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RESEARCH REPORT

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Review of Non-Nuclear Density Gauges as Possible Replacements for ITD's Nuclear Density Gauges

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16. Abstract

This report examines the possibility of replacing nuclear density gauges (NDGs) with non-nuclear density gauges (NNDGs) to measure density of hot mix asphalt (HMA) and unbound pavement layers in the field. The research team evaluated the effectiveness of five NNDGs for measuring density of HMA and unbound material compaction. A variety of global and local factors were evaluated to determine which factors had a significant effect on the HMA devices. The findings show that, while both NDG and NNDG could produce results that are statistically significantly different from core densities for some projects, calibrated HMA NNDG results perform as well as the current Idaho Transportation Department (ITD) NDG practice. Surface moisture was found to have effects on the NNDG measurements of HMA density. Recommendations were made to modify the test protocol of NNDGs.

The team compared the density values and moisture contents of unbound materials (e.g. base, subbase, or subgrade) measured from NNDGs to those obtained using traditional devices: NDG (density and moisture), sand cone (density) and laboratory oven (moisture content). Each NNDG for unbound soils required calibration to a traditional device. Overall, the results indicate that measurements by NNDGs on unbound materials are not consistently accurate or precise enough to replace NDGs.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.4		mm	mm	millimeters	0.039	inches	in
ft	feet	0.3048		m	m	meters	3.28	feet	ft
yd	yards	0.914		m	m	meters	1.09	yards	yd
mi	Miles (statute)	1.61		km	km	kilometers	0.621	Miles (statute)	mi
		AREA					AREA		
in^2	square inches	645.2	millimeters squared	cm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.0929	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	km^2	kilometers squared	0.39	square miles	mi^2
mi^2	square miles	2.59	kilometers squared	km^2	ha	hectares (10,000 m^2)	2.471	acres	ac
ac	acres	0.4046	hectares	ha					
		MASS (weight)					MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g	g	grams	0.0353	Ounces (avdp)	oz
lb	Pounds (avdp)	0.454	kilograms	kg	kg	kilograms	2.205	Pounds (avdp)	lb
T	Short tons (2000 lb)	0.907	megagrams	mg	mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME					VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces (US)	fl oz
gal	Gallons (liq)	3.785	liters	liters	liters	liters	0.264	Gallons (liq)	gal
ft^3	cubic feet	0.0283	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
Note: Volumes greater than 1000 L shall be shown in m^3									
		TEMPERATURE (exact)					TEMPERATURE (exact)		
^{o}F	Fahrenheit temperature	5/9 (^{o}F-32)	Celsius temperature	^{o}C	^{o}C	Celsius temperature	9/5 ^{o}C+32	Fahrenheit temperature	^{o}F
		ILLUMINATION					ILLUMINATION		
fc	Foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2	cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

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List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio
CIV	Clegg Impact Value
CMV	Compaction Meter Value
CRABS	Cement Recycled Asphalt Base Stabilization
DCP	Dynamic Cone Penetrometer
DOT	Department of Transportation
EDG	Electrical Density Gauge
EIS	Electrical Impedance Spectroscopy
FDR	Full Depth Reclamation
FOP	Field Operating Procedure
FWD	Falling Weight Deflectometer
GLM	General Linear Model
GPR	Ground Penetrating Radar
HMA	Hot Mix Asphalt
IC	Intelligent Compaction
ITD	Idaho Transportation Department
LFWD	Light Falling Weight Deflectometer
LWD	Light Weight Deflectometer
MCU	Master Calibration Unit
MDI	Moisture + Density Indicator
MDP	Machine Drive Power
NDG	Nuclear Density Gauge
NMAS	Nominal Maximum Aggregate Size
NNDG	Non-Nuclear Density Gauge
NRC	Nuclear Regulatory Commission
pcf	Pound-force per cubic foot
PI	Penetration Index
PLT	Plate Load Test
PT	PaveTracker Plus
PQI	Pavement Quality Indicator
PSF	Pounds-Force per Square Foot
PSPA	Portable Seismic Property Analyzer
QA	Quality Assurance
QC	Quality Control
R^2	Coefficient of Determination
RICM	Roller-Integrated Compaction Monitoring
SDG	Soil Density Gauge
WAQTC	Western Alliance for Quality Transportation Construction

Glossary

Term	Definition
Accuracy	Accuracy of a measurement system is the degree of closeness of measurements of a quantity to that quantity's actual (true) value.
Average Correction Method (Offset Method)	Average correction method (offset method) is used to determine the average difference between the core density values and the gauge readings. The subsequent readings were adjusted by this average offset value for the remainder of the project.
Calibration	Calibration is a comparison between measurements – one of known magnitude or correctness made or set with one device and another measurement made in as similar a way as possible with a second device.
Coefficient of Determination (R^2)	In statistics, the coefficient of determination, denoted R^2 and pronounced R squared, indicates how well data points fit a statistical model – sometimes simply a line or curve.
Correction Factor	The amount of deviation in a measurement that is accounted for in the calibration process. You can either add the correction factor to the measured value or adjust the measuring instrument.
Correlation	In statistics, dependence is any statistical relationship between two random variables or two sets of data. Correlation refers to any of a broad class of statistical relationships involving dependence.
Paired t-test	Given two paired sets X_i and Y_i of n measured values, the paired t-test determines whether they differ from each other in a significant way under the assumptions that the paired differences are independent and identically normally distributed.
Repeatability	Repeatability or test–retest reliability is the variation in measurements taken by a single person or instrument on the same item and under the same conditions.
Reproducibility	Reproducibility is the ability of an entire experiment or study to be reproduced, either by the researcher or by someone else working independently.
Student's t-test	A t-test is any statistical hypothesis test in which the test statistic follows a Student's t distribution if the null hypothesis is supported.
Validation	Validation is intended to ensure a product, service, or system (or portion thereof, or set thereof) result in a product, service, or system (or portion thereof, or set thereof) that meets the operational needs of the user.

Executive Summary

Introduction

The density of in-place hot mix asphalt (HMA) and unbound materials may be the single factor that most affects the performance of a properly designed pavement. Nuclear density gauges allow rapid assessment of in-place density during construction. However, nuclear gauges have many disadvantages, including their utilization of a radioactive source that is heavily regulated. Disadvantages associated with NDGs include the risk of personnel exposure to radiation, more training requirements, inconvenient handling and storage requirements, and the high cost of maintenance and disposal. Therefore, the pavement industry needs an alternative density device that is non-nuclear and can still provide accurate density measurements.

This study examines the possibility of replacing nuclear density gauges (NDGs) currently used by the Idaho Transportation Department (ITD) with non-nuclear density gauges (NNDGs). NNDGs have the potential to offer the same benefits as NDGs while eliminating the need to meet special nuclear regulations and address the safety concerns and costs associated with NDG ownership.

The research team evaluated five commercially available NNDGs based on literature review. Two of the devices, the TransTech Pavement Quality Indicator (PQI) and Troxler PaveTracker (PT) Plus, can be used to measure HMA density in the field. The other three devices are the Humboldt Electrical Density Gauge (EDG) and TransTech Soil Density Gauge (SDG) 200 that can be used to measure the density of unbound soils in the field, and Humboldt GeoGauge measures soil stiffness based on applied load and resulting deflections.

For the HMA materials, PQI and PT were evaluated at 14 pavement test strips across Idaho. Laboratory studies were also conducted using these two devices. The NNDGs were correlated with the core density values at test strip locations determined by ITD. Once correlated, the team compared the NNDG and NDG density values to additional core density values for validation. Several factors were evaluated to determine their effects on the NNDG readings. On a global (project-specific) scale, these factors included:

- HMA class.
- Lift thickness.
- Nominal maximum aggregate size (NMAS).
- Principal aggregate source and mineralogy.
- Percentage of binder absorption.

On a local (test location-specific) scale, the factors included:

- Fines on the surface.
- Moisture on the surface.
- Paint and markings on the surface.

- Mat temperature.
- Correlation core size (6 in. vs. 4 in.).

PQI and PT were also evaluated during roller pattern setups and along longitudinal joints.

For the unbound materials, 3 NNDGs were evaluated at 21 project sites. These sites featured a variety of base and soil materials. Most sites had ¾-inch or ⅝-inch NMAS bases; the remaining sites included fine-grained soil, sand, gravel fill, and full-depth reclamation bases. EDG and SDG tests were conducted to determine the wet density, dry density, and moisture content values of the soils. EDG required field correlation to a traditional device using both NDG and sand cone tests at three test locations at each project site. SDG required only the material characteristics of the soils as its input data in order to operate. Then, these values were correlated with corresponding values obtained from traditional devices, including NDG (density and moisture), sand cone (density), and laboratory oven (moisture). The team also correlated the GeoGauge stiffness and modulus values with density and moisture content values obtained using the traditional density and moisture measuring devices.

Key Findings

HMA Devices

After correlation, both NDG and NNDG could produce results that are statistically significantly different from validation core densities for some projects. However, correlated HMA NNDG results perform as well as the current ITD NDG practice. Based on general linear model analysis, the team did not find any of the global factors to be a statistically significant cause of gauge error. The presence of fines and paint on the surface did not have a statistically significant effect on gauge error, based on the results of paired, two-tailed t-tests. However, the presence of moisture on the surface did have a significant impact on the gauge measurements. PQI 301 used an H_2O Index parameter to measure surface moisture conditions. The research team recommends an H_2O Index to be less than 5.0 for use with PQI. However, measuring moisture on the surface was not available for the PT and PQI 380 models. The research team found that towel-drying the moist surface is an effective approach to minimizing the measurement errors and thus recommends towel drying the surface if moisture is present for use with the PQI 301, PQI 380, or PT tests.

It was also found that the use of 6-inch cores leads to less error than the use of 4-inch cores. The NNDGs do not produce the same roller density pattern as the NDG.

Unbound Devices

The sand cone density values were highly variable and inconsistent. After the team correlated the NNDG results with the sand cone density values, the NNDG results still did not agree well with the sand cone data for validation. The GeoGauge modulus and stiffness values showed no consistent correlation with the density values and moisture contents.

Results obtained from EDG with NDG correlation (known as “soil model” correlation) agreed well with NDG validation measurements, based on statistical t-test results. Results obtained from EDG with sand cone correlation, agreed poorly with sand cone validation measurements. After 3-point correlation, the SDG readings produced the most favorable validation with NDG density, sand cone density, and oven moisture content values for the entire data set, whereas the uncorrected and 1-point correlated SDG data were less favorable than the 3-point correlation.

When the individual material subsets, instead of all the materials as a whole, were analyzed, it was found poor agreement between the NNDG readings and traditional device measurements. The applicability of each NNDG device seemed to depend on the material type (fines, sands, or granular materials) and parameters (density value or moisture content). EDG results showed a good wet density agreement with NDG readings for sand and a fair agreement with NDG readings for granular materials, but performed poorly in determining the density of fine-grained soils. SDG had a good moisture correlation with NDG readings for the granular materials, but performed poorly in precisely determining the moisture in fine-grained and sand material. As a whole, EDG with the NDG soil model and the 3-point correlated SDG generally provided reasonable estimates of density and moisture contents when compared to the NDG density and oven moisture results. However, the gauges were often imprecise, especially when used in fine-grained soils, and sometimes produced results that differed significantly from those obtained using NDG and oven.

Recommendations and Implementation

The team recommends that the following procedures should be included in the current operation manual of NNDG. The surface of a testing location should be towel-dried after rain or if excessive moisture is present on the surface if testing is desired. The NNDGs’ measurements of HMA density can be conducted with or without fines. However, the use of fines must remain consistent after correlation. The surface should be clear of paint, debris, and other anomalies. No conclusion can be drawn on the effectiveness of the NNDG readings of the longitudinal joint density, due to lack of sufficient cores along the longitudinal joint. The team recommends continuing the research into the accuracy of NDG and NNDG readings along pavement joints. The use of 6-inch cores is recommended for correlation to improve the accuracy of the gauge pattern currently prescribed in ITD’s field operating procedure (FOP) for American Association of State Highway and Transportation Officials (AASHTO) T-343. The accuracy of NNDGs during production paving was not studied in this project; rather, field tests only during the construction of the test strips were conducted. The monitoring of accuracy of HMA NNDGs is recommended.

The team does not recommend the use of any of the NNDGs tested for unbound materials for the implementation of compaction at this time. However, the plate-based EDG eliminated the moisture banding issue that is associated with the dart-based EDG, which makes the plate-based EDG very promising and warrants further study

.

Chapter 1
Introduction

Background and Problem Statement

Density is one of the most important factors that affect the performance of asphalt pavement. Proper density in HMA, base, embankment, and subgrade layers is a key factor in ensuring a long-lasting roadway that meets performance expectations. Transportation agencies and contractors must have reliable devices and methods to measure and determine *in situ* density. Traditional methods include the coring of HMA pavement and the sand cone and/or rubber balloon methods for unbound bases and subgrades. Although these methods could be accurate, they are time-consuming, destructive, and costly.

Due to the drawbacks associated with these traditional methods, many transportation agencies, including the Idaho Transportation Department (ITD), employ nuclear density gauges (NDGs) to determine the *in situ* density of pavements and soils. Although NDGs are reasonably accurate and can produce results rapidly, NDGs have their own set of drawbacks. NDGs operate by measuring the scatter of gamma radiation. Because such nuclear material is heavily regulated, the use of NDGs requires more training and licensing. Furthermore, NDG possession and use may be restricted on certain federal and/or military property. The storage and transportation of NDGs are additional inconvenient and expensive considerations.

Over the past 15 years, researchers have undertaken extensive research and development into non-nuclear density gauges (NNDGs) as alternatives to NDGs. NNDGs can potentially offer all of the benefits of NDGs while eliminating the need for licenses and costs associated with NDG ownership. This report evaluates five NNDGs as possible replacements for ITD's nuclear gauge inventory. This study evaluates the following commercially available NNDGs:

For HMA:

- Pavement Quality Indicator (PQI) from Trans Tech Systems, Inc.
- PaveTracker Plus Model 2701-B (PT) from Troxler Electronic Labs.

For unbound material:

- Electrical Density Gauge Model C (EDG) from Humboldt Manufacturing.
- Soil Density Gauge 200 (SDG) from Trans Tech Systems, Inc.
- GeoGauge from Humboldt Manufacturing.

Except for GeoGauge, these devices measure one or more electrical material parameters and relate the electrical measurement to density value and moisture content. GeoGauge measures soil stiffness based on applied load and the resulting deflections. The literature review section of this report provides discussion of additional devices and technologies also.

Objectives

Per the Request for Proposal, the primary objective of this study is to compare the accuracy of selected NNDGs with the accuracy of NDGs and traditional methods when these devices are used to determine the *in situ* density of HMA and unbound materials in Idaho. Specifically, the objectives are to:

1. Compare the performance of calibrated NNDGs to ITD's existing NDGs, based on laboratory and field test results and statistical analyses.

2. Evaluate the five NNDGs in terms of their capabilities, features, and associated costs for use on HMA and unbound materials, based on a literature review and laboratory and field tests.

3. Provide recommendations to ITD regarding the possible replacement of its current inventory of NDGs.

Report Organization

This report is divided into 6 chapters and 3 appendices.

- Chapter 1 introduces the background and problem statements.
- Chapter 2 presents a review of NNDG literature and a summary of a survey, conducted by the research team, of state department of transportation (DOT) personnel about NNDGs.
- Chapter 3 introduces the field and laboratory testing programs used in this study for both HMA and unbound devices.
- Chapter 4 presents the results and statistical analyses of the field and laboratory test data.
- Chapter 5 reviews the advantages, limitations, and costs of implementing NNDGs.
- Chapter 6 presents significant conclusions and recommendations.

Chapter 2
Literature Review and Survey

Many devices that offer some potential to replace NDGs in measuring the degree of compaction in HMA and unbound materials are commercially available. The research team selected five commercially available NNDGS for evaluation for Idaho's pavements, based on literature review. However, the research team did review studies on several other devices and found that most NNDGs are designed to be used exclusively for either HMA or unbound materials only. Hence, this literature review discusses devices designed for HMA separately from the discussion of devices that are more suited for unbound materials. In addition to a review of the literature, the research team developed a questionnaire and sent it to all state DOTs to assess the overall opinions and experience with NNDGs of DOT personnel nationwide.

Nuclear Density Devices (NDG) for HMA

The NDG consists of an emission of a beam of radiative particles and a receipt of these particles reflected by the materials. The percentage of particles received by the sensor can be used to measure the density of the test material. NDG has been used extensively by highway agencies during construction across the U.S.

Non-Nuclear Devices for HMA

The research team reviewed PQI and PT for this study. At the start of the study, these two devices were the most prominent NNDGs for HMA available on the commercial market. The team also evaluated PQI 380, the newest PQI commercial model, only in later laboratory studies.

Theory

Many materials, including asphalt and soils, are classified as dielectrics, a type of insulator, because electrical current cannot flow freely in these materials. However, the atoms of dielectric material will respond to the presence of an electric field. Charges within a medium will reorient themselves and become polarized. The permittivity of the medium represents how easily the molecules in the medium can be polarized.(1) In a broader sense, permittivity is the resistance of a medium to an electric field. The dielectric constant of a medium is the ratio of the permittivity of the medium to the permittivity of the free space. An electrical impedance measurement at a single known frequency can determine the dielectric constant.(2)

The dielectric constant of air has a value of 1.0. Asphalt binder and aggregate generally have dielectric constant values of 5.0 to 6.0, although the dielectric constant of different aggregate types can vary. The overall (bulk) dielectric constant of an entire HMA mat is a weighted (by volume) average of the air and

HMA constituents.[2] As air voids are reduced in the HMA during compaction, the bulk dielectric constant and the density increase.

Both PQI and PT operate on this same electrical principle. The fundamental differences between the two devices include the operating frequency and the shape of the sensor. PQI features a toroidal sensor with a transmitter at the center of the gauge and the receiver on the edge. The electric field passes through the pavement medium, as illustrated in Figure 1.[3]. The PQI operating frequency is 1 MHz.[4] PT uses an operating frequency of about 50 MHz and features a Z-shaped sensor, as shown in Figure 2.[5] Both devices feature different on-board equations to account for errors related to water presence and temperature differences in the material. The gauges can be correlated using another density method in order to correct for their bias and thereby measure "true" density, or they can be used "right out of the case" for relative density measurements (e.g., identifying areas of relatively lower density).[6]

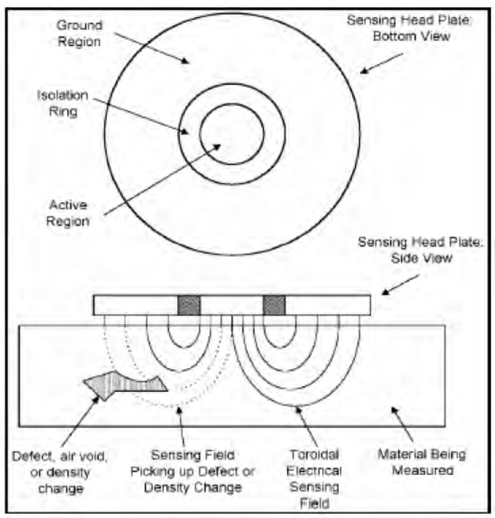

Figure 1. Operational and Receiver Diagrams for Trans Tech PQI[3]

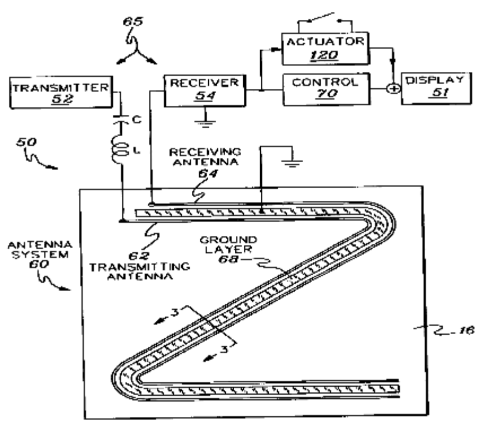

Figure 2. Operational and Receiver Diagrams for Troxler PaveTracker[5]

Pavement Quality Indicator

Over the past 10 years researchers have studied the PQI 300 and 301 models extensively. Figure 3 shows the PQI 301 used in this study (referred to hereafter as the PQI).

Figure 3. Pavement Quality Indicator 301

Romero in 2002 indicated that high internal moisture content can cause problems with the PQI readings and concluded that an H_20 index reading of less than 5.0 was necessary to obtain meaningful density measurements.[36] Romero concluded that PQI 300 is suitable for QC to measure relative changes in density; however, Romero noted that the difficulty in correlating the device daily in the field made it unsuitable for QA work.[3]

Allen et al. in 2003 used two PQI 300s operated by two different teams; one gauge's results closely agreed with the laboratory cores, whereas the other agreed poorly with the NDG results in the middle of the specimen. The results showed the importance of experience in operating the machine, as the more experienced group obtained the better results. Due to the inconsistencies between the two PQI 300 devices, Allen et. al. concluded that PQI is suitable for QC but that more research and development of the device are needed before it can be used for QA.[2]

Sebesta et al. in 2003 concluded that mix temperature and moisture affect PQI, PT, and the Troxler 3450 NDGs. However, as long as the site was not excessively wet, PQI provided stable readings. The effect of the lift thickness input leads to only 0.3 pounds per cubic foot (pcf) difference in device readings when the thickness input changed from 1 to 8 inches. PQI readings had a smaller standard deviation than NDG in laboratory testing (0.5 pcf for PQI vs. 1 pcf for NDG). The field results indicated that the PQI results agreed with the core results for the mainline and joint density profiles whether correlated or not, thus making PQI an acceptable alternative to NDG. In general, PQI provided a more accurate estimate of density differentials than NDG.[7]

Sargand et al. in 2005 argued that many studies on NNDG effectiveness are flawed. The authors contend that many studies contain questionable statistical analyses, do not combine enough data to make an adequate sample size, and do not follow the manufacturer recommendations for correlating NDGs daily as recommended, thereby biasing the results towards NNDGs. Without daily correlation, NNDG results differ from both core density values and NDG results with statistical significance. After applying daily mix-specific offsets to gauge the results, as recommended by the manufacturers, the PQI results agreed better with the core density than did the NDG results. Thus, PQI is was recommended for both QC and QA work, provided that it is calibrated daily.(8) Sargand et al. also concluded that the NNDG readings decreased appreciably with increased surface moisture, and the gauge readings were higher than the core density values with internal moisture and no surface moisture. They also found that the maximum surface moisture level at which moisture is not a significant factor is 0.05 pounds-force per square foot (psf).(8)

Schmitt et al. reported in 2006 that air void content, asphalt content, pavement thickness, and the specific gravity of the aggregate can all affect the differences between NDG and NNDG readings.(9) The PQI 301 was not useful for detecting non-uniformity in HMA compaction, concluded Larsen and Henault in 2006. PQI 301 showed a wider range of density values in a more uniform HMA layer, and vice versa.(10)

Williams reported in 2008 that moisture, surface debris, and the presence of paint markings on the surface of the material can significantly affect PQI accuracy as well.(11) Williams also concluded that, when properly calibrated, PQI can be used for quality control (QC), but not for quality assurance (QA).(11) Mason in 2009 found that traffic level (presumably related to the design of the mix) and binder content were both statistically significant factors that affected PQI readings after correction.(12)

Ziari et al. in 2010 found that measurements taken at the edges of asphalt pavements were lower than those taken at the center of the pavement. The author asserted that correlation of PQI is highly critical, and Ziari's results indicate that PQI measurements did not differ significantly, with a probability of 95 percent. They also determined that PQI 301 is sufficient for both QC and QA.(13)

Apeagyei and Diefenderfer in 2011 tested PQI 301 in the laboratory and at field test sites in Virginia, without correlation. In the laboratory study, the authors found that PQI 301 had the highest relative bias and error and poorest correlation to core density compared to the other devices tested (NDG and PaveTracker Plus). The authors concluded that the PQI 301 results did not agree well with the core density values or NDG measurements and, thus, that the device was not suitable for measuring asphalt concrete density for QA purposes. These researchers did not make a recommendation for QC use.(14)

Research by Sully-Miller Company in 2011 has shown that PQI readings are affected by changes in the HMA aggregate gradation, the aggregate source, and the temperature between the reference materials used to calibrate the gauge and the field materials.(6)

Cho et al. in 2011 found that although NDG had a slightly higher accuracy than PQI with cores, the average difference between the NDG and PQI results was not significant, and PQI delivered more consistent results and had a smaller standard deviation than NDG. The authors concluded that the cores used to correlate PQI should have a density between 89 percent and 93 percent of maximum theoretical density. Otherwise, PQI measurement is not as accurate. In addition, eight such cores should be used to achieve optimum correlation.[15]

PaveTracker

Figure 4 shows the PT used in this study. It is comparable in size to PQI, takes readings in 2 seconds, and requires no warm-up time.

Figure 4. PaveTracker Plus

Romero in 2002 concluded that the first generation PaveTracker was not suitable for QA purposes or for determining pay factors but was accurate for QC applications. Romero found that PT measurements were statistically different than the core density measurements in 82 percent of 38 total projects, and had a high accuracy with core density values in 55 percent of the projects and a low correlation in 14 percent of the projects. Romero concluded that proper correlation is critical for NNDGs and that the difficulty of keeping the PT accurately calibrated in the field makes it unsuitable for QA.[3]

Sargand et al. in 2005 determined that surface temperature does not significantly affect PT performance and that PT performs better with fine mixtures than with coarse mixtures. They found that both surface and internal moisture significantly affects gauge readings. Also, the area of the laboratory specimens that they used to evaluate the device affected the accuracy of PT, with larger specimens producing relatively higher density readings in comparison to smaller specimens. They also determined that it is critical that the specimen to be measured is thicker than the PT's measuring depth capability, which is approximately 1.75 inches. Sargand et al. determined PT to be suitable for QC purposes, but not for QA testing.[8]

Schmitt et al. in 2006 found that PT consistently reported lower values than NDG. They showed that NNDGs' biases change between mixture types or paving days within the same project. Schmitt et al. recommended daily correlation for each project.[9] Larsen and Henault in 2006 concluded that PT is not useful for measuring non-uniformity in density of asphalt layer.[10] Williams in 2008 concluded that moisture, surface debris, the presence of paint, and gauge orientation significantly impact PT accuracy. PT was the most variable device with the weakest agreement with core density values when compared to PQI 300 and NDGs. Williams deemed PT to be inadequate for use as a QA tool.[11]

Mason in 2009 found that PT readings agree well with core density values, but PT must be correlated each day with cores in order to remain accurate. The author concluded that PT was unsuitable for QA but could be used for QC.[12]

Apeagyei and Diefenderfer in 2011 determined that PT readings did not agree well with field core results. Similar to PQI, however, the PT results were not correlated with cores for each pavement. The authors' laboratory study concluded that the PT measurements did not agree well with core density values or NDG measurements and that PT was less sensitive than the NDG. PT performed better than PQI 301 in terms of its validation with measured core density values, relative bias, and relative errors. Apeagyei and Diefenderfer determined that neither of the HMA NNDGs in this study was acceptable for density acceptance measurements in Virginia. They made no recommendation for its use for quality control purposes.[14]

In summary, mixed findings were reported by the researchers. The use of NNDG warrants rigorous study prior to implementation.

Additional Technologies for HMA Compaction

In addition to coring, NDGs, and electromagnetic NNDGs, other devices and technologies are available to measure the density and stiffness parameters of the HMA layer. A current research trend is the development of so-called "full coverage" density measuring technology. This research takes the approach that rather than testing a few spots, testing the entire pavement will reveal any potential problem areas early, in time to fix any problems with the pavement during compaction.

