values correlated well across all soils tested. However, dry density values changed very little within a single given soil type, indicating the SDG had difficulty identifying small density changes with increasing roller passes. When corrected to a single NDG dry density value, the correlation improved, however, the SDG still had difficulty identifying small density changes during compaction. The authors recommended that the SDG could be used in military contingency construction scenarios provided the density could be corrected with at least one density measurement from another device (NDG, etc.). The SDG was not recommended for QC/QA use in permanent infrastructure construction.

2.2.3 Moisture + Density Indicator

The MDI, shown in Figure 2.3, works similarly to the EDG and SDG, but uses time domain reflectometry to determine the dielectric soil properties. Reflectometry measures the responses of an electrical pulse generated through four probes that are driven into the ground (Brown, 2007). Similar to the EDG, the MDI requires a soil specific model to determine dry density. The MDI model is developed in laboratory rather than the field using compacted soil from the site. As of 2011, Durham Geo Slope Indicator has discontinued the marketing and sale of the MDI.

Figure 2.3. Moisture + Density Indicator (Nazarian, 2011)

Rathje et al. (2006) noted problems with MDI measurements in clayey soils and that the MDI didn’t always produce accurate results in sandy soils either. When used on laboratory compacted sand specimens, the MDI more accurately determined the moisture content of the sand compared to clay samples. MDI dry density results for sand were consistent but not the same as the values from the sand cone test and EDG. The authors also noted practical issues including difficulty in getting quick readings with the MDI in select cases and hammering in the probes in very stiff soil. Despite this, they noted the MDI had good potential use in the future if improved upon.

Brown (2007) tested the MDI and EDG with the NDG on a variety of soils. The study showed that the MDI dry density results consistently produced a lower in-situ dry density compared to the NDG. Brown speculated that this was due to the testing apparatus (four probes driven into an area eight inches in diameter), which loosened compacted soil resulting in a lower dry density value. Moisture contents showed a weak linear relationship in comparison to the NDG.

Bennert and Maher (2008) compared the MDI to the NDG and EDG on five test projects. In general, measured MDI values did not correlate well with NDG values. Differences up to 12.53% were noted between the two devices for dry density measurements. The MDI generally recorded a lower density than the NDG. Moisture content values were more agreeable. The authors speculated that differences in density readings between the NDG and MDI were due to the MDI's soil constant calibration procedure. The authors recommended the development of a calibration constant database, larger spikes, and spikes of varying lengths to record density at different depths.

2.3 STIFFNESS AND MODULUS BASED DEVICES AND METHODS

In present pavement design practices, the resilient modulus (M_r), or soil modulus, has become an important design input parameter. M_r and corresponding soil stiffness have largely replaced older strength based values including the California Bearing Ratio and Hveem R value (Puppala, 2008). Modulus and stiffness are considered to be more important factors than density and moisture content because they can better predict overall pavement performance. Factors that influence the modulus of geomaterials include the state of stress, moisture content, density, stress history, gradation and Atterberg limits (Nazarian et al., 2011). Until recently, measuring stiffness and modulus was impractical. Today there are a number of devices designed to measure stiffness and modulus that will be further discussed in this report.

2.3.1 GeoGauge

The Humboldt Manufacturing GeoGauge, shown in Figure 2.4, directly measures soil stiffness by vibrating a rigid ring-shaped foot at different steady state frequencies and measuring the soil's response. The technology was originally developed by the military to detect land mines in the ground (Abu-Farsakh et al., 2004). The GeoGauge rapidly measures the stiffness and modulus of the soil being tested. The device is placed on top of compacted soil with at least 60 percent of the foot area in contact with the soil (Rathje et al., 2006). If the 60 percent contact area cannot be achieved, a thin layer of sand can be placed between the device and the soil. The influence depth of the GeoGauge ranges between 7.5 and 8 inches (Abu-Farsakh et al., 2004). This is considered acceptable for in-situ testing because typical pavement layers are constructed in 6 to 12 in. lifts. Multiple studies have shown that there is poor or no correlation between GeoGauge stiffness and dry density (Rathje et al., 2006; Bloomquist et al., 2003). There is also no consistent correlation between measured GeoGauge stiffness and moisture content (Bloomquist et al., 2003).

Lenke et al. (2001) evaluated the GeoGauge in a laboratory setting on a silty-sand. In the lab, the GeoGauge produced meaningful stiffness values when the distance to horizontal boundaries was 12 inches deep and the distance to any lateral boundary was 9 inches. The testing results showed a change in stiffness with moisture content. The stiffness started at

22MN/m with a moisture content of 4%, peaked with a stiffness value of 25 and an M.C. of 8%, and stiffness continued to reduce with increasing moisture content. The corresponding Proctor curve for the soil had a peak dry density of 116 pcf with a moisture content of 12%. These results suggest that the peak stiffness occurs at a lower moisture content than maximum dry density. Although this report showed positive results for the GeoGauge, the authors also concluded that a laboratory testing method to determine a maximum stiffness value remained elusive.

Figure 2.4. GeoGauge

Bloomquist et al. (2003) showed that significant factors in the repeatability and precision of the GeoGauge are largely dependent on the condition of the soil surface and the placement and operation of the device by the operator. Device inclination also affected the stiffness value. The study found that using sand to help with seating caused the stiffness value to increase in 11 out of 14 trials performed with wet and dry sand compared to no sand. The authors also developed a new handle for the GeoGauge, in order to assist with proper seating and therefore better repeatability.

Abu-Farsakh et al. (2004) stated the GeoGauge was the most user-friendly device tested in their study, which also tested the dynamic cone penetrometer and the light falling weight deflectometer. The authors reported the GeoGauge was easy to operate and gave rapid results. Modulus results for the GeoGauge had good correlations to falling weight deflectometer (FWD) and Plate Load Test (PLT) moduli values with the coefficient of correlation (R^2) values ranging from 0.81 to 0.90 for field tests. Laboratory tests were more scattered; R^2 values ranged from 0.52 to 0.83 for laboratory tests. The study also concluded that the GeoGauge measurements were very sensitive to minor cracking in cement and lime treated soils. Furthermore, GeoGauge stiffness peaked at dry of optimum, suggesting that soils should be compacted dry of optimum to provide higher support and stability.

Rathje et al. (2006) opted not to include the GeoGauge in their 2006 study. The authors were concerned about obtaining proper seating and measurement repeatability. This study pointed to a number of previous studies that showed difficulties in obtaining proper seating. When sand was introduced as a remedy (as specified by the manufacturer), significant alterations to measurements were sometimes reported.

Von Quintus et al. (2009) found the GeoGauge was successful 79% of time in identifying areas with anomalies. The coefficient of variation was 15%, which was lower than other stiffness devices measured and the standard deviation ranged between 0.3 and 3.5 ksi depending on the material. The authors found the GeoGauge resilient modulus values correlated well laboratory developed modulus, except in fine-grained soils. The authors recommended the GeoGauge for QC and QA and suggested the GeoGauge be calibrated to project materials to improve accuracy.

2.3.2 Light Falling Weight Deflectometer

Falling weight deflectometers (FWDs) are another stiffness measuring very useful and accurate in estimating moduli of pavement and unbound materials. FWDs, however, are cumbersome to use on bases and subgrades due to the irregular surface and poor maneuverability on an active construction site (Siekmeier et al., 2009). The light falling weight deflectometer (LFWD), or light weight deflectometer (LWD), is a portable version of the larger, trailer mounted FWD. The FWD and the LWD determine the stiffness and modulus of pavement materials by measuring the material's response under the impact of a known load dropped from a known height. The LWD testing procedure is standardized by ASTM E 2583, "Standard Test Method for Measuring Deflections with a Light Weight Deflectometer."

Abu-Farsakh et al. (2004) showed that the LWD moduli values correlated very closely to back-calculated FWD values, with an R^2 value of 0.94. LWD also correlated well with lab tests, with field R^2 values ranging from 0.83 to 0.94. The influence depth of the LWD was found to be between 10.5 and 11.0 inches depending on soil stiffness. The LWD did have repeatability issues when tested on weak subgrades. Overall, the authors suggested that the LWD could serve as a suitable alternative to the plate load test and FWD.

Petersen et al. (2007) tested the LWD primarily for embankment compaction. Their study concluded that the LWD was an effective test for determining soft spots in the test section. All soils tested, however, exhibited a high variability of measured stiffness with R^2 values ranging between 0.26 and 0.52. In-situ stiffness measurements did not have any correlation to laboratory predicted stiffness values. Due to this lack of correlation, field QC procedures based on lab stiffness could not be developed.

Vennapusa (2008) compared three different LWD models (the Zorn, Keros, and Dynatest) to each other and to the static plate load test. The major factors found to influence the LWD modulus are the size of the loading plate, plate contact stress, type and location of deflection transducer (accelerometer vs. geophone), plate rigidity, loading rate, and buffer stiffness. It was found that LWDs that use accelerometers to measure plate deflection (Zorn model) measure larger deflections than LWDs that use a geophone to measure deflection (Keros and Dynatest models). Modulus values varied among the devices depending on the plate size; the Keros modulus averaged 1.75 to 2.16 times greater than the Zorn. The Dynatest modulus averaged 1.7 times greater than the Zorn modulus. The Zorn measured deflections 1.5 greater than the Keros. In general, modulus values increased with decreasing plate diameters. Measurement variability was lower in the Zorn model compared to the Keros and Dynatest models.

Siekmeier et al. (2009) tested the LWD (along with the dynamic cone penetrometer) on granular and fine grained soils to develop target LWD test values for soils. The target values were matched to specific soil gradations and moisture contents. The authors called for standardization in the manufacturing of LWDs. Manufacturers develop different models that produce different results due to the lack of a national standard. However, the authors concluded that the LWD should be more widely implemented.

Hossain and Apeagyei (2010) tested the LWD against the GeoGauge and dynamic cone penetrometer to determine its suitability in determining soil modulus on seven test roads. The researchers noted a general increase in stiffness with increasing density for the LWD and GeoGauge. While moisture content has a significant influence on the LWD, there was no clear trend between stiffness and moisture content for the LWD. The authors speculated that the high variability in moduli measurements could be related to the development of pore water pressure and capillary suction during testing. The authors concluded that the LWD should not be used for quality assurance and quality control without further research.

2.4 SUMMARY OF STIFFNESS AND MODULUS METHODS

In summary, there currently exists no clear, consistent correlation that relates soil moduli and stiffness to dry unit weight and moisture content for any soil type. Previous studies have shown potentially good relationships between stiffness and density and moisture for select devices, but no consistent relationship has been found. In most cases, stiffness based devices can provide only a general assessment of compactness as related to relative compaction (Rathje et al., 2006). In addition to the lack of correlation to other compaction properties noted above, there are a number of additional limitations that prevent a more wide scale use of modulus based field specifications and testing. Results from Nazarian et al. (2011) show that laboratory results for M_r are often moderately or significantly different from field results, and relatively little research has been performed to tie the design moduli of compacted geomaterials to field measured moduli. Among the reasons, as stated by select State DOTs, for lack of implementation of modulus based specification include (Nazarian et al., 2011):

- Modulus testing requires a higher level of training
- Unreliable results
- Difficulty in determining a general moisture adjustment factor (to improve modulus)
- Lack of resources to research and implement changes
- Expensive and time consuming

Due to these limitations and others, modulus testing and specification development has been slow for many states to accept. In a survey by Puppala (2008), only 15% of state DOT respondents stated they were “well satisfied” with current methods to determine resilient modulus. The remaining respondents were either not satisfied or satisfied, but thought methods could still be improved. As of 2011, only Minnesota had developed field modulus specifications, Missouri and Texas were in draft stages of development, and additional states were still in research stages (Nazarian et al., 2011).

2.5 OTHER UNBOUND COMPACTION MEASURING DEVICES

2.5.1 Portable Seismic Property Analyzer

The portable seismic property analyzer (PSPA), a portable version of the larger seismic pavement analyzer, measures the dispersion of surface waves of the pavement medium to relate to material elastic properties, including modulus (Rathje et al., 2006). The PSPA can measure elastic modulus for a variety of mediums including asphalt, concrete, base, and subgrade. The device consists of a wave source, two geophone wave receivers, and a data acquisition system. A primary drawback of this device is the expense, as the device generally costs between $20,000 and $30,000 (Rathje et al., 2006; Nazarian et al., 2011).

Rathje et al. (2006) studied the PSPA on five soil types and determined that the PSPA could be used for a general assessment of dry density, but that it was not precise enough to fully replace the NDG. In sandy soil, the modulus generally increased with dry density, although a significant amount of scatter was observed. In clayey soils, the water content was found to influence the PSPA modulus more so than the dry density. The authors also felt the lack of ability to measure water content was a drawback to the device.

Von Quintus et al. (2009) found the PSPA technology performed well in both hot mix asphalt and unbound layers. The device had a 93% and 86% success rates in determining anomalies in HMA and unbound materials respectively. For bound pavement, PSPA measured moduli were comparable to laboratory measured moduli. The PSPA required mixture specific calibration. However, calibration can be performed in the laboratory. When temperature was accounted for, PSPA modulus values measured immediately after compaction were similar to modulus values measured in the following days. For unbound materials, the authors determined the PSPA could be calibrated to laboratory moisture-density relationships. The PSPA did produce a higher than normal dispersion over a wide range of conditions and materials. The authors also noted the PSPA requires more extensive training to operate relative to other non-nuclear devices.

2.5.2 Dynamic Cone Penetrometer

The dynamic cone penetrometer (DCP) measures the penetration rate (distance per blow) of a cone being pushed through pavements and soils. This penetration rate is known commonly as the DCP penetration index (PI or DPI). The DCP provides a continuous assessment of in-situ soil strength. It can also be used to determine layer thickness and uniformity (Abu-Farskh et al., 2004). The DCP test procedure is standardized by ASTM D 6951, "Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications." No standard relationship between penetration rate and compaction level currently exists, although DCP penetration has been correlated with the CBR for pavement design (Rathje et al., 2006).

Salgado and Yoon (2003) tested the DCP at seven sites in Indiana. Four sites contained clayey sands, one contained well graded sand with clay and two contained poorly graded sands.

The researchers found the penetration index decreased when dry density increased, and penetration index slightly increased as moisture content increased. An equation was developed relating the soil dry density to the PI. For clayey sands and well graded sands, there was also some correlation between unconfined compressive strength and PI, as PI generally decreased as compressive strength increased. The authors developed an equation relating the modulus to the PI, although the authors recommend this equation be used with caution as it was based on a weak correlation and highly scattered data. The authors recommended the DCP be used in conjunction with other traditional testing methods due to the uncertainty in the results. The DCP was not recommended for use in gravely soils.

Abu-Farsakh et al. (2004) tested the DCP on a variety of soils and compared measured results to LWD, GeoGauge, FWD, CBR and PLT results. The authors noted the DCP could take deeper measurements than the LWD and the GeoGauge. Several good correlations were developed between DCP measurements and the FWD, PLT, and CBR values. DCP had an especially good correlation to CBR values, with field R^2 values of 0.93.

Rathje et al. (2006) found that the DCP measurements mostly disagreed with NDG measurements for clayey soils, was somewhat accurate in fine gravels (50% agreement with NDG), and was most accurate in sand (100% agreement in 8 test spots). Overall the authors concluded the DCP is not suitable to replace the NDG, but did provide a good general assessment of compacted dry unit weight.

Siekmeier et al. (2009) tested the DCP, along with the LWD, on granular and fine grained soils to develop target DCP values for the tested soils. These target values were matched to a grading number (determined by a sieve analysis) and moisture content. The authors further concluded that more standardized testing procedures are needed for the use of the DCP, noting that the methods for obtaining PI values are varied and involve different seating drops and measurement drops. The authors recommended three seating drops and five to ten measurement drops depending on material type. The report encouraged expanded use of the device.

Hossain and Apeagyei tested the LWD against the DCP and GeoGauge on seven test roads in Virginia. No correlation was found between the results of the three devices. The authors found a strong correlation (R^2= 0.97) between DCP stiffness and moisture content. DCP soil stiffness varied inversely with moisture content, indicating higher moisture content is associated with a lower stiffness value and vice versa. There was no clear correlation between DCP stiffness and soil density.

2.5.3 Clegg Hammer

Originally developed in the 1960s, the Clegg Hammer measures the deceleration of a free falling mass (hammer) upon impact with the soil. The hammer is dropped from a set height and an accelerometer measures the hammer's deceleration upon impact in units of Clegg Impact Values (CIV). The CIV can then be correlated to soil strength and CBR (Farrag, 2006). The operation of the Clegg Hammer is standardized by ASTM D5874, "Standard Test Method for Determination of the Impact Value of a Soil."

Rathje et al. (2006) found the Clegg Hammer provided the most accurate evaluation of all the field soils tested in their study, compared to the standard DCP and PANDA Dynamic Cone Penetrometer. The authors concluded that CIVs were more influenced by water content than by soil dry unit weight in clayey soils. CIV generally increased with dry unit weight in sandy soil, although there was significant scatter with the data. There was no correlation between CIV and dry unit weights in fine or coarse gravel. The authors ultimately concluded the Clegg Hammer was not suitable to replace nuclear gauges because of its lack of precision.

2.6 INTELLIGENT COMPACTION

Intelligent compaction (IC), or roller-integrated compaction monitoring (RICM), is the ability of a compaction roller to self-measure the compaction level. IC rollers directly measure the stiffness response of the soil or pavement during compaction. IC technology has been under development in Europe for the past 30 years, and research into IC has increased significantly in the last 10 years (White et al., 2011). IC rollers are equipped with (Petersen and Peterson, 2006):

- Accelerometers to measure drum movement
- Onboard electronics to record sensor output and stiffness
- Linkage to machine controls to adjust compactive effect according to measured stiffness
- Other instruments to record distance measurements, location, date and time, and other data.

There are a variety of IC measuring technologies, two of the most common being the compaction meter value (CVM) and machine drive power (MDP).

Briaud and Seo (2003) developed a summary of intelligent compaction and presented research needs for its use in the United States. The advantages of IC include:

- Instantaneous and complete evaluation of the zone being compacted
- Helps remediate weak spots and avoid over compaction
- Reduces number of necessary roller passes
- Provides more uniformity to the compacted layer
- Provides a soil modulus at all locations where the roller traveled

The major drawback to IC is the initial expense to contractors, as IC-equipped rollers cost more than traditional rollers. Construction contract types also influence the development and acceptance of intelligent compaction. In Europe, design-build contracts, awarded on a best-value basis, are widely used and much more common than in the United States. Responsibility lies on the contractor to ensure proper compaction and produce a quality product. In the U.S., most transportation agencies (owners) have specifications for quality control and assurance to be performed either by the agency itself or a third-party inspection/testing firm. It's the responsibility of the agency inspectors to ensure proper compaction is met. Briaud and Seo (2003) theorized that these fundamental contract differences have caused IC to be more readily accepted in Europe than the U.S. Briaud and Seo also addressed research needs including better understanding the relationship between modulus and water content, demonstration projects which show that IC leads to better compaction for the associated higher cost compared to conventional compaction, and development of IC specifications in the United States.

Petersen and Peterson (2006) tested an IC-equipped Caterpillar compactor against measurements from the GeoGauge, LWD, and DCP. The results for each device had no correlation to one another, except for a good correlation between LWD and GeoGauge measurements (R^2 value of 0.4) and between IC (CMV) and DCP measurements (R^2 value of 0.4).