Ground Penetrating Radar (GPR)

GPR measures the reflected waves of a material-penetrating electromagnetic pulse. GPR has long been in use as a nondestructive imaging tool in geotechnical engineering. Researchers have used this technology primarily to evaluate subsurface layers and in pavement engineering to determine pavement structure thicknesses and to detect underground utilities and distress severity.[16] Modern air-coupled GPR systems can be mounted on vehicles, as shown in Figure 5, and can take readings while the vehicle is moving. Currently, research is focused on applying GPR technology to measuring HMA density. Similar to the other electromagnetic methods, the GPR method measures the dielectric constant and relates the dielectric constant to volumetric properties. GPR is advantageous because it can provide wider coverage and faster measurement of pavement density when compared to hand-operated devices such as PQI and PT. Similar factors that pose problems with the other electromagnetic NNDGs also affect GPR, especially the effect of water. Current research is evaluating various specific gravity models that best predict volumetric properties from the mixture dielectric constant. Al-Qadi et al. found that in deploying their new "ALL" (Al-Qadi-Lahouar-Leng) mixture model, the density prediction error for the GPR was between 0.5 percent and 1.1 percent, whereas the average prediction error for the NDG was between 1.2 percent and 3.1 percent.(16)

Figure 5. Air Coupled GPR System(16)

Infrared Imaging System

The infrared imaging system involves a bar attached to a rolling compactor that uses infrared sensors to measure the temperature of the pavement as it is being compacted. According to Scullion et al., temperature differences in excess of 25°F indicate potential segregation in the HMA mat. By measuring the temperature of 100 percent of the HMA mat as its being compacted, Scullion et al. were able to examine areas with significant temperature differentials for segregation.(17)

Overall, these full-field measurement devices are still under research and development. Researchers have not studied them as extensively as PQI and PT to investigate the density of HMA.

Non-Nuclear Density Devices for Unbound Materials

Researchers have developed a few devices 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.

Electrical Density Gauge

EDG, shown in Figure 6, measures the electrical properties of soils through the use of high-frequency radio waves traveling between metal darts driven into the soil.(18) EDG relates the measured impedance to the wet density value and the ratio of capacitance and resistance to moisture content.(19) It requires a soil-specific model in order to determine the dry density of the soil.(18) Typically, the development of a soil model consists of taking measurements with EDG and another "true" density and moisture measuring device (i.e., NDG, sand cone, or oven, etc.) at a minimum of three locations. The "true" values are input into EDG to relate the measured electrical parameters to the moisture/density parameters for each soil. Humboldt recommends that the soil model for EDG be created in the field with either a NDG, sand cone, or other density measuring method to assist in creating the soil model. Other researchers have developed, discussed, and analyzed the implementation of a laboratory correlation procedure.(20,21,22) However, neither Humboldt nor American Society for Testing and Materials (ASTM) provides a formally standardized or recommended laboratory correlation method.

Figure 6. Team Members Setting Up the Electrical Density Gauge C Model

Rathje et al. in 2006 noted that EDG would not operate on highly plastic clays.(23) Due to this and other field restraints, the remaining EDG tests were part of a laboratory testing program. Rathje et al. tested EDG on poorly graded sand specimens. The device consistently reported the same dry unit weight for each specimen; although these results were different from the values obtained using a sand cone and values obtained using MDI. The authors noted that the spikes were sometimes difficult to hammer into the soil.

Brown in 2007 compared EDG and MDI with NDG on a variety of soils, including gravel sub-base, sand, and granular backfill. Brown concluded that the EDG results for dry density compared well with the NDG readings, especially in fine-grained and sandy material. The moisture content values obtained from EDG showed a weak linear relationship with the NDG results.(18)

Bennert and Maher in 2008 found that EDG had a better agreement with NDG readings than MDI. However, the authors expected this outcome because their experiments involved an older EDG model that they calibrated in the field using NDG.(20)

Cho et al. in 2011 tested EDG, NDG, and LWD against the drive cylinder method (referred to in their study as the "standard measurement") at 2 soil test sites. The NDG readings agreed best with the standard measurement for density value and moisture content. EDG did produce similar results to NDG before Cho et al. applied correlation factors to improve the NDG results. The authors speculated that if they had developed similar correlation factors for EDG, EDG would have produced overall results that would have been comparable to the NDG results.(15)

Berney and Kyzar in 2012 compared EDG, SDG, a steel shot replacement device, and the sand cone to NDG in terms of density measurements, and also compared EDG, SDG, NDG, and a variety of other devices to a laboratory oven in terms of moisture content results. The authors found a higher dry density variation with EDG than with the correlated SDG and sand cone. The authors measured the total analytical error based on device bias, standard deviation, and mean to determine the accuracy of the moisture measurements. The total analytical error of EDG was slightly higher (meaning less precise and less accurate) than the correlated SDG and NDG results. The authors noted that as a whole, EDG performed well but required complex correlation.(24)

Meehan and Hertz in 2013 evaluated EDG in field and laboratory experiments in Delaware. They conducted their tests at 2 field sites: 20 locations at 1 site and 29 at the other. The authors used all the test locations at each site to build the site specific soil model. Two types of soil model were developed at each site: one which applied an internal temperature correction and one which did not apply an internal temperature correction. The correlation data (or soil model inputs) were very scattered. They also took an EDG density measurement at each location, which they then compared to the NDG measurements. They did not find strong agreement between the EDG and NDG results, although they used the entire NDG data set to establish the soil model. EDG produced greater variability than NDG at the site with variable soils, indicating that multiple soil models may be required for soils with high variability. The authors ultimately decided to explore alternative methods of establishing the soil model due to the difficulties they had in establishing the model in the field. They developed a laboratory correlation model using a large mold. However, further laboratory tests proved to produce similarly scattered results. Meehan and Hertz later used laboratory soil models in outdoor “large box” testing, and compared the EDG, NDG, drive cylinder, and sand cone results. NDG and the drive cylinder showed the best agreement. These researchers found that EDG produced more density scatter than NDG, but less than the sand cone. They also found that EDG produced more moisture scatter than both NDG and the sand cone. For all testing, the internal temperature correction did not significantly improve the EDG results.(21)

Soil Density Gauge

Similar to EDG, SDG (shown in Figure 7) measures the dielectric soil properties through the use of high frequency radio waves. Based on technology similar to PQI, SDG creates an electromagnetic field using a transmitter and receiver. In order to determine the values of both moisture and density, SDG uses an electrical impedance spectroscopy (EIS) measurement. EIS is the measurement of impedance at a variety of frequencies and is able to separate the effects of water and soil for the measurement. Whereas PQI requires taking a measurement only at a single frequency to determine the density of HMA, SDG takes measurements at over 80 frequencies, ranging between 300 kHz and 40 MHz, to measure soil density and moisture content.(25) Unlike EDG and MDI, SDG does not include darts or stakes to drive into the soil, making its use completely nondestructive.

Figure 7. Soil Density Gauge 200

In Thailand, Wacharanon et al. tested 2 beta SDG models on 3 types of pavement materials.(26) They tested a sand embankment, soil-aggregate sub-base, and crushed rock base. The authors concluded that SDG shows good potential for future use in construction phase evaluation. They also noted that with quicker measurement times, more locations could be tested, thereby increasing the overall test coverage area.(26)

Pluta and Hewitt concluded that accounting for the specific surface area of the material under test conditions would improve the accuracy of SDG when compared to NDG.(25) When the authors applied surface area adjustments to the data, they were able to reduce the average wet density error between NDG and SDG by 119 percent.(25)

Berney and Kyzar reported that out of four devices (SDG, EDG, sand cone, and steel shot) they compared to NDG, SDG showed the lowest density deviations from NDG density values. Their study also found the total analytical error for SDG moisture content to be less than that for all the devices tested, except for 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 value. The uncorrected SDG readings produced higher deviations compared to NDG density and oven moisture content. The authors concluded that when correlation for density and moisture content were possible, SDG was the best non-nuclear device evaluated.(24)

Mejias-Santiago et al. studied the performance of SDG on 16 fine-grained soils. The authors reported improved SDG performance when they input more measured soil properties, instead of default values, into the gauge. Compared to the NDG readings, the SDG dry density values agreed well across all the soils tested. However, the dry density values changed very little within a single given soil type, indicating that SDG had difficulty identifying small density changes with increasing roller passes. When correlated with a single NDG dry density value, the accuracy improved. However, SDG still had difficulty identifying small density changes during compaction. The authors recommended that SDG be used in military contingency construction scenarios, provided the density values could be correlated using at least one density measurement from another device (e.g., sand cone). The authors did not recommend SDG for QC/QA purposes in permanent infrastructure construction.(27)

Moisture + Density Indicator

MDI, shown in Figure 8, works similarly to EDG and SDG, but uses time domain reflectometry (TDR) to determine the dielectric soil properties. TDR measures the responses of an electrical pulse generated through four probes driven into the ground.(18) Similar to EDG, MDI requires a soil-specific model to determine dry density values. The MDI soil model can be developed in the 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 MDI.

Figure 8. Moisture + Density Indicator(22)

Problems were noted with MDI measurements in clayey soils and noted also that MDI did not always produce accurate results in sandy soils either by Rathje et.al. When used on laboratory-compacted sand specimens, MDI determined the moisture content of the sand more accurately than of the clay. MDI dry density results for sand were consistent but not the same as the values obtained from the sand cone test and EDG. The authors also noted practical problems, including difficulty in obtaining quick readings using MDI in select cases and in hammering in the probes in very stiff soil. Despite these problems, they noted that MDI had the potential for future use if it was improved.(23)

Brown tested MDI and EDG with NDG on a variety of soils. This study showed that the MDI dry density results consistently produced a lower *in situ* dry density value when compared to NDG results. Brown speculated that this outcome was due to the test apparatus (4 probes driven into an area 8 inches in diameter), which loosened the compacted soil, thereby resulting in low dry density values. Moisture contents obtained from MDI showed a weak linear relationship to those obtained from NDG.(18)

Bennert and Maher compared MDI to NDG and EDG in five test projects. In general, the measured MDI values did not agree well with the NDG values. The authors noted differences up to 12.53 percent between the 2 devices for the dry density measurements. MDI generally recorded lower density values than NDG. Moisture content values were more agreeable between the two devices. The authors speculated that the differences in density readings between NDG and MDI were due to the MDI's correlation procedure. The authors recommended the development of a correlation constant database, larger spikes, and spikes of varying lengths to record density values at different depths.[20]

The literature indicates that researchers have studied these density devices extensively. However, the findings are mixed, and each device has its own advantages and disadvantages when compared to NDG. Further evaluation of these devices, especially their new models, is needed.

Devices for Stiffness and Strength of Unbound Materials

In pavement design, the resilient modulus, or soil modulus, has become an important design input parameter. The resilient modulus and corresponding soil stiffness values have largely replaced older strength-based values, including the California bearing ratio (CBR) and Hveem R value.[28] 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 affect the modulus of geomaterials include: the state of stress, moisture content, density, stress history, gradation and Atterberg limits.[22] Until recently, measuring stiffness and modulus values was impractical. Today, numerous devices are available that are designed to measure stiffness and modulus values; this report provides further discussion of these devices. In addition, other devices are also available to measure the strength of unbound materials.

GeoGauge

Humboldt Manufacturing's GeoGauge, shown in Figure 9, directly measures soil stiffness by vibrating a rigid ring-shaped foot at different steady-state frequencies and measuring the soil's response. The US military originally developed this technology to detect land mines.[29] The GeoGauge can rapidly measure 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.[23] If 60 percent contact area cannot be achieved, a thin layer of sand can be placed between the device and the soil. The effective depth capability of the GeoGauge ranges between 7.5 and 8 inches.[29] This range is considered acceptable for *in situ* testing because typical pavement layers are constructed in 6 to 12 in. lifts. GeoGauge testing is standardized in ASTM D6758, *Standard Test Method for Measuring Stiffness and Apparent Modulus of Soil and Soil-Aggregate In-Place by Electro-Mechanical Method*.[30] Several studies show very poor or no correlation at all between GeoGauge stiffness values and dry unit weight.[23,31] Several studies also show no correlation between measured stiffness value and moisture content.[31]

Figure 9. GeoGauge Used in This Study

Lenke et al. evaluated the GeoGauge in a laboratory setting on silty sand. In the laboratory, the GeoGauge produced meaningful stiffness values when the distance to the horizontal boundaries of the soil container was at least 12 inches in depth, and the distance to any lateral boundary was at least 9 in. The test results showed a change in stiffness with moisture content. The stiffness measurement started at 5,025 psi (22 MN/m) with a moisture content of 4 percent, peaked with a stiffness value of 5,711 psi (25 MN/m) and a moisture content of 8 percent, and then the stiffness value continued to decrease with increases in the moisture content. The corresponding Proctor curve for the soil had a peak dry density of 116 pcf with a moisture content of 12 percent. These results suggest that the peak stiffness occurs at lower moisture content than the 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.(32)

Bloomquist et al. showed that the significant factors associated with the repeatability of the GeoGauge are largely dependent on the condition of the soil surface and the placement and operation of the device by the operator. The inclination of the device also affects the stiffness value recorded. The study found that when compared to no sand, using sand to help with seating caused the stiffness value to increase in 11 of 14 trials that used both wet and dry sand. The authors also developed a new handle for the GeoGauge to assist with proper seating and, therefore, improved its repeatability.(31)

Abu-Farsakh et al. stated that the GeoGauge was the most user-friendly device they tested in their study, which included the dynamic cone penetrometer (DCP) and the LWD (discussed in detail in the next sections). The authors reported that the GeoGauge was easy to operate and gave rapid results. The modulus results for the GeoGauge had good agreement with the FWD and plate load test (PLT) modulus values, with the coefficient of determination (R^2) values ranging from 0.81 to 0.90 for field tests. Laboratory test results were more scattered than the field test results; the R^2 ranged from 0.52 to 0.83 in the laboratory. This study also concluded that the GeoGauge measurements were very sensitive to minor cracking in cement- and lime-treated soils. Furthermore, the GeoGauge stiffness values peaked at lower moisture contents than the optimum moisture content, indicating that soils should be compacted dry of optimum moisture content to provide good support and stability.(29)

Rathje et al. 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 these researchers introduced sand as a remedy (as specified by the manufacturer), they sometimes reported significant changes to the measurements.(23)

The GeoGauge was found to be successful 79 percent of the time in identifying areas with anomalies as identified by Von Quintus et al. The coefficient of variation was 15 percent, which was lower than that measured using the other stiffness devices. The standard deviation ranged between 300 psi and 3,500 psi, depending on the material. The authors found that the GeoGauge resilient modulus values correlated well with laboratory modulus values over a wide range of materials. The authors recommended the GeoGauge for QC and QA purposes and suggested that the GeoGauge should be calibrated to project materials to improve its accuracy.(33)

Light Falling Weight Deflectometer

FWDs are very useful and accurate in estimating the modulus values 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.(34) Light falling weight deflectometer (LFWD or LWD) is a portable version of the larger, trailer-mounted FWD. FWD and LWD can determine the stiffness and modulus values 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*.(35)

Abu-Farsakh et al. showed that the LWD modulus value is very close to the back-calculated FWD value, with R^2 of 0.94. The LWD results also correlated well with the lab test results, with the field values of R^2 ranging from 0.83 to 0.94. The effective depth of LWD ranges between 10.5 and 11.0 in., depending on the soil stiffness. LWD did have repeatability problems when testing weak subgrade. Overall, the authors suggested that LWD could serve as a suitable alternative to plate load test (PLT) and FWD.(29)

The LWD was tested primarily for embankment compaction by Petersen et.al. They concluded that LWD was an effective test device for determining soft spots in the test section. All soils tested, however, exhibited a high variability of measured stiffness values, with values of R^2 ranging between 0.26 and 0.52. *In situ* stiffness measurements did not have any correlation with laboratory-predicted stiffness values. Due to this lack of correlation, Petersen et al. were unable to develop field QC procedures based on laboratory stiffness values.(36)

Vennapusa compared three different LWD models (Zorn, Keros, and Dynatest) to each other and to the static PLT. Vennapusa found that the major factors that affect the LWD modulus are:

- The size of the loading plate.
- Plate contact stress.
- Type and location of the deflection transducer (accelerometer vs. geophone).

- Plate rigidity.
- Loading rate.
- Buffer stiffness.

Vennapusa also 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). The modulus values varied among the devices depending on the plate size; the modulus values obtained from the Keros LWD averaged 1.75 to 2.16 times higher than those measured from the Zorn LWD. The Dynatest modulus values averaged 1.7 times higher than those obtained from the Zorn model. In general, the modulus values increased with a decrease in the plate diameters. Measurement variability was lower in the Zorn model than in the Keros and Dynatest models.[37]

Siekmeier et al. tested LWD (along with DCP) on granular and fine-grained soils to develop target LWD test values for soils. They matched the target values to specific soil gradations and moisture contents. The authors called for standardization in the manufacturing of LWDs based on the fact that manufacturers develop different models that produce different results due to the lack of a national standard. However, the authors concluded that LWDs should be used more widely.[34]

Hossain and Apeagyei tested LWD against the GeoGauge and DCP to determine its suitability in determining soil modulus values for seven test roads. The researchers noted a general increase in stiffness values with an increase in density values for LWD and the GeoGauge. Although moisture content had a significant effect on LWD, the researchers observed no clear trend between stiffness and moisture content for LWD. The authors also found no correlation between the moisture content and measured stiffness values. They speculated that the high variability in modulus measurements could be related to the development of pore water pressure and capillary suction during testing. The authors concluded that LWD should not be used for QA/QC purposes without further research.[38]

Portable Seismic Property Analyzer

The PSPA, a portable version of the larger seismic pavement analyzer, measures the dispersion of surface waves of the pavement medium in terms of the material's elastic properties, including the modulus.[23] PSPA can measure the elastic modulus for a variety of media, 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 that it is expensive, costing between $20,000 and $30,000.[22,23]

Rathje et al. studied the use of PSPA with five soil types and determined that PSPA could be used for a general assessment of dry density, but that it was not precise enough to fully replace NDGs. In sandy soil, they found that the modulus value generally increased with dry density. In clayey soils, Rathje et al. found that the water content affected the PSPA modulus more than the dry density affected it. The authors also felt that the inability of the device to measure water content was a drawback to its use.[23]

Von Quintus et al. found that the PSPA technology performed well for both HMA and unbound layers. The device had 93 percent and 86 percent success rates in determining anomalies in HMA and unbound materials, respectively. For HMA, modulus values measured by PSPA were comparable to modulus values measured in the laboratory. PSPA requires mixture-specific correlation; however, such correlation can be performed in the laboratory. When accounted for temperature, the PSPA modulus values that were measured immediately after compaction were similar to the modulus values measured during the following days. For unbound materials, the authors determined that PSPA could be correlated with laboratory moisture-density relationships. PSPA did produce a higher than normal dispersion over a wide range of conditions and materials. The authors also noted that PSPA requires more training to operate relative to other NNDGs.(33)

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). DCP provides a continuous assessment of *in situ* soil strength. It can also be used to determine layer thickness and uniformity.(29) The DCP test procedure is standardized in ASTM D6951, *Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications*.(39) No standard relationship between penetration rate and compaction level currently exists, although Bennert and Maher correlated DCP penetration with CBR for pavement design.(20)

Salgado and Yoon tested DCP at seven sites in Indiana. Four sites contained clayey sands, one contained well-graded sand with clay, and two contained poorly graded sand. The researchers found that PI decreased when the dry density increased, and that PI slightly increased as the moisture content increased. They developed an equation to relate the soil dry density to PI. The authors also developed an equation that related the modulus to PI, although they recommended that this equation be used with caution as it was based on a weak correlation and highly scattered data. The authors recommend DCP be used in conjunction with other traditional testing methods due to the uncertainty of the results. They do not recommend DCP for use in gravelly soils.(40)

Abu-Farsakh et al. tested DCP on a variety of soils and compared the measured results to LWD, GeoGauge, FWD, CBR and PLT results. The authors noted that DCP could take deeper measurements than LWD and the GeoGauge. They developed several good relationships between the DCP measurements and the FWD, PLT, and CBR values. The DCP results had an especially good relationship with the CBR values, with field R^2 values of 0.93.(29)

Rathje et al. found that DCP measurements mostly disagreed with NDG measurements for clayey soils, was somewhat accurate in fine gravels (50 percent agreement with NDG), and was most accurate in sand (100 percent agreement in 8 test locations). Overall, the authors concluded that DCP is not suitable to replace NDG, but that it is able to provide a good general assessment of compacted dry unit weight.(23)

Siekmeier et al. tested DCP, along with LWD, on granular and fine-grained soils to develop target DCP values for the tested soils. They matched these target values to a grading number (determined by sieve analysis) and moisture content. The authors concluded that more standardized testing procedures are needed for the use of DCP, noting that the methods used to obtain PI values are varied and involve different seating drops and measurement drops. The authors recommend three seating drops and five to ten measurement drops, depending on material type. The report encouraged the expanded use of the device.(34)

Hossain and Apeagyei tested LWD against DCP and GeoGauge on seven test roads in Virginia. They found no agreement among the results of the three devices. However, the authors found a strong agreement (R^2 = 0.97) between DCP stiffness and moisture content. DCP soil stiffness values varied inversely with moisture content, indicating that high moisture content is associated with a low stiffness value and vice versa. The authors found no clear agreement between DCP stiffness and soil density.(38)

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 operator drops the hammer from a set height, and an accelerometer measures the hammer's deceleration upon impact in units of Clegg impact values (CIVs). Researchers can then correlate CIVs to soil strength and CBR.(41) The operation of the Clegg Hammer is standardized in ASTM D5874, *Standard Test Method for Determination of the Impact Value of a Soil*.(42)

Rathje et al. found that the Clegg Hammer provides the most accurate evaluation of all the field soils tested in their study when compared to the standard DCP and Panda DCP. The authors concluded that water content affects CIV more than the soil dry unit weight affects it in clayey soils. CIVs generally increased with dry unit weight in sandy soil, although the data showed significant scatter. The authors found no agreement between CIV and dry unit weights in fine or coarse gravel. The authors ultimately concluded that the Clegg Hammer was not suitable to replace NDGs because of its lack of precision.(23)

Summary of Stiffness and Strength Methods

In summary, no clear, consistent agreement currently exists that relates soil modulus and stiffness values 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 they do not reveal any consistent relationship. In most cases, impact and stiffness-based devices can provide only a general assessment of compactness.(23) In addition to the lack of correlation with other compaction properties are several additional limitations that prevent the wide-scale use of modulus-based field specifications and testing. Results from the Nazarian et al. study show that laboratory resilient modulus results are often moderately or significantly different from the field results, and relatively little research is available that ties the design modulus of compacted geomaterials to field-measured modulus values. According to selected state DOTs, the reasons for the lack of modulus-based specifications include:(22)

- Modulus testing requires a higher level of training than other types of testing.
- Modulus tests can produce unreliable results.
- Determining a general moisture adjustment factor (to improve the modulus) is difficult.
- The resources needed to research and implement changes are lacking.
- Modulus testing is expensive and time-consuming.

Due to these and other limitations, modulus testing and specification development have been slow processes for many state DOTs. In a survey by Puppala, only 15 percent of state DOT respondents stated that they were "well satisfied" with the current methods available to determine the resilient modulus. The remaining respondents were either "not satisfied" or "satisfied", but thought the methods could still be improved.(28) As of 2011, only Minnesota had developed any field modulus specifications, Missouri and Texas were in draft stages of development, and several other states were still in the research stages.(22)

Intelligent Compaction (IC)

In addition to the non-nuclear density gauges or the stiffness/modulus measuring devices, IC, or roller-integrated compaction monitoring (RICM), is technology that allows a compaction roller to self-measure the compaction level of bound or unbound materials. IC rollers directly measure the stiffness response of the soil or HMA 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.(43) IC rollers are equipped with:(44)

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

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

Briaud and Seo developed a summary of IC capabilities and presented research needs for its use in the US.(45) The advantages of IC include that it:

- Evaluates the zone that is being compacted instantaneously and completely.
- Helps remediate weak spots and avoids over-compaction.
- Reduces the number of necessary roller passes.
- Provides uniformity to the compacted layer.
- Provides a soil modulus at all locations that the roller passes.

The major drawback to IC is the initial expense to contractors, because IC-equipped rollers cost more than traditional rollers. Construction contract types also can affect the development and acceptance of IC. In Europe, design-build contracts, awarded on a best-value basis, are in wide use and are much more common than in the US. Responsibility lies with the contractor to ensure proper compaction and produce a quality product. In the US, most transportation agencies (owners) have specifications for QC/QA that the agency itself or a third-party inspection/testing firm implements. The agency inspectors are responsible for ensuring that the compaction specifications are met. Briaud and Seo theorized that these fundamental contract differences make it so that IC is more readily accepted in Europe than in the US. They also addressed research needs that included further investigation into the relationship between modulus and water content, demonstration projects showing that IC leads to better compaction for the associated higher cost compared to conventional compaction, and development of IC specifications in the US.[(45)]

An IC-equipped Caterpillar compactor against the GeoGauge, LWD, and DCP was tested by Petersen and Petersen. The results for each device showed no correlation with one another, except for a correlation between the LWD and GeoGauge measurements (R^2 value of 0.4) and between the IC (CMV) and DCP measurements (R^2 value of 0.4).[(44)]

Vennapusa's report details a variety of advantages and improvements to RICM technology. It presents two case studies of geostatistical analysis being used to characterize and quantify non-uniformity in compacted unbound materials. RICM also can serve as a reliable indicator of the 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 values and DPI values (R^2 values from 0.6 to 0.7). Vennapusa found no correlation between the CMV and LWD values and concluded that this outcome was due to large differences in the state of stress under the devices. The CMV values obtained at high amplitudes did not correlate well with those obtained using point measurement devices due to the effect of CMV at high amplitudes.[(37)]

One limitation of the RICM technology is that it is built only into newer rollers and cannot be purchased separately and mounted onto existing rollers. Scullion et al. 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. They tested the roller data against data acquired from DCP, LFWD, and NDG. The results showed that the roller responses were repeatable and could be used to identify weak spots in the subgrade. The roller responses, however, did not correlate with measured stiffness or density data, and Scullion et al. therefore recommended further evaluation.[(17)]

Summary

Many devices that have the potential to replace NDGs currently exist; however, no single device has emerged as a leader to replace NDGs. The many reasons for this inability to find a single device include: lack of accuracy, mixed performance results, costs, ease of use, and/or the need for new agency standards. PQI and PT have shown considerable potential to replace NDGs for HMA applications, although studies differ with regard to the accuracy and repeatability of these devices for QC and QA applications. Many studies have found PQI to be suitable for QC, but few studies have found it suitable to replace NDGs.[5,6,7,8,11,13,15] Some studies have found PT to be suitable for QC, but no study reviewed recommends this device to replace NDGs for QA.[6,8,12] However, with the recent development of NNDGS for HMA density, these devices warrant an evaluation.

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 should be used for QC purposes. Stiffness/modulus measuring devices are growing in consideration due to their ability to measure the modulus *in situ* and to compare that measurement to the design modulus. However, studies show that results obtained from field stiffness devices do not always agree with laboratory modulus values or with one another, which warrants careful evaluation. Additionally, most agencies need new stiffness/modulus-based construction standards to be developed. Nonetheless, the use of NNDGs for the density measurements of unbound materials warrants renewed evaluation, especially if NNDGs can potentially replace NDGs.

Some stiffness/modulus-based devices, including LWD and PSPA, can be used to measure compaction for both pavement 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.[27]

Department of Transportation Survey

In order to improve the understanding of the state-of-practice regarding the use of NNDGs by highway agencies, the research team sent out a survey to various state and provincial DOTs throughout the US and Canada. The survey inquired about the respondent's experience with and opinions of currently available NNDG technology. Appendix A contains detailed survey response information.

Of the 40 respondents, 37 percent had experience with NNDGs. When asked if they had performed research or established standards for NNDGs, 52.5 percent reported that they had conducted some research or experiments, but only 15 percent had established standards for any type of NNDG technology. The NNDG that most agencies (69 percent) reported experience with was PQI. Among unbound devices, the GeoGauge was the most familiar to respondents, with 52 percent of the agencies noting some experience with the device. Most agencies indicated that, based on one or more of the NNDGs they had evaluated, they would require further studies before they could make a decision to replace current NDGs.

In response to the survey question regarding the acceptable accuracy required for NNDG to replace current NDGs, most of the agencies preferred a minimum correlation with a currently used testing device or test method, such as NDG, sand cone, or cores. For HMA, minimum R^2 value would need to range from 0.7 to 0.99, with the maximum deviation from true density (which is essentially the same requirement as a minimum correlation with cores) ranging from 0.5 to 2.0 pcf. For unbound materials, the minimum R^2 value varied by agency between 0.8 to 0.99, and a maximum deviation from true density ranging from 0.5 to 3.0 pcf. Some agencies indicated that they intended to continue to use NDGs or that new standards would have to be developed that relied on stiffness instead of density for the pass/fail criteria for NNDGs. In addition, these agencies indicated that the gauges must be accurate enough to meet their current standards or be at least as accurate as NDGs, or that currently the gauges were acceptable by the agency only for QC purposes.