Vennapusa's (2008) report detailed a variety of advantages and improvements to RICM technology. Two case studies of using geostatistical analysis to characterize and quantify non-uniformity in compacted unbound materials were presented. RICM was also found to be a reliable indicator of compaction quality of cohesive soils and is a good alternative to the heavy rolling test. During field testing, CMV values showed good relationships with FWD modulus and DCP penetration index (R^2 values from 0.6 to 0.7). No correlation was shown between CMV and LWD values. The author concluded this was due to large differences in the state of stress under the devices. CMV values taken at high amplitudes did not have a good correlation with point measurement devices, due to the effect of RMV at high amplitudes.

One limitation of IC technology is that it is only built into newer rollers and cannot be purchased separately and mounted onto existing rollers. Scullion et al. (2005) sought to develop similar technology that could be added to existing rollers. The authors used the term "instrumented roller" to describe these regular rollers equipped with IC-like technology. The roller was tested against data acquired from the DCP, LWD, and NDG. The results showed that roller responses were repeatable and could be used to identify weak spots in the subgrade. Roller responses, however, did not correlate to measured stiffness or density data, and further evaluation was recommended.

2.7 LITERATURE SUMMARY

Many devices currently exist with the potential to replace the nuclear density gauge for compaction control of unbound materials. However, no single device has emerged as a leader to replace the NDG. There are many reasons for this, including a lack of accuracy and precision, mixed performance results, cost, ease of use, or the need for new agency standards.

Electromagnetic density measuring devices for unbound materials are still relatively new to the commercial market and have not found wide acceptance yet. No study reviewed has given a full recommendation that electromagnetic devices be used for QC purposes. Stiffness/modulus measuring devices are growing in consideration due to their ability to measure modulus in-situ and compare that to the design modulus. However, field stiffness devices have had difficulty agreeing with laboratory modulus values and agreeing with one another in previous studies. Additionally, for most agencies, new stiffness/modulus-based construction standards would need to be developed. Intelligent compaction may be the wave of the future for compaction quality control.

Some stiffness/modulus and impact devices based devices, including the LWD and PSPA, can be used to measure compaction for both bound pavement and unbound materials. However, there are no commercially available non-nuclear devices that can measure the density and moisture content of both hot mix asphalt and unbound materials. Presently, Trans Tech is developing a combined asphalt and soil density evaluator with the potential to merge the density measuring abilities of the PQI and SDG devices (Mejias-Santiago et al., 2013).

2.8 STATE DOT SURVEY

To better understand the state of the practice on the use of NNDGs by the highway agencies, a survey regarding NNDG use was conducted by the Idaho Transportation Department and Washington State University and sent to various state and province departments of transportation throughout the United States and Canada. The survey inquired about experience with and opinions of currently available NNDG technology, for both bound pavements and unbound applications. Detailed survey response information is presented in Appendix A of the thesis by Timm (2012). Some questions asked about NNDG devices as a whole for both bound and unbound applications. Key results for the unbound devices and NNDGs as a whole are presented in Timm's report.

15 of 40 respondents reported using NNDGs to measure density and moisture content of unbound and/or bound materials. However, 21 (of 40) respondents reported having conducted some research with NNDGSs. Only 6 (of 40) respondents reported that they had developed standards for NNDG use. The GeoGauge was the most familiar unbound device, with 52% (12 of 23 respondents to this question) of the agencies noting some experience with the device. A majority of agencies (59%) indicated that on the basis of the one or more of the NNDGs they had evaluated, further studies would be required before a decision could be made to replace current NDGs. 37% of agencies reported that a least one NNDG was acceptable to replace the NDG, while 33% of agencies reported they did not feel any currently available device was acceptable to replace the NDG. Agencies could have more than one response to the question.

When asked what the agency would view as an acceptable measure of accuracy for an NNDG to replace current NDGs for unbound applications, the majority of agencies (59%) preferred a deviation of true density to be less than a certain tolerable density. Responses varied from 0.5 to 3 pcf for the maximum acceptable variation from true density. 40% of agencies desired a minimum correlation with the NDG, with desired minimum R^2 values ranging between 0.8 and 0.99 depending on the agency. 32% of agencies desired a minimum correlation with the sand cone, with desired minimum R^2 values being greater than or equal to 0.85. Again, multiple responses per agency were permitted.

Agencies were asked to rank the most important criteria for NNDGs on a 1-5 scale, with 5 being the most important. The criteria included accuracy, cost, ease of use, speed, and “other”. Accuracy was clearly the number one criteria, with ease of use and cost a close tie for second, and speed fourth. Other agencies were mostly concerned with repeatability of results, and a few expressed that the NNDGs would have to be accepted by industry and provide similar or better results than current NDGs.

CHAPTER 3: FIELD TESTING OVERVIEW

3.1 INTRODUCTION

The EDG, SDG, and GeoGauge were chosen to be evaluated in the field study. For the SDG and EDG, density and moisture contents measured by each device were compared with sand cone densities, NDG densities, and oven moisture contents. For the GeoGauge, measured stiffness and modulus values were compared with dry density (sand cone and NDG) and moisture content (oven). On full depth recycle (FDR) and cement recycled asphalt base stabilization (CRABS) projects, SDG and GeoGauge measurements were compared with NDG backscatter density measurements.

3.2 MATERIALS

A total of 21 bases, fills, and subgrades from the state of Idaho were tested at sites over three construction seasons, as shown in Table 3.1. The GeoGauge was evaluated at 20 sites, the EDG at 18 sites, and the SDG at 16 sites. Most sites were Idaho Transportation Department (ITD) and local agency construction projects. Other materials were tested from stockpiles at ITD maintenance facilities. Because testing could take up to seven hours to perform, the team would usually test in an area of little, if any, construction activity in order to avoid interfering with the contractor's work. For a variety of reasons and constraints, not all device data was collected at all project sites.

Table 3.2 shows device data collected at each project site. A majority of the materials were granular base material, with a nominal maximum aggregate size of ¾" or smaller. Other materials tested included coarse fills, sands, slits, and clays. Two project featured testing of full depth recycled (FDR) bases, one a cement recycled asphalt base stabilization (CRABS) project and the other with emulsified asphalt stabilization.

Table 3.1. Unbound Field Project Information

Project Name	ITD Project Key	Project Year	Material Description
I-84 Nampa Subgrade	10916	1	Fine Sand Subgrade
I-84 Nampa Base	10916	1	3/4" Granular Base
US 95 Payette River Bridge	02842	1	Granular Burrow
US 95 Garwood to Sagle Frontage Road	11978	1	3/4"Granular Base
SH 8 Moscow	12001	1	Silt (Loess) Subgrade
US 95 Lapwai Bridges	9472	2	3/4" Base
SH 55 Cascade	9346	2	3/4" Base
SH 162 Four Corners	8810	2	Clay Subgrade
College Avenue (Moscow)	Local Project (City of Moscow)	2	3/4"Fill
US 20/26 Caldwell	Local Project (City of Caldwell)	2	Fine Sand Subgrade
US 20/26 Caldwell	Local Project (City of Caldwell)	2	3/4"Base
US 95 Garwood to Sagle Mainline	09780 & 11893	2	3/4" Base
Mullan Ave (Post Falls)	Local Project (City of Post Falls)	2	5/8” Base
SH 16 Extension Access Road	12915	2	3/4" Base
US 95 Wilder Phase 2	11566	2	CRABS
US 95 Cottonwood	12003	2	FDR with Emulsified Asphalt
ITD Potlatch Maintenance Yard		3	Loess Subgrade
ITD Moscow Maintenance Yard		3	3/4" Base
ITD Moscow Maintenance Yard		3	Tan Sand
ITD Moscow Maintenance Yard		3	Black Coarse Sand
ITD Moscow Maintenance Yard		3	Loess Subgrade

Table 3.2. Unbound Data Obtained at Projects

	Data Obtained at Project					
Project	**GeoGauge**	**SDG**	**EDG w/ SC Model**	**EDG w/ NDG Model**	**NDG**	**SC**
I-84 Subgrade	Yes	No	Yes	No	Yes	Yes
I-84 Base	Yes	No	Yes	No	Yes	Yes
US 95 Payette	Yes	No	Yes	No	Yes[2]	Yes
US 95 Frontage	No	No	Yes	No	Yes	Yes
SH 8	Yes	No	Yes	No	No	Yes
US 95 Lapwai	Yes	Yes	No	Yes	Yes	Yes[1]
SH 55	Yes	Yes	Yes	Yes	Yes	Yes
SH 162 Four Corners	Yes	Yes	No	Yes	Yes	Yes[1]
College Ave	Yes	Yes	Yes	Yes	Yes[1]	Yes
US 20/26 Subgrade	Yes	Yes	No	No	Yes	No
US 20/26 Base	Yes	Yes	Yes	Yes	Yes	Yes
US 95 Athol	Yes	Yes	Yes	Yes	Yes	Yes
Mullan Ave	Yes	Yes	Yes	Yes	Yes	Yes
SH 16	Yes	Yes	Yes	Yes	Yes	Yes
Potlatch Subgrade	Yes	Yes	No	No	Yes	Yes[1]
Moscow ¾” Base	Yes	Yes	No	No	Yes	Yes[1]
Moscow Sand	Yes	Yes	No	Yes	Yes	No
Moscow Coarse Sand	Yes	Yes	No	Yes	Yes	No
Moscow Subgrade	Yes	Yes	No	Yes	Yes	No
US 95 Wilder	Yes	Yes	No	No	Yes[2]	No
US 95 Cottonwood	Yes	Yes	No	No	Yes[2]	No

1. Partial data set only
2. NDG Backscatter readings only.

3.3 EXPERIMENTAL PROCEDURES

3.3.1 Sand Cone Method

The sand cone (SC) procedure followed ASTM D1556-07, "Standard Test Method for Density and Unit Weight of Soil in Place by the Sand-Cone Methdod." SC, shown in Figure 3.1, involves the removal of in-situ soil and replacement with a sand of known density. By measuring the mass of the soil used in replacement, the volume of the hole can be determined. With the hole volume and mass of the removed soil known, the density of the removed soil can be determined. For most testing spots, removed material was collected in sealed plastic bags and returned to the laboratory for measurement. Moist sample weights were taken. Following ASTM D2216-10, "Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass," samples were then dried in the laboratory oven to determine moisture content.

For certain spots used in the EDG calibration, field determination of SC density and moisture were required in the field. In these cases, samples were weighed in the field and moisture was measured using a microwave oven following ASTM D4643-10, "Standard Test Method for Determination of Water (Moisture) Content of Soil by the Microwave Oven."

Figure 3.1. Sand Cone Apparatus

3.3.2 Nuclear Density Gauge

NDG testing methods followed Idaho Transportation Department (ITD) field operating procedures for AASHTO T 310-11, "In-Place Density and Moisture Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)," Method B. A pin hole was constructed, and the NDG probe placed 4 to 6 inches into the hole. Two one-minute readings were taken, with the gauge rotated 90° from the first measurement. The research group did not have direct access to an NDG and relied on ITD or contractor personnel for nuclear readings. A variety of nuclear gauges were used in this study. NDG models included Troxler 3440, 3430, and 3411-B models and Instrotek Explorer 3500, CPN MC-3, and CPN MC-1 models.

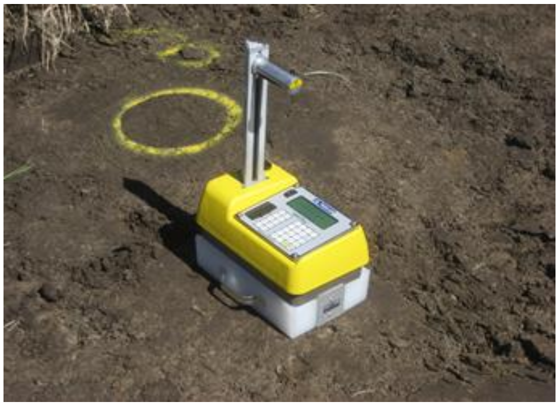

Figure 3.2. Troxler 3440 Nuclear Density Gauge

3.3.3 Electrical Density Gauge

EDG testing followed ASTM D7698-11, "Standard Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance Method." The EDG required the placement of four metal darts, each 6 inches long, into the soil. Darts were placed in a "plus sign" pattern, with two opposite darts 12 inches apart. Two electrical measurements were taken, one for each set of opposite dart pairs, and averaged together. In order to correlate physical properties to electrical properties at each site, a project specific calibration procedure, known as setting up a “soil model”, was required at each site. Three testing spots, the minimum required for soil model setup, were selected and EDG impedance measurements were taken. Moisture and wet density measurements were taken at the same soil model locations using other traditional methods (SC and NDG). Density and moisture values from the traditional devices were input into the EDG and the impedance measurements were paired with a moisture and density value at each spot. Using these pairings, the EDG linearly correlated future electrical measurements to wet density and moisture content. NDG and sand cone based soil models were established at each site. Further moisture/density measurements were taken without the aid of the traditional device, and the remaining locations were used as validation locations, or “job site” locations.

3.3.4 Soil Density Gauge

At the time of the field study, the SDG did not yet have an approved ASTM standard. Thus, manufacturer’s recommendations were followed. SDG testing consists of placing the gauge on a relative flat area of soil and taking a measurement. Unlike the sand cone, NDG, and EDG, SDG testing was completely non-intrusive. The SDG required material data in order to operate, which included maximum dry density and optimum moisture content, gradation, and Atterberg limits (for fine grained soils only). This input information was determined from AASHTO T 180, “Standard Method of Test for Moisture-Density Relations of Soils Using a 4.54-kg (10 lb) Rammer and a 457-mm (18-in.) Drop (or Idaho T-74 curve),” AASHTO T 27, “Sieve Analysis of Fine and Coarse Aggregates),” and AASHTO T 89, “Standard Method of Test for Determining the Liquid Limit of Soils,” and AASHTO T 90, “Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils,” respectively. SDG readings were taken in both a five shot clover leaf pattern. When space was limited on a site or testing spot, the clover pattern was shrunk or, in some cases, all five individual readings were taken in the same spot. The SDG required five independent readings and automatically averaged the results together at the end of the five shot sequence.

3.3.5 GeoGauge

GeoGauge testing followed ASTM D6758-08, "Standard Test Method for Measuring Stiffness and Apparent Modulus of Soil and Soil-Aggregate In-Place by Electro-Mechanical Method." The device was placed on the soil and rotated approximately 45° to 90° to seat the gauge. If the footprint of the gauge was not clearly visible upon removal of the gauge, moist sand cone sand was placed to assist gauge seating following manufacturer's recommendations. Two independent readings were taken and averaged together. If the modulus difference between the two sets of readings was higher than 1 ksi, a third measurement was taken and the two nearest measurements were averaged. The third measurement was thrown out. Both modulus and stiffness were recorded.

3.4 FIELD TESTING: TRADIATIONAL UNBOUND MATERIALS

Field testing of unbound material began by selecting up to ten testing spots. Prior to testing, if needed, loose material was shoveled away from a spot in order to obtain a relatively smooth, flat spot to test on. Yellow paint was used to outline and mark each spot. The goal was to test each device at the exactly the same spot, hence it was desired that the devices be tested in an order from least destructive to most destructive. The ideal device testing sequence consisted of:

1. SDG
2. GeoGauge
3. NDG

4. Perform three sand cone tests for EDG calibration
5. EDG
6. Perform remaining sand cone tests

The testing pattern is shown in Figure 3.3. The sand cone was taken outside of the NDG/NNDG device footprint, as the holes left by the NDG and EDG could affect the sand cone density measurement. The sand cone was taken 12 inches or less away from the footprint, in line with the path of the roller. The desired sequence was not always possible and was based heavily on the availability of the NDG technician. Often, the NDG shots had to be taken at the beginning of the sequence. In those cases, as shown in Figure 3.4, the other devices were tested very near the NDG test location. In Figure 3.4, the yellow outline marks the testing location of the SDG and EDG, the white sand marks the location of the GeoGauge. The NDG hole is slightly to the left of the outline. The sand cone is shown to the right of the outline. The depth of measurements for the SDG and NDG were 6 inches, the same depth as the EDG darts.

Three (of ten) sand cones were taken prior to EDG testing to calibrate the EDG in the field. For these three locations, in-situ moisture content was determined by placing a portion of the extracted sand cone sample in a microwave oven for drying.

3.5 FIELD TESTING: FDR/CRABS BASE PROJECTS

In-situ base and pavement recycling projects are popular in Idaho. Typical projects feature some sort of full or partial depth pulverizing of the HMA and granular base layer. The pulverized layer is then mixed with an additive and re-compacted. The new base is bound by the additives. ITD conducts a modified WAQTC TM-8, "In-Place Density of Bituminous Mixes Using the Nuclear Moisture-Density Gauge", procedure to measure compaction in the new base layer rather than a direct transmission method as prescribed in ASSHTO T 310. On CRABS projects, ITD technicians setup the roller pattern using to determine the “break over point”, similar to the break over process used in HMA. On other FDR projects, the contractor sets up the roller pattern and ITD performs a minimum of three density checks each production day on the compacted material using a backscatter measurement to ensure the compaction is near the break over compaction level.

Due to the popularity of these projects, if a non-nuclear gauge is to replace the NDG, it should have the ability to also measure compaction in these recycled “bound” bases. The sand cone and EDG were not chosen for this testing due the time and difficulty of conducting the tests in the very stiff material. Additionally, the destructive nature of the tests, especially the sand cone, could create detrimental defects in the bound base layer. NNDGs for pavement, including the PQI and PaveTracker, were considered for this type of testing but were found to be unstable due to the changing water content on the surface of the base layer during and after compaction. The SDG and GeoGauge were determined to be suitable for bound base testing.

When setting up the CRABS roller pattern, the GeoGauge and SDG were used alongside the NDG and their ability to predict the roller pattern was compared to that of the NDG. A single GeoGauge measurement was taken and five SDG readings were taken in a single spot and averaged. Additionally, the GeoGauge and SDG were also used to take measurements at single spot over the course of a couple hours, to analyze the measurement changes as the material stiffened.

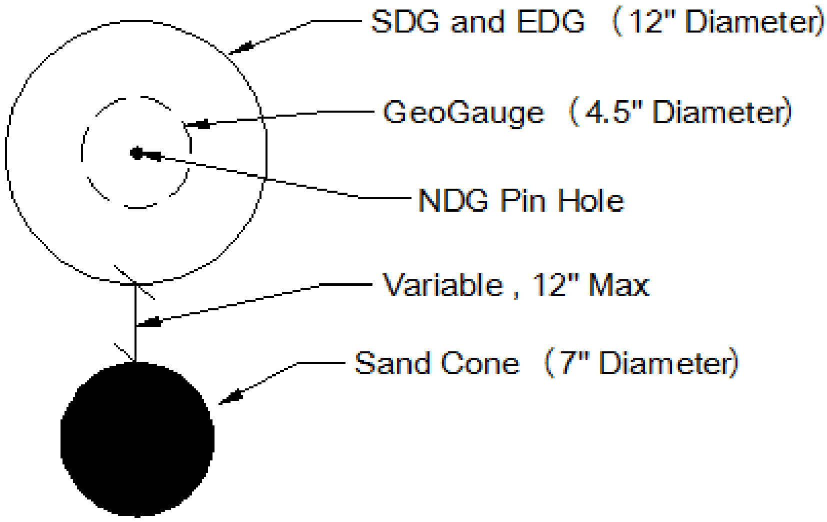

Figure 3.3. Unbound Field Testing Pattern

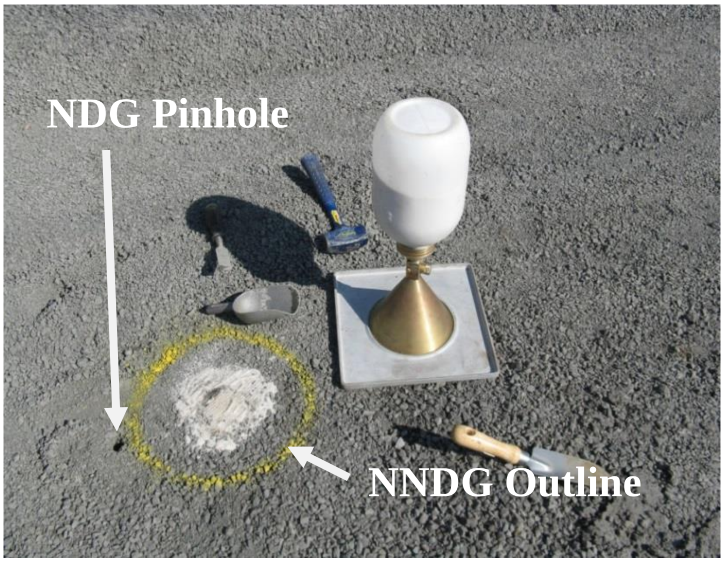

Figure 3.4. Modified Unbound Testing Layout

CHAPTER 4: FIELD TESTING RESULTS

4.1 INTRODUCTION

The collected data in the field on unbound materials were analyzed to evaluate the effectiveness of the EDG, SDG, and GeoGauge. The analysis of the EDG and SDG consisted of paired, two tailed t-tests and correlation comparisons between NNDG results and results from traditional reference devices: SC, NDG, and laboratory oven. Comparisons were made for the parameters of dry density (SC and NDG were reference devices), moisture content (oven, NDG) and wet density (SC, NDG).