The survey also asked the agencies to rank the most important criteria for NNDGs in terms of accuracy, cost, ease of use, speed, and other on a scale of 1 to 5, with 5 being the most important criterion. The respondents ranked accuracy as the most important criterion, with ease of use and cost a close tie for second, and speed fourth. Other agencies were concerned mostly with the repeatability of results, and a few noted that industry would have to accept NNDGs and that NNDGs must provide similar or better results than current NDGs.

Chapter 3
Field and Laboratory Testing Overview

This chapter presents the testing conducted in the field and laboratory to assess the effectiveness of NNDGs in determination of density of HMA and unbound materials.

HMA Devices

The research team selected PQI and PT for evaluation and tested these devices at 14 paving project sites across Idaho. The research team conducted field testing over a 2 year period (2011 and 2012); the team also conducted laboratory testing over a 2 year period (2012 and 2013). Most of the field sites were located in ITD Districts 1, 2, and 3, with a single project located in District 5. The overall data set also included PQI data from two previous internal ITD studies. Table 1 presents a summary of the projects. Note that the individual projects are referenced according to their project nickname throughout the report.

Identifying the factors that are known to affect NNDG density readings is important in evaluating the performance of each gauge. These influencing factors fall into two types: global and local. Global pavement factors are associated with each paving operation or project phase. The global factors evaluated in this study include HMA class (related to traffic level), lift thickness, nominal maximum aggregate size (NMAS), aggregate mineralogy, and percentage of binder absorption. Local factors are anomalies that may be present only on certain parts of the pavement surface or at certain times. The local factors evaluated in this study include HMA temperature, moisture presence, sand/debris presence, and paint/markings on the surface.

During the winter months, the team tested PQI and PT on laboratory-constructed slabs to evaluate the effects of HMA temperature and moisture in detail in a well-controlled environment. Temperature was difficult to test adequately in the field due to other testing demands. The team found that surface moisture significantly affected both devices in the field. Therefore, the team further evaluated the presence of moisture to better understand and capture its effect.

Field Experiments

The research team conducted field tests during the construction of pavement acceptance test strips. The test strips were built in accordance with ITD IR 125, *Acceptance Test Strip for Hot Mix Asphalt (HMA) Pavement*.[46] One of the purposes of the test strips was to calibrate the density reported by NDGs to the specific asphalt mix that was being tested. The research team took density readings using PQI and PT once the compaction of the paving surface was completed. Because the research group did not have direct access to NDGs for the study, the team relied on ITD and contractor personnel to share the NDG density readings. Depending on the availability of the personnel and the devices, most locations that could be tested using NNDGs also were tested using NDGs. Occasionally, the research team could obtain data from in-use ITD PQI when available.

Table 1. HMA Field Project Information

Project Name	Project Nickname	ITD Project Key Number	HMA Class 4	Lift Thickness (in.)	NMAS (in.)	Principal Aggregate Mineralogy	Binder Absorption (P_{ba}) (%)
SH-51/SH-78 Grandview: MP 60 to Snake River Bridge	SH-78	11575	3	1.80	0.50	Alluvial	0.83
I-84 Nampa: Franklin Blvd. to 11th Avenue	I-84	10916	6	2.70	0.75	Alluvial	0.62
SH-8 Moscow: White Place to South Fork Palouse River Bridge	SH-8	12001	4	1.80	0.50	Basalt	0.97
I-90 Pinehurst to Elizabeth Park Road	I-90	10498	5	2.00	0.50	Quartz	0.10
US-12 Kooskia: Post Office Creek Bridge to Warm Springs Pack Bridge	US-12 Kooskia	12007	3	2.40	0.75	Basalt	1.34
US-95 Frontage Road: Boekel to Ohio Match Road	US-95 Frontage	11978	3	1.20	0.50	Quartz	0.49
US-95: Lewiston Hill[1]	US-95 Lewiston	11029 & 11485	5	1.92	0.75	Basalt	1.05
Beaver Creek Road Shoshone County[1]	Beaver Creek	09024	3	3.00	0.75	Quartz	0.72
US-95: Wilder to I-84[2]	US-95 Wilder	11566 & 13019	4	1.9 (Stage 1) 3.1 (Stage 2) 1.8 (Stage 3)	0.50	Alluvial	0.96
SH-37: Lowery Lane to Portage Canyon Road[3]	SH-37	11629	2	1.8	0.50	Alluvial	0.44
SH-55 Cascade: Payette River Bridge North to Payette River Bridge South	SH-55	9346	4	3	0.50	Alluvial	0.71
US-95: Garwood to Sagle Stage	US-95 Athol	09780 &11893	5	2	0.75	Quartz	0.52
SH-162: Red Rock Road to Kamiah	SH-162 Kamiah	12002	3	1.8	0.50	Basalt	0.60
US-95: Smokey Boulder Road to Hazard Creek Bridge	US-95 Smokey	11572	4	2.4	0.50	Basalt	1.02
SH-162: Four Corners to MP 13.1	SH-162 Four Corners	8810	3	2.4	0.75	Basalt	0.67
US-12: Orofino to Greer	US-12 Orofino	12998	4	1.8	0.50	Basalt	0.72

[1] Internal ITD research project.
[2] Project of US-95 Wilder to I-84 is foaming WMA mixes.
[3] The research team performed correlations for 2 different asphalt contents (5.8 percent and 6.0 percent) on the SH-37 project.
[4] Class SP2 = 50 gyrations, Class SP3 = 75 gyrations, Class SP4 = 90 gyrations, Class SP5 = 100 gyrations, Class SP6 = 125 gyrations.

The test protocols for NNDGs correlation in this study followed American Association of State Highway and Transportation Officials (AASHTO) T 343, *Density of In-Place Hot Mix Asphalt (HMA) Pavement by Electronic Surface Contact Devices*, Method C, and ITD's *Field Operating Procedure for AASHTO T 343* using additional research test methods.[47] The test protocols for NDGs followed WAQTC TM 8, *In-Place Density of Bituminous Mixes Using the Nuclear Moisture-Density Gauge*.[48] The field tests utilized a variety of nuclear gauges. Most of ITD's pavement NDGs consist of Troxler 4640-B models and some Troxler 3440 and 3430 models. The contractors and consultants also used a few Instrotek 3500 Xplorer models.

During the compaction process, the team took NNDG readings alongside NDG readings between every roller pass until the team could identify Maximum Roller Pass Density. The Maximum Roller Pass Density is the point at which each additional roller pass adds no more than ½ pcf. The number of roller passes at which the density reading stops increasing is the number of passes that is used to compact the pavement during the production phase of the project.

After the compaction process, ITD randomly selected the correlation locations (typically 5) and the research team selected another few locations for validation. The number of validation locations varies, depending on the number which was approved by ITD field personnel. The team took 5 PQI readings at each location and recorded the average results. This method is based on the average mode of the device. Figure 10(a) shows the PQI measurement pattern for average mode that is based on the pattern prescribed in ITD's *Field Operating Procedure for AASHTO T 343*.[47] For the 2011 projects the team averaged 2 PT readings, with the gauge rotated 180° between readings as recommended by the manufacturer. For the 2012 projects, the research team changed the PT pattern to a pattern similar to that of the PQI shown in Figure 10(b) and took 5 average mode readings. The purpose of the new PT pattern was to match the same area that was being evaluated by PQI. The team placed the PT's sensor on top of the center of the PQI measurement areas. However, because the PT base plate is only 6 inches in diameter, compared to 10-inches in diameter of the PQI base plate, the PT measurement areas did not exactly overlap the PQI measurement areas. Figure 10(c) presents the combined overlapped footprints for both devices.

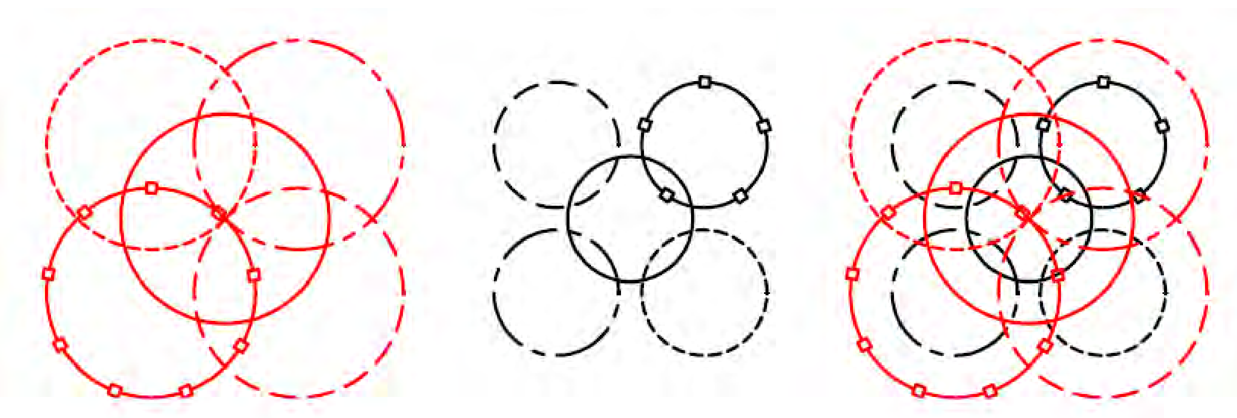

Figure 10. (a) PQI Measurement Pattern, (b) PT Measurement Pattern, (c) Combined Measurement Pattern

The research team conducted NNDG testing at the correlation locations without surface fines and again after it added fines for the NDG readings. For local factor testing at the validation locations, the research team took readings first on the bare HMA surface. Then, the research team applied fines to the surface to fill in the surface voids. The research team then brushed off as much of the fines as possible, sprayed the surface with water, and then repeated taking the measurements. As soon as the water had evaporated, the research team sprayed the surface with a water-based spray paint and took readings.

The team also performed testing at up to 7 locations along the longitudinal joint locations at some of the project sites. The team selected test locations such that the distance between the device and the edge of the asphalt mat was equal to the lift thickness or a minimum of 2 in. from the edge. For the NDG, one single one-minute count measurement was taken perpendicular to the joint at each spot. At the same spot, one single "continuous mode" NNDG reading was taken at the same spot. However, given the size of the machines' test surfaces, sometimes the team was unable to obtain such a close distance and maintain full contact between the gauge base plate and the pavement. Instead, the team performed the tests as close to the joint as possible while maintaining full contact between the pavement and the NNDG test plate. If two lanes were paved, the team took readings when the joint was unconfined. When the other lane was paved and the joint became confined, the team took readings at the confined joint. If one lane was being paved with a curb on one side of the pavement and an unconfined joint on the other, the team took measurements along the confined joint and again on the unconfined side of the lane. If one lane was being paved with two unconfined joints, the team tested that location only on one of unconfined sides of the lane. The research team originally planned to core the joint locations. However, most of the ITD field personnel expressed concern over this plan. Therefore, the team abandoned the plan for most of the projects. The team extracted longitudinal joint cores only at the SH-78 project site for NNDG comparison. In some instances, NDG joint density values were available, and the team was able to use these values as comparisons for analysis. The team compared other longitudinal joint density values to those of the correlation and research locations to see if NNDGs could detect the presumably lower density areas near the joints.

The team also took repeated readings at a single location at a few of the project sites as the pavement temperature dropped. However, this process took a long time, which delayed the coring by ITD or contractors; thus, the team discontinued this effort for the rest of the projects. The team further evaluated temperature effects in detailed laboratory studies.

In summary, the field test procedures used for this study are as follows:

- Input asphalt mix design information as specified in manufacturer's manual.
- Perform roller pattern testing with NNDGs in continuous mode during compaction.
- Test ITD correlation locations (5 to 7 spots) in average mode to correlate the gauges.
- Obtain NDG readings at correlation locations with fines (performed by ITD or contractor).
- Retest correlation locations with fines.
- Obtain cores at correlation locations (performed by ITD or contractor).
- Perform local factor testing at additional validation locations in average mode for surface fines (shown in Figure 11), surface moisture (shown in Figure 12), and surface markings (shown in Figure 13).
- When possible, obtain NDG readings at validation locations.
- When possible, perform extensive moisture and temperature testing.
- When possible, take additional readings at longitudinal joints.

Figure 11. Surface Fines

Figure 12. Application of Water

Figure 13. Application of Markings

The research team performed all the tasks unless otherwise noted. The research team was unable to accomplish all of the above procedures for every project, especially for the local factor testing, due to construction constraints. For instance, the coring process hindered the lengthy process of local factor testing. Table 2 shows the data obtained from individual projects.

Table 2. HMA Data Obtained at Project Sites

Data Obtained at Project Sites						
Project	**PQI**	**PaveTracker**	**Local Factors**	**Longitudinal Joints**	**Temperature**	**Roller Pattern**
SH-78	Yes	Yes	Yes	Yes	No	No
I-84	Yes	Yes	Yes	Yes	No	No
SH-8	Yes	Yes	Yes	Yes	No	Yes
I-90	Yes	Yes	Yes	No	No	Yes
US-12 Kooskia	Yes	Yes[1]	Yes	No	No	Yes
US-95 Frontage	Yes[2]	No	Yes	No	No	No
US-95 Lewiston	Yes	No	No	No	No	No
Beaver Creek Road	Yes	No	Yes[4]	No	No	No
US-95 Wilder	Yes	Yes	Yes	Yes	No	Yes
SH-37	Yes	Yes	Yes	Yes	Yes	Yes
SH-55	Yes	Yes	No	Yes	No	No
US-95 Garwood	Yes	Yes	Yes[3]	No	No	Yes
SH-162 Kamiah	Yes	Yes	No	No	No	No
US-95 Smokey	Yes	Yes	No	No	Yes	No
SH-162 Four Corners	Yes	Yes	Yes[3]	No	Yes	Yes
US-12 Orofino	Yes	Yes	Yes[3]	No	Yes	No

[1] PaveTracker broke during data collection; therefore, the team was unable to collect all of the data for this project.
[2] The team removed all data due to suspiciously poor correlations between NNDG/NDG density values and core density values.
[3] Water only.
[4] Fines only.

After the research team completed the testing, the model name/number of the NDG used by each contractor and ITD was recorded. Cores were extracted from the correlation and validation locations. ITD then measured the density values of the correlation cores. The research team then determined the density of each validation core.(49) The research team contacted ITD at the conclusion of each project in order to obtain the core density values at the correlation locations.

Laboratory Testing

Laboratory testing was conducted to observe the effects of temperature and moisture on the performance of NNDGs. The team prepared the first 2 HMA slabs using a mix design provided by POE Asphalt Company and compacted the remaining 10 slabs using loose mix taken from field projects and compacted in the laboratory. The loose mix samples were separated into 10 equal mass pans and heated them for 2 hours in a 320°F (160°C) oven. Then, the team poured the HMA mix into the slab mold and compacted it using a vibratory compactor. Table 3 provides a list of the laboratory slabs and their respective projects.

Table 3. HMA Laboratory Slab Information

Slab Number	Year of Construction	Project
1 & 2	2012	POE Asphalt Mix
3	2012	I-90
4	2012	US-95 Frontage
5	2012	US-12 Kooskia
6	2012	US-95 Wilder
7	2013	SH-37
8	2013	US-95 Athol
9	2013	SH-162 Kamiah
10	2013	US-95 Smokey
11	2013	SH-162 Four Corners
12	2013	US-12 Orofino

The dimensions of the mold used to compact the HMA samples are 21.625 in. x 23.875 in. x 8 in. The researcher placed a 6 in. tall wooden block topped with a metal plate inside the mold to achieve the desired slab thickness of 2 in., which resulted in a compacted slab volume of 0.623 ft^3. The target air voids of the slabs were targeted to 7 percent.

The team first sprayed the mold with WD-40 to prevent the asphalt from sticking to the sides of the mold or the block inside. Once the HMA was compacted into the mold as evenly as possible, the team removed the plate compactor and unbolted the steel sides from around the sample to eliminate any potential interference with the gauges from the steel pieces. Figure 14 presents the compaction process. The vibratory compactor did not produce a smooth, evenly compacted surface compared to HMA surfaces compacted by rollers in the field. The bottom side of the slab was very smooth.

Figure 14. Laboratory Compaction Using Vibratory Plate Compactor

Temperature Testing

During the 2012 testing, the research team tested only PQI 301 and PT. The researchers added fines to the slab surface after compaction and prior to temperature testing to help ensure full contact between the gauge and paving surface. The first NNDG was immediately placed on the slab and took temperature and density readings without moving the gauge as the slab cooled. After testing the first gauge, the researchers placed the sample into the oven while it was still on top of the wooden block and reheated it to 248°F (120°C) for approximately 2 hours before testing the sample (at the same location) using the second gauge.

For the 2013 testing, the researchers tested a new PQI 380 and new PT (same PaveTracker Plus model, referred to as PT New in this study) in addition to PQI 301 and PT (referred to as PT Old in this study) from the 2012 testing. The slabs were flipped prior to testing and conducted tests on the smooth side of the sample. Due to concerns related to the gauge overheating while it sat on the hot surface during temperature testing, the researchers reheated the slab to only 194°F (90°C) for 2 hours. Then the gauges were placed on the slab without movement between tests. The temperature at the start of the testing was usually around 150°F (65.56°C), which was at the upper end of QA test temperatures in the field. The researchers repeated this process for the remaining three gauges. The test sequence of the devices (PQI 301, PQI 380, PT New, and PT Old) differed for each slab in order to observe the effects that the test sequence may have on the gauges in this testing scenario.

Moisture Testing

Testing for moisture in the field and laboratory proved to be challenging due to the difficulty in quantitatively measuring the amount of water on the surface of the pavement. PQI 301 reports a value known as the H_2O Index, a quantitative number that indicates the amount of water on the surface. As water accumulates on the surface, the H_2O Index value goes up. The H_2O Index feature is not available for the PT and PQI 380 gauges. Thus, for all the devices, researchers quantified moisture using the PQI 301 H_2O Index value.

During the 2012 moisture testing, the team first flipped the slabs onto the smooth side. Then water was applied to the specimen using a spray bottle and a reading was taken. Additional water was applied before another reading was taken, and so on. Due to the need to add moisture between readings, a team marked the gauge location in order to replace the gauge as close as possible to its original location and orientation to minimize procedural error. Once the team completely flooded the surface, the gauge was placed on the surface without moving. The team then took readings every few minutes as the water drained down into the HMA in order to test the effects of internal water on the gauge readings. Once the research team took the readings, the slabs were allowed to dry for several days and moisture testing was conducted using the second gauge.

In the 2013 testing, the team again conducted moisture experiments on the smooth side by taking 5 continuous measurements on the dry surface with 3 levels of increasing water: light, medium, and heavy. Then the surface was thoroughly towel-dried and 5 continuous readings were taken to examine the effects of removing water from the surface.

After the team completed all the temperature and moisture testing for all NNDGs, the slabs were cored at each test location using an electric drill and coring bit. The readings were corrected based on the field correlation offsets and the correlated readings were compared to the measured core density values.

Unbound Devices

The research team selected EDG, SDG, and GeoGauge for evaluation in the field study of unbound materials. The density values and moisture contents measured by SDG or EDG were compared to the sand cone density values, NDG density values, and/or oven moisture contents. For the GeoGauge, the team measured the stiffness and modulus values and compared these values to the density values (sand cone and NDG) and moisture content (oven). For the full-depth reclamation (FDR) and cement recycled asphalt base stabilization (CRABS) projects, the SDG and GeoGauge measurements were compared to NDG backscatter density measurements.

Materials

The research team tested a total of 21 bases, fills, and subgrades at sites over three construction seasons, as shown in Table 4 which included GeoGauge at 20 sites, EDG at 18 sites, and SDG at 16 sites. Most sites were ITD and local agency construction projects. The team tested other materials from stockpiles at ITD maintenance facilities. Because testing could take up to 7 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, the team could not collect all device data at all the project sites. Table 5 shows the device data from each project site. Most of the materials were granular base materials, with a NMAS of ¾ in. or smaller. Other materials tested include coarse fills, sands, slits, and clays. One project featured testing on a CRABS base and another project featured testing on an FDR base using emulsified asphalt stabilization.

Table 4. Unbound Field Project Information

Project Name	ITD Project Key	Construction Year	Material Description
I-84 Nampa Subgrade	10916	2011	Fine Sand Subgrade
I-84 Nampa Base	10916	2011	¾ in. Granular Base
US-95 Payette River Bridge	02842	2011	Granular Burrow
US-95 Garwood to Sagle Frontage Road	11978	2011	¾ in. Granular Base
SH-8 Moscow	12001	2011	Silt (Loess) Subgrade
US-95 Lapwai Bridges	09472	2012	¾ in. Base
SH-55 Cascade	09346	2012	¾ in. Base
SH-162 Four Corners	08810	2012	Clay Subgrade
College Avenue (Moscow)	Local Project (City of Moscow)	2012	¾ in. Fill
US-20/26 Caldwell	Local Project (City of Caldwell)	2012	Fine Sand Subgrade
US-20/26 Caldwell	Local Project (City of Caldwell)	2012	¾ in. Base
US-95 Garwood to Sagle Mainline	09780 & 11893	2012	¾ in. Base
Mullan Ave. (Post Falls)	Local Project (City of Post Falls)	2012	⅝ in. Base
SH-16 Extension Access Road	12915	2012	¾ in. Base
US-95 Wilder Phase 2	11566	2012	CRABS
US-95 Cottonwood	12003	2012	FDR with Emulsified Asphalt
ITD Potlatch Maintenance Yard	N/A	2013	Loess Subgrade
ITD Moscow Maintenance Yard	N/A	2013	¾ in. Base
ITD Moscow Maintenance Yard	N/A	2013	Tan Sand
ITD Moscow Maintenance Yard	N/A	2013	Black Coarse Sand
ITD Moscow Maintenance Yard	N/A	2013	Loess Subgrade

Table 5. Data Obtained at Project Sites for Unbound Materials

Project	GeoGauge	SDG	EDG with SC Model	EDG with NDG Model	NDG	Sand Cone
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 in. 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.*

Experimental Procedures

Sand Cone Method

The sand cone procedure used in this study follows ASTM D1556-07, *Standard Test Method for Density and Unit Weight of Soil in Place by the Sand Cone Method*.(50) The sand cone method involves the removal of *in situ* soil and replacing it with a sand of known density. By measuring the mass of the soil used in the replacement sand, the volume of the hole is determined. Based on the mass of the removed soil and volume of the hole, the wet density of the *in situ* soil is determined. For most of the test locations, the removed materials were sealed in plastic bags and returned it to the laboratory to measure the moisture content. In accordance with ASTM D2216-10, *Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass*, the team then dried the samples in the laboratory oven to determine the moisture content.(51) For certain locations used in the EDG correlation based on the sand cone field density and moisture values, the samples were weighed in the field and the moisture content was determined using a microwave oven following ASTM D4643-10, *Standard Test Method for Determination of Water (Moisture) Content of Soil by Microwave Heating*.(52)

Nuclear Density Gauge

The NDG test methods followed ITD field operating procedures found in AASHTO T310, *Standard Test Method for In-Place Density and Moisture Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth), Method B*.(53) The research team did not have direct access to NDGs and relied on ITD or contractor personnel for nuclear readings. The NDG technician constructed a pin hole and placed the NDG probe 4 to 6 in. into the hole. Two 1-minute readings were taken, with the gauge rotated 90° from the first measurement. This study used a variety of NDG models: Troxler 3440, 3430, and 3411-B and Instrotek Explorer 3500, CPN MC-3, and CPN MC-1. Figure 15 shows a Troxler 3440 NDG.

Figure 15. Troxler 3440 Nuclear Density Gauge

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.*(54) EDG required the placement of 4 metal darts, each 6 in. long, into the soil. The team placed the 4 darts at the 12, 3, 6, and 9 o'clock positions, with each pair of opposite darts 12 in. apart. Two electrical measurements were taken, one for each set of opposite dart pairs, and were averaged. A project-specific correlation procedure, known as setting up a soil model, was required at each site in order to correlate the physical properties to the electrical properties. The team selected three test spots, the minimum number required for soil model setup, and took EDG electrical measurements. Moisture and wet density measurements were also taken at the same soil model locations using other traditional methods (sand cone and NDG). The density and moisture values obtained from the traditional devices were input into EDG and the impedance measurements obtained by EDG paired with a density and moisture values at each location. Using these pairings, the EDG linearly correlated future impedance measurements to wet density values and moisture content. The team took additional moisture/density measurements without the aid of the traditional device and used the remaining locations as validation locations.

Soil Density Gauge

At the time of the field study, SDG did not yet have an approved ASTM standard. Therefore, the research team followed the manufacturer's recommendations. The SDG testing consisted of placing the gauge on a relatively flat area of soil and taking a measurement. Unlike the sand cone, NDG, or EDG tests, the SDG test is completely nonintrusive. The SDG requires soil properties in order to operate; these properties include maximum dry density values, optimum moisture content, gradation, and Atterberg limits (for fine-grained soils only). These input data are obtained 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*, 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.(55,56,57,58) The researchers took SDG readings in a five-shot cloverleaf pattern. When space was limited on a site or test spot, the team scaled down the cloverleaf pattern or, in some cases, took all five individual readings in the same spot. The SDG required 5 independent readings and automatically averaged the results at the end of the 5-shot sequence.

GeoGauge

GeoGauge testing followed ASTM D 6758, *Standard Test Method for Measuring Stiffness and Apparent Modulus of Soil and Soil-Aggregate In-Place by Electro-Mechanical Method*.(30) The device was placed on the soil and rotated it approximately 45° to 90° to seat it. If the footprint of the gauge was not clearly visible upon removal of the gauge, the team used moist sand to help seat the gauge, following manufacturer's recommendations. Two independent readings were taken and averaged. If the modulus difference between the 2 sets of readings was higher than 1 ksi, a third measurement was taken. The two nearest measurements were averaged, and discarded the third measurement. The team recorded both the modulus and stiffness values.

Field Testing: Traditional Unbound Materials

The field testing of the unbound materials began by selecting up to ten test spots. Prior to testing, the team shoveled away any loose material from a test spot, if necessary, in order to create a relatively smooth and flat test area. Yellow paint was used to outline and mark each spot. The goal was to test each device at exactly the same spot; hence, the devices were tested in order from least destructive to most destructive. The ideal device testing sequence was:

1. SDG.
2. GeoGauge.
3. NDG.
4. Three sand cone tests for EDG correlation.
5. EDG.
6. Remaining sand cone tests.

Figure 16 shows the testing pattern. The team took the sand cone measurements outside of the NDG/NNDG device footprint because the holes left by NDG and EDG could affect the sand cone density measurements. The team took the sand cone measurements 12 in. or less away from the footprint, in line with the path of the roller. The desired sequence was not always possible to achieve and depended heavily on the availability of the NDG technician. Often, the technician had to take the NDG shots at the beginning of the sequence. In those cases, as shown in Figure 17, the technician tested the other devices very near the NDG test location. In Figure 17, Modified Unbound Testing Layout, the dotted black circle (labeled "NNDG Outline") marks the test location of SDG and EDG, and the white circle inside the hatched black circle marks the location of the GeoGauge. The NDG hole is slightly to the left of the outline and to the right of the sand cone.

The team took three sand cone measurements prior to EDG testing to correlate EDG in the field. For these three locations, the *in situ* moisture content was determined by placing a portion of the extracted soil sample in a microwave oven to dry.