4.2 t-test RESULTS

Student's t-tests were performed by comparing density and moisture content results from NNDGs and traditional devices. A *p*-value of 0.05 was selected as the level of significance. Results are shown in Table 4.1; underlined p-values indicate the NNDG data are statistically different from reference data. EDG and reference data were not significantly different in most cases, except the wet density from the EDG with NDG soil model compared with wet density from sand cone tests.

The uncorrected SDG's readings are statistically significantly different from SC and NDG density and oven moisture content. In order to improve SDG data, project specific correction factors were applied. For each project, the SDG measurement was corrected to equal the reference measurement at the first testing spot. SDG readings, at spots 2 through *n* (typically 10), were adjusted by this same correction offset. This procedure is known as the 1-point correction method.

As can be seen in Table 4.1, the 1-point SDG correction method produced better *p*-values, but results were still found to be significantly different when compared to sand cone and oven values. For more accurate results, a 3-point correction method was employed. In this method, the correction factor is the differences between the average of the first three SDG readings and the average three readings from a reference device. The correction factor was then applied to SDG measurements at locations 4 through *n* (typically 10). As seen in Table 4.1, after the 3-point correction was applied, none of the SDG *p*-values indicated a significant difference between SDG results and reference device results.

Table 4.1. *p*-Value Summary from Paired Student's t-tests

	Density				**Moisture Content**	
	Wet Density		**Dry Density**			
	SC	**NDG**	**SC**	**NDG**	**Oven (SC)**	**NDG**
EDG w/ SC Model	0.09	0.13	0.13	0.91	0.57	0.29
EDG w/ NDG Model	<u>0.028</u>	0.16	0.051	0.20	0.65	0.51
Uncorrected SDG	<u>2.87E-5</u>	<u>6.91E-4</u>	<u>6.20E-5</u>	<u>9.58E-4</u>	<u>0.022</u>	0.21
SDG (1pt Correction)	<u>0.02</u>	0.44	<u>0.007</u>	0.066	<u>0.009</u>	0.11
SDG (3pt Correction)	0.80	0.21	0.92	0.94	0.88	0.88

4.3 MOISTURE AND DENSTIY CORRELATION

Because the t-test results only informs us whether there was a statistically significant difference in measurements between the NNDGs and reference values, more rigorous quantification of the difference or indifference was needed. Therefore, the correlation between the NNDG results and reference values were evaluated. NNDG and reference device pairings that were found to be statistically significant from the t-test analysis were not further analyzed in the correlation analysis.

The key values in the correlation comparison are the slope and correlation coefficient (R^2) of the acquired linear trendline. In this analysis, ranges of R^2 values are attached to descriptors: "very good", "good", "fair", and "poor". The R^2 ranges associated with these descriptors and their applicability to QA/QC are presented in Table 4.2. These ranges were selected based on the literature review in Chapter 2 and state department of transportation survey results (Timm, 2012).

Table 4.2. Descriptor Terms and QA/QC Viability for Unbound Correlation R^2 Ranges

R^2 Range	Descriptor	Applicability to QA/QC
>0.80	***Very Good***	***Suitable for QA/QC***
0.6 to 0.8	***Good***	***Unsuitable for QA, possibly suitable for QC***
0.4 to 0.6	***Fair***	***Not consistently suitable for QC***
<0.4	***Poor***	***Not suitable for QC***

4.3.1 Dry Density

EDG and SDG dry density values were compared with dry density values calculated from sand cone or NDG.

4.3.1.1 NNDG vs. NDG

The correlation between the EDG (based on NDG and SC soil models) and NDG dry density is displayed in Figure 4.1. In the figure, the method in parenthesis after EDG is the method used to set up soil model in EDG. A very good correlation coefficient was seen (R^2=0.9) with a slope of near one when EDG with NDG soil model is used. EDG data with SC model correlated poorly (R^2=0.25) with the NDG. Figure 4.2 displays correlations between corrected SDG and NDG dry density. Note that the reference device used to correct the SDG was the NDG. The 1-point corrected SDG density has a good correlation (R^2=0.71) with NDG density. When the 3-point correction method was used, SDG dry density correlated very well with the NDG (R^2=0.85). The slopes of correlation trend lines are very close to 1. The EDG with NDG soil model and 3-point corrected SDG correlations had the strongest correlation with NDG density of the data sets analyzed.

The range of dry densities across all soils tested is very large, approximately 50 pcf which may overshadow the measurement error for individual materials. In order to reduce the range for correlation analysis, data from these sets was further separated into coarse material (bases and sands) and fine materials (silts and clays). A material was classified as coarse if greater than 50% of the particles were retained by the #200 sieve and otherwise fine materials, in accordance with USCS classification. Because the coarse material dry density range continued to remain fairly large, the coarse materials were further broken into base and sand subsets. Base materials have nominal maximum aggregate sizes of 3/4" or 5/8". All other coarse materials not considered bases were considered sands, with a majority (50% or more) of particles passing the #4 sieve. Figure 4.3 shows the separated density sets for the EDG, and Figure 4.4 shows the separated set for the 3-point corrected SDG. The slopes are very close to one, but the R^2 values reduced for each subset when compared to the overall set. The EDG correlated fairly with the NDG for base material (R^2=0.43) and good for the sands (R^2=0.79). However, the EDG correlated very poorly for fine materials (R^2=0.17). The SDG correlated fairly with the NDG for fine materials (R^2=0.57) and very well with sands (R^2=0.82). However, the SDG correlated poorly with the NDG for base materials (R^2=0.36).

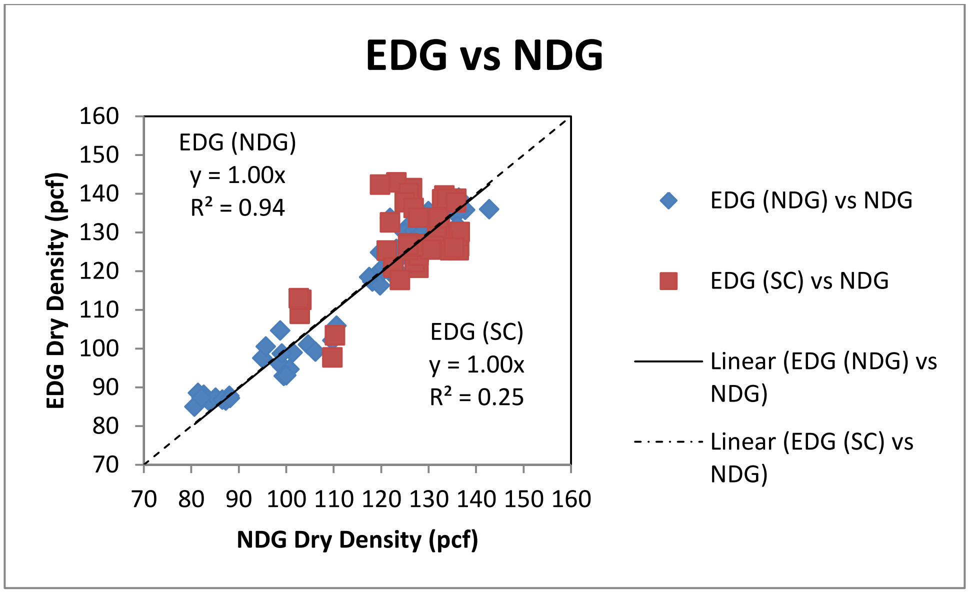

Figure 4.1. Dry Density Correlation: EDG vs. NDG

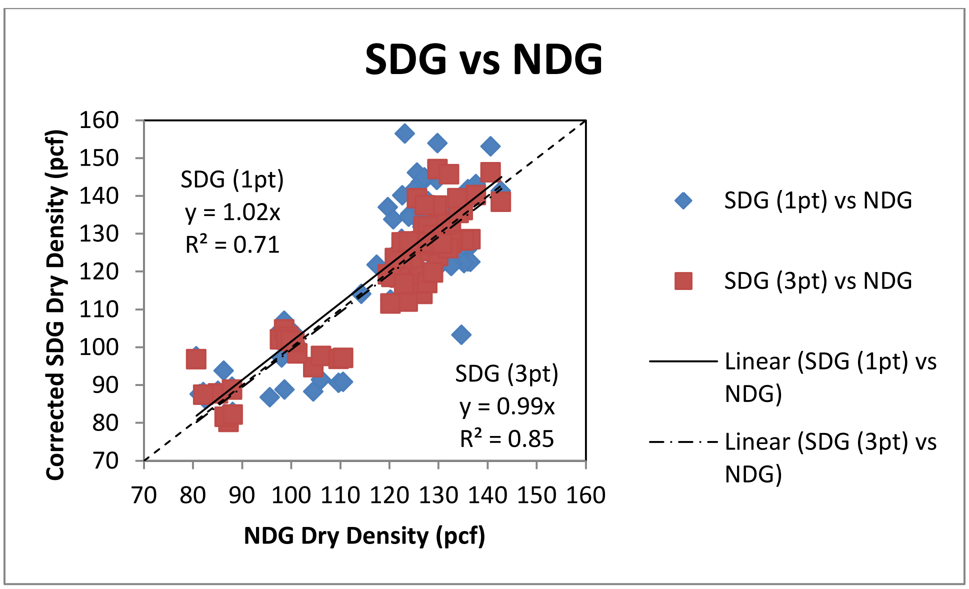

Figure 4.2. Dry Density Correlation: SDG vs. NDG

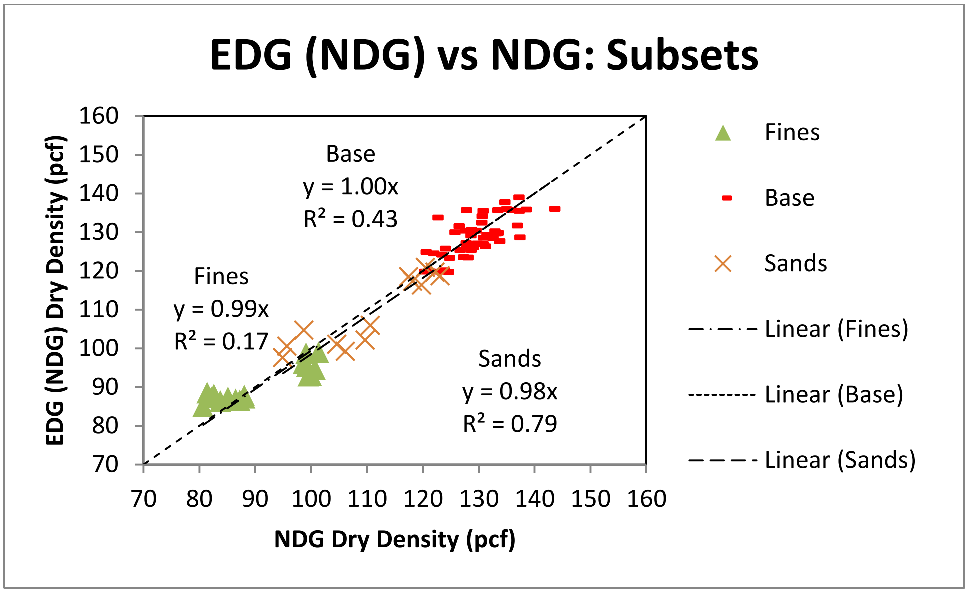

Figure 4.3. Dry Density Correlation: EDG (NDG Soil Model) vs. NDG with Material Subsets

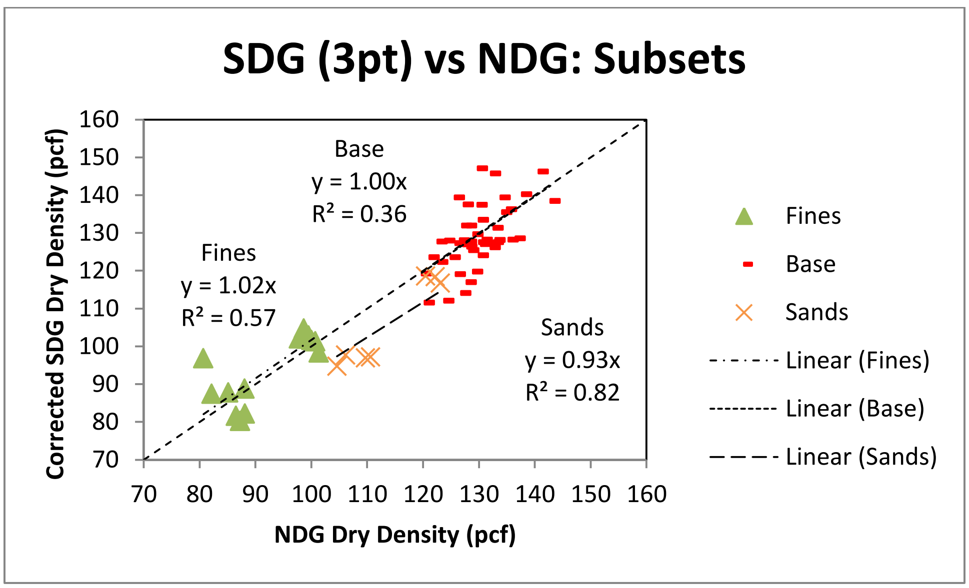

Figure 4.4. Dry Density Correlation: SDG (3-Point Corrected by NDG) vs. NDG with Material Subsets

4.3.1.2 NNDG vs. Sand Cone

Figure 4.5 compares dry density for the EDG with NDG or SC soil models compared to the sand cone. For both soil model results, the slopes are near one. Correlation coefficients were poor for the EDG with NDG soil model (R^2= 0.36) and fair for the EDG with SC soil model (R^2=0.45). The EDG results with SC reference values are not as favorable as the results using when the NDG was used as the reference device. Since t-test results indicate there was a significant difference between 1-point corrected SDG dry density and SC density, only the 3-point corrected SDG density was plotted against SC density in Figure 4.6. The SDG data was corrected using SC densities. Similar to the EDG analysis, a slope near one was observed. However, the R^2 value is lower when compared with the results when the NDG is used as the reference device.

Based on these results, sand cone-based soil models and corrections for the EDG and SDG respectively provide poor to fair results with significant scatter. The EDG with soil model based on NDG and 3-point corrected (by the NDG) SDG provided significantly improved results when the NDG was used as the reference device.

4.3.2 Moisture Content

Moisture contents measured by the EDG and SDG were compared with moisture contents from the laboratory oven drying of soils from sand cone tests, which was considered to be the true moisture content. SDG moisture content values were corrected with oven values. As shown in Figure 4.7, the EDG with NDG soil model data correlated better with oven moisture content than EDG with SC soil model data. The R^2 value for EDG with SC soil model data is still in the "good" range (R^2=0.6), but is not as favorable as the EDG with NDG soil model correlation (R^2=0.96). The 3-point corrected SDG data also provided a very good correlation with oven moisture content (R^2=0.93), as shown in Figure 4.8 (1-point corrected SDG data was not analyzed due to poor t-test results).