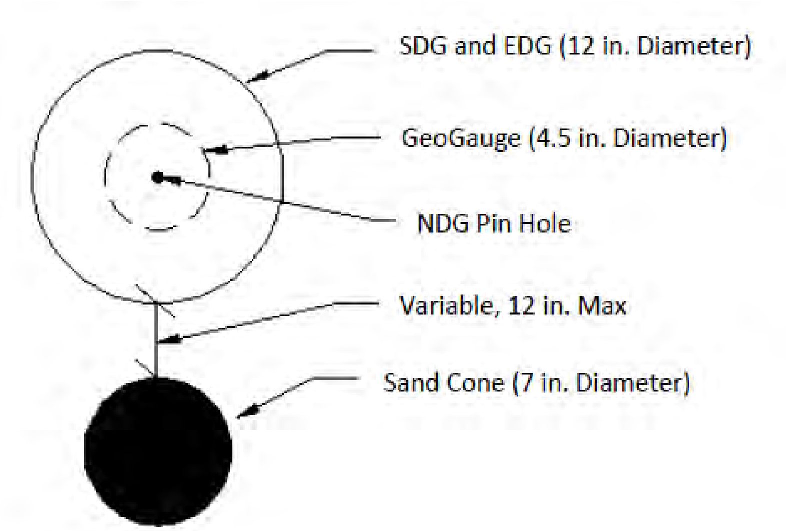

Figure 16. Unbound Field Testing Pattern

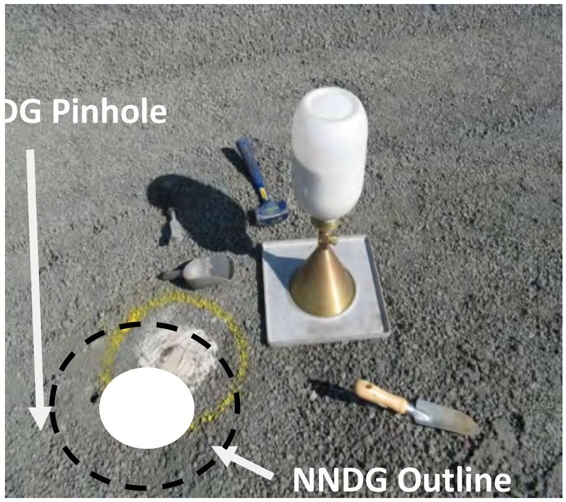

Figure 17. Modified Unbound Testing Layout

Field Testing: FDR/CRABS Base Projects

In situ base and pavement recycling projects are popular in Idaho. Typical projects feature full-depth pulverization of the HMA and granular base layers. The contractor then mixes the pulverized layer with an additive (e.g. cement or emulsion) and compacts the layer again. The new base is bound together by additives. ITD conducted a modified WAQTC TM-8 procedure to measure the compaction density in the new base layer rather than a direct transmission method.[48] For CRABS projects, the contractor set up his own roller pattern and ITD technicians take the acceptance tests, , which is similar to the determination of maximum roller pass density used for HMA. For 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 an NDG backscatter measurement to ensure that the compaction is near the break-over compaction level.

Due to the popularity of these projects, if a NNDG is to replace NDG, it also should have the ability to measure the compaction of these recycled “bound” bases. The team did not select the sand cone and EDG for such testing due to time constraints and the difficulty in conducting the destructive tests in very stiff material. The team considered the HMA pavement devices, PQI and PT, for this type of testing but found them to be unstable due to the changing water content on the surface of the base layer during and after compaction. The team determined that SDG and GeoGauge were suitable for bound base testing trials.

When setting up the CRABS roller pattern, GeoGauge and SDG tests were conducted to compare their ability to predict the roller pattern with the ability of NDG. The team took a single GeoGauge measurement and then took five SDG readings at a single spot and averaged them. For the emulsified asphalt stabilized FDR project, the team also used GeoGauge and SDG to take measurements at a single location over the course of a couple of hours to analyze the measurement changes as the material stiffened.

Chapter 4
Results and Analysis

Once the field and laboratory tests were completed, the team analyzed the data to determine each NNDG device's capability to replace NDG.

Evaluation of HMA Devices

Correlation Methods

The correlation of raw NNDG readings with core density values is critical in order to obtain accurate HMA density values. The team correlated NNDGs by determining the offset between the core density values and the gauge readings. The subsequent readings were adjusted by this offset value for the remainder of the project. This offset method is the method that ITD uses to correlated all NDGs per WAQTC TM 8 and the method prescribed in AASHTO T 343 for NNDGs.[47,48]

Global Factor Analysis

Validation Results

The team compared the correlated NDG and NNDG density measurements with the validation core density values to validate the accuracy of the devices. Table 6 shows the project-specific offset constants for PQI, PT, and any other ITD PQI devices used at the project field sites. The correlation factors were highly variable across projects, highlighting the importance of project-specific core correlation. Detailed project data (without the use of fines) are shown in Appendix B.

When the data from all projects were plotted together, Figures 18 and 19 show the validation results for PQI and PT when compared to validation core density, respectively, when 5 correlation locations were used to determine correlation factors. NDG results were also correlated with core density in these figures. Validation for both the NDG and NNDG readings had slopes of 1.00. Without surface fines, PQI data agreed with the core density values (R^2 = 0.88) nearly as well as NDG (R^2 = 0.89). With the use of fines, the PQI readings exhibited a slightly higher agreement (R^2 = 0.89). Without fines, the PT data resulted in a R^2 of 0.83, and with fines, a R^2 of 0.84. Overall, the level of accuracy of the NNDGs and NDGs was fairly close when compared to the core density values. The PQI agreements with core density values were comparable to those of the NDG; and the PT agreement with core density values were slightly lower than those of the PQI or NDG.

Table 6. Project-Specific Offset Values

Project	WSU PQI Correlation Factors		ITD PQI Correlation Factors			PT Correlation Factors		NDG Correlation Factors	
	HMA Without Fines	HMA With Fines	Gauge Number	HMA Without Fines	HMA With Fines	HMA Without Fines	HMA With Fines	HMA Without Fines	HMA With Fines
I-84	21.8	21.50	-	-	-	16.5	13.50	1.88	-
SH-78	22.3	22.10	ITD #753	21.9	-	16.7	17.90	1.73	-
			ITD #896	22.0	-	-	-		
I-90	26.6	26.10	-	-	-	20.3	18.50	-	-0.77
SH-8	2.2	3.40	-	-	-	-18.5	-20.70	-	-1.20
US-12 Kooskia	16.9	-	ITD #817	17.3	-	-	-	0.38	-
			ITD #818	17.1	-	-	-		
US-95 Frontage	22.5	-	-	-	-	-	-	-	-
US-95 Lewiston	-	-	NR	0.1	-	-	-	-	-
Beaver Creek	-	-	NR	26.6	26.5	-	-	-	-
US-95 Wilder Phase 1	17.9	20.10	ITD#819	19.6	-	13.4	14.56	-	-2.80
US-95 Wilder Phase 2	20.0	-	ITD#819	20.1	-	15.8	-	-4.2	-
US-95 Wilder Phase 3	17.4	-	ITD#819	17.2	-	14.2	-	-2.55	-
SH-37 5.8% AC	22.5	-	-	-	-	19.0	-	1.5	-
SH-37 6.0% AC	24.2	-	-	-	-	19.7	-	1.66	-
SH-55	21.6	-	-	-	-	21.4	-	-0.38	-
US-95 Athol	27.0	-	-	-	-	22.4	-	-	-
SH-162 Kamiah	19.4	-	-	-	-	4.9	-	0.6	-
US-95 Smokey	17.7	-	-	-	-	1.8	-	-	-
SH-162 Four Corners	-	20.10	-	-	-	2.3	-	-	-2.06
US-12 Orofino	18.9	-	-	-	-	2.4	-	-	-
Maximum	26.64	26.54		26.60	26.50	22.40	18.50	1.88	-0.77
Minimum	0.10	3.40		0.10	26.50	-18.50	-20.70	-4.20	-2.80
Range	26.54	23.14		26.50	0	40.9	39.20	6.08	2.03

"-" = indicates that the measurement was not taken by a device

NR = Not Reported

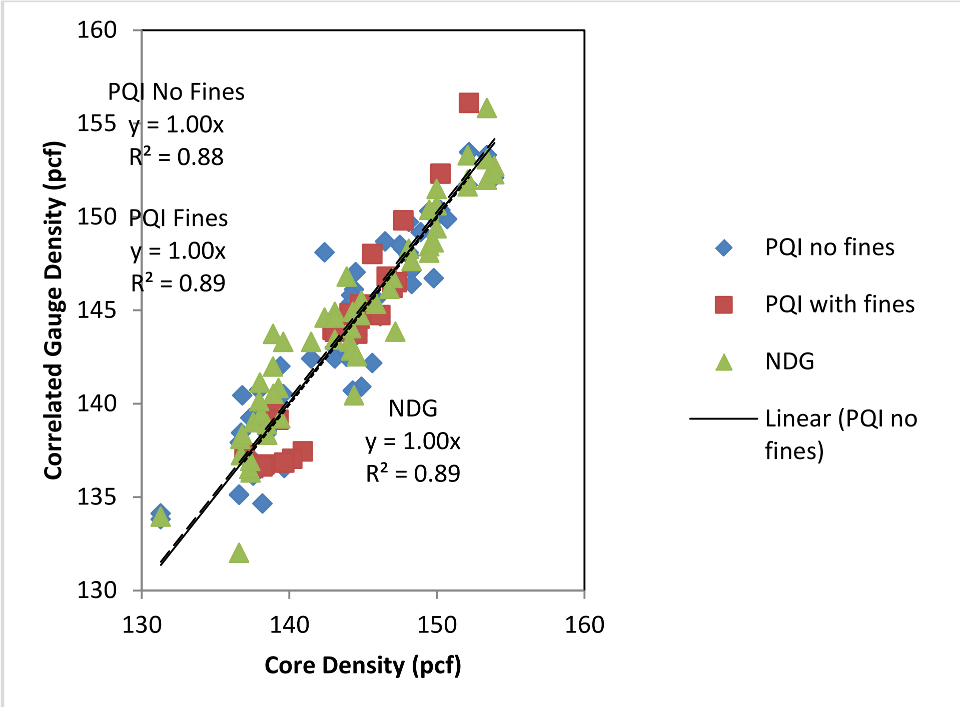

Figure 18. PQI and NDG Validations with Core Densities

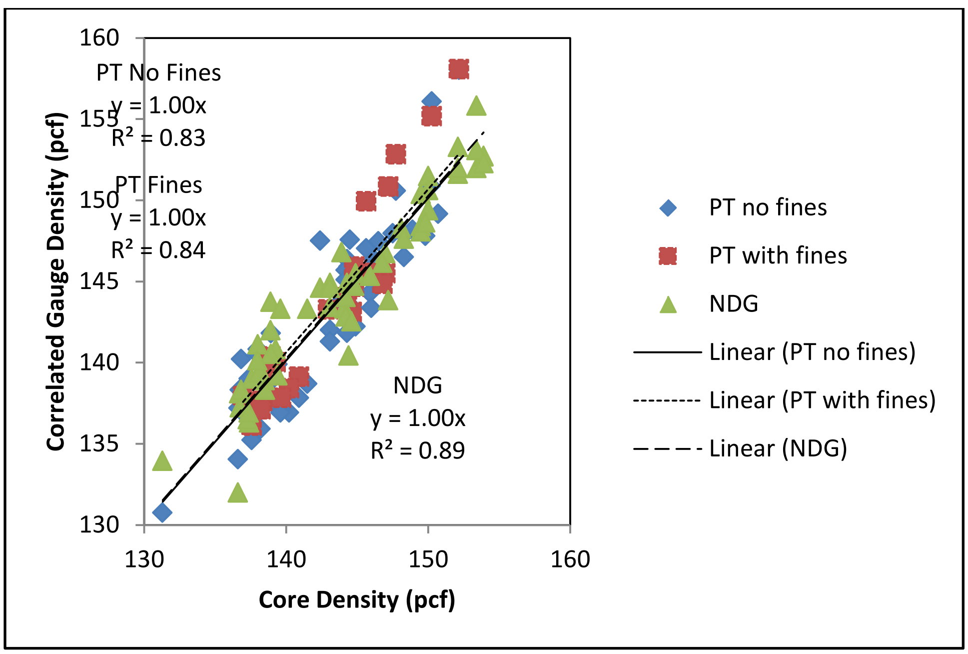

Figure 19. PT and NDG Validation with Core Densities

For individual projects, paired t-tests were conducted to determine whether there is statistically significant difference between the correlated NDG, PQI and PT readings and the validation core density for each project, as shown in Tables 7, 8, and 9, respectively. Due to the constraints on site, only limited number of correlated readings were taken for some projects; however, paired t-test is valid in these cases.[59] When the p-value is equal to or less than 0.05, the hypothesis that there is no statistically significant difference is rejected and there is statistically significant difference. Otherwise, the hypothesis is accepted. It can be seen that for NDG, the hypotheses for 8 out of 11 projects (72.7 percent) are accepted; for PQI, the hypotheses for 11 out of 14 projects (78.6 percent) were accepted; and for PT, the hypotheses for 9 out of 12 projects (75.0 percent) were accepted. None of NDG, PQI or PT produced 100 percent acceptance of hypothesis. PQI has highest percentage of acceptance, followed by PT and NDG. Detailed field measurements are shown in Appendix B.

Table 7. Paired t-Test Results for NDG Results

NDG		**Paired t-Test**	
Projects	**Number of Data Points**	**P(T<=t) two-tail**	**Accept or Reject**
SH-78 MP-60	2	0.1400	Accepted
US-95 Lewiston Hill	5	0.3400	Accepted
Beaver Creek	2	0.7478	Accepted
US-95 Wilder Phase 1	4	0.7781	Accepted
US-95 Wilder Phase 2	2	0.3228	Accepted
US-95 Wilder Phase 3	2	0.8327	Accepted
SH-37 5.8 AC	4	0.0918	Accepted
SH-37 6.0 AC	5	0.0278	Rejected
SH-55 Cascade	8	0.0242	Rejected
US-95 Athol	9	0.0241	Rejected
SH-162 NP	2	0.3765	Accepted
Total Number of Projects	-	**11**	
Number of Projects Accepted	-	**8**	

Table 8. Paired t-Test Results for PQI Results

PQI		Paired T-test	
Projects	**Number of Data Points**	**P(T<=t) two-tail**	**Accept or Reject**
SH-78 MP-60	2	0.00	Rejected
SH-8	4	0.45	Accepted
US-95 Lewiston Hill	5	0.87	Accepted
Beaver Creek	2	0.01	Rejected
I-90 Pinehurst	4	0.36	Accepted
US-95 Wilder Phase 1	9	0.21	Accepted
US-95 Wilder Phase 2	2	0.42	Accepted
US-95 Wilder Phase 3	2	0.03	Rejected
SH-37 5.8% AC	4	0.18	Accepted
SH-37 6.0% AC	5	0.35	Accepted
US-95 Smokey	3	0.82	Accepted
SH-55 Cascade	6	0.01	Rejected
US-95 Athol	7	0.44	Accepted
US-12 Orofino	5	0.37	Accepted
Total Number of Projects	**-**	**14**	
Number of Projects Accepted	**-**	**11**	

Table 9. Paired t-Test Results for PT Results

PT		Paired t-test	
Projects	**Number of Data Points**	**P(T<=t) two-tail**	**Accept or Reject**
SH-78 MP-60	2	0.61	Accepted
SH-8	4	0.35	Accepted
I-90 Pinehurst	4	0.96	Accepted
US-95 Wilder Phase 1	9	0.05	Rejected
US-95 Wilder Phase 2	2	0.63	Accepted
US-95 Wilder Phase 3	2	0.17	Accepted
SH-37 5.8 AC	4	0.14	Accepted
SH-37 6.0 AC	4	0.76	Accepted
SH-55 Cascade	6	0.00	Rejected
US-95 Athol	7	0.36	Accepted
US-95 Smokey	3	0.66	Accepted
US-12 Orofino	5	0.45	Accepted
Total Number of Projects	-	**12**	
Number of Projects Accepted	-	**9**	

Statistical Analysis

This research used statistical analysis for the correlated NNDG data set to determine whether any global factors had a statistically significant effect on the results of the NNDG testing. The researchers performed general linear model (GLM) univariate analysis in PASW Statistics 18.[60] The dependent variable is the percentage of error (% error) between the corrected NNDG density and core density values. The global factors are the independent variables. The team tested null hypotheses on the effects of the global factors on the percentage of error. If any global factor showed statistically significant effects on the percentage of error, further *post hoc* analysis was conducted to determine which value(s) within the significant factor (such as quartz, basalt, and alluvial in specific aggregate type) was significantly different from the other value(s).

Tables 10 and 11 present the PQI and PT analysis results based on the 5-point average difference correlation method, respectively. The column of key importance in both tables is the far right "Sig." (i.e., significance) column. Values under 0.05 in this column indicate that the corresponding global factor is significant with 95 percent confidence. The analysis found that no global factors were statistically significant for either device.

Table 10. PQI Statistical Analysis Results after Correlation

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	Hypothesis	0.330	1.000	0.330	0.499	.482
	Error	46.147	69.720	0.662[a]		
Agg. Type	Hypothesis	2.585	2.000	1.293	2.010	.142
	Error	43.087	67.000	0.643[b]		
Class	Hypothesis	3.937	3.000	1.312	2.041	.117
	Error	43.087	67.000	0.643[b]		
Lift Th.	Hypothesis	0.625	1.000	0.625	0.971	.328
	Error	43.087	67.000	0.643[b]		
Agg. Size	Hypothesis	0.318	1.000	0.318	0.495	.484
	Error	43.087	67.000	0.643[b]		
Absorption	Hypothesis	0.002	1.000	0.002	0.004	.953
	Error	43.087	67.000	0.643[b]		

a. 028 MS (Class) + .972 MS (Error)

b. MS (Error)

Dependent Variable: Error Percentage

Table 11. PT Statistical Analysis Results after Correlation

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	Hypothesis	0.057	1.000	0.057	0.063	0.803
	Error	44.955	49.988	0.899[a]		
AggType	Hypothesis	1.038	1.000	1.038	1.152	0.288
	Error	43.238	48.000	0.901[b]		
Class	Hypothesis	1.726	2.000	0.863	0.958	0.391
	Error	43.238	48.000	0.901[b]		
AggSize	Hypothesis	0.318	1.000	0.318	0.353	0.555
	Error	43.238	48.000	0.901[b]		
Lift Th.	Hypothesis	0.215	1.000	0.215	0.239	0.627
	Error	43.238	48.000	0.901[b]		
Absorption	Hypothesis	0.121	1.000	0.121	0.134	0.716
	Error	43.238	48.000	0.901[b]		

a. 0.038 MS (Class) + .962 MS (Error)

b. MS (Error)

Dependent Variable: Error Percentage

Local Factor Analysis

Roller Pattern Testing

The research team conducted testing to determine if NNDGs could accurately establish a roller pattern for field compaction. Although ITD does not establish roller patterns in the field, contractors use them to find the number of roller passes required to achieve maximum roller pass density. The team evaluated NNDGs to determine if NNDG roller patterns could reasonably match NDG-established roller patterns. One NNDG and one NDG measurement per pass was recoded. NDG measurements were performed at one spot by QC consultant. A Single continuous NNDG measurement was taken per pass at another spot. Figures 20 and 21 show the correlated PQI and PT density trends with roller passes for the various projects. Figures 22, 23, and 24 show specific data from US-95 Wilder Phase 2, US-95 Wilder Phase 3, and SH-162 Four Corners projects, respectively, which are the project sites where NNDGs were used to identify roller patterns alongside NDGs. The contractor QC personnel determined the number of roller passes required to establish a roller pattern for each project. Uncorrelated NDG readings were used by contractor to establish the number of passes to reach maximum roller pass density. However, in Figures 20 through 24, the team used the correlated values for the NNDGs to be able to clearly and visually compare the NNDG density values to the uncorrelated NDG density values in one chart, even though at the time of testing the roller pattern, there are no cores taken yet. Correlated readings were used in the plots during data analysis because the uncorrelated NNDG density values could be significantly different from the uncorrected NDG density values. The scale of density in the figures would be very large and the comparisons cannot be visualized easily.

The nature of establishing a roller pattern with an NDG varied somewhat, but usually featured a rise in the density readings, possibly followed by a slight dip in density value, known as a *false break*, before increasing and then dropping again. Figures 23 and 24 show that the pattern ends after the second drop in NDG density value, or break-over, from the peak. In some cases, a false break is not present, as in the case of the US-95 Wilder Phase 2 project site shown in Figure 22.

The results are varied among the project sites due to the fact that the established pattern is a function of the HMA mix, roller, and the judgment of the NDG operator. NNDGs rarely produced the same density curve as the NDG in this study. The notable exception is for PT, shown in Figure 22, in which PT had a very similar pattern to NDG. PT usually produced some sort of a false break, then a peak followed by a drop. PQI did not often display a peak and drop; rather, the PQI density value tended to climb, then possibly drop, and then continued to climb again. The results indicate that PQI and PT had difficulty in consistently displaying a clear maximum roller pass density. It is noted that the roller density pattern is also affected by the variability inherent in each gauge, including NNDG and NDG.

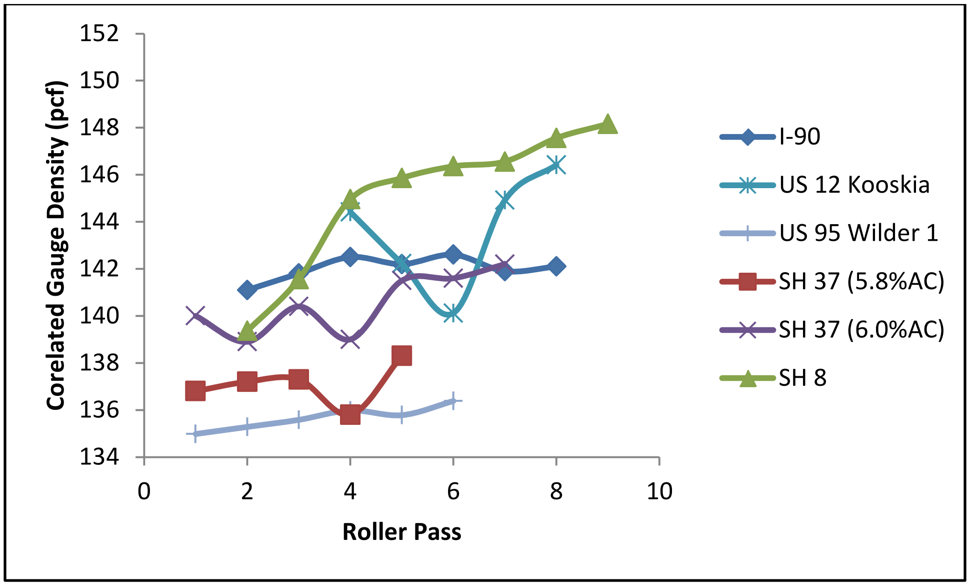

Figure 20. Correlated PQI Density Reading per Roller Pass for Six Project Sites

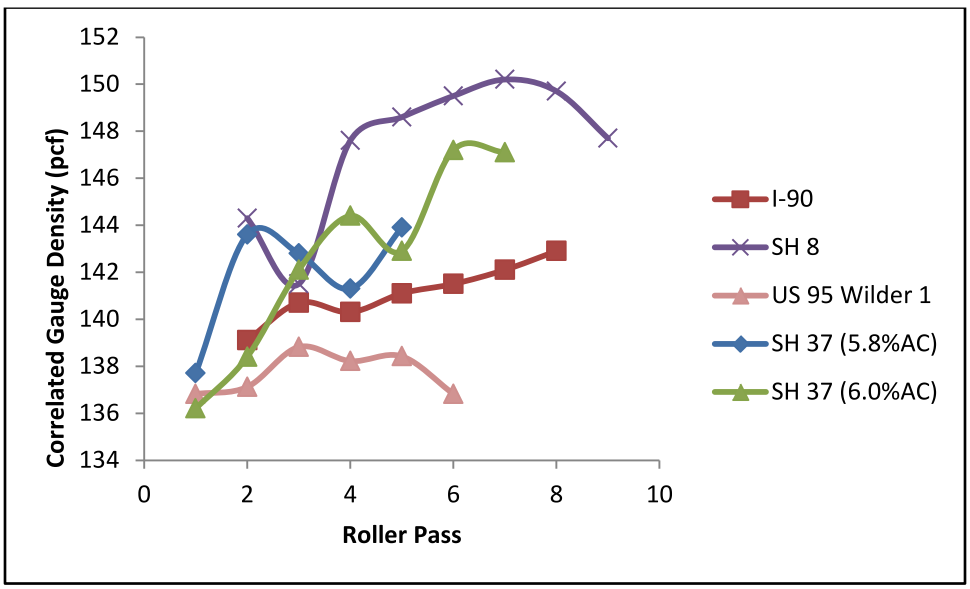

Figure 21. Correlated PT Density Reading per Roller Pass for Five Project Sites

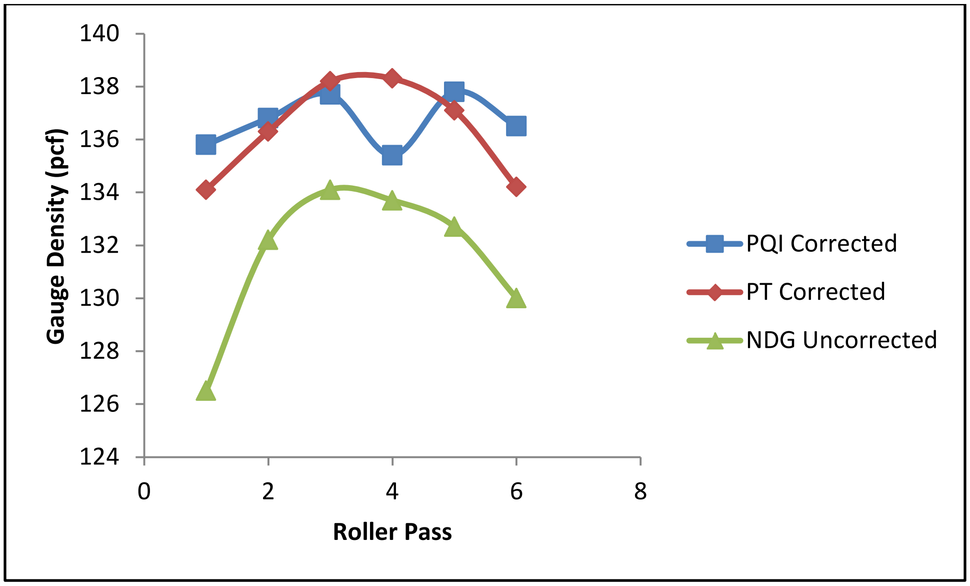

Figure 22. Gauge Density per Roller Pass on US-95 Wilder Phase 2

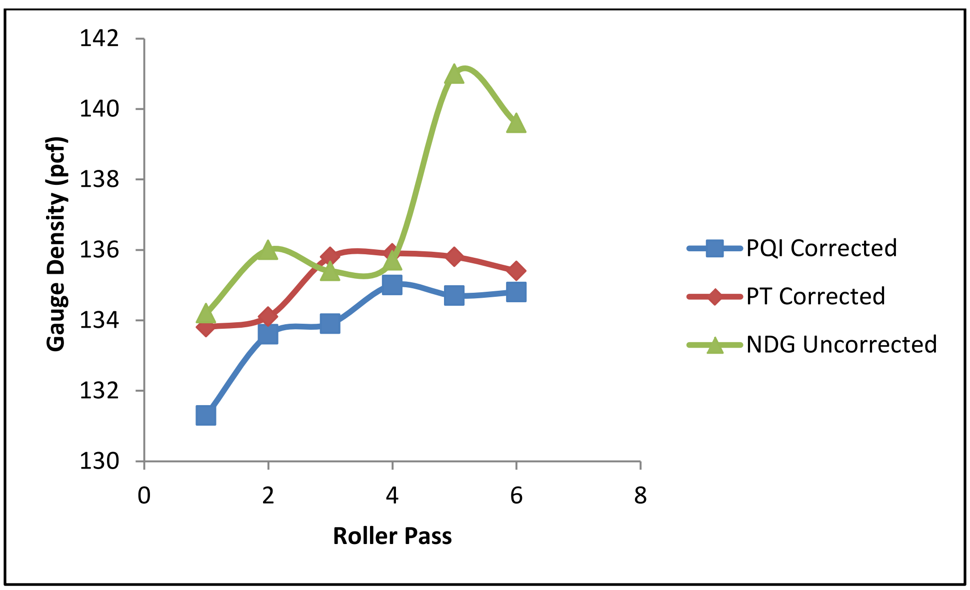

Figure 23. Gauge Density per Roller Pass on US-95 Wilder Phase 3

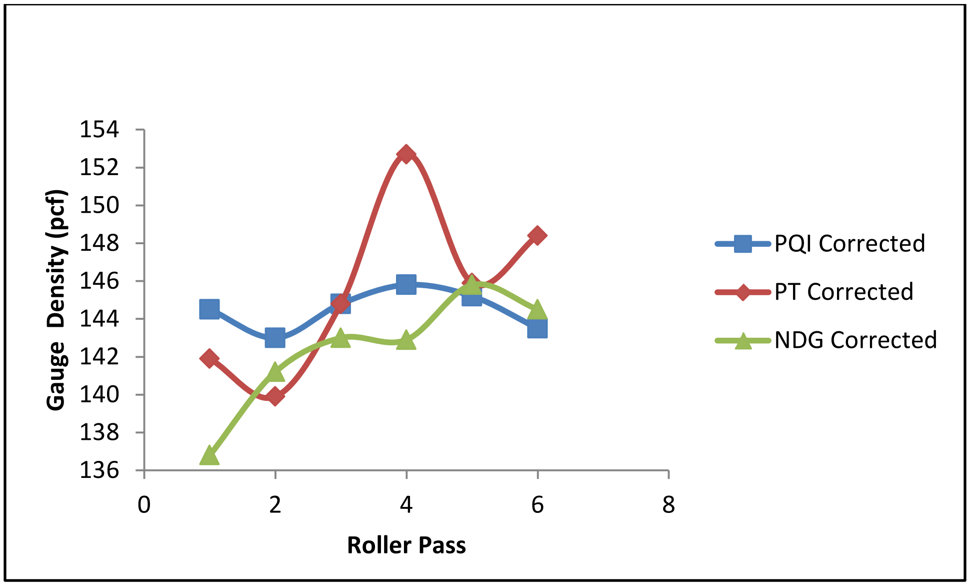

Figure 24. Gauge Density per Roller Pass on SH-162 Four Corners

Surface Fines/Debris

This study examined the effects of surface fine/debris on the NNDG readings. Tables 12 and 13 show the gauge density values with and without surface fines, as well as the percentage of error of the validation core density values for both PQI and PT. These tables also show the *p*-values obtained from two-tailed, paired t-tests. A *p*-value of 0.05 with 95 percent confidence was used.

Table 12. PQI Readings With and Without Surface Fines

PQI With and Without Fines							
Projects	Raw Readings		Correlated Readings				Core Density (pcf)
			No Fines		With Fines		
	No Fines Raw (pcf)	With Fines Raw (pcf)	Density (pcf)	% Error from Core	Density (pcf)	% Error from Core	
SH-78	117.5	117.3	139.8	0.65	139.4	0.36	138.9
	117.4	117.5	139.7	0.58	139.6	0.50	138.9
I-90	117.5	117.8	144.1	0.78	143.9	0.66	143.0
	117.1	117.6	143.7	0.66	143.7	0.64	144.6
	117.7	118.4	144.3	0.35	144.5	0.19	144.8
	118.1	118.6	144.7	1.03	144.7	1.01	146.2
	118.1	118.6	144.7	0.27	144.7	0.29	144.3
SH-8	151.3	152.7	153.5	0.87	156.1	2.58	152.2
	148.2	148.9	150.4	0.09	152.3	1.36	150.3
	146.1	146.4	148.3	0.39	149.8	1.40	147.7
	140.0	144.6	142.2	2.36	148.0	1.62	145.6
US-95 Wilder Phase 1	118.7	118.8	136.6	1.26	138.9	0.43	138.3
	119.5	119.5	137.4	2.52	139.6	0.94	140.9
	119.2	119.4	137.1	0.07	139.5	1.85	137.0
	119.0	119.1	136.9	2.39	139.2	0.73	140.2
	118.6	118.9	136.5	2.28	139.0	0.47	139.7
	118.2	118.6	136.1	1.07	138.7	0.82	137.6
	116.7	118.7	134.6	3.91	138.8	7.16	129.5
Beaver Creek	118.4	118.3	145.0	0.62	144.8	0.49	144.1
	118.0	117.3	144.6	1.05	143.8	0.49	143.1
Average Error (%):				**1.16**		**1.20**	
t-Test:			**0.89**				

Table 13. PaveTracker Readings With and Without Surface Fines

PaveTracker With and Without Fines							
	Raw Readings		Correlated Readings				
			No Fines		With Fines		
Project	No Fines Raw (pcf)	With Fines Raw (pcf)	Density (pcf)	% Error from Core	Density (pcf)	% Error from Core	Core Density (pcf)
SH-78	122.0	121.6	138.7	0.10	139.5	0.40	138.9
	122.7	122.5	139.4	0.30	140.4	1.10	138.9
I-90	120.9	124.8	141.2	1.20	143.3	0.20	143.0
	123.1	124.6	143.4	0.90	143.1	1.10	144.6
	124.7	126.2	145.0	0.20	144.7	0.10	144.8
	126.0	127.0	146.3	0.10	145.5	0.50	146.2
	126.0	125.5	146.3	1.40	144.0	0.20	144.3
SH-8	176.5	178.8	158.0	3.80	158.1	3.90	152.2
	174.6	175.9	156.1	3.90	155.2	3.30	150.3
	169.1	173.5	150.6	1.90	152.8	3.40	147.7
	165.5	170.6	147.0	0.90	149.9	2.90	145.6
US-95 Wilder Phase 1	124.1	124.2	137.5	0.60	138.8	0.40	138.3
	124.4	125.7	137.8	2.20	140.3	0.40	140.9
	123.5	124.5	136.9	0.10	139.1	1.60	137.0
	123.5	125	136.9	2.40	139.6	0.40	140.2
	123.7	124.4	137.1	1.80	139.0	0.50	139.7
	121.8	122.7	135.2	1.70	137.3	0.20	137.6
	122.5	123.7	135.9	4.90	138.3	6.80	129.5
Average Error (%):				**1.58**		**1.52**	
t-Test:			**0.83**				

The *p*-values for each correlation method were above 0.05, indicating that surface fines did not significantly affect the percentage of error with 95 percent confidence. The use of fines had very little overall effect. However, the presence of fines can cause a change in the uncorrelated density measurements compared to the no-fines cases. Technicians should be consistent in their use of fines or no-fines on the surface.

Surface Markings (Paint)

Tables 14 and 15 present the results of the gauge readings with and without paint on the pavement surface for PQI and PT, respectively. The team compared the percentage of error values with paint and without paint and computed paired, two-tail t-test values for gauge.

Table 14. PQI With and Without Surface Paint

Project	Raw Readings		Correlated Readings				
			No Paint		With Paint		
	No Paint Raw (pcf)	With Paint Raw (pcf)	Density (pcf)	% Error from Core	Density (pcf)	% Error from Core	Core Density (pcf)
SH-78	117.5	117.5	139.8	0.6	139.8	0.6	138.9
	117.4	117.7	139.7	0.6	140.0	0.8	138.9
I-90	117.5	117.8	144.1	0.8	144.4	1.0	143.0
	117.1	117.8	143.7	0.7	144.4	0.2	144.6
	117.7	117.9	144.3	0.4	144.5	0.2	144.8
	118.1	118.4	144.7	1.0	145.0	0.8	146.2
	118.1	118.4	144.7	0.3	145.0	0.5	144.3
SH-8	151.3	150.9	153.5	0.9	153.1	0.6	152.2
	148.2	150.7	150.4	0.1	152.9	1.8	150.3
	146.1	146.0	148.3	0.4	148.2	0.3	147.7
	140.0	140.0	142.2	2.4	142.2	2.4	145.6
US-95 Wilder Phase 1	118.7	118.4	136.6	1.3	136.3	1.5	138.3
	119.5	119.3	137.4	2.5	137.2	2.7	140.9
	119.2	119.3	137.1	0.1	137.2	0.1	137.0
	119.0	117.8	136.9	2.4	135.7	3.2	140.2
	118.6	119.0	136.5	2.3	136.9	2.0	139.7
Average Error (%):			**1.03**		**1.17**		
t-Test:			**0.31**				

Table 15. PaveTracker With and Without Surface Paint

Project	Raw Readings		Correlated Readings				
			No Paint		With Paint		
	No Paint Raw (pcf)	With Paint Raw (pcf)	Density (pcf)	% Error from Core	Density (pcf)	% Error from Core	Core Density (pcf)
SH-78	122.0	120.2	138.7	0.12	136.9	1.42	138.9
	122.7	122.5	139.4	0.35	139.2	0.24	138.9
I-90	120.9	123.0	141.2	1.22	143.3	0.21	143.0
	123.1	122.5	143.4	0.88	142.8	1.29	144.6
	124.7	123.1	145.0	0.15	143.4	0.95	144.8
	126.0	127.3	146.3	0.08	147.6	0.94	146.2
	126.0	127.3	146.3	1.40	147.6	2.27	144.3
SH-8	176.5	177.6	158.0	3.84	159.1	4.56	152.2
	174.6	173.9	156.1	3.87	155.4	3.40	150.3
	169.1	171.6	150.6	1.92	153.1	3.65	147.7
	165.5	158.2	147.0	0.95	139.7	4.06	145.6
US-95 Wilder Phase 1	124.1	124.6	137.5	0.59	138.0	0.22	138.3
	124.4	125.6	137.8	2.21	139.0	1.36	140.9
	123.5	125.9	136.9	0.05	139.3	1.70	137.0
	123.5	125.3	136.9	2.37	138.7	1.08	140.2
	123.7	123.5	137.1	1.83	136.9	1.98	139.7
Average Error (%):			**1.36**		**1.83**		
t-Test:			**0.13**				

The results show that the *p*-values of the paired Student's t-tests of the percentage of error are greater than 0.05 for all gauge and correlation combinations, indicating that surface paint has no significant effect on the percentage of error with 95 percent confidence. However, the average error was higher with paint than without paint for all scenarios. For improved accuracy, the surface should be free from excessive markings. Markings to outline gauges on the pavement surface should have a minimal impact on the accuracy of the gauges.

Surface Moisture

Field Evaluation of Moisture Effects

This study examined the effects of moisture on NNDG readings. Moisture from roller and/or rainfall may be present on the pavement surface in the field. Figures 25 and 26 show the effects of moisture on NNDG readings for PQI and PT, respectively. For both devices, the change in reported density is plotted against the change in H_2O Index for HMA. Except for a few outliers, the PQI density values significantly decrease linearly with an increase in water content, and the effect can be up to 16.0 pcf. When compared to the PQI results, the PT results are more scattered, and the error could be up to 21.5 pcf.

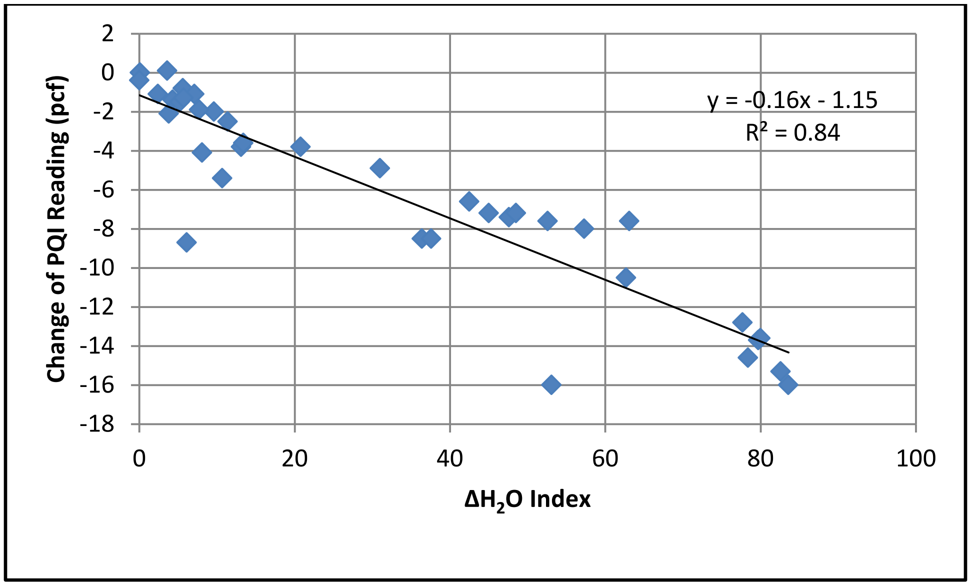

Figure 25. PQI 301 Field Density Change with Change in Moisture Content

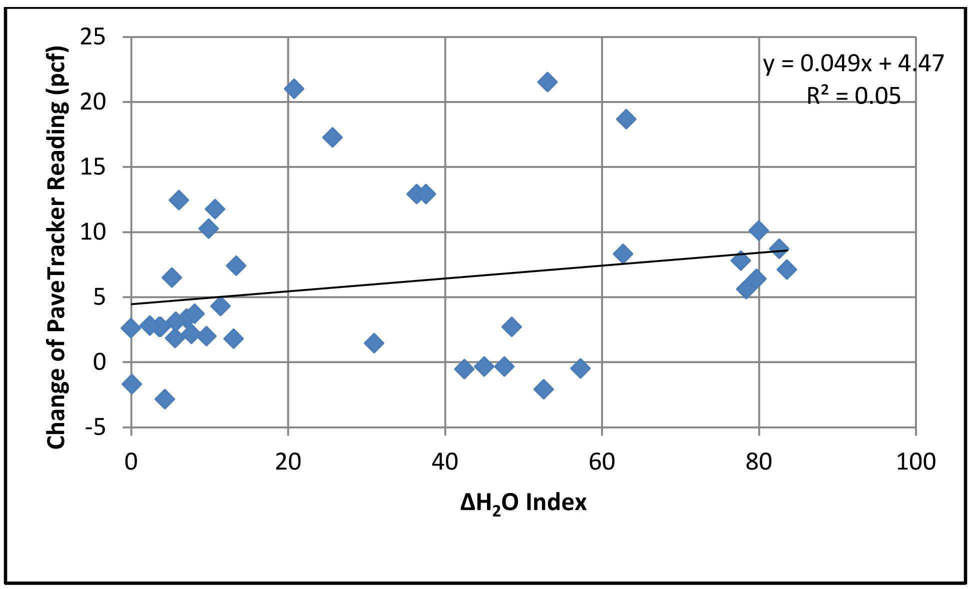

Figure 26. PT Field Density Change with Change in Moisture Content

The team conducted field evaluations of NDG measurements at two project sites to examine the effects of water on the surface of the pavement. At the SH-55 site, researchers sprayed varying amounts of water at each research location. Table 16 shows a comparison between wet and dry readings taken at this site. The ITD or contractor's field personnel first took dry NDG readings and then applied a specific amount of moisture to the surface. An increase in the number of "sprays" of water increased the amount of water at a given spot. Spots 1 and 2 each had 10 spray applications, Spots 3 and 4 had 20 spray applications, and Spots 5 and 6 had 15 spray applications. The team did not apply water to Spot 7 for the second measurement. For 4 of the 6 spots tested with water, the percentage of error of the NDG density value obtained from the core was higher with the application of water. In 4 of the 6 spots, the NDG density measurements increased with the application of water. It appears that water may have had some effects (up to 4.3 pcf) on the NDG density measurements. Spot 7, however, did not have water applied, yet the density measurement still increased with the second measurement. This outcome was likely due to the inherent variation of the gauge resulting from placement of the gauge during the second measurement.

The team also tested NDG with moisture at the SH-162 Four Corners site and Table 17 shows the results. For this project, a direct comparison of NDG to NNDGs was possible. The team used the H_2O Index from PQI to quantify the moisture at a single location. The NDG and NNDGs first took dry measurements. Then, a significant amount of water was applied and all the gauges were tested again. The NDG density values did change up to 3.5 pcf, which was not as large as the density change that the NNDGs reported. The team allowed the site to air dry and then took 2 additional density measurements. After air drying, both the PQI and NDG density values returned to near-dry density values, whereas the PT density values remained somewhat high. Overall, water may have had some effect on the NDG density measurements, but the effect was less, compared to the water effect on NNDGs.

Table 16. NDG Density Change with Moisture Content at SH-55 Site

Spot No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
No. of Sprays	10.00	10.00	20.00	20.00	15.00	15.00	0
Correlated Dry NDG Density before Spray (pcf)	138.00	141.90	141.30	139.10	137.70	139.10	139.80
Correlated Wet NDG Density after Spray (pcf)	138.20	141.20	142.80	142.80	138.50	136.90	141.90
Core Density	136.70	138.00	139.90	138.50	137.40	136.80	138.00
% Error Dry	0.95	2.83	1.00	0.43	0.22	1.68	1.30
% Error Wet	1.10	2.32	2.07	3.10	0.80	0.07	2.83

Laboratory Evaluation of Moisture Effects

Due to construction constraints in the field, the research team conducted an extensive study of the effects of moisture on the NNDG measurements in the laboratory. Figures 27, 28, 29, and 30 present the laboratory moisture results for all of the 2013 test slabs for PQI 301, Old PT, PQI 380, and New PT, respectively. PQI 301, as in the field, generally had decreasing density readings with increasing moisture content, except for 2 slabs where the PQI 301 density values increased with an increase in moisture content. The slopes of the relationship between the change in H_2O Index and change in PQI 301 readings in the laboratory and field are very close: approximately 0.15. The other 3 devices, PQI 380, PT and PT Plus, all reported increasing density values with an increasing H_2O Index. A similar trend was evident for the 2012 test slabs (Slabs 1 through 6), as illustrated in Figure 31 for the Old PT on Slab 2. Clearly, an increase in moisture content causes an increase in density measurements compared to the dry condition.

Table 17. NDG and NNDG Density Change with Moisture at SH-162 Four Corners Site

Density	PQI H_2O Index			
	3.9 (dry)	66.3	15.7	10.0
PQI Correlated Density (pcf)	145.9	137.9	145.7	146.6
PT Correlated Density (pcf)	143.7	164.0	154.4	150.6
NDG Correlated Density (pcf)	143.8	145.9	144.3	144.8
Core Density (pcf)	147.3	147.3	147.3	147.3

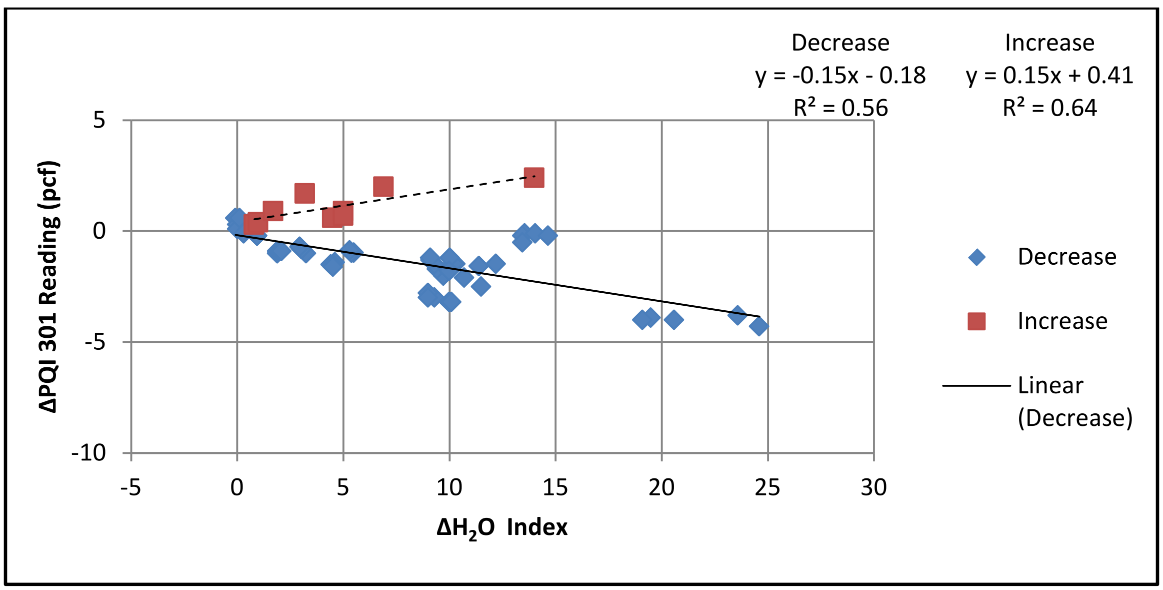

Figure 27. PQI 301 Laboratory Density Change with Change in Moisture Content for 2013 Slabs

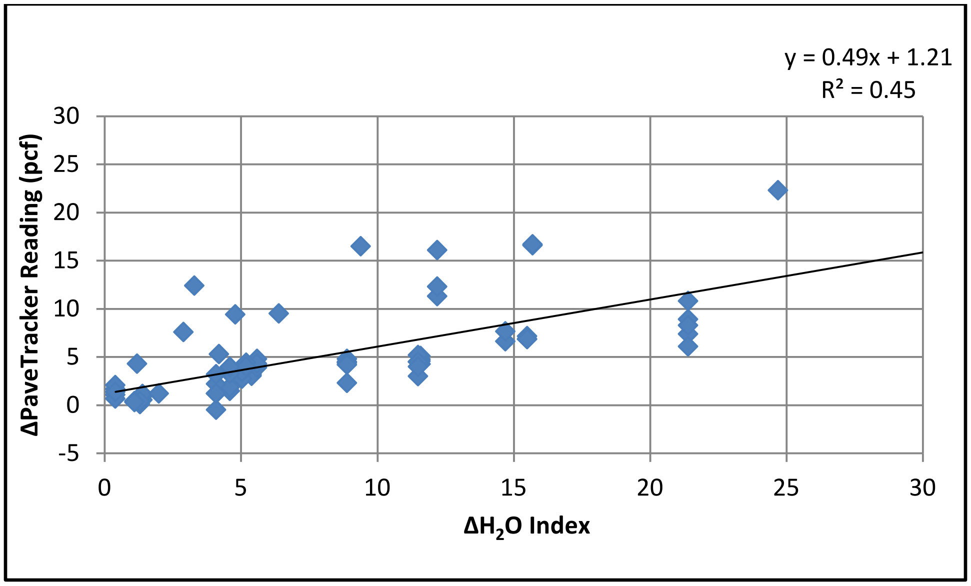

Figure 28. PT Old Laboratory Density Change with Change in Moisture Content for 2013 Slabs

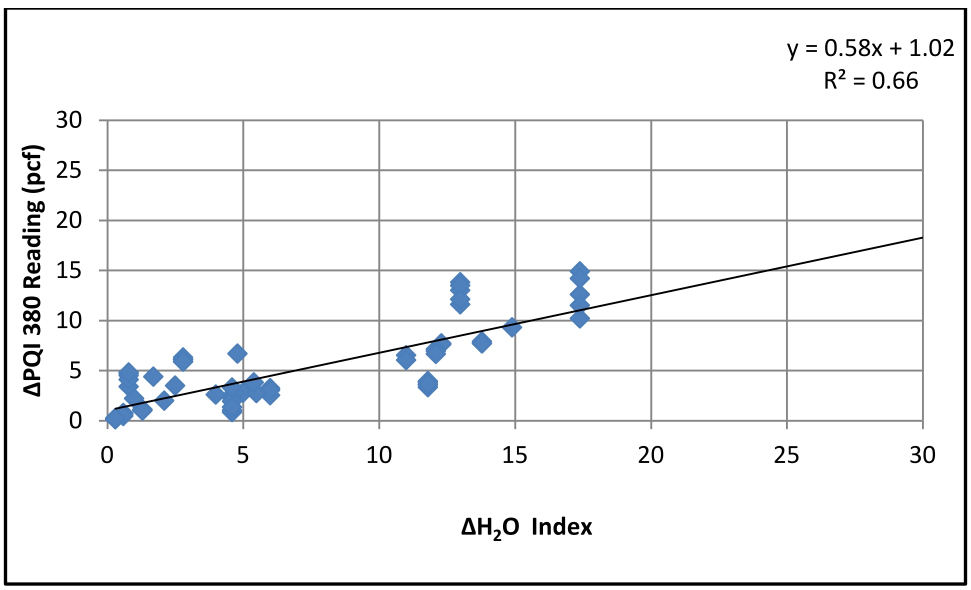

Figure 29. PQI 380 Laboratory Density Change with Change in Moisture Content for 2013 Slabs

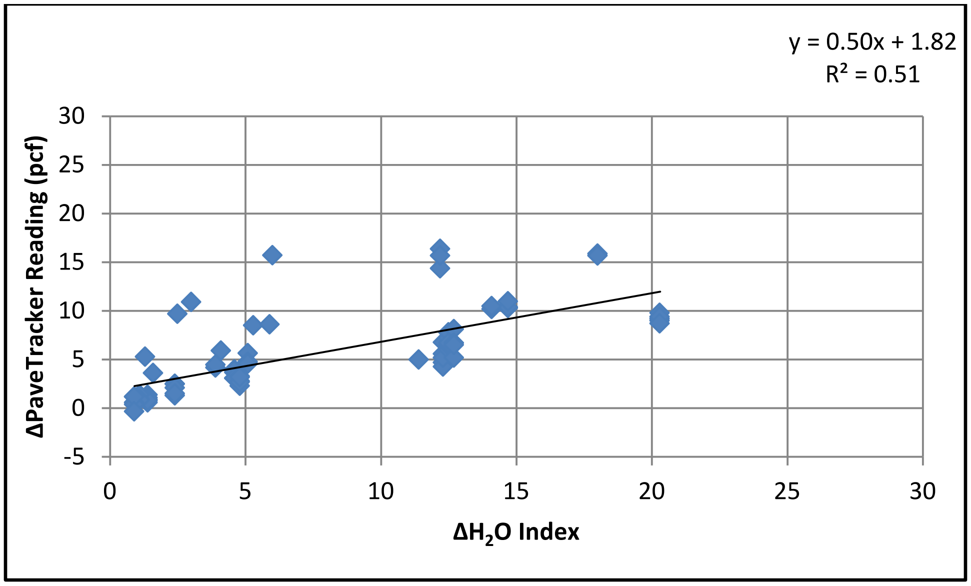

Figure 30. PT New Laboratory Density Change with Change in Moisture Content for 2013 Slabs

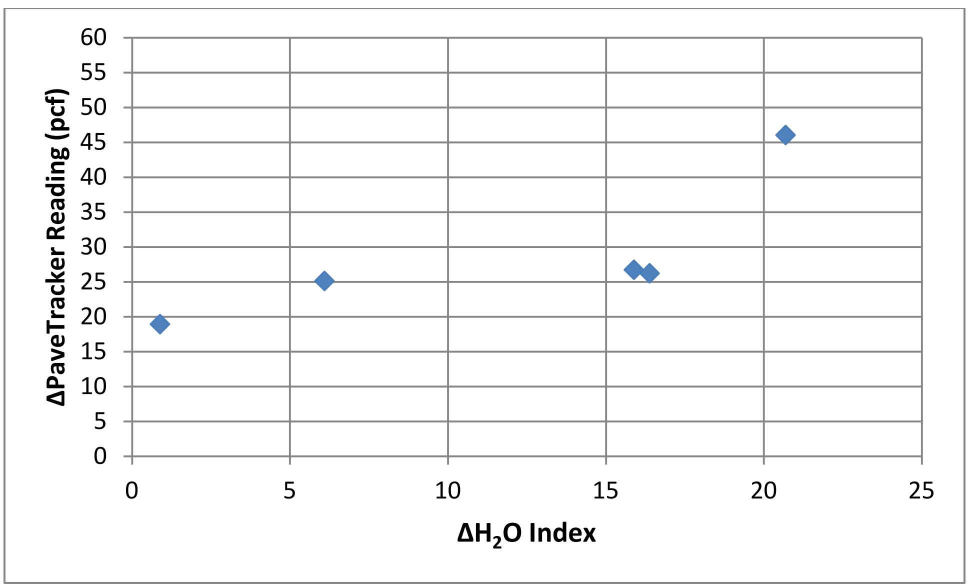

Figure 31. PT Old Laboratory Density Change with Moisture Content for Slab 2 (2012)

The team dried the slab surface with a paper towel to mitigate the effect of moisture on the NNDG measurements. Figures 32, 33, 34, and 35 show measurements for PQI 301, PT Old, PQI 380, and PT New, respectively, taken on Slab 9. The four surface conditions used for these tests are dry, wet, and patted dry with a towel, and fines placement after drying. The team took five continuous density readings at each stage for each device. PQI H_2O Index measurements were taken prior to taking the density measurements for the other devices. Clearly, water caused a change in density value for all of the NNDG devices. When the researcher dried the surface with a paper towel, the H_2O Index value did not return to the original H_2O Index value. However, drying did help the density measurement considerably in its ability to "return" to the original, dry condition density value. Adding fines after drying caused the H_2O Index to increase again, which negatively impacted the density measurement. The addition of fines appears to be detrimental which may be due to the absorption of moisture in asphalt by the fines; however, the team investigated this scenario only on Slab 9.