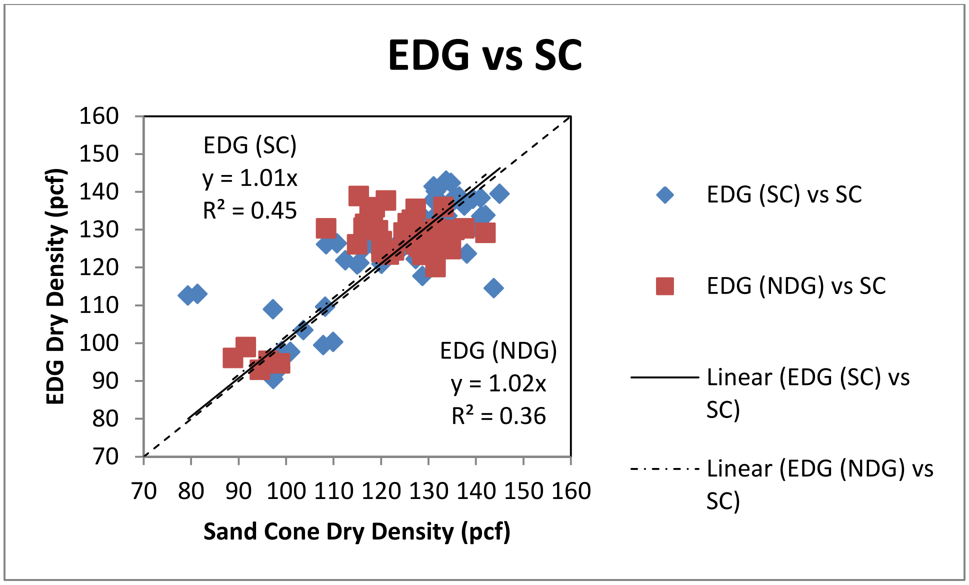

Figure 4.5. Dry Density Correlation: EDG vs. SC

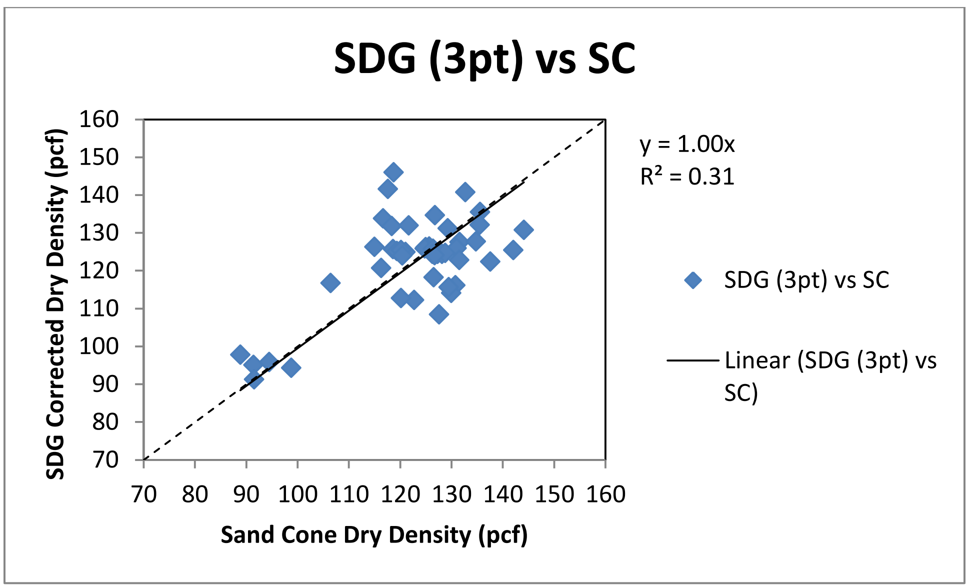

Figure 4.6. Dry Density Correlation: SDG vs. SC

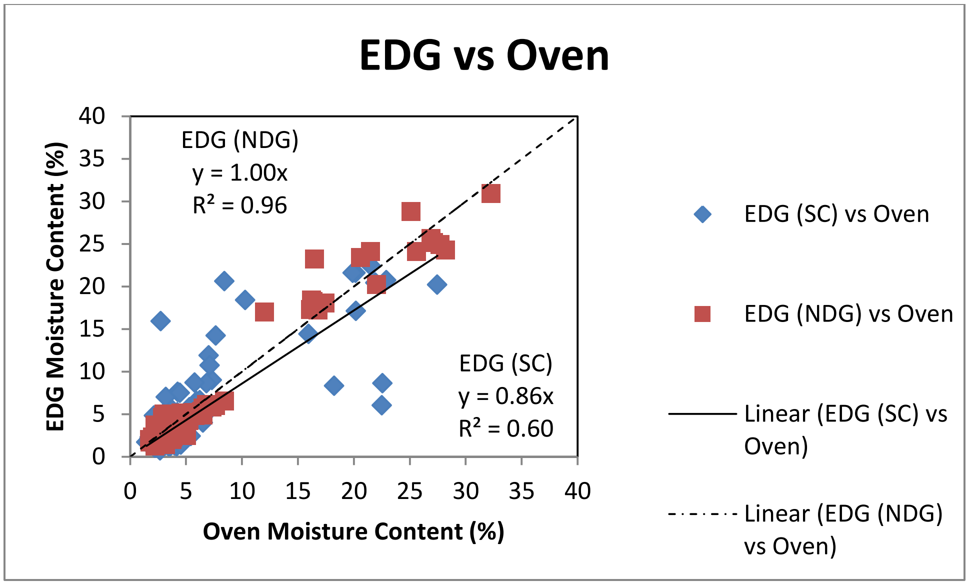

Figure 4.7. Moisture Content Correlation: EDG vs. Oven

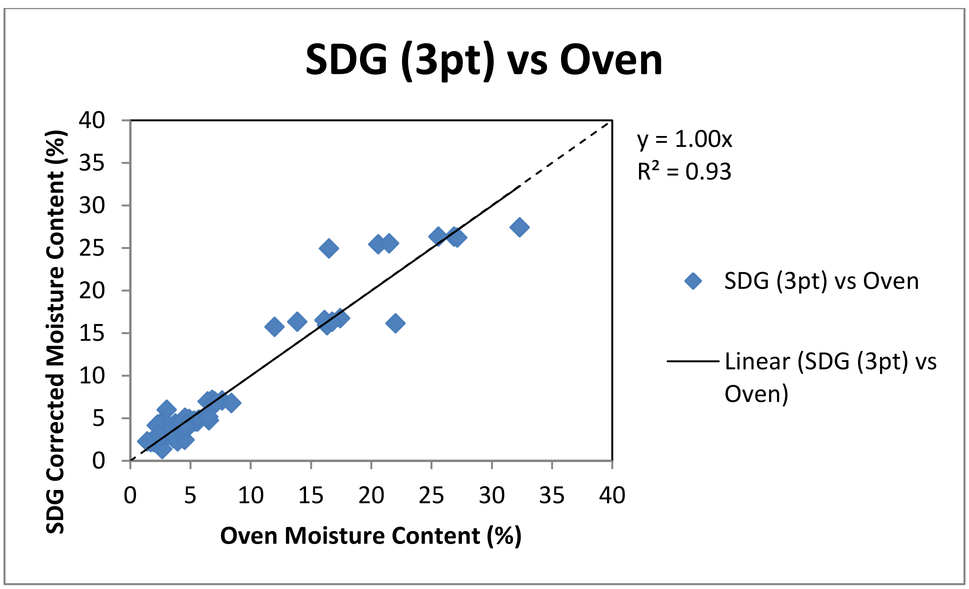

Figure 4.8. Moisture Content Correlation: SDG vs. Oven

Similar to the dry density results, the most favorable results were found with the EDG with NDG soil model and 3-point corrected SDG. Hence, similar to the dry density results, the data for each device was split into individual material subsets: fines, base, and sands. The subset correlation plots are shown in Figure 4.9 for the EDG and Figure 4.10 for the SDG.

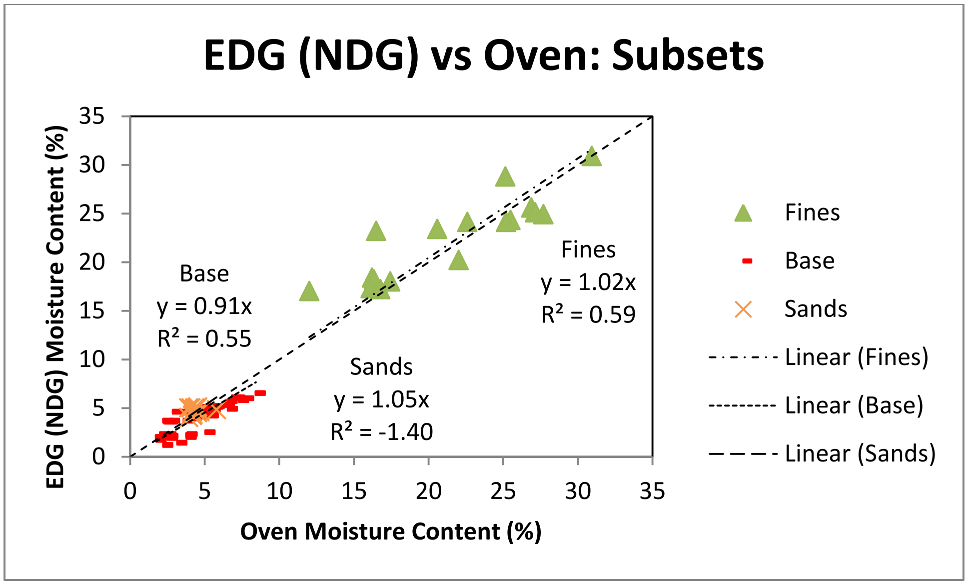

Figure 4.9. Moisture Content Correlation: EDG (with NDG Soil Model) vs. Oven with Material Subsets

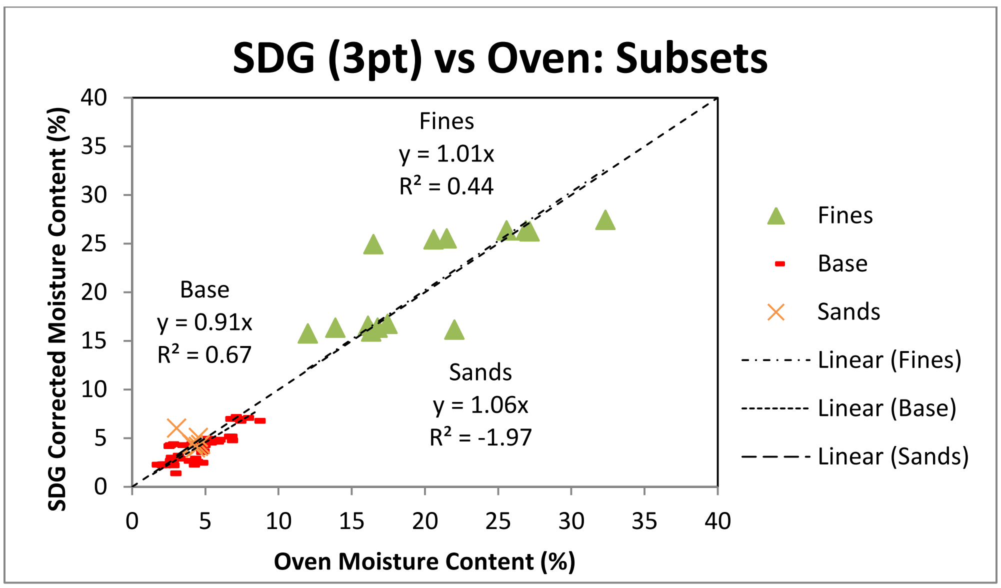

Figure 4.10. Moisture Content: SDG (3-Point Corrected by Oven) vs. Oven with Material Subsets

For both fine and base materials, EDG data correlate fair with oven data. SDG base data correlate well with the oven data, while fines data correlate fairly. Sands data for both the EDG and SDG correlated poorly with sands data for the oven. Although the SDG R^2 value is good for fine materials, a data banding effect is noticeable. This can be observed by the two, almost horizontal lines of data points in the fines subset in Figure 4.10. In the fines subset, oven moisture content varies significantly, while SDG moisture contents vary very little. The banding effect has been observed in other SDG research (Mejias-Santiago, 2013). The banding effect is somewhat noticeable, but less prominent with the EDG.

Like the dry density results, the moisture results indicate that the devices report a very good overall moisture trend compared with laboratory oven values. However, when material subsets were analyzed, R^2 values reduced and other problems, such as SDG data banding for fine material, became noticeable. The most promising results were produced by the 3-point corrected SDG on base materials. Good R^2 values indicate the SDG could be used to measure base moisture content for QC purposes. However, poorer results in fines and sands limit the moisture QC applicability of the SDG. The EDG produced fair R^2 values for all material subsets except sands, but did not show consistent accuracy or precision needed for QC applications.

4.3.3 Wet Density Correlation

Although dry density is often the desired value when comparing field density to maximum density determined in the laboratory, wet density is of key interest because both devices directly compute wet density based on measured electrical relationships. Wet density, along with moisture content, is used to calculate dry density. Comparing NNDG wet density with wet density data from reference devices can give insight into how well the NNDG measures wet density. The NNDG may be measuring wet density accurately, but due to poor measurement of moisture content, the resultant dry density values are also poor. Similar to the dry density analysis, the EDG and SDG wet densities were compared with NDG and SC wet densities.

4.3.3.1 NNDG vs. NDG

The correlation between the EDG and NDG wet density is displayed in Figure 4.11. EDG data established using both NDG and SC soil models are shown in this figure. A very good correlation coefficient was seen (R^2=0.9) with a near 1:1 slope when EDG with NDG soil model is used. EDG data with SC model correlated very poorly (R^2=-0.44) with the NDG. Figure 4.12 displays correlations between corrected SDG and NDG wet density. 1-point corrected SDG density had a good correlation (R^2=0.63) with NDG density. When the 3-point correction method was used, SDG wet density still correlated well with the NDG (R^2=0.76). The slopes of all correlation trend lines for both devices were very close to 1:1.

Similar as dry density, the EDG with NDG soil model and 3-point corrected SDG correlations had the strongest correlation with NDG density of the data sets analyzed. Like the dry density results, the data for each device was split into individual material subsets: fines, base, and sands. Figure 4.13 shows the separated density sets for the EDG, and Figure 4.14 shows the separated set for the 3-point corrected SDG. The slopes stay very close to 1, but the R^2 values again reduce for each subset compared with the overall set. The EDG correlated very well with the NDG for sands (R^2=0.82), fairly with the NDG for base material (R^2=0.54) and very poorly with the NDG for fines (R^2=-0.66). The SDG correlated well with the NDG for fines and very well for sands (R^2=0.62 for fines and R^2=0.82 for sands), but correlated only fairly with the NDG for base materials (R^2=0.44).

4.3.3.2 NNDG vs. Sand Cone

Figure 4.15 compares wet density for the EDG with SC soil model with SC wet density. The R^2 value is poor in this correlation (R^2= 0.20). The 3-point corrected SDG density was plotted against SC density in Figure 4.16. Similar to the EDG analysis, the slope is near 1, but the correlation coefficient (R^2=0.05) is lower compared with the results when the NDG is used as the reference device. Similar to dry density results, the wet density correlation of NNDG data with SC data are not as favorable as the NNDG data correlated with NDG data.

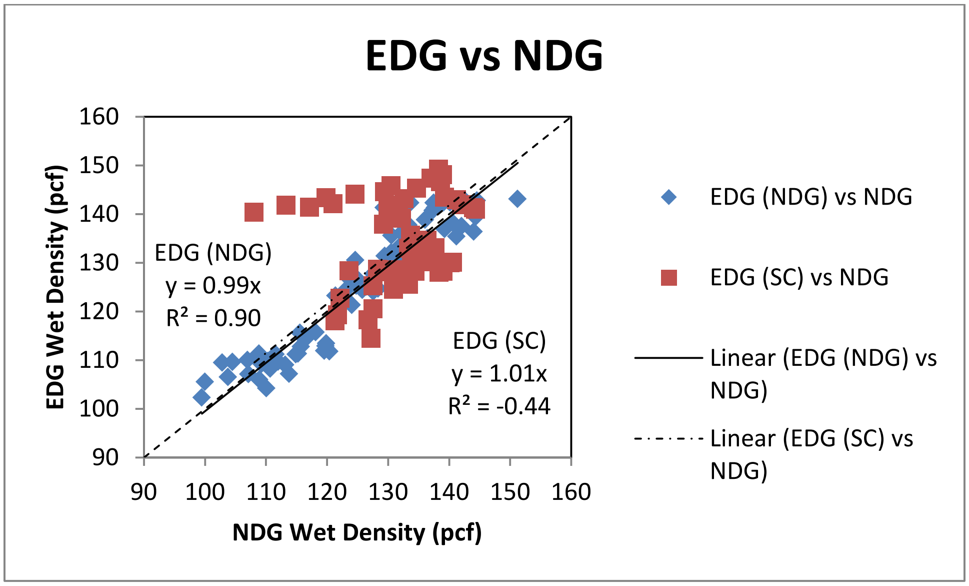

Figure 4.11. Wet Density Correlation: EDG vs. NDG

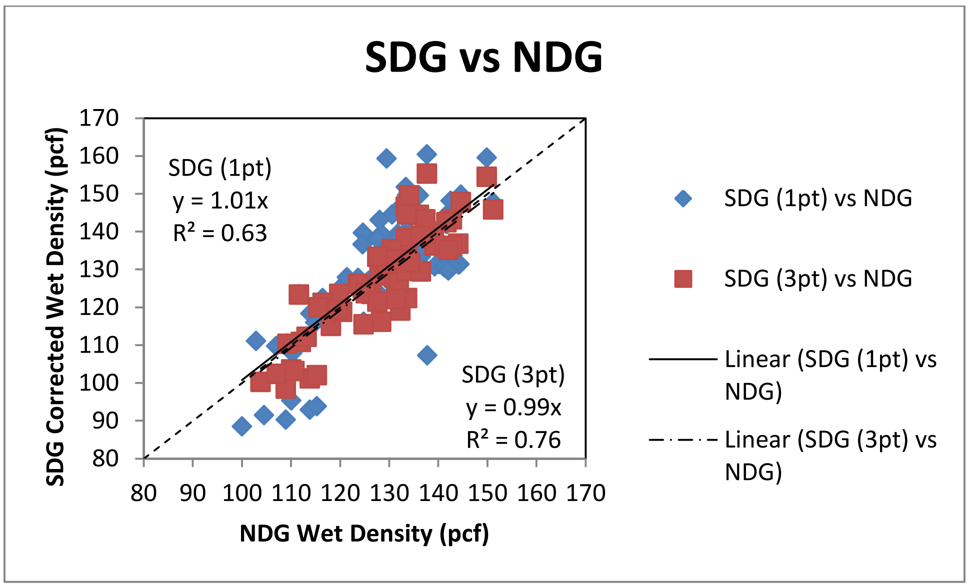

Figure 4.12. Wet Density Correlation: SDG vs. NDG

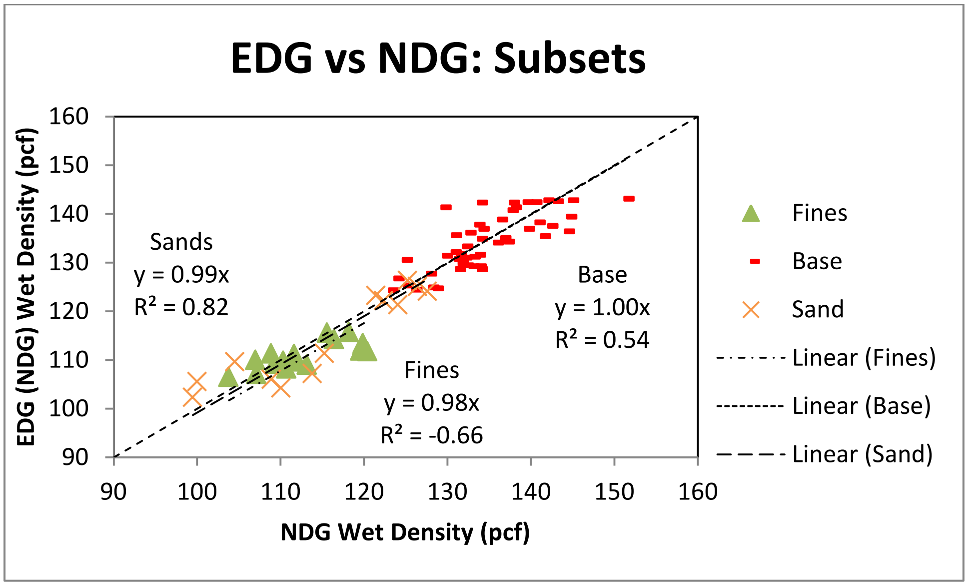

Figure 4.13. Wet Density Correlation: EDG (NDG Soil Model) vs. NDG with Material Subsets

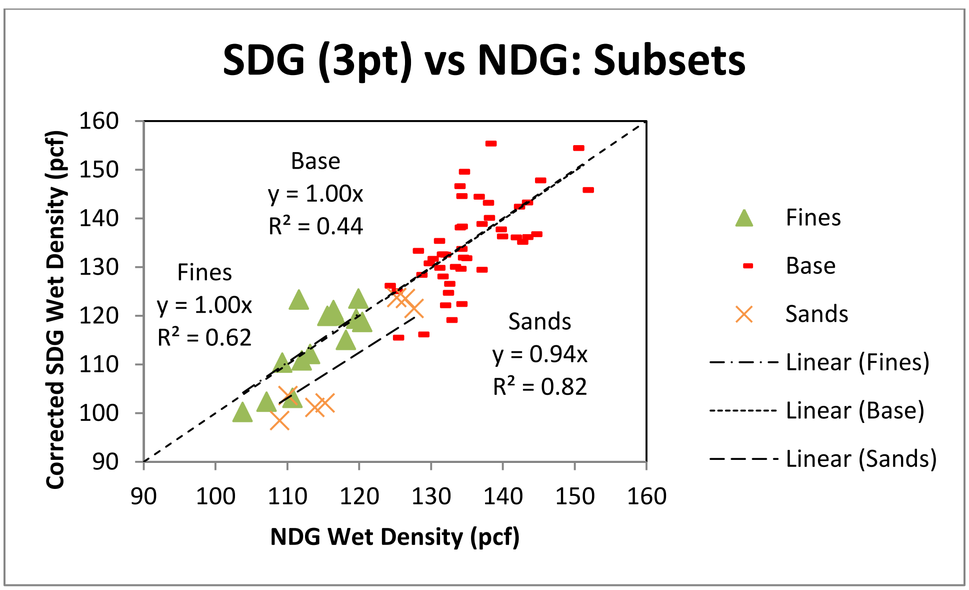

Figure 4.14. Wet Density Correlation: SDG (3-Point Corrected by NDG) vs. NDG with Material Subsets