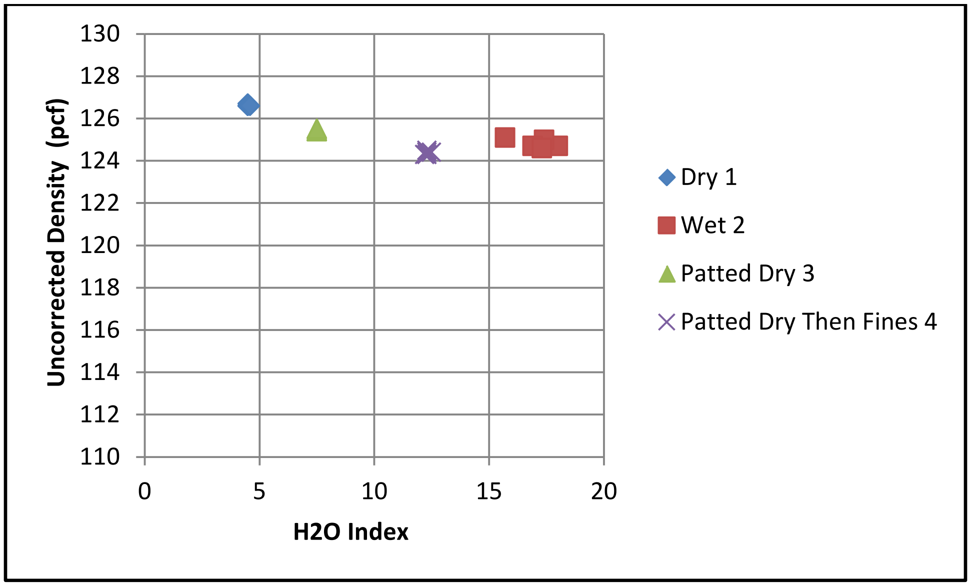

Figure 32. PQI 301 Density Change with Moisture on Slab 9

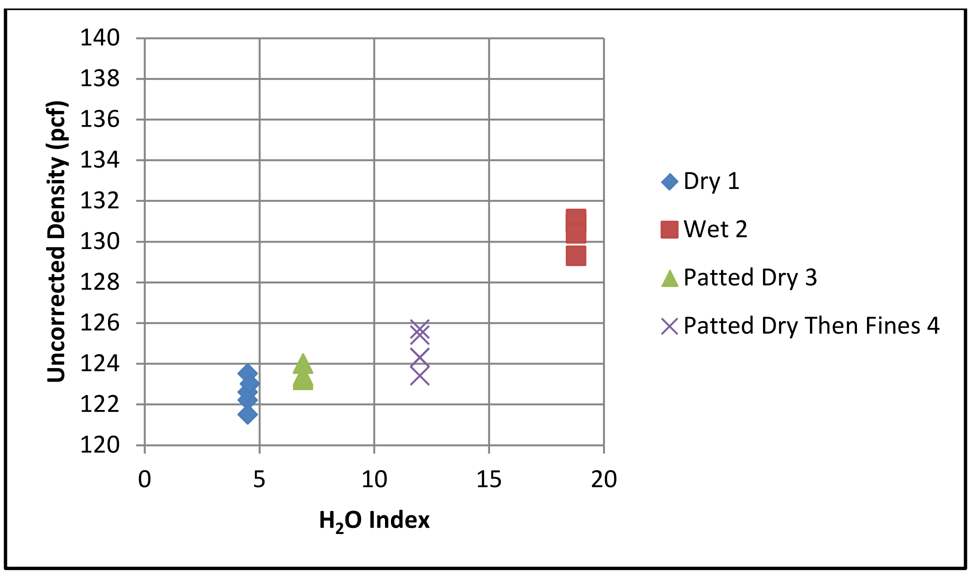

Figure 33. PT Old Density Change with Moisture on Slab 9

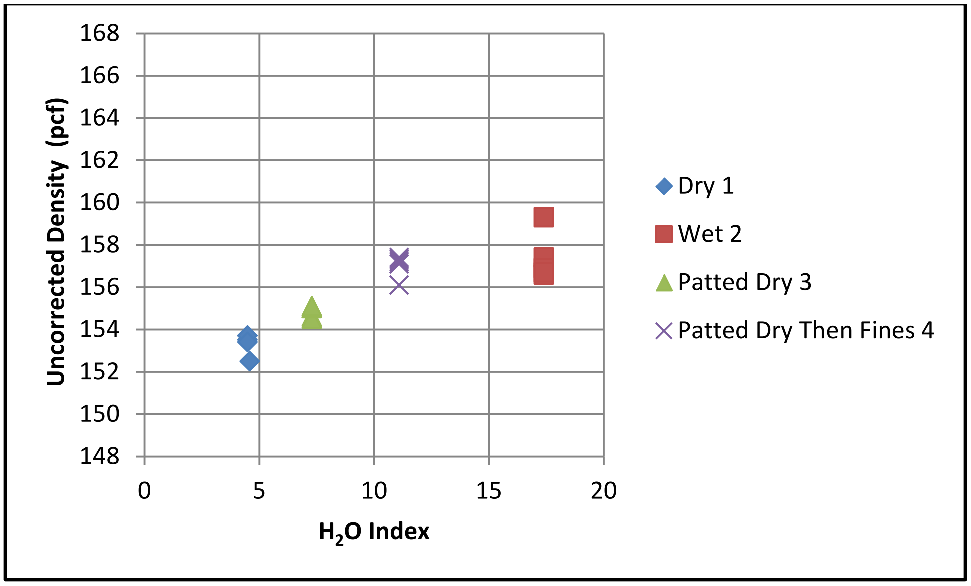

Figure 34. PQI 380 Density Change with Moisture on Slab 9

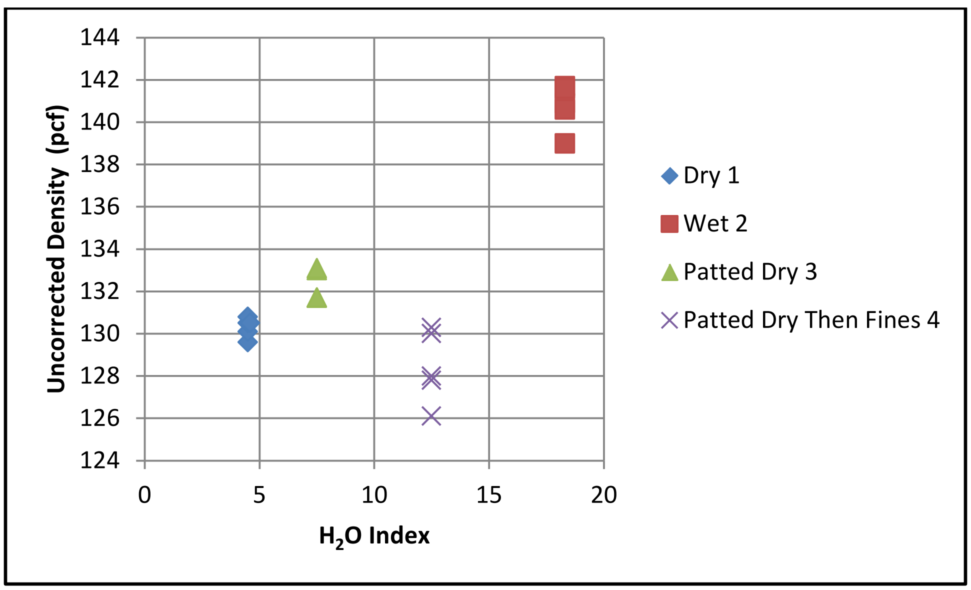

Figure 35. PT New Density Change with Moisture on Slab 9

The water and drying effects were further examined for Slabs 10, 11, and 12. The team took measurements for the conditions of dry, three stages of wet, and patted dry. The three stages of wet conditions consisted of increasing the moisture on the surface with a light water stage, medium water stage, and heavy water stage. The density and H_2O values typically changed slightly between the dry and light water stages. As expected, the change in density values was greater with an increase in surface water. Drying the slab after the heavy water stage quickly reduced the H_2O Index to near-dry levels. In each case, the average reported density value during the towel-dry stage was ±2 pcf from the average density value of the dry stage. In most cases, the change between the dry and towel-dry density values was less than 1 pcf. Figure 36, 37, 38, and 39 present the plots for the Slab 10 data for PQI 301, PT Old, PQI 380, and PT New, respectively. Figure 40, 41, 42, and 43 present the plots for the Slab 11 data for PQI 301, PT Old, PQI 380, and PT New, respectively. Figure 44, 45, 46, and 47 present the plots for the Slab 12 data for PQI 301, PT Old, PQI 380, and PT New, respectively.

The research team selected the tolerable range of density variation caused by moisture as 3.6 pcf, which is the 2 standard deviation density, based on ASTM 7113-10, *Standard Test Method for Density of Bituminous Paving Mixtures in Place by the Electromagnetic Surface Contact Methods*. It is the maximum allowable measurement variation for 2 properly conducted measurements on the same material by a single operator.[61] For the towel-dry scenario, the maximum variation between the average dry density value and the towel-dry density value also was well below 3.6 pcf.

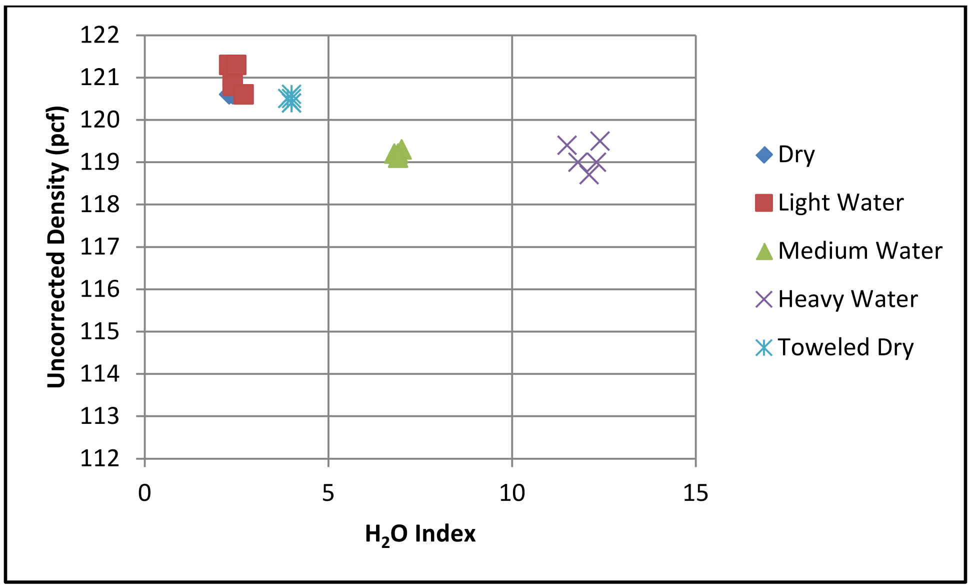

Figure 36. PQI 301 Density Change with Moisture on Slab 10

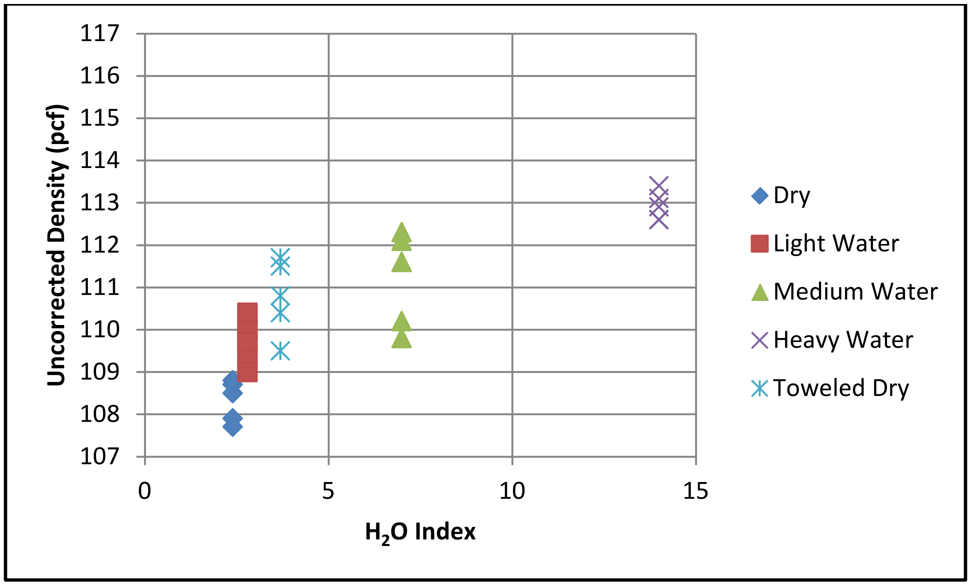

Figure 37. PT Old Density Change with Moisture on Slab 10

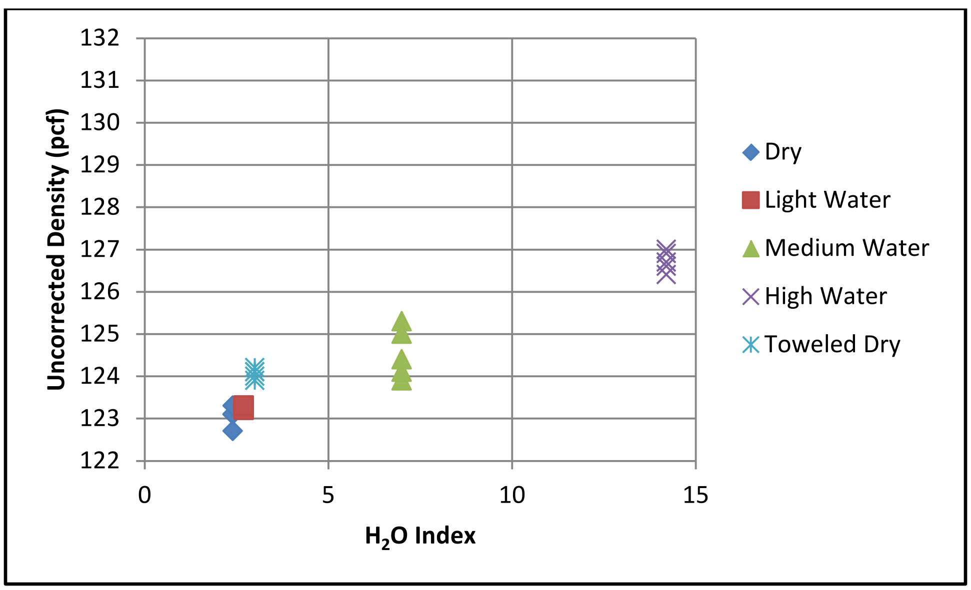

Figure 38. PQI 380 Density Change with Moisture on Slab 10

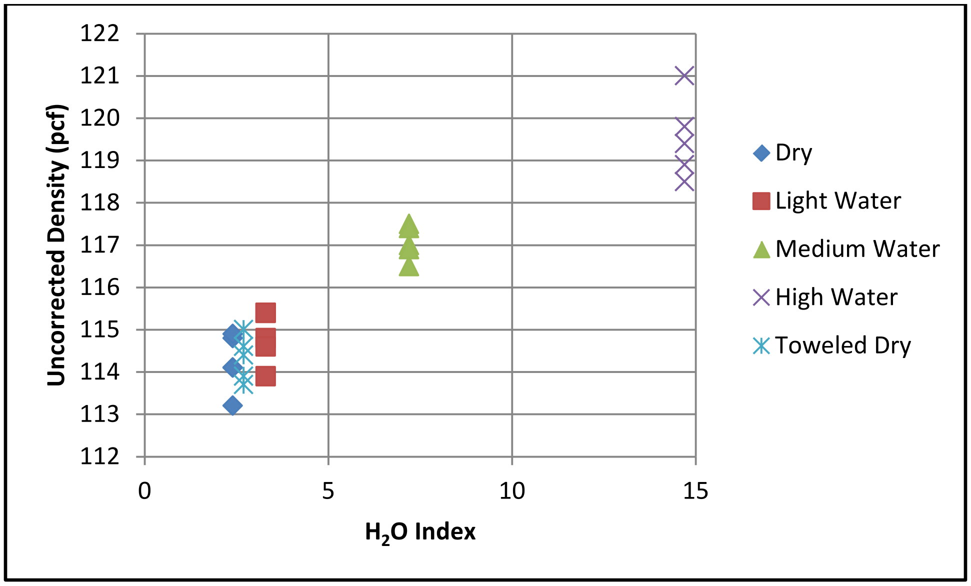

Figure 39. PT New Density Change with Moisture on Slab 10

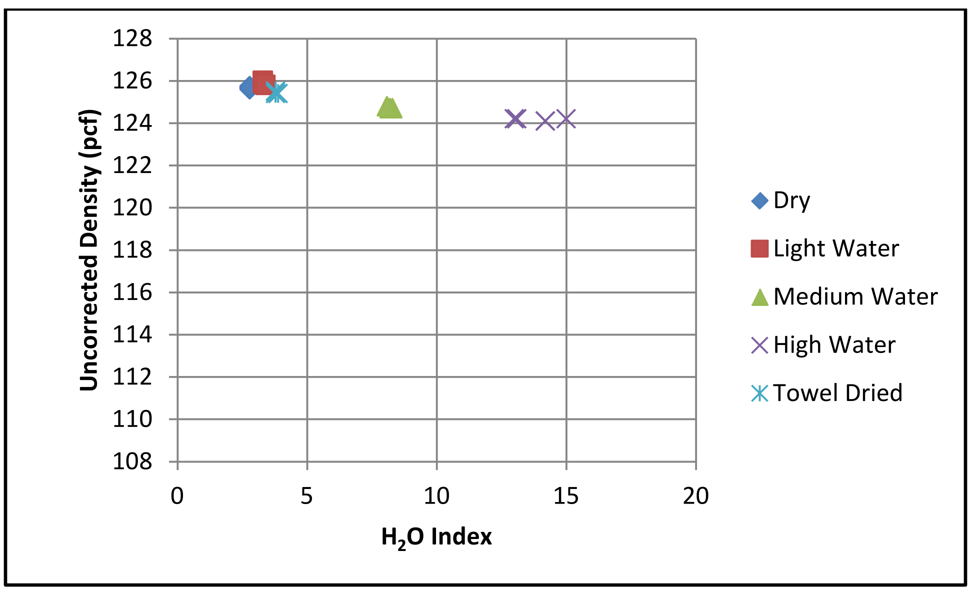

Figure 40. PQI 301 Density Change with Moisture on Slab 11

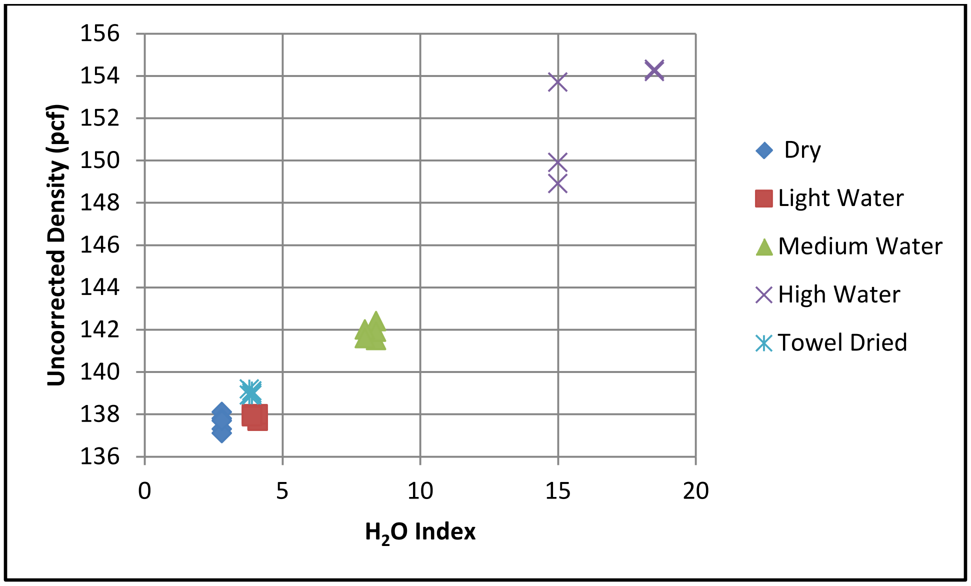

Figure 41. PT Old Density Change with Moisture on Slab 11

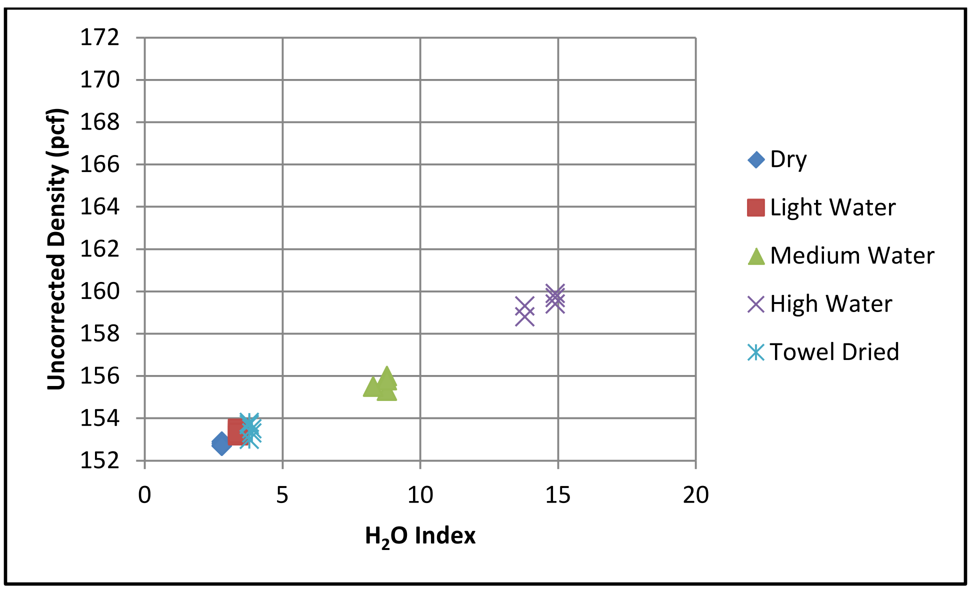

Figure 42. PQI 380 Density Change with Moisture on Slab 11

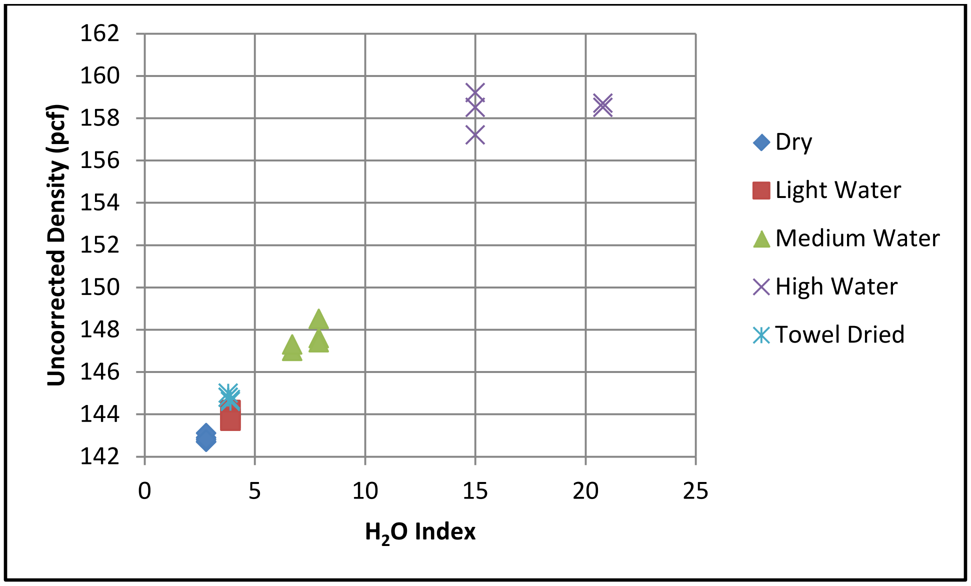

Figure 43. PT New Density Change with Moisture on Slab 11

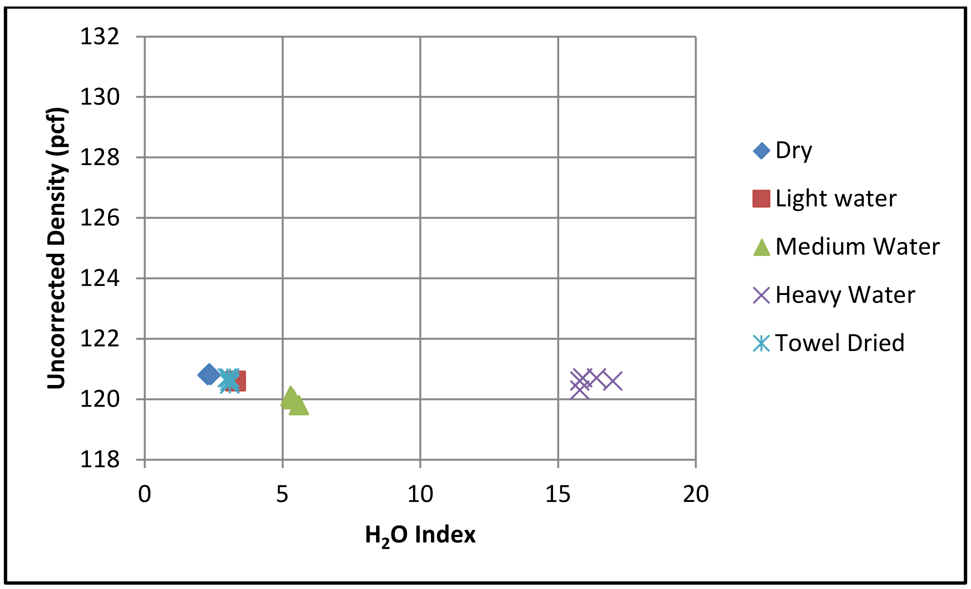

Figure 44. PQI 301 Density Change with Moisture on Slab 12

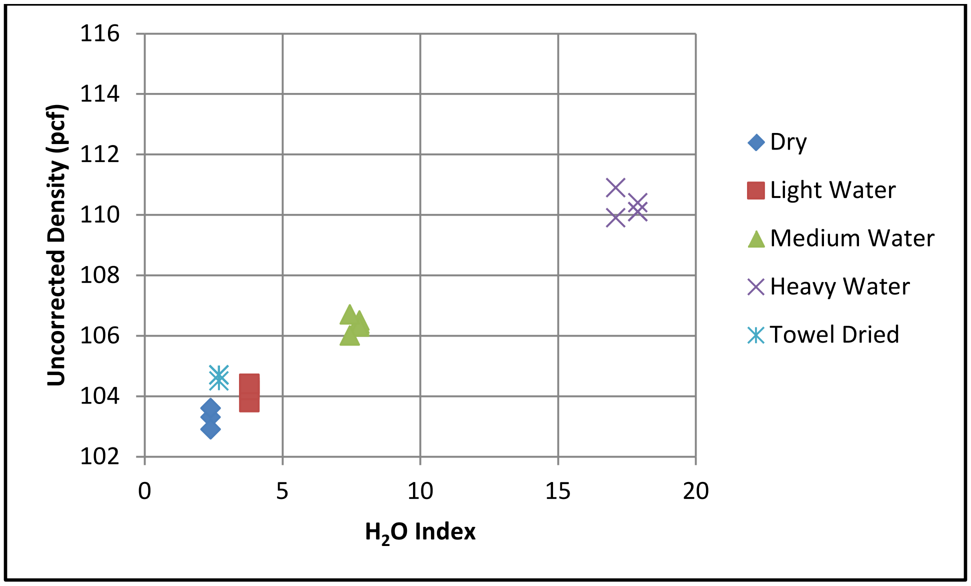

Figure 45. PT Old Density Change with Moisture on Slab 12

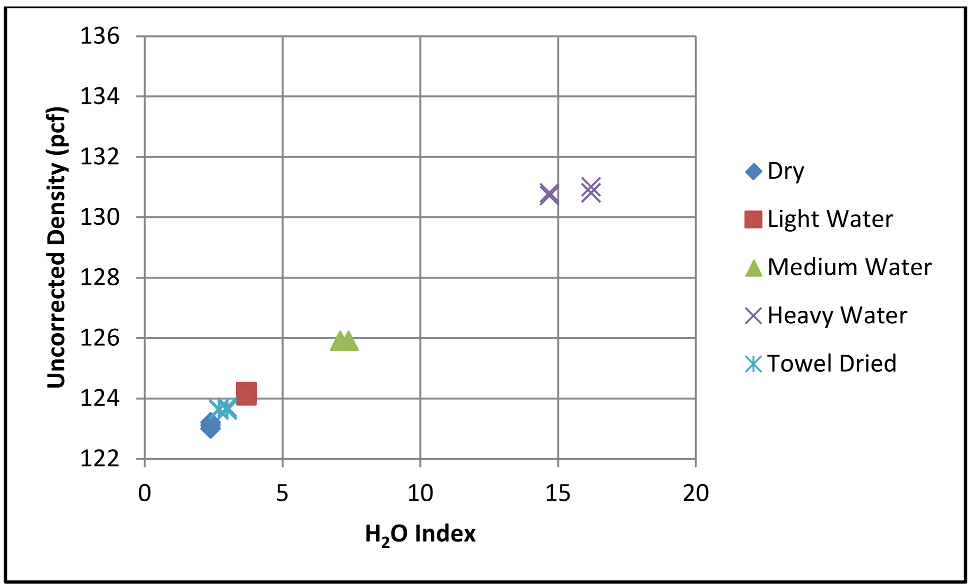

Figure 46. PQI 380 Density Change with Moisture on Slab 12

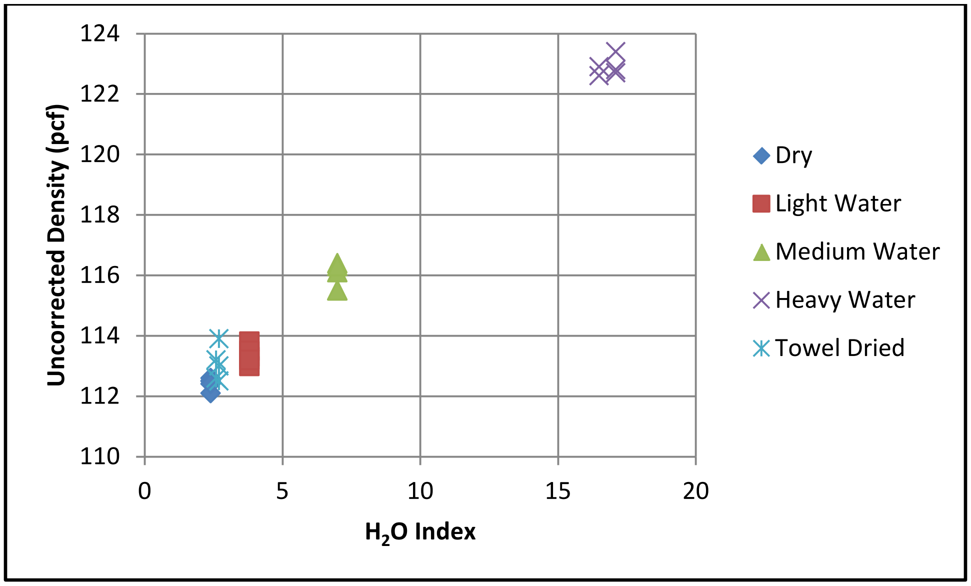

Figure 47. PT New Density Change with Moisture on Slab 12

Moisture is a difficult parameter to take into account with the HMA pavement NNDGs. This study used the PQI 301's H_2O Index to measure the amount of water on the surface. Although the research team generally observed a linearly decreasing density trend with increasing moisture for PQI 301, outliers were also evident. In some PQI 301 cases, increasing the moisture content caused the density value to increase rather than decrease. Despite the manufacturers' claims that moisture does not have a significant effect on density measurements, PT and PQI 380 reported increases in density values with an increase in surface moisture. Neither PT nor PQI 380 offers the user the ability to quantify the amount of water on the surface. These problems make the task of accurately correcting for moisture very difficult. Even a relatively small amount of water can cause changes in density readings. Fortunately, the process of thoroughly drying the pavement surface produced density measurements very close to the dry condition measurements. In summary, when moisture is present on a pavement surface, the surface can be dried with a paper towel to bring the moisture condition to the near-dry condition. However, fines are not recommended to use underneath the gauge after towel-drying.

Temperature

This study also evaluated the effects of temperature on NNDG density measurements. However, the team found that analyzing the effects across a wide temperature range in the field was somewhat difficult. Also, the intermediate and finish rollers altered the compaction and surface conditions, which made accurate field testing in the high temperature range impossible. Because additional testing became necessary after the finish rolling, the team decided to focus on testing samples in a controlled laboratory environment to better understand the effects of temperature. Two field case studies, discussed at the end of this section, supplemented the laboratory studies.

As was the case for the moisture analysis, the team selected 3.6 pcf as the tolerable range of density variation caused by temperature change, based on ASTM D7113-10, *Standard Test Method for Density of Bituminous Paving Mixtures in Place by the Electromagnetic Surface Contact Methods*.(61) This value is the maximum allowable measurement variation for two properly conducted measurements on the same material taken by a single operator.

Laboratory Evaluation of Temperature Effects

For the initial laboratory tests, NNDGs remained stationary on the slab while the slab cooled. This method was advantageous because the vibratory plate compactor does not compact the slabs as uniformly as the compaction roller does in the field. Thus, even a slight movement from the original spot could affect the density readings. For example, the operator removed the gauges after each temperature reading for Slab 7, shown in Figure 48, which resulted in highly variable trends. The team used this leave-in-place method for all the other slabs. However, the leave-in-place method also has drawbacks. Leaving gauges on the surface for extended periods is not representative of real QA/QC test conditions where the gauges are on the surface only for short periods of time. The manufacturers also warn that leaving the gauges on hot surfaces for extended periods of time could damage the internal electronics of the device. In order to address this issue, the team limited the temperatures to lower than 160°F for the temperature tests.

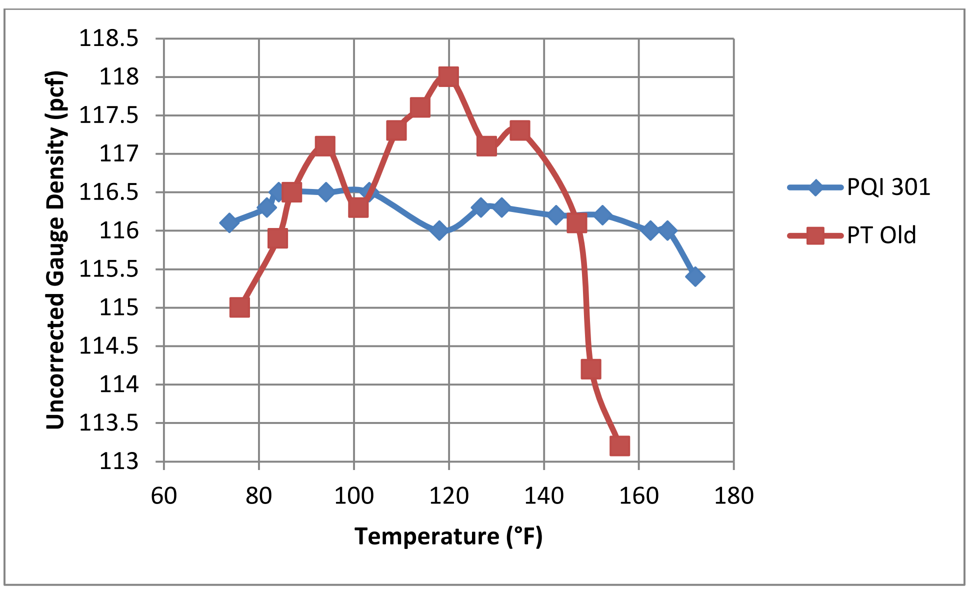

Figure 48. PQI 301 and PT Old Temperature Tests on Slab 7

Figures 49 and 50 respectively show the results of the 2012 slab temperature tests for PQI and PT. The team tested Slabs 2-6; Slab 1 was tested only at an initial and final temperature, whereas Slabs 2 - 6 were tested multiple times during slab cooling. Therefore, the Slab 1 results are not included with the results for Slabs 2 - 6.

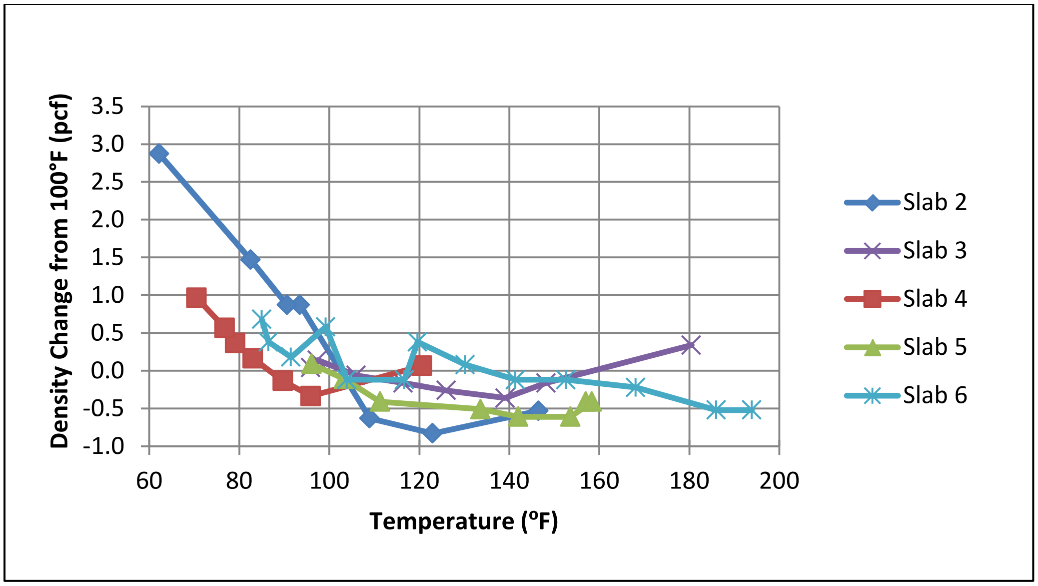

Figure 49. PQI 301 Temperature Tests on 2012 Slabs

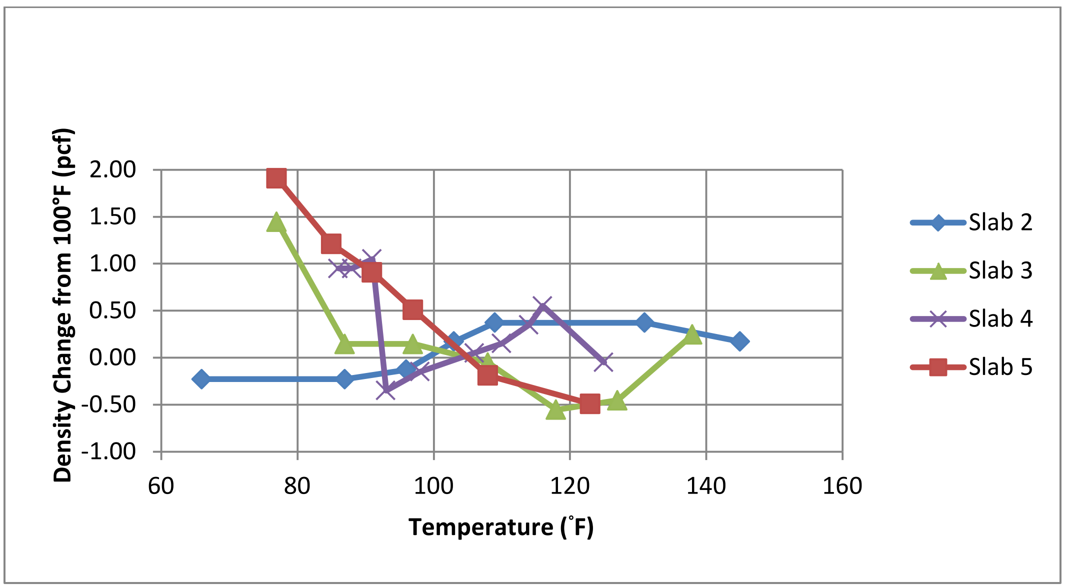

Figure 50. PT Old Temperature Tests on 2012 Slabs

Note: PT Old was not tested on Slab 6 due to a gauge malfunction.

Figures 51, 52, 53, and 54 show the results of the 2013 slab temperature testing for PQI 301, PT, PQI 380, and PT Plus, respectively. The team tested Slabs 8 - 12 in 2013. The Slab 7 results are not included due to the high testing variability mentioned previously. It was not possible to determine a temperature at which the NNDGs would read the density values accurately because the NNDG readings must be correlated using the field core density values. However, the offset value between the NNDG readings and field core density values depends on the temperature at which the NNDG readings are taken. Furthermore, when the team applied the field correlation values to the laboratory tests, the correlated density values of the laboratory cores were almost always lower than the actual core density values, which might be due to the relatively low density of the laboratory slabs. Therefore, the research team examined only the relative effect of temperature on the readings. These figures all display the change in density values from the density reported at or very near a gauge temperature of 100°F. The team selected 100°F as the reference point because it is near the middle of the range of testing (60°F to 140°F). Testing usually started around 140°F ~ 150°F and ended around 60°F ~ 80°F.

The temperature results show some variability among the project mixes. Overall, as the temperature dropped, the PQI 301 readings decreased and then increased. However, these changing temperatures are project-specific. For PT and PQI 380, as the temperature dropped, the readings decreased, and may or may not have stabilized, depending on the specific mix.

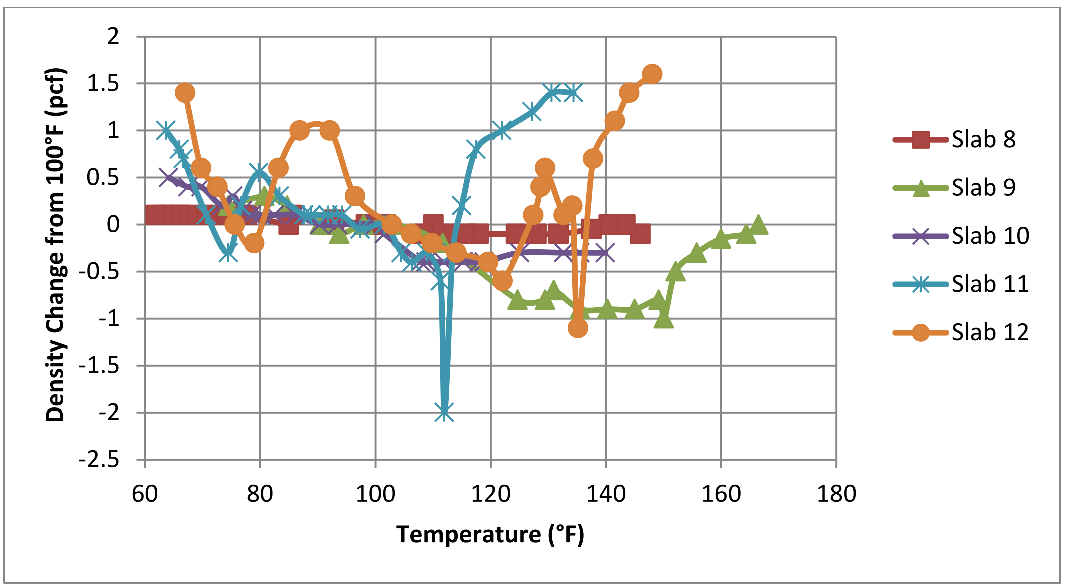

Figure 51. PQI 301 Temperature Tests on 2013 Slabs

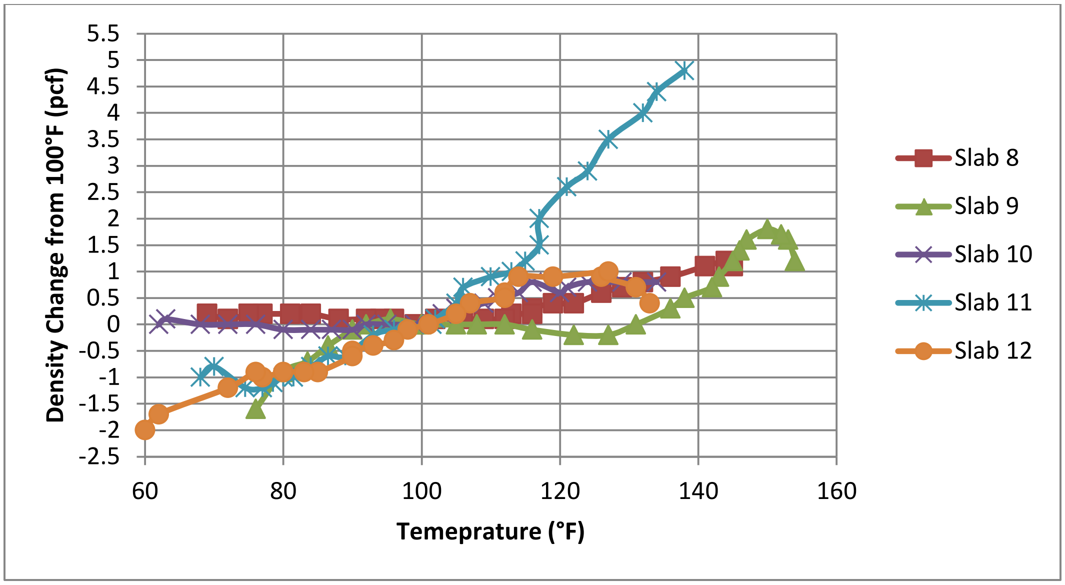

Figure 52. PT Old Temperature Tests on 2013 Slabs

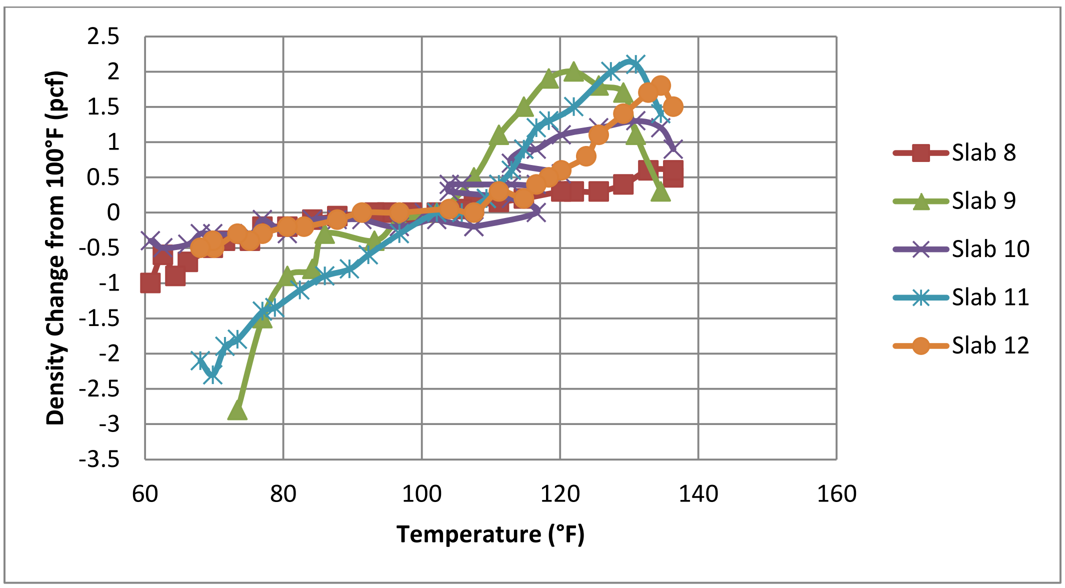

Figure 53. PQI 380 Temperature Tests on 2013 Slabs

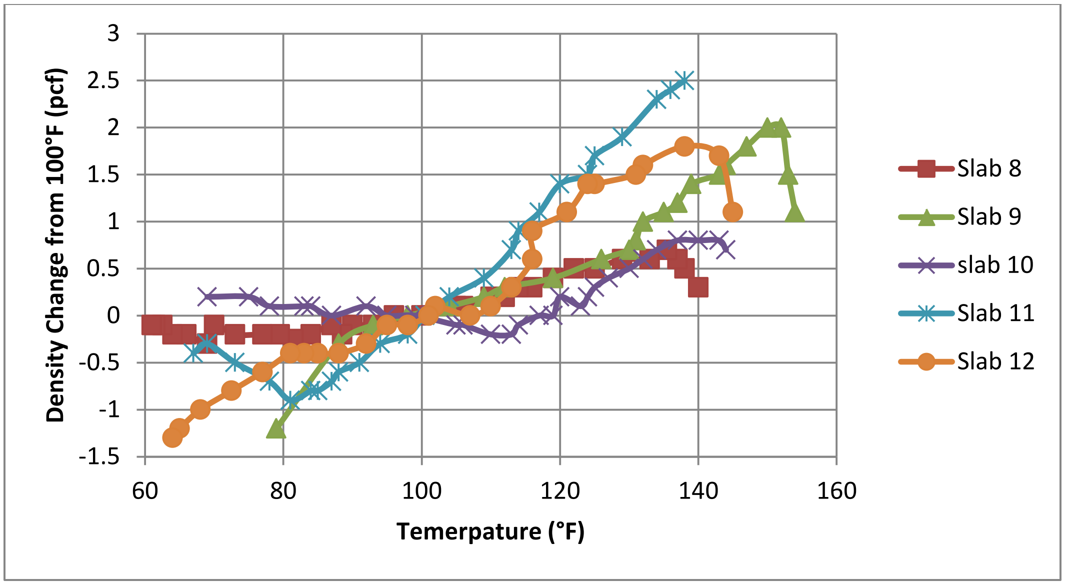

Figure 54. PT New Temperature Tests on 2013 Slabs

PQI 380 testing on Slab 10 presented an interesting case study; Figure 55 shows the singular density trend. The team tested Slab 10 on a partly cloudy day in which the sun heated the gauge, and then cloud coverage cooled the slab. Although the gauge temperature sporadically increased, the density value continued to fall, which indicates that the temperature parameter itself may not have been the sole reason for the change in density value. Nonetheless, the change in density value is very small.

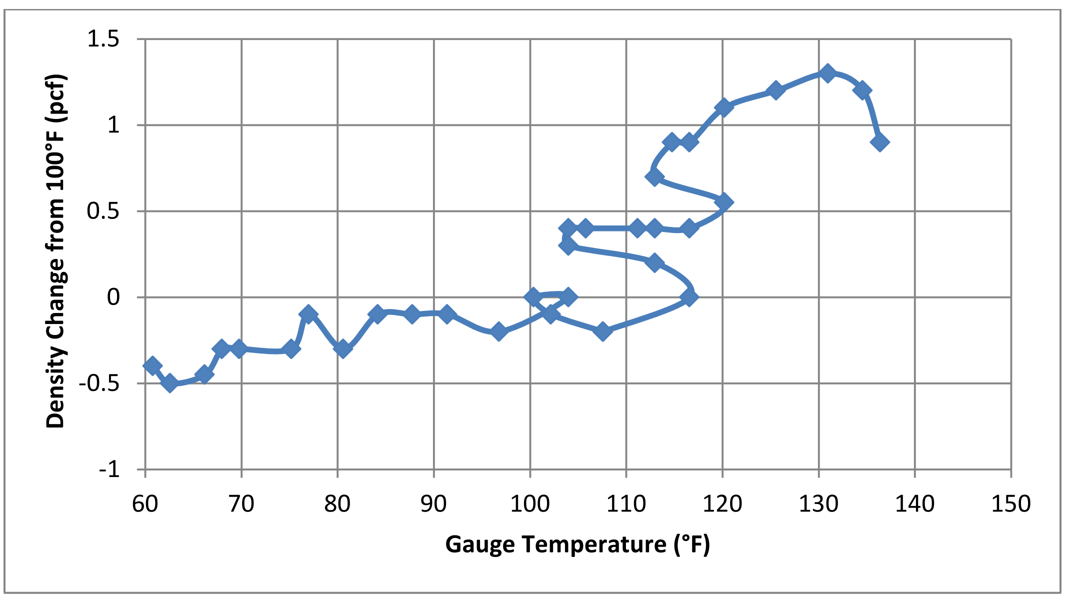

Figure 55. PQI 380 Temperature Test on Slab 10

Overall, the temperature effects on the NNDG reading are small, with a variation of within ±1.5 pcf which is well below the 3.6 pcf in ASTM D7113-10.[61] However, the concern here is that the readings for

PT (both Old and New) and PQI 380 decreased as the temperature lowered, which could result in a biased selection of testing temperatures.

Field Temperature

The research team also investigated the effect of temperature by conducting field tests at two project sites. Figure 56 presents the field temperature test trends for the SH-162 Four Corners project. Figure 57 shows the same trend from the US-12 Orofino project. In the SH-162 Four Corners case, the team conducted the tests after the intermediate roller and before the finish roller processes, whereas in the US-12 Orofino case, the team began testing after the finish roller process. In both cases, the team performed the tests at a single spot without interference by the roller. The gauges were lifted from the spots between readings.

The team performed tests at the SH-162 Four Corners site to evaluate the effects of temperature in the field for a temperature range higher than the range seen at the US-12 Orofino site. Only a relative change in density value was observed for a temperature range between 130°F and 150°F for the 2 rollers. The researchers saw little change for both devices, particularly when they used the slope correction method. The PQI density measurement changed less than 0.5 pcf across the temperature range, and the PT changed less than 1 pcf using the slope correction method and 2 pcf using the average correction method.

Figure 57; indicate the importance of testing near the average correlation temperature. The solid vertical line represents the average correlation temperature for PQI, and the dashed vertical line represents the average correlation temperature for PT. The average correlation temperature was the average field temperature when the researchers took the raw density measurements. The average correlation temperatures for each device in this field study were 83.9°F and 85.2°F for PQI and PT, respectively.

When the team measured the corrected gauge density values at or near the average correlation temperature, the difference between the measured density and core density values was less than 0.5 pcf for both devices and correlation methods. The variation in PQI density values compared to the core density values was less than 1 pcf across the entire temperature range, except for the final measurement that was below 70°F.