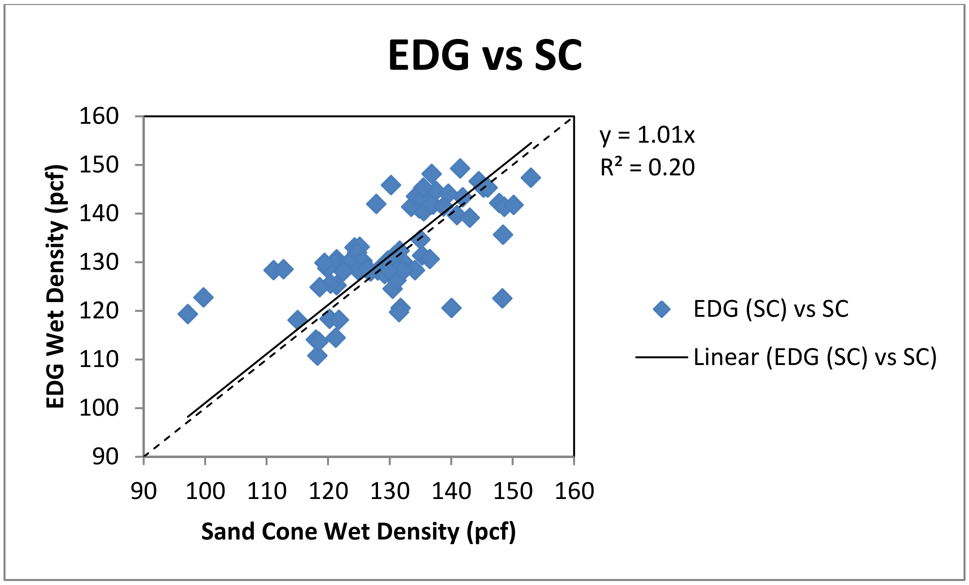

Figure 4.15. Wet Density Correlation: EDG vs. SC

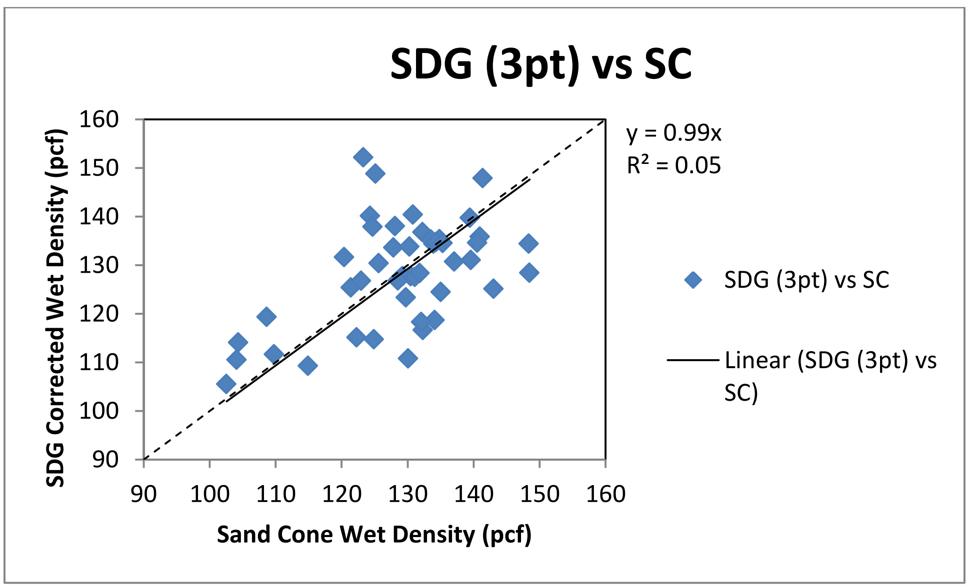

Figure 4.16. Wet Density Correlation: SDG vs. SC

4.4 EDG EXPERIMENTS ON SOIL MODEL SIZE

The EDG data acquired for t-test and correlation analysis was all based on 3-point soil models. Further experiments were conducted to study the effects of increasing the soil model size on the EDG outputs (wet density, dry density and moisture content). Specifically, these experiments sought to determine if soil models based on more than three data points produce more accurate EDG outputs. Soil model size experiments and analysis were only conducted on Year 3 (2013) materials. Only the NDG was used to establish the soil models.

The setup of EDG soil models was altered from the regular soil model procedure used by the team. Rather than establishing the soil model at only three locations, soil model was established at all locations tested. The EDG allows users to remove locations from the soil model, as long as a minimum of three locations are still present in the soil model. After soil model readings were taken at all locations for a given soil, three soil model sizes were established:

- A typical 3-point model. The operator removed all soil model locations except the three locations that gave the best range of material density and moisture properties (in the operator's best judgment).
- A 5-point soil model. The procedure was similar to establishing the 3-point soil model except that five locations remained in the soil model rather than three.
- An all-point soil model. All of the locations tested were used in the soil model. Between 5 and 10 locations were tested depending on the material.

Increasing the soil model size is believed to increase the accuracy of the results. Using an "all-point" soil model (that is, using all tested locations for calibration) is not realistic for construction practice. However, it can verify the accuracy of the soil model size (3-points) used in this study. "All-point" like soil models have be used in previous evaluation of the EDG (Meehan and Hertz, 2013).

Immediately after conducting tests for a soil model, "job site" measurements were also taken. The "job site" measurements typically produce density and moisture content once the soil model had been established. In this testing, the "job site" measurements did not produce readings since the soil model had not been completely established. Rather, the EDG stores the electrical parameters from the "job site" measurement. The soil model was established after field testing. After the establishment of the three soil models (3-point, 5-point, and all-point), the "job site" measurements produced density and moisture content values at each location for each soil model.

Figure 4.17 shows wet density correlation for the EDG and NDG for 3-point, 5-point, and all-point soil models. Very little change is observed in the trend lines for different soil models. The R^2 values for the 3-point soil model are actually slightly higher than for the 5-point soil model (R^2=0.86 for 3-point soil model and 0.82 for 5-point soil model). However, the correlation coefficients for the 3-point and all-point models are nearly identical (R^2=0.86 for both). Figure 4.18 shows dry density correlation for 3-point, 5-point, and all-point soil models. Similar to wet density, R^2 values change very little between each correlation (R^2 = 0.93 or 0.92 for all correlations).

Figure 4.19 shows moisture correlation between NDG moisture content and the moisture contents from EDG with 3-point, 5-point, and all-point soil models. Similar to density results, very little change is observed between the three soil model sizes. The slopes and R^2 values are nearly the same for each data set.

These results showed that soil model size did not have a significant impact on the accuracy of EDG. In some cases, larger soil models slightly reduced the accuracy of the gauge. Hence, larger soil models will not necessarily produce better results. However, EDG soil models should be setup in accordance with ASTM D7698-11 to incorporate a good variation of moisture and density values expected in the field.

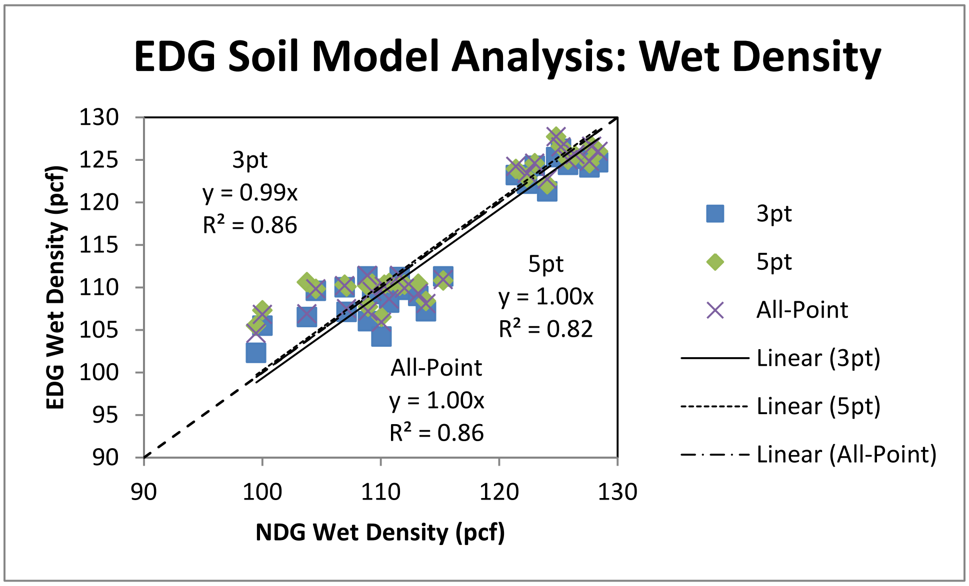

Figure 4.17. EDG Wet Density vs. NDG Wet Density when 3-point, 5-point, and All-Point Soil Models are used

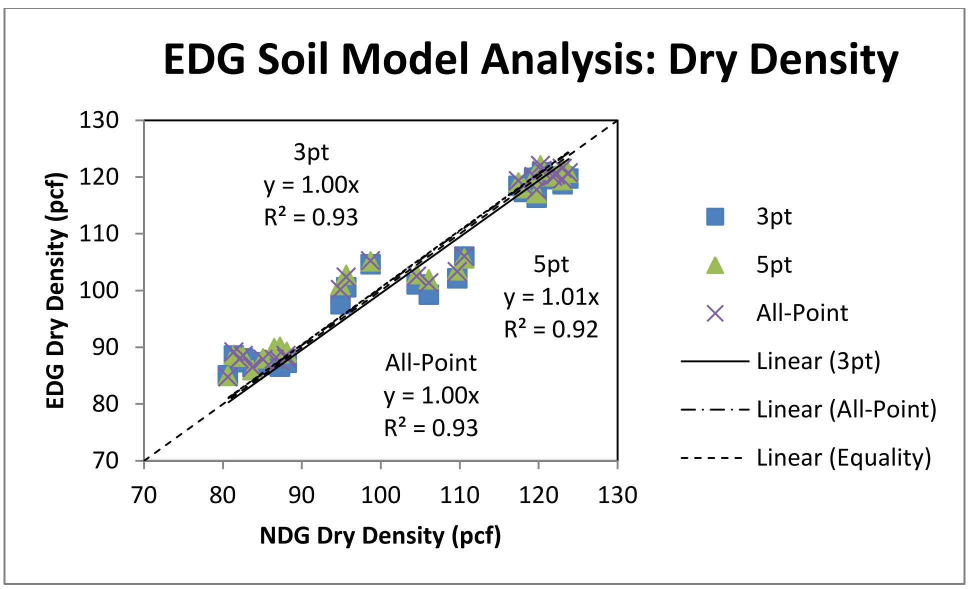

Figure 4.18. EDG Dry Density vs. NDG Dry Density when 3-point, 5-point, and All-Point Soil Models are used

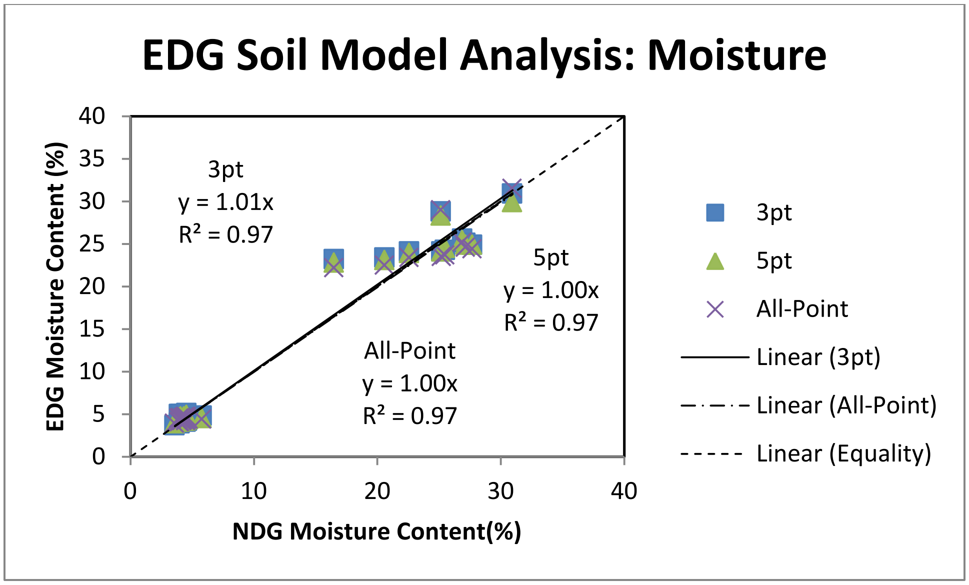

Figure 4.19. EDG Moisture Content vs. NDG Moisture Content when 3-point, 5-point, and All-Point Soil Models are used

4.5 EVALUATION OF AN ALTERNATIVE PROTOTYPE TO REPLACE EDG DART MEASUREMENTS

For 2013 soil testing, Dennis Anderson of Electrical Density Gauge Company, LLC provided Washington State University a prototype device designed to replace EDG darts for density and moisture content measurements. A picture of the "plate" prototype device is displayed in Figure 4.20. The plate device is one method that Humboldt and the Electrical Density Gauge Company are evaluating to replace the current dart method, shown in Figure 4.21. The plate device is minimally destructive and requires less time to setup than the dart method. The plate does require a minimal amount of rubbing into the surface in order to establish good contact between the metal rods and the soil. The depth of measurement is approximately 10 inches, which is the spacing between the two metal rods.

The plate device features two parallel, metal rods connected by a square piece of hard plastic. Metal screws connect the rods to the plastic. The screws are also used to provide a clamping point for the EDG's alligator clamps. All other EDG components can be used with the plate prototype. The plate device was originally supposed to be used with a newer EDG H-4114SD.3F model. Due to a problem with the newer model's battery, both dart and plate measurements were taken with the older EDG C model.

Figure 4.20. EDG Plate Prototype Device

Figure 4.21. EDG Dart Setup

EDG plate and dart wet density measurements were compared to NDG wet density measurements. Results for both the plate and dart methods were analyzed using 3-point, 5-point, and all-point soil models. Figure 4.22 shows the wet density comparison for 3-point soil model data, Figure 4.23 shows the wet density comparison for 5-point soil model data, and Figure 4.24 shows the wet density comparison when all data points were used in the soil model. The R^2 value for the dart data tended to be higher than plate data, except when all points were used in the soil model. In the all-point case (Figure 4.24), the R^2 for the dart and plate data are nearly equal. The plate correlations, while not as good as the dart correlations, are still reasonably good.

Dry density results from the plate and dart methods were compared to calculated NDG dry densities. Figure 4.25 shows the dry density comparison for 3-point soil model data, Figure 4.26 shows the dry density comparison for 5-point soil model data, and Figure 4.27 shows the dry density comparison when all data points were used in the soil model. The plate method compared very favorable with the dart method for the 5-point and all point soil model data. The dart method was more favorable in the 3-point soil model comparison.

EDG plate and dart moisture content measurements were compared with NDG moisture content measurements. Again, results for both the plate and dart methods were analyzed using 3-point, 5-point, and all-point soil models. Figure 4.28 shows the moisture content comparison for 3-point soil model data, Figure 4.29 shows the moisture content comparison for 5-point soil model data, and Figure 4.30 shows the moisture content comparison when all data points were used in the soil model. Oven moisture samples were not taken at all locations. Oven results that were taken are displayed in each figure to approximately represent the actual range of moisture content. The R^2 values for the dart and plate correlations were very good and very close to one another. The plate method was especially accurate in measuring higher moisture contents (20% to 35% range), and appear to reduce moisture data banding that is slightly noticeable in the dart measurements.

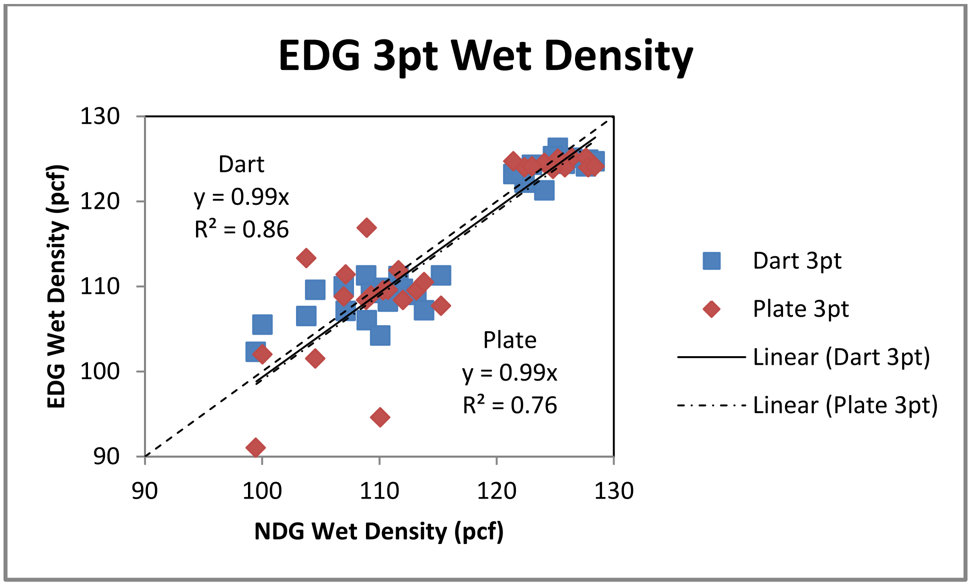

Figure 4.22. EDG Dart and Plate Wet Density Comparison with 3-Point Soil Model Data

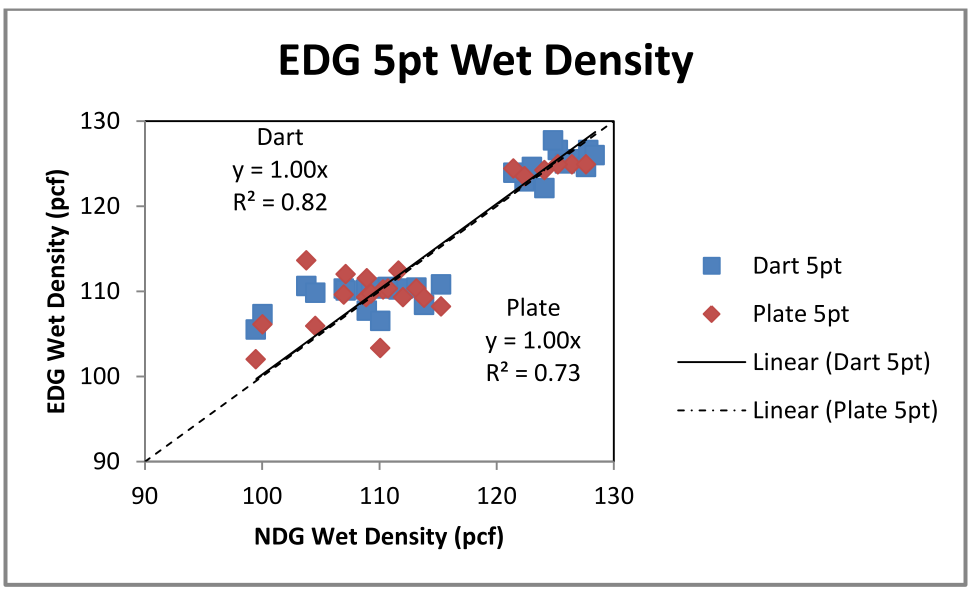

Figure 4.23. EDG Dart and Plate Wet Density Comparison with 5-Point Soil Model Data

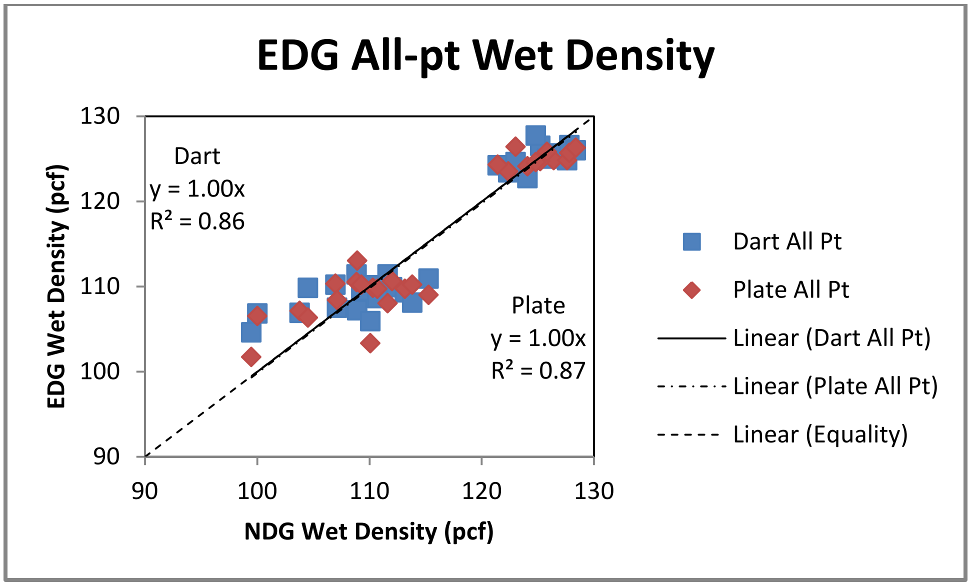

Figure 4.24. EDG Dart and Plate Wet Density Comparison with All Tested Points in the Soil Model

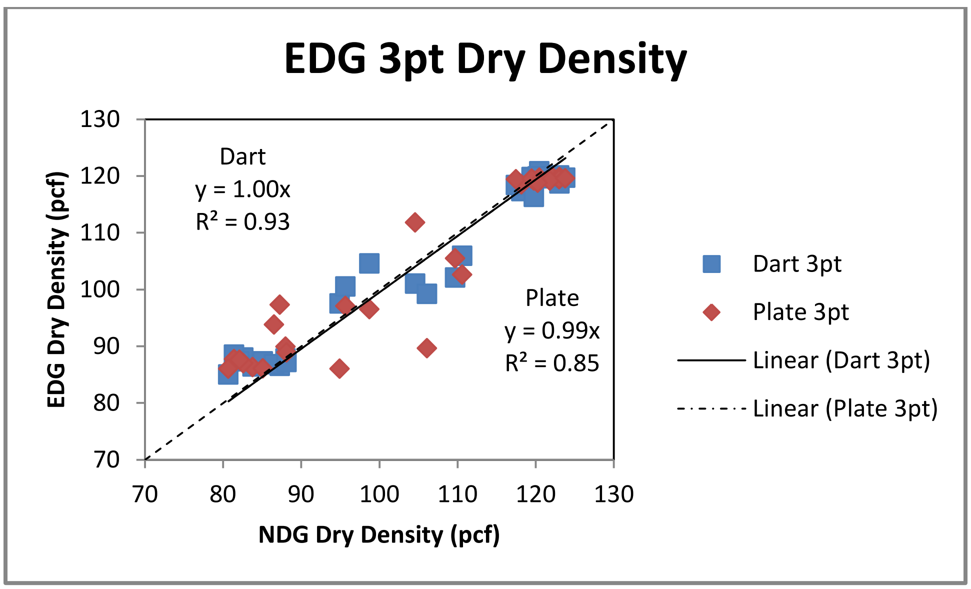

Figure 4.25. EDG Dart and Plate Dry Density Comparison with 5-Point Soil Model Data

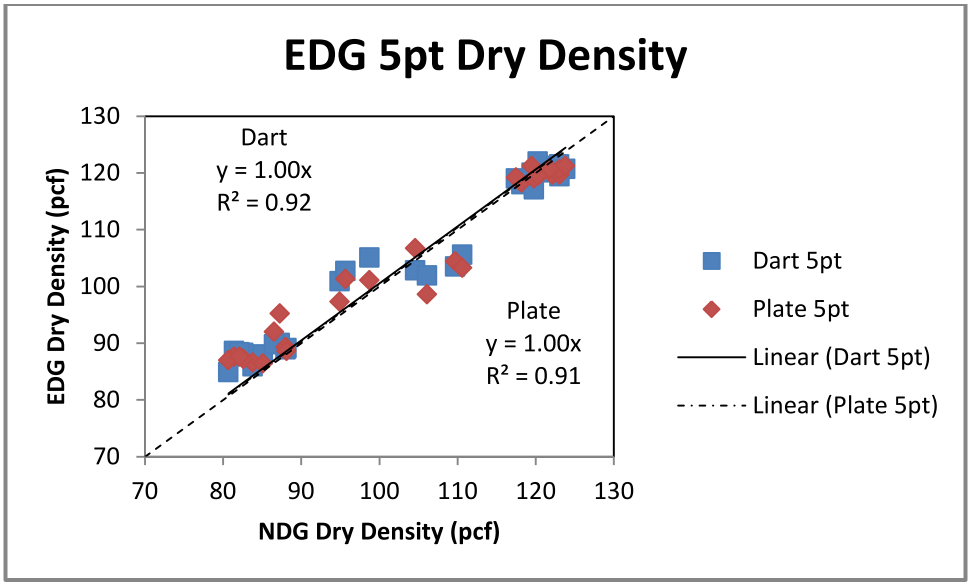

Figure 4.26. EDG Dart and Plate Dry Density Comparison with 5-Point Soil Model Data

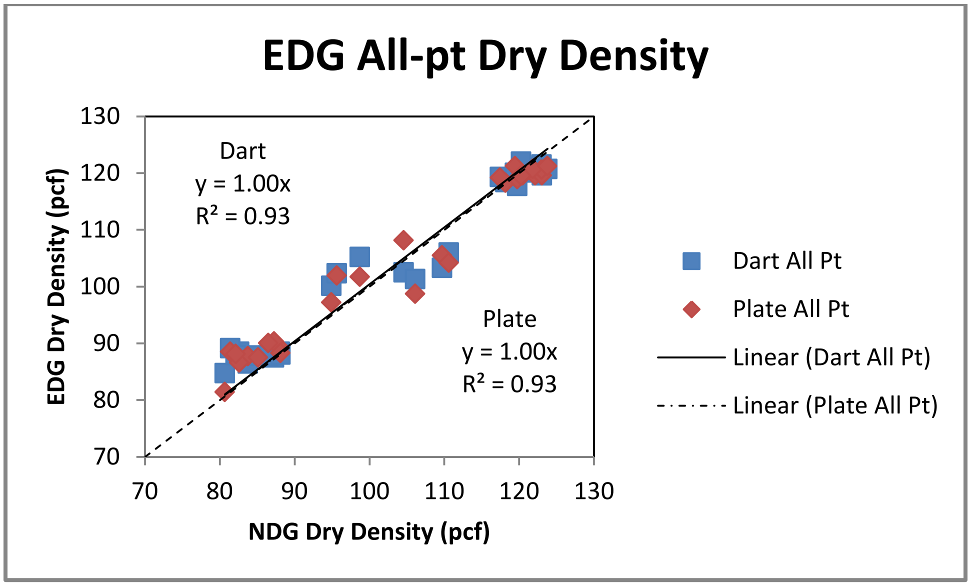

Figure 4.27. EDG Dart and Plate Dry Density Comparison with All Tested Points in the Soil Model

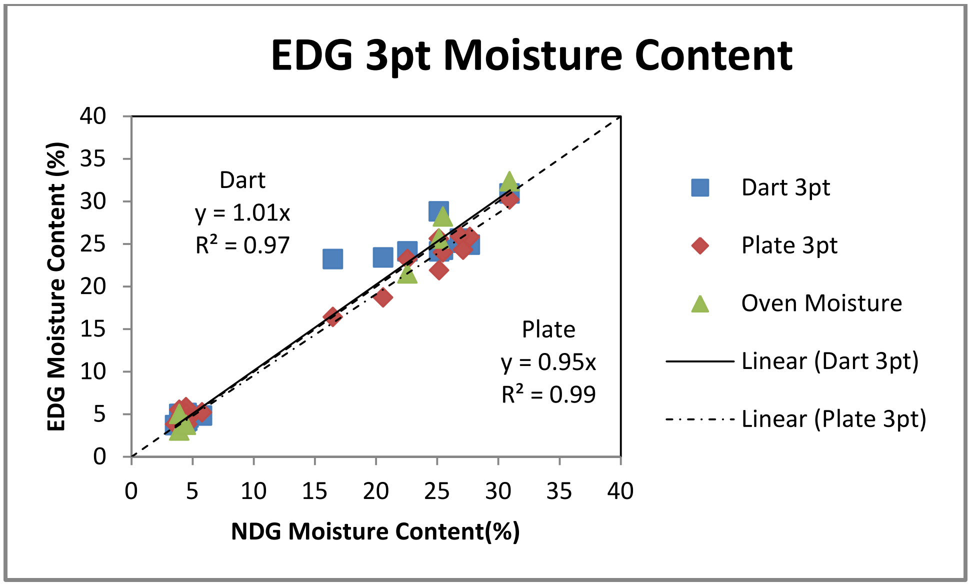

Figure 4.28. EDG Dart and Plate Moisture Content Comparison with 3-Point Soil Model Data

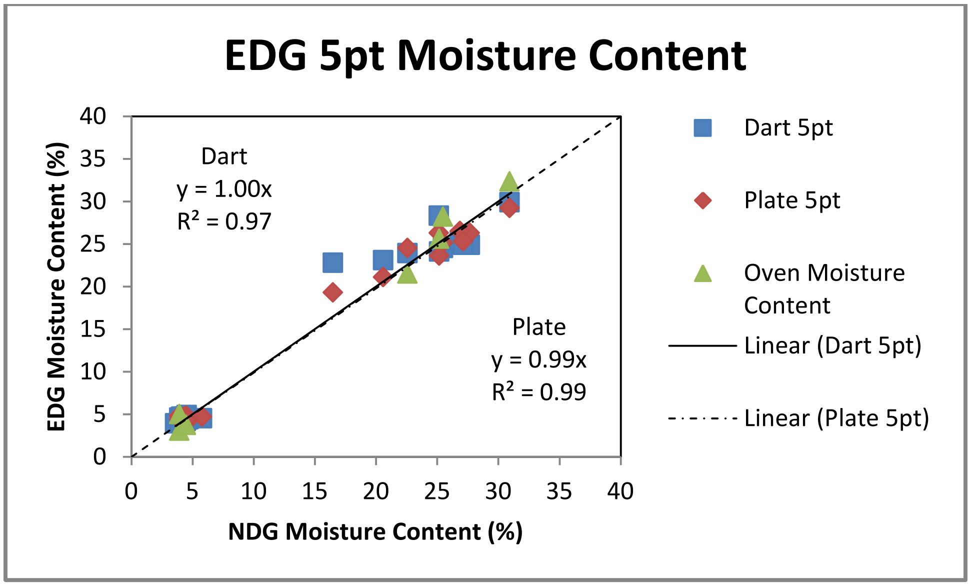

Figure 4.29. EDG Dart and Plate Moisture Content Comparison with 5-Point Soil Model Data

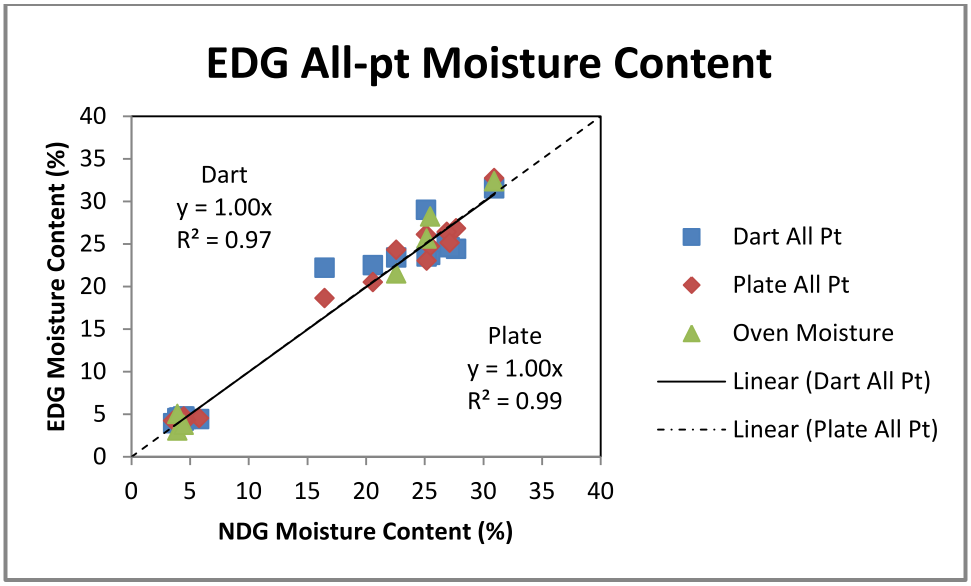

Figure 4.30. EDG Dart and Plate Moisture Content Comparison with All Tested Points in the Soil Model

The plate prototype is a promising device to replace darts for EDG measurements. The darts more accurately predicted wet density than the plate device. Dry density results, however, were very similar between the two methods. Considering the depth of measurement for the plate device is larger (10 inches) than the dart and NDG measurement (6 inches), some variation was expected. Moisture measurements were nearly equal with the plate slightly having slightly better performance. The plate device appears to reduce data banding in EDG moisture measurements. The results also show that more soil model points may be needed to produce more accurate results for the plate method. Further research and testing of the plate prototype is encouraged.

4.6 GEOGAUGE STIFFNESS AND MODULUS RESULTS

GeoGauge stiffness results for all tested projects were plotted against NDG dry density in Figure 4.31, SC dry density in Figure 4.32, and oven moisture content in Figure 4.33. GeoGauge modulus results were plotted against NDG dry density in Figure 4.34, SC dry density in Figure 4.35, and oven moisture content in Figure 4.36. No consistent trends were identified in any of the comparisons. The lack of correlation between stiffness/modulus parameters and moisture/density is consistent with pervious research (Bloomquist et al., 2003; Rathje et al., 2006; Nazarian et al., 2011). No trends between stiffness/modulus and moisture/density were found on a project level basis. Unless modulus and stiffness specifications are established, the GeoGauge will not provide relevant information to agency and contractor personnel. The GeoGauge can provide some insight into the uniformity of the unbound layer, but the uniformity reported by the GeoGauge may not match the uniformity reported by a moisture/density measuring device.