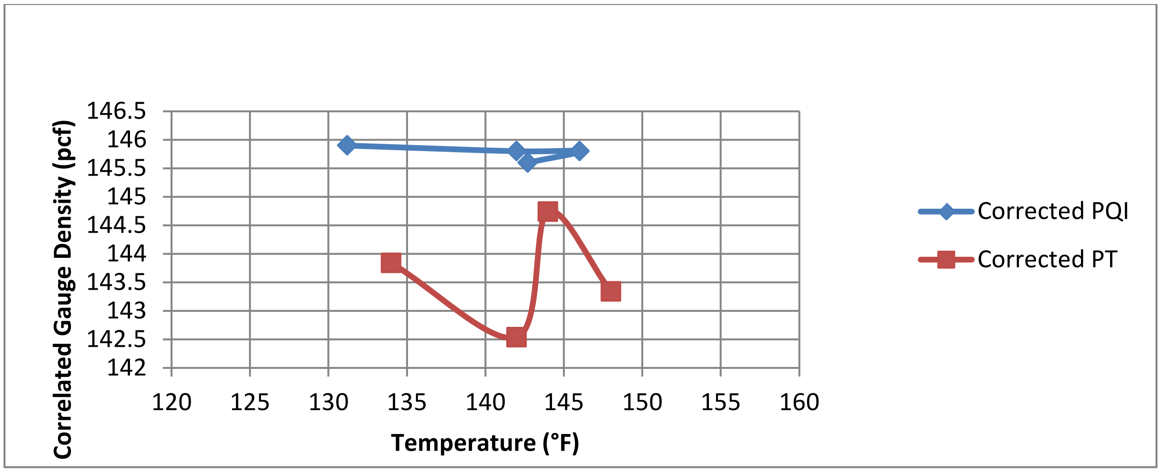

Figure 56. Field Temperature Test Results from SH-162 Four Corners

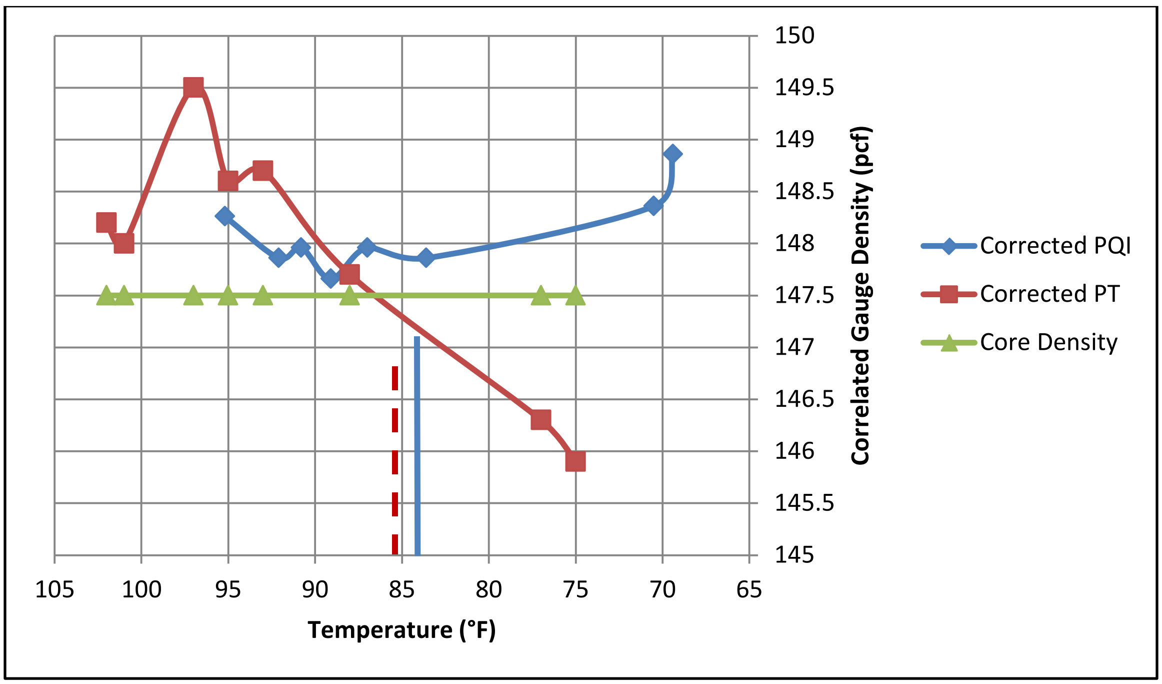

Figure 57. Field Temperature Test Results from US-12 Orofino

Longitudinal Joints

The research team took NNDG readings along the longitudinal joints to determine if the gauges could accurately measure joint density. The team initially correlated NNDG reading at joint using correlation factors from the center-of-mat, which were based on the correlation locations selected by ITD for each respective project. Figure 58 shows the correlated NNDG joint readings plotted against the joint core, or correlated NDG density, whichever was available for the given project. PQI showed very little sensitivity in terms of joint measurements. Although the core/NDG density values changed significantly, the corrected PQI density values changed very little. The PT measurements showed more sensitivity, but they were not necessarily precise.

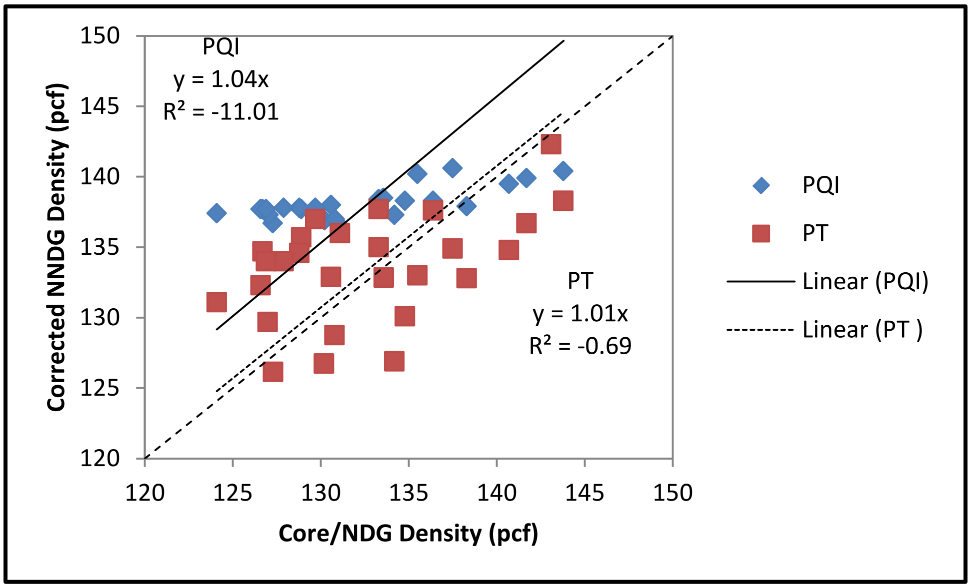

Figure 58. NNDG Joint Density Correlation with Center-of-Mat Average Correction Factors

Data from the SH-78 is the only project that had coring at longitudinal joints. The team developed a new slope correction equation and offset for this project using data from the first 2 joint locations and the first 3 center-of-mat locations. The remaining 9 locations from center and joint were used for validation. The developed slope equations are shown in Figure 59 for both PQI and PT. Values of R^2 for both NNDGs are good ($R^2 > 0.7$). The correlated gauge densities are plotted vs. the validation core densities in Figure 60. R^2 for PQI slope correlated data is very good ($R^2 = 0.88$), while the R^2 for PQI average correlated data is very poor. The R^2 for PT average correlated data is much higher than the R^2 for PT slope corrected data ($R^2 = 0.88$ for average correlation and $R^2 = 0.47$ for slope correlation). The results indicate that when core correlation is performed, good NNDG results along the joints can be obtained, but more data and research is needed.

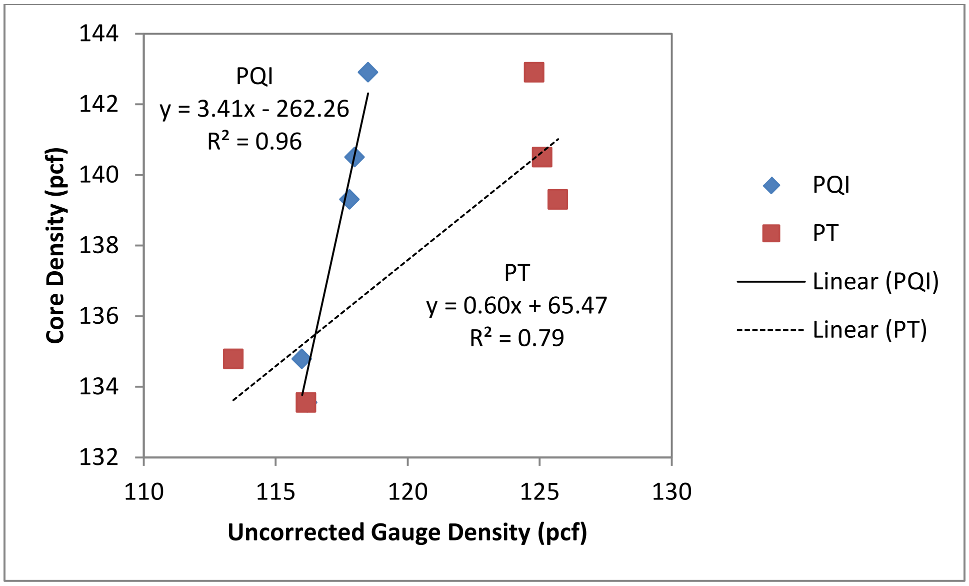

Figure 59. Slope Correlation for SH-78 with Two Joint Locations and Three Center Locations

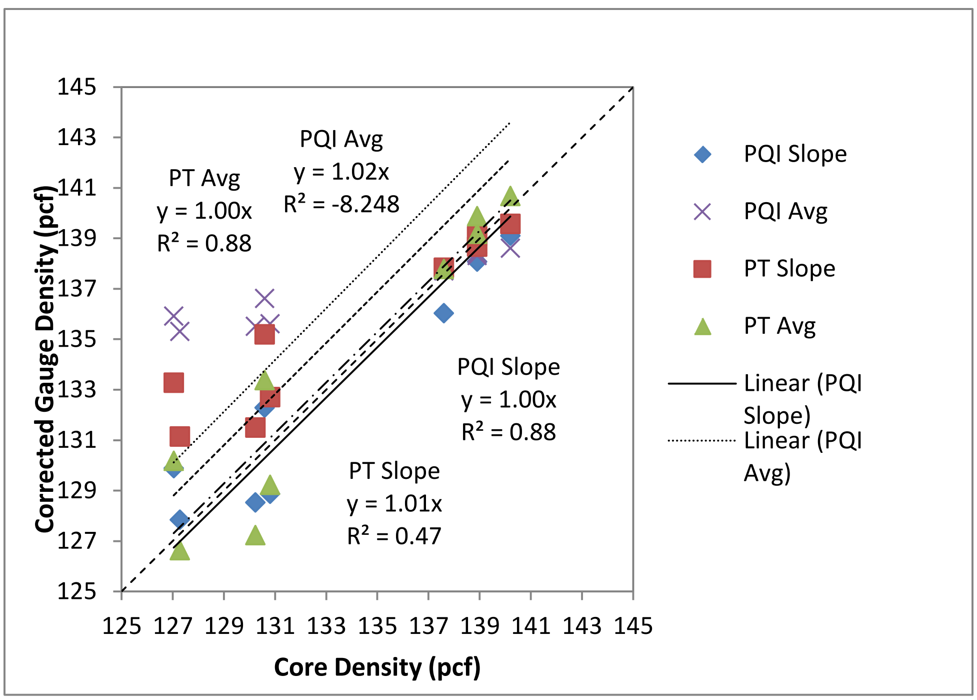

Figure 60. PQI and PT Validation Using Combined Joint and Center-of-Mat Correlation on SH-78

Effects of Core Diameter

The research team also examined the effect of core diameter on NNDG correlations. Currently, AASHTO T-343 specifies that 6 in. cores must be taken to correlate NNDGs.[47] WAQTC TM-8 requires only 4 in. cores.[48] The use of 4 in. cores for correlation is advantageous for the following reasons:

- Less time is required to extract a 4 in. core than a 6 in. core. Although the quality of the drilling equipment plays a major role in the speed of the process, the team found that coring 4 in. cores usually was much faster than extracting 6 in. cores, especially for thin lift overlay projects.

- The extraction process for 4 in. cores makes a smaller hole in the test strip and requires less labor and material to fill the hole than is the case for 6 in. cores.

In order to compare the effects of core sizes, the team conducted unpaired, two-tailed t-tests between the percentage of error of the core density values obtained from 4 in. and 6 in. core extraction projects. Table 18 shows unpaired t-test *p*-values for each NNDG and correlation method. The results show that the difference in error between the use of 4 in. and 6 in. cores is not statistically significant for both gauge types and all correlation methods.

Table 18. t-Test *p*-Values for PQI and PT

Correlation Method	PQI *p*-Values	PT *p*-Values
Average	0.39	0.19

The team also examined the average error between the correlated gauge density values and the validation core density values for project sites with known 6 in. cores and 4 in. cores. The following project sites featured correlation with 4 in. cores: I-90, SH-8, SH-37, SH-55, and US-95 Athol. The following project sites featured correlation with 6 in. cores: SH-78, US-12 Kooskia, US-95 Wilder (all phases), and US-95 Smokey. All of the other project sites either have unrecorded core sizes or lack sufficient data to include in the comparisons. The team used only dry measurements without fines and paint in the comparisons.

Figure 61 shows the average errors for each gauge type for the project sites based on the use of 4 and 6 in. cores. The results show that for both gauge types, the projects that used 6 in. cores had less error than the projects that used 4 in. cores. Therefore, in order to achieve the most accurate measurements, the team continues to recommend the use of 6 in. cores to correlate the gauges.

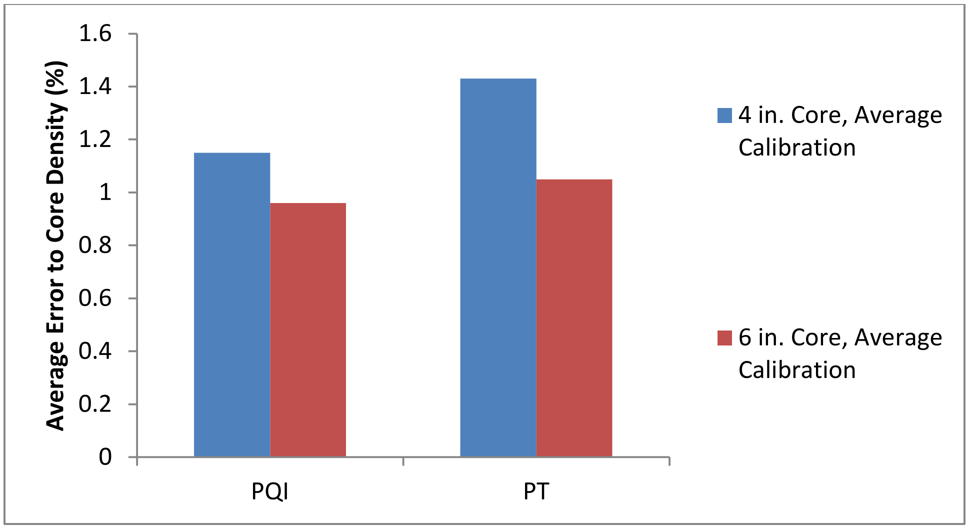

Figure 61. Average Error from Core for PQI and PT for 4-inch and 6-inch Core Projects

PQI and PT Analysis Summary

The research team conducted the correlation analysis on density measured by PT and PQI, and analyzed influence of global and local factors on the measured density, it is found the following results and conclusions.

- Based on data analysis of individual projects, both NDG and NNDG could produce readings that are statistically significantly different from the core densities for some projects. PQI has highest percentage of projects for which the PQI readings have no statistically significant difference from the core densities, followed by PT and NDG.
- After correlation, the global factors, including HMA class, lift thickness, HMA NMAS, aggregate mineralogy, and binder absorption did not statistically affect the correlated devices.
- PQI and PT were unable to consistently determine the same roller pattern as NDG.
- The effects of fines and surface paint had no statistically significant impact on density measurements.
- Moisture had a significant impact on NNDG density measurements. In the case of a damp HMA surface, the team recommends drying the surface with a paper towel or waiting for the location to dry, without the use of fines underneath the device.
- The temperature effects on the NNDG readings were not statistically significant.

- The NNDG density values had an overall poor agreement with joint cores when the correlation factors were obtained from the center-of-mat. The correlation process that used the cores from the joints improved the agreement between the correlated NNDG readings and the core/NDG density values. The few results obtained for longitudinal joints with core density values showed that slope correlated PQI and average correlated PT have a reasonable potential to measure joint density accurately and NDG might not be accurate in measuring the density along the joint.

- The use of 6 in. cores for correction reduced the error measurements more than the use of 4 in. cores.

Evaluation of Devices for Unbound Materials

The research team analyzed the collected field data for unbound materials to evaluate the effectiveness of EDG, SDG, and GeoGauge. Analysis of EDG and SDG consisted of paired, two tailed t-tests and validation comparisons between the NNDG results and the results obtained from traditional reference devices: sand cone, NDG, and laboratory oven. The team made comparisons in terms of dry density (sand cone and NDG as the reference devices), moisture content (oven or NDG) and wet density (sand cone or NDG).

Student's t-Test Results

The research team performed Student's t-tests by comparing the density values and moisture content results obtained from NNDGs and traditional devices because different devices were run at one spot. The team selected a *p*-value of 0.05 as the level of significance. Table 19 presents the results; the underlined p-values indicate the NNDG data that are statistically different from the reference data. The EDG results and reference data did not differ significantly in most cases, except the case when the wet density values obtained from EDG using the NDG soil model was compared with the wet density values obtained from sand cone tests.

Table 19. *p*-Value Summary from Paired Student's t-Tests

	Density				Moisture Content	
	Wet Density		Dry Density			
	Sand Cone	NDG	Sand Cone	NDG	Oven (SC)	NDG
EDG w/ SC Model	0.090	0.13	0.130	0.91	0.570	0.29
EDG w/ NDG Model	<u>0.028</u>	0.16	0.051	0.20	0.650	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 (1-pt. Correction)	<u>0.02</u>	0.44	<u>0.007</u>	0.066	<u>0.009</u>	0.11
SDG (3-pt. Correction)	0.80	0.21	0.920	0.94	0.880	0.88

The uncorrelated SDG readings shown in Table 19 are statistically significantly different from the density values and moisture contents obtained from the sand cone, NDG, and oven (for moisture content only).

In order to improve the SDG data, the team applied project-specific correlation factors. For each project, the team correlated the SDG measurement by equaling the reference measurement at the first test spot. The team adjusted the remaining SDG readings at Spots 2 through *n* (typically 10) by this same correlation factor. This procedure is known as the 1-point correlation method.

Table 19 shows that the 1-point SDG correlation method produced better *p*-values than uncorrelated results, but the results still differed significantly compared to the sand cone and oven values. For more accurate results, the team employed a 3-point correlation method whereby the correlation factor is the difference between the average of the first 3 SDG readings and the average of the 3 readings obtained from a reference device. The team then applied a correlation factor to the SDG measurements at Spots 4 through 10. Table 19 shows that after the application of the 3-point correlation method, none of the SDG *p*-values indicate a significant difference between the SDG results and the reference device results.

Moisture and Density Correlation

Because the t-test results indicate only whether a statistically significant difference exists between the NNDG measurements and the reference values, more rigorous quantification of the difference or lack of difference is needed. Therefore, the team evaluated the comparison between the NNDG results and the reference values. The team did not further analyze the NNDG and reference device pairings that the t-test analysis found statistically significant difference for the correlation analysis.

The key values in the correlation comparison are the slope and R^2 of the acquired linear trend-line. In this analysis, the range of the R^2 is attached to descriptors as "very good," "good," "fair," and "poor." Table 20 presents the R^2 ranges associated with these descriptors and their applicability to QA/QC. The team selected these ranges based on the literature review presented in Chapter 2 and the survey results (Appendix A).

Table 20. Descriptor Terms and QA/QC Viability for Unbound Material 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

Dry Density

The team compared the EDG and SDG dry density values to the dry density values calculated from the sand cone or NDG results.

NNDG vs. NDG

Figure 62 shows the comparison between the EDG (based on NDG or sand cone soil models) and NDG dry density values. The method in parentheses after EDG is the method used to set up the soil model in EDG. A very good coefficient of determination (R^2 = 0.9) with a slope of near one is evident when the EDG with NDG soil model is used. The EDG data with the sand cone model agreed poorly (R^2 = 0.25) with the NDG data. Figure 63 shows the comparisons between the correlated SDG and NDG dry density values. Note that NDG was the reference device used to correlate the SDG data. The 1-point correlated SDG density values agree well (R^2 = 0.71) with the NDG density values. The 3-point correlation SDG dry density values agree very well (R^2 = 0.85) with the NDG density values. The slope of the relationship is very close to 1:1. The EDG with NDG soil model and 3-point correlated SDG correlations show the strongest agreement with NDG density values of the analyzed data sets.

The range of dry density values across all soils tested was very large, approximately 50 pcf, which may have overshadowed the percentage of error for the individual materials. In order to narrow this range for analysis, the team further separated the data from these sets into coarse-grained materials (base materials and sands) and fine-grained materials (silts and clays). The team classified a material as coarse-grained if more than 50 percent of the particles were retained on the No. 200 sieve, and otherwise as fine-grained, in accordance with the Unified Soil Classification System. Because the coarse material dry density range continued to remain fairly large, the team broke down the coarse materials further into base materials and sand subsets. The base materials had ¾ in. or ⅝ in. NMAS. The team considered all the other coarse materials as sands.

Figure 64 shows the separated density sets for EDG with NDG soil model, and Figure 65 shows the separated sets for the 3-point correlated SDG. The slopes are very close to 1:1, but the values of R^2 decrease for each subset when compared to the overall set. The EDG results have a fair agreement with the NDG results for the base material (R^2 = 0.43) and good for the sands (R^2 = 0.79). In addition, the EDG results are shown to agree very poorly for the fine materials (R^2 = 0.17). The SDG results agree fairly with the NDG results for fine materials (R^2 = 0.57). In addition, the SDG results are shown to agree poorly with the NDG results for base materials (R^2 = 0.37), but very well for sands (R^2 = 0.82).

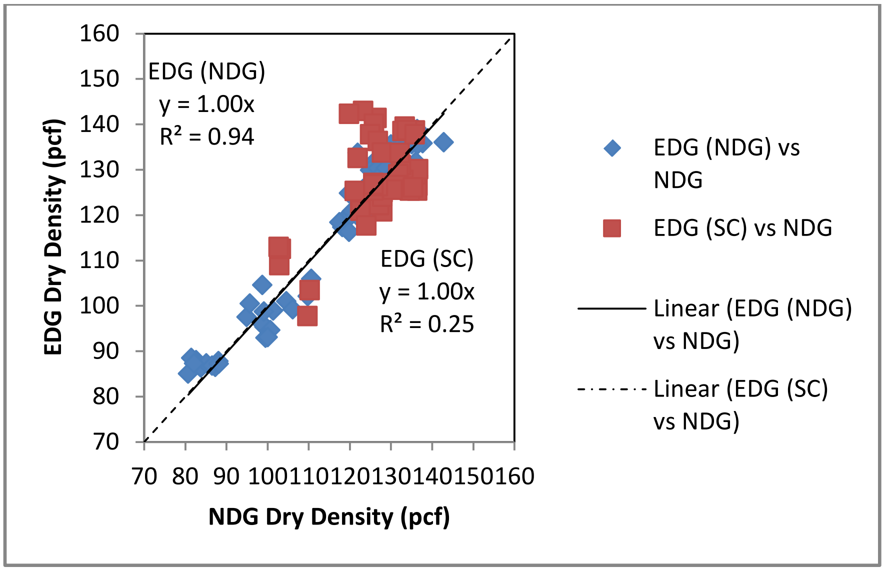

Figure 62. Dry Density Validation: EDG vs. NDG

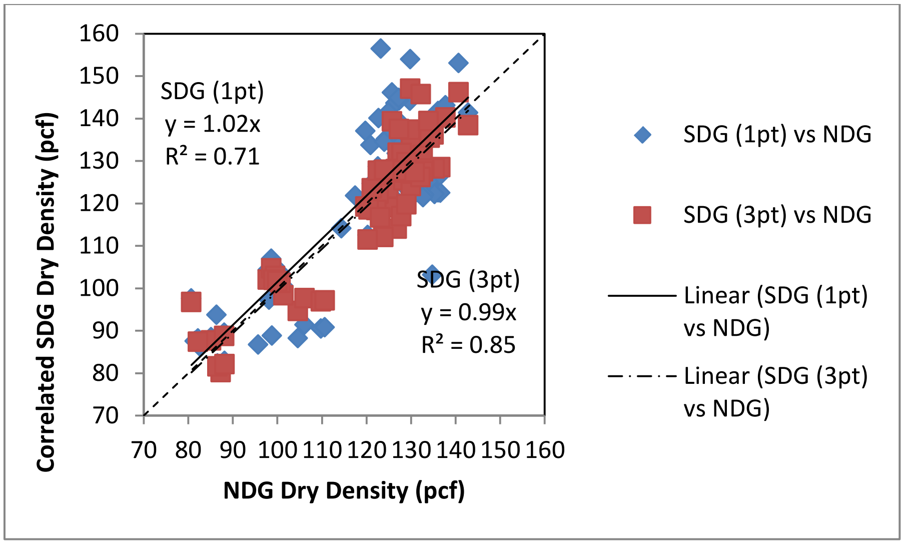

Figure 63. Dry Density Validation: SDG vs. NDG

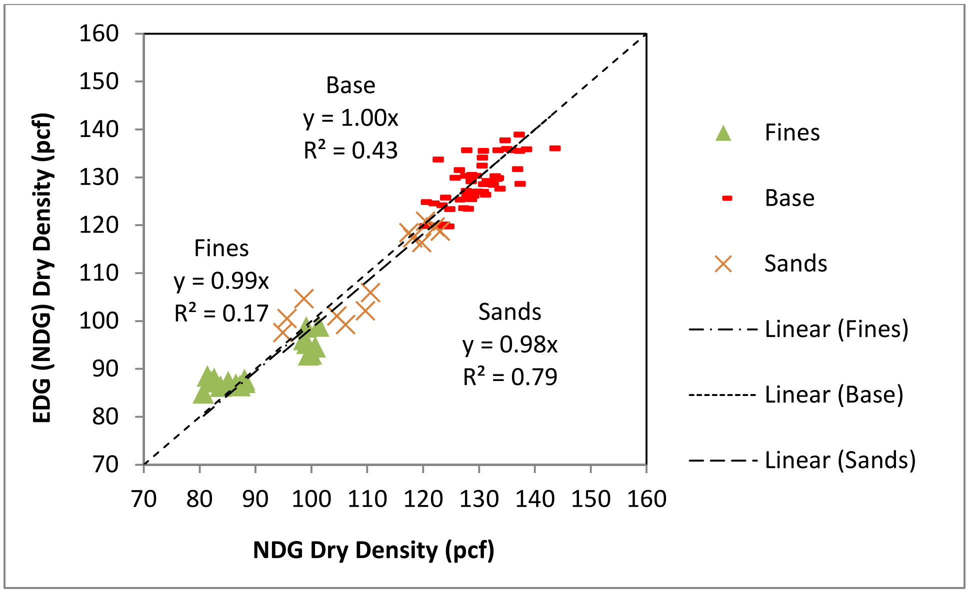

Figure 64. Dry Density Validation: EDG (NDG Soil Model) vs. NDG with Material Subsets

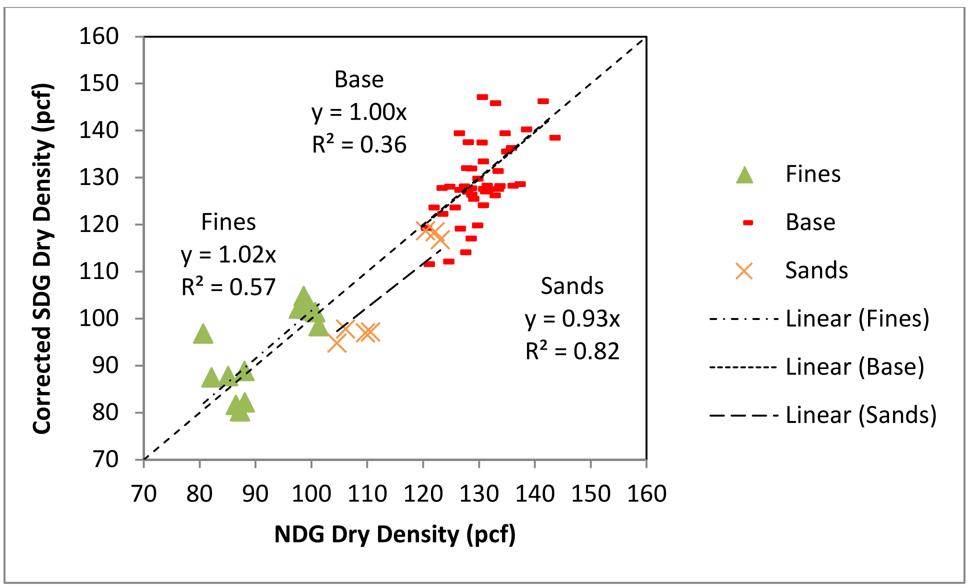

Figure 65. Dry Density Validation: SDG (3-Point Correlation by NDG) vs. NDG with Material Subsets

<u>NNDG vs. Sand Cone</u>

Figure 66 shows a comparison of the dry density values for EDG with NDG or sand cone soil models with those for the sand cone. The slope is near 1:1. The values of R^2 are poor for EDG with the NDG soil model (R^2 = 0.36) and fair for the EDG with the sand cone soil model (R^2 = 0.45). The results with the sand cone reference values are not as favorable