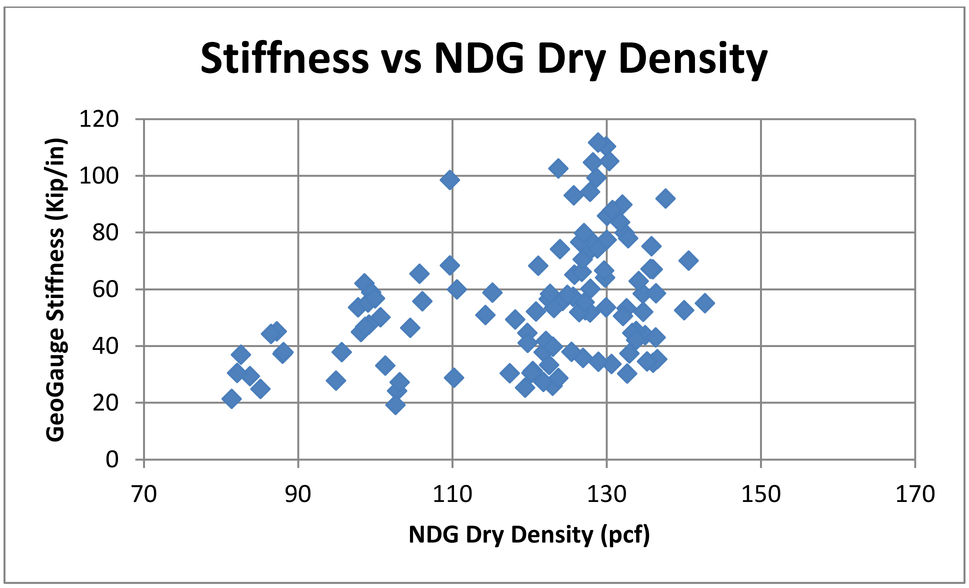

Figure 4.31. GeoGauge Stiffness vs. NDG Wet Density

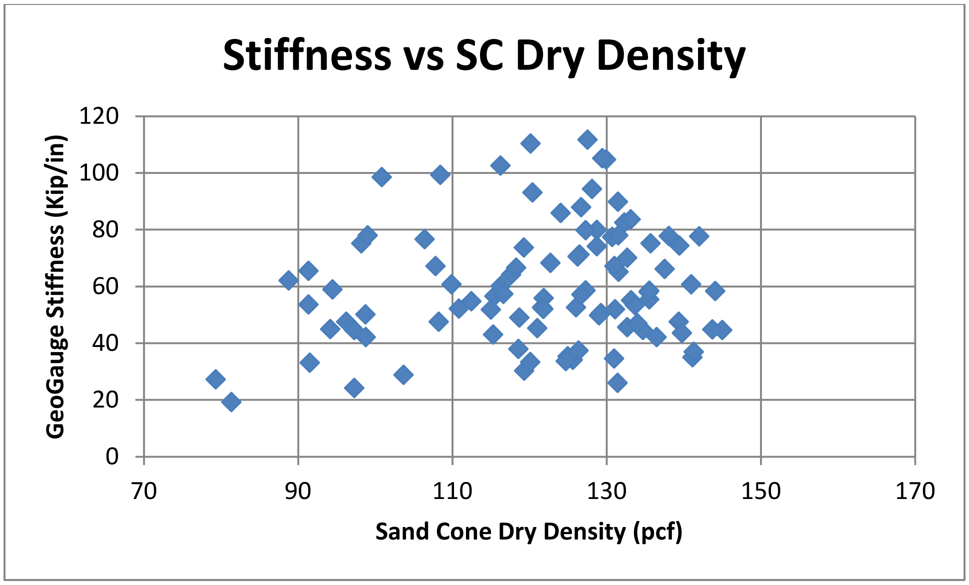

Figure 4.32. GeoGauge Stiffness vs. SC Wet Density

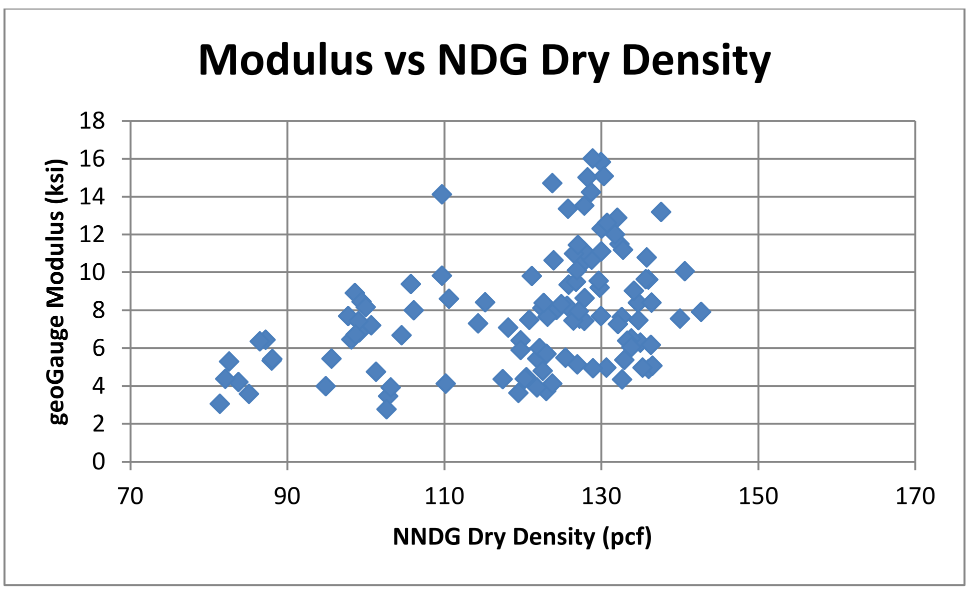

Figure 4.33. GeoGauge Modulus vs. NDG Dry Density

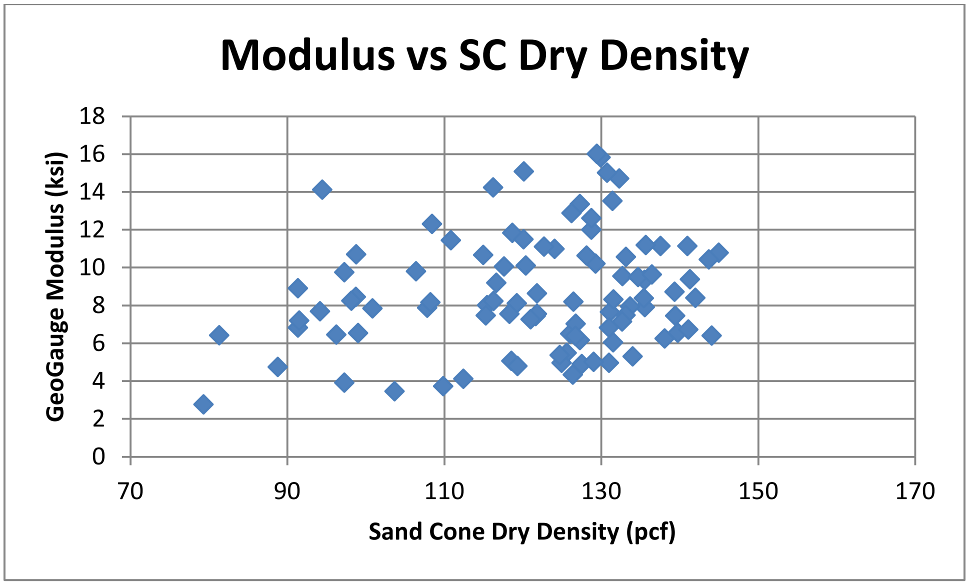

Figure 4.34. GeoGauge Stiffness vs. SC Dry Density

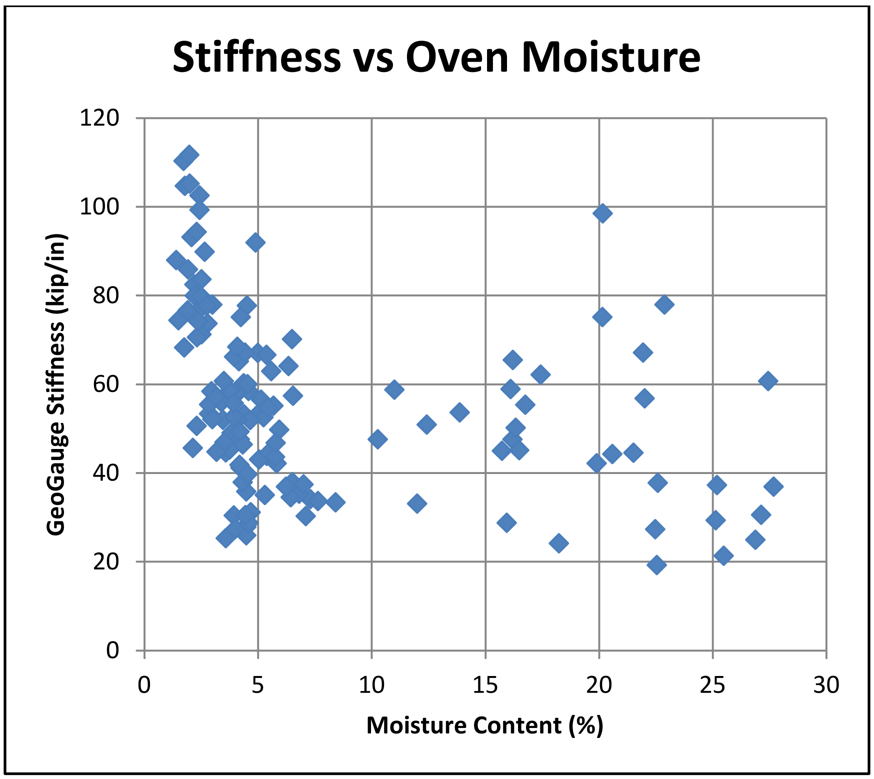

Figure 4.35. GeoGauge Stiffness vs. Oven Moisture Content

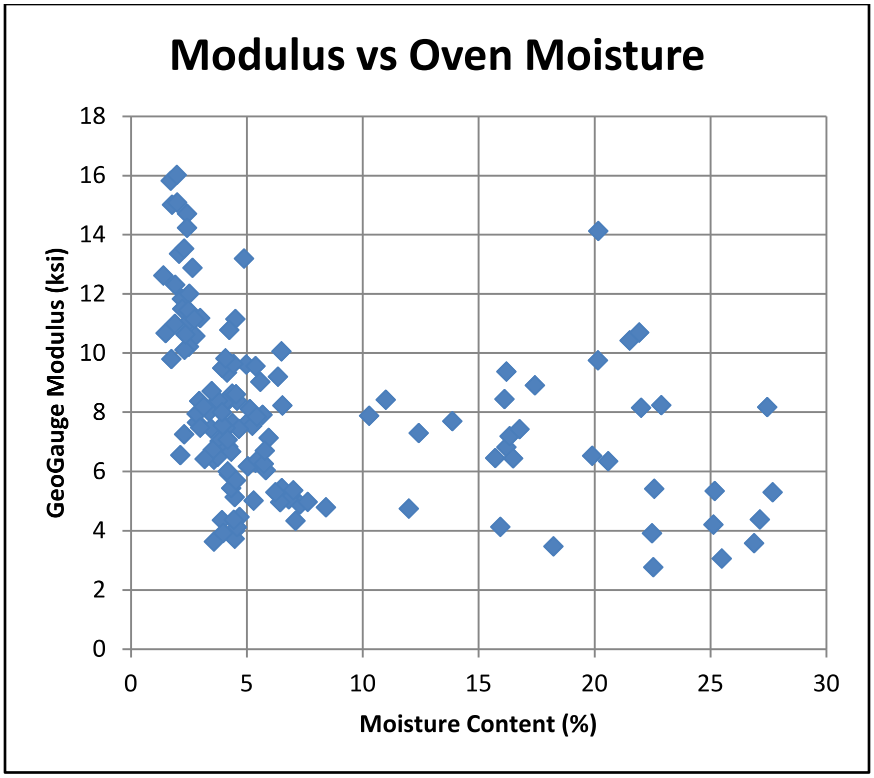

Figure 4.36. GeoGauge Modulus vs. Oven Moisture Content

4.7 CRABS AND FDR BASE TESTING RESULTS

On CRABS and FDR projects, SDG density and GeoGauge stiffness were compared with NDG density to determine if either non-nuclear device could adequately determine a roller break-over point as compared with a NDG. Per ITD specifications, the required compaction is completed on a CRABS project when the final, finish roller pass adds no more than 0.5 pcf to the previous density measurement (Idaho Transportation Department, 2011). Roller passes were a combination of static and vibratory based on instruction from ITD field personnel. The roller pattern is re-established periodically (usually every 1000 feet) to adjust for changes in the maximum density of the base material. FDR base density roller patterns are established very similar to CRABS roller patterns, except that contractor personnel establish number of roller passes.

4.7.1 CRABS Testing at US 95 Wilder

Figures 4.37, 4.38, and 4.39 show density trends per roller pass from the SDG and NDG for three roller pattern setups on US 95 Wilder, a CRABS project. Figures 4.40, 4.41, and 4.42 show GeoGauge stiffness per roller pass for the same three roller setups. From the figures, it's apparent that the SDG and GeoGauge were not able to precisely match the pattern of the NDG.

The NDG had difficultly precisely measuring the 0.5 pcf requirement in a reasonable number of passes. In all three roller setups, the NDG predicted that the density was highest on the 11^{th} or 12^{th} roller pass, but failed in all three roller setups to meet the 0.5 pcf requirement after those passes. The peak pass reported by the SDG was pass 8 in Figure 4.37, pass 10 in Figure 4.38 and pass 13 in Figure 4.39. The SDG was also unable to measure the 0.5 pcf specification requirement after the peak density pass. While the density of the SDG and NDG varied significantly, the overall density trend increased.

The GeoGauge also did not match the density pattern of the NDG. The overall stiffness trend was unpredictable. In Figure 4.40, the stiffness slowly increased. In Figure 4.41, stiffness decreased than began to increase after seven roller passes. In Figure 4.42, the overall trend remained fairly flat, although stiffness jumps are observed. In comparison with SDG results, GeoGauge results are more sporadic and the data suggests the GeoGauge is not precise enough to consistently establish a break over point on a roller pattern.

4.7.2 FDR Testing at US 95 Cottonwood

The SDG and GeoGauge were also used to setup roller pattern on US 95 Cottonwood, an FDR with emulsified asphalt project. The contractor personnel established the break over point, based on the NDG measurements. In this case, the contractor was only looking to achieve a break over point with the NDG. The roller setup was completed once this occurred. Figure 4.43

shows the SDG and NDG wet density. The SDG has a false break on the fourth pass then continued to increase even after the end of NDG testing. The GeoGauge trend, shown in Figure 4.44, remained inconsistent, with large variations in stiffness values.

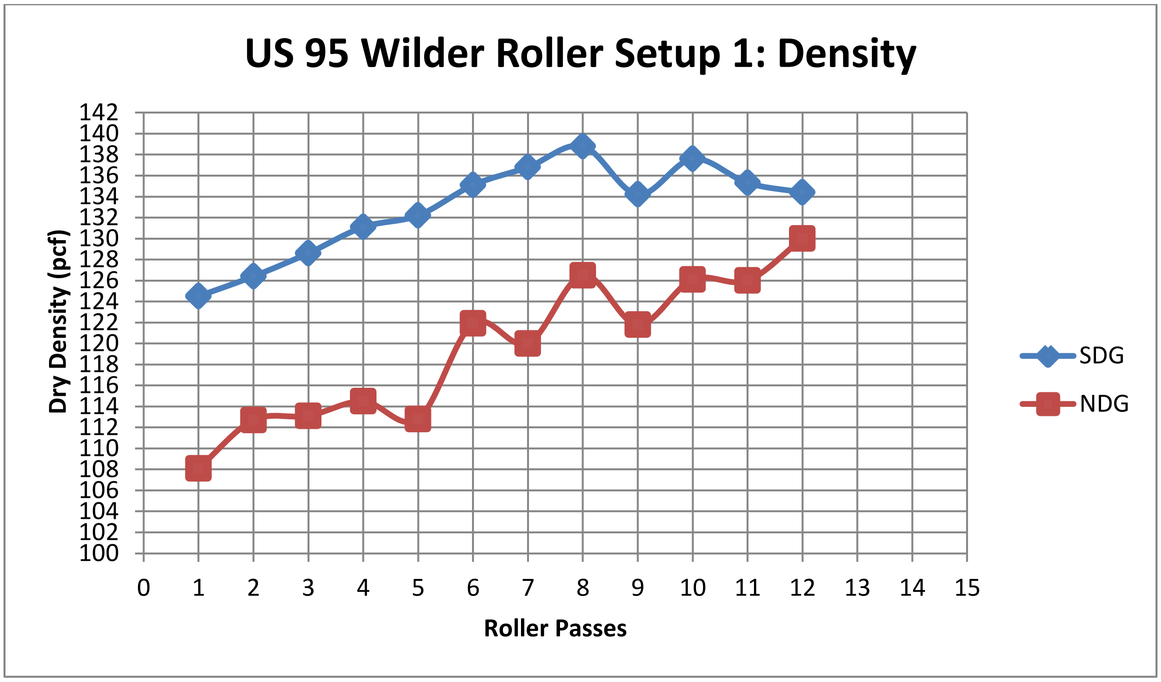

Figure 4.37. NDG and SDG Roller Pattern Setup 1 at US 95 Wilder

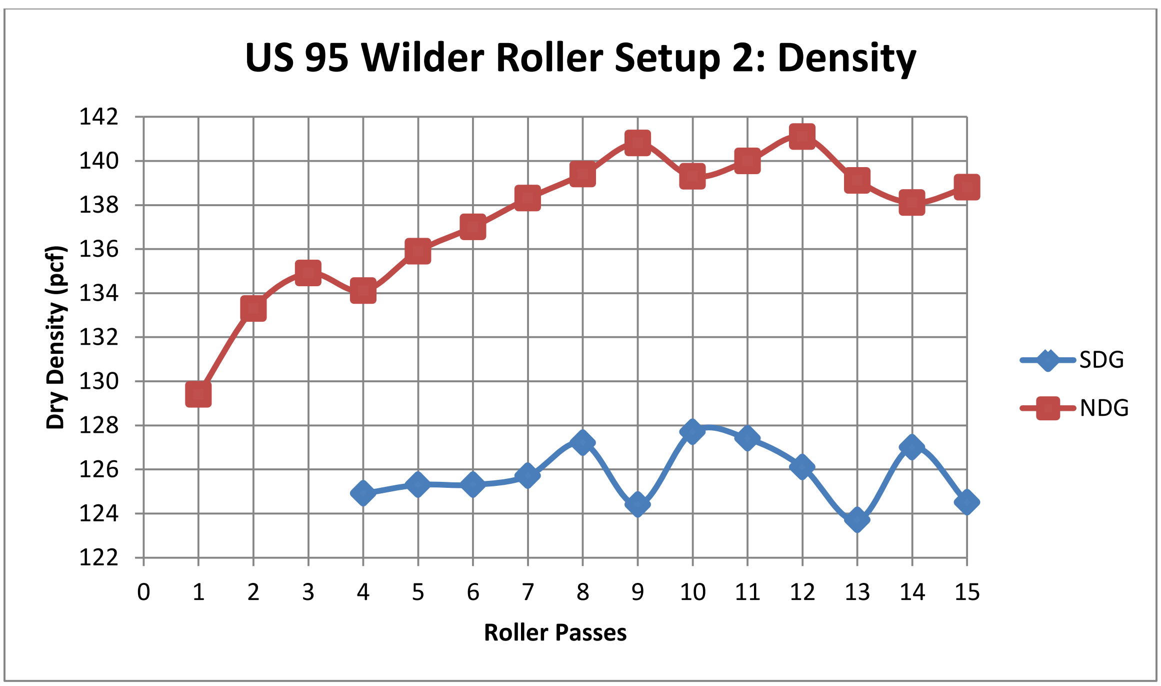

Figure 4.38. NDG and SDG Roller Pattern Setup 2 at US 95 Wilder

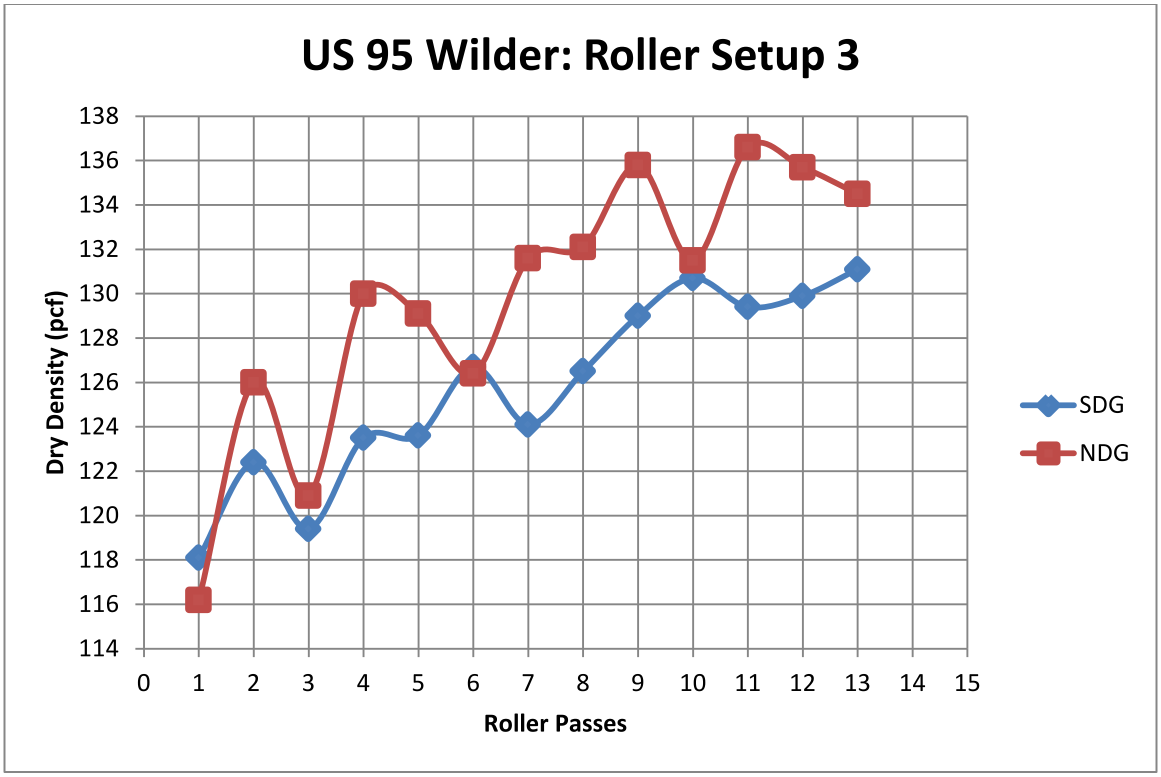

Figure 4.39. NDG and SDG Roller Pattern Setup 3 at US 95 Wilder

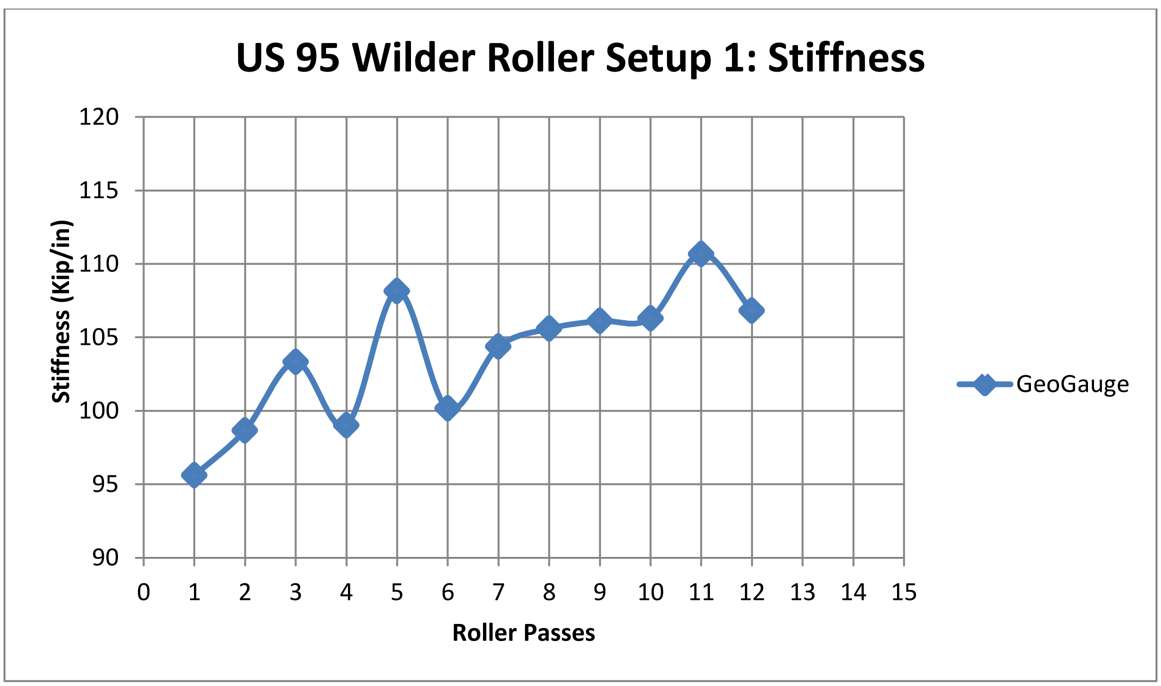

Figure 4.40. GeoGauge Roller Pattern Setup 1 at US 95 Wilder

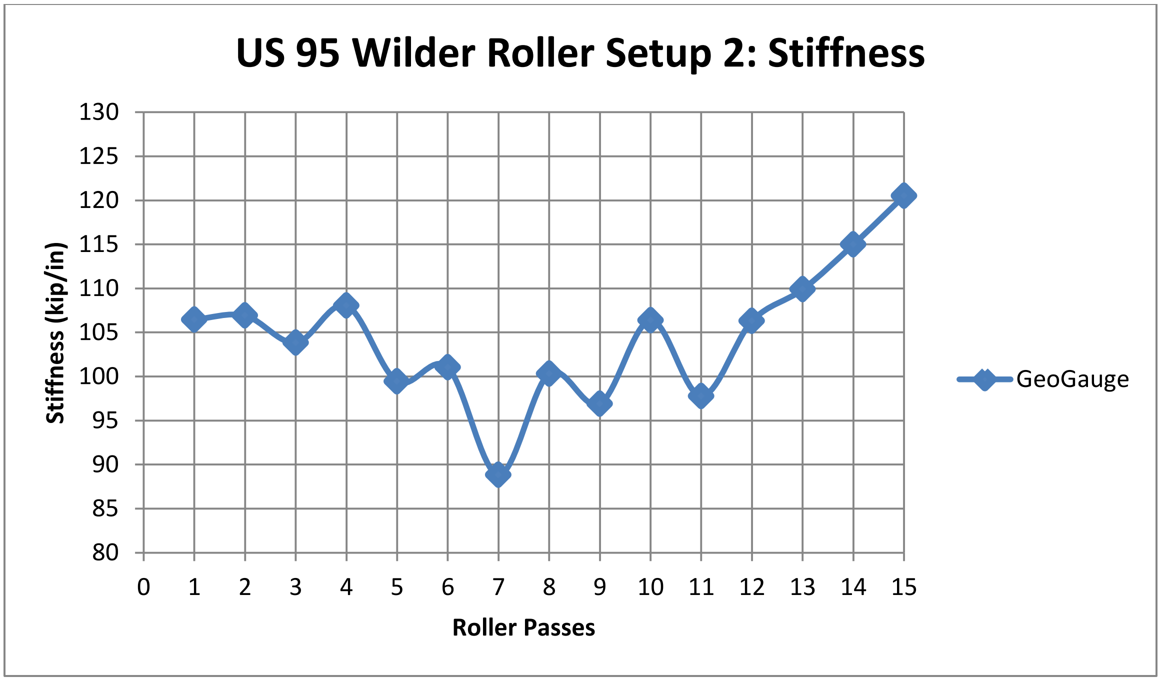

Figure 4.41. GeoGauge Roller Pattern Setup 2 at US 95 Wilder

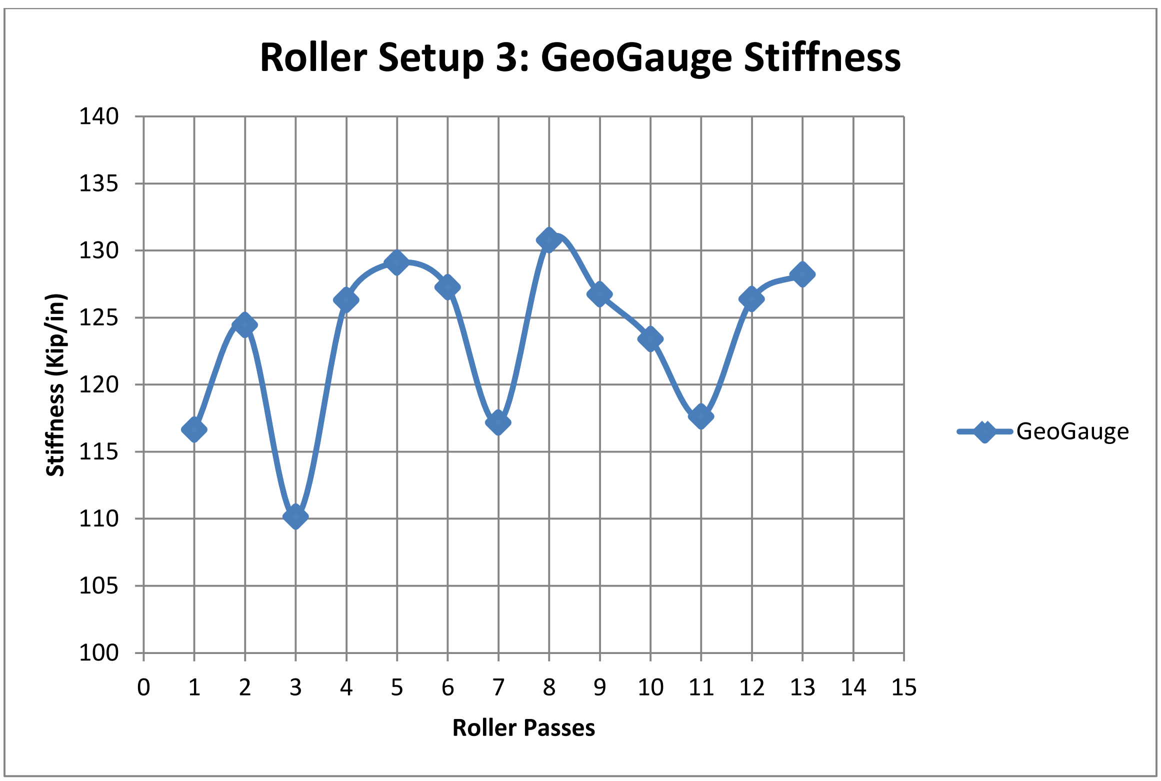

Figure 4.42. GeoGauge Roller Pattern Setup 3 at US 95 Wilder

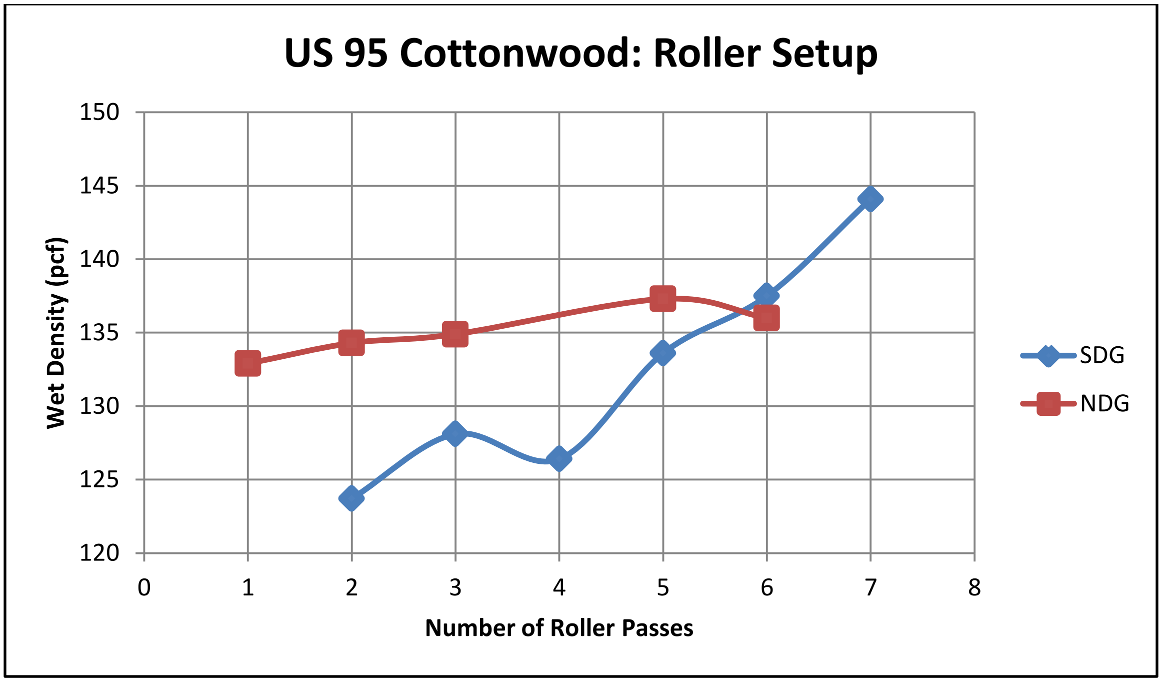

Figure 4.43. SDG and NDG Roller Pattern Setup at US 95 Cottonwood

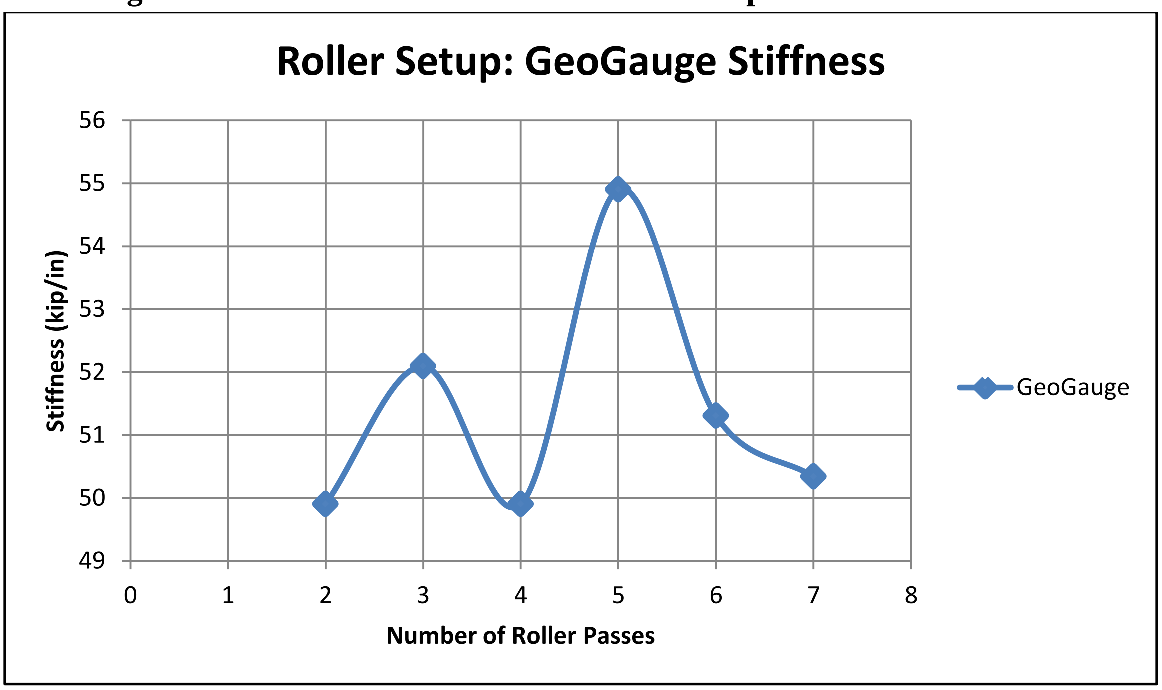

Figure 4.44. GeoGauge Roller Pattern Setup at US 95 Cottonwood

On FDR with emulsified asphalt projects in Idaho, contractor personnel established roller patterns and ITD personnel verified the density of the FDR base by using the backscatter NDG method at some time later in the day. On the US 95 Cottonwood project, the SDG and GeoGauge were tested at the roller setup location at two and four hour intervals after the last roller pass to observe any changes in moisture/density and stiffness/modulus measurement, respectively. The SDG density and moisture content and GeoGauge stiffness and modulus results are shown in Table 4.3. The SDG reported large drops in wet density, dry density and moisture content. The loss of moisture should be expected (through evaporation in the case of emulsified asphalt). A decrease in dry density, however, should not be expected. GeoGauge stiffness and modulus values increased, indicating that the material was getting stronger as the day progressed. This is expected, as the asphalt hardened and gained strength as the water evaporated.

The FDR results indicate the GeoGauge is correctly reporting an increase in material stiffness with time; however, the GeoGauge can't be used in the same testing manner as the NDG. Dry density remains constant with time, while stiffness does not. The SDG correctly reports a decrease in wet density and moisture content with time. However, the rate of wet density and moisture content should change proportionally such that dry density (which should not change with time) remains constant. This could be an indication that the SDG either lacks sensitivity to a change in moisture content or is oversensitive to a change in wet density. In comparison to other unbound testing, the SDG more likely lacks moisture sensitivity and clearly showed a lack of moisture sensitivity in fine grained soils (see Figure 4.10).

The change in results (density/moisture for the SDG and stiffness/modulus for the GeoGauge) shown by both devices indicate that neither device can accurately predict the density immediately after the roller pattern when the measurement is taken at a “later time” after compaction. With the NDG, the “later time” density measurement is compared to the peak density established during the roller pattern setup. However, the SDG and GeoGauge “later time” (2 hours and 4 hours) results change significantly compared to the results immediately after compaction. Hence, neither device can produce accurate results in “later time” testing and replace the NDG in this manner of testing.

Table 4.3. SDG and GeoGauge Measurements Over Time for FDR Base at US 95 Cottonwood

		Last Roller Pass	2 HR	4HR
SDG Same	**Wet Density (pcf)**	144.1	131.4	124.6
	Dry Density (pcf)	135.4	124.1	118
	Moisture Content (%)	6.4	5.9	5.6
SDG Clover	**Wet Density (pcf)**	x	132.2	130.3
	Dry Density (pcf)	x	124.7	122.8
	Moisture Content (%)	x	6.1	6.1
GeoGauge (Avg)	**Stiffness (kip/in)**	50.34	68.01	73.62
	Modulus (ksi)	7.22	9.76	10.56

x. SDG Clover Measurements were not taken during the roller pattern setup.

Based on these observations, the GeoGauge could not identify the break point and is not effective in establishing the roller pattern. At times, especially at US 95 Wilder, the SDG showed some potential to determine roller break points. However, the SDG also had a tendancy to break over or falsely break over before the NDG. Further evaluation of the SDG in this manner of testing is recommended. Note that the number of roller passes and total increase in density on the US 95 Cottonwood project was much less than the number of passes and total density increase for the roller pattern setups on the US 95 Wilder project. It is unknown how both gauges would have responded to increased roller passes on the US 95 Cottonwood project.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Proper density in pavement, base, and subgrade layers are key factors in ensuring a long lasting, good performing road. Due to the costs related to nuclear safety issues of the NDGs, extensive research and development into non-nuclear devices to measure density and compaction has been performed in the last two decades. This study reviewed three non-nuclear devices with the potential to replace the NDG for compaction control of unbound materials: The Humboldt EDG, Trans Tech SDG 200, and the Humboldt GeoGauge. The objective of this research was to compare the accuracy and precision of non-nuclear devices to existing nuclear gauges and other traditional moisture/density measuring methods (specifically the sand cone and laboratory oven) and evaluate each device based on their unique capabilities, features and cost of operation.

Based on results of a literature review and extensive field testing, this study concludes the following:

- EDG with NDG soil model and 3-point corrected SDG produced the most favorable t-test and correlations to NDG density and oven moisture content for the entire data set. Uncorrected and 1-point corrected SDG were less favorable. EDG with SC soil model did not correlate well with SC, NDG, and oven data. SDG measurements corrected by the SC also did not correlate well with SC and oven data.
- When smaller material subsets were analyzed, lower correlations were seen between NNDGs and reference measurements. The EDG had good dry density correlation for sands, fair correlation for bases, and poor correlation with the NDG for fine-grained soils. The SDG had a very good dry density correlation with the NDG for sands, a fair correlation for fines, but a poor correlation for base material. EDG moisture correlation

had a fair correlation to oven moisture for bases and fines, but a poor correlation for sands. The SDG had a good correlation to oven moisture for bases, a fair correlation for fines, but a poor correlation for sands. Data banding for the moisture content in fine grained soils indicated the SDG was not sensitive to moisture change in fine grained soils.

- The EDG with NDG soil model and the 3-point corrected SDG generally provided good to fair estimates of wet density, dry density and moisture content compared to NDG and oven results. However, the gauges were often imprecise, especially in fine soil, and sometimes produced results significantly different from the NDG and oven. Because of these differences and inconsistencies, the EDG and SDG are not recommended for quality control (QC) and quality acceptance (QA) purposes at this time.
- Sand cone densities were highly variable and inconsistent. When NNDGs were calibrated and corrected to SC densities, the NNDGs did not correlate well to SC data.
- A larger number of spots in the soil model did not significantly change the EDG job site results. Soil models with 3, 5, and all (up to 10) points did not have significant correlation differences from one another.
- A minimally destructive prototype to replace metal darts for EDG electrical measurement showed good potential to replace the darts. The plate was not as accurate as the darts in measuring wet density, but showed improvement in comparison to the dart method as more soil model locations were used. The plate method was slightly more accurate than the darts in measuring moisture content in fine grained soils.
- GeoGauge modulus and stiffness showed no correlation to density and moisture content, which was as expected based on previous research.

- The SDG showed some potential to determine roller break-over on CRABS and FDR projects in comparison to a backscatter NDG. The GeoGauge did not consistently determine break-over. Neither the SDG nor the GeoGauge are recommended for post-roller pattern density measurements on CRABS and FDR bases.

5.2 RECOMMENDATIONS FOR FURTHER STUDIES

- The SDG 200 should be further examined for use in establishing density break-over roller patterns on CRABs and FDR projects. NNDG use on CRABS and FDR projects was not extensively evaluated in this study. However, a few tested roller setups showed the SDG had a reasonable ability to establish break over points, although it did not consistently match the break over pattern of the NDG.
- Humboldt and the Electrical Density Gauge Company should continue testing of the "plate" prototype device to replace the metal darts for EDG measurements.
- Further studies are recommended to evaluate the stiffness-based devices for quality control and quality assurance.
- Researchers should continue to evaluate new NNDG models as they become available on the commercial market. NNDG technology has advanced significantly in the last decade and additional product advancement will be made in the future.

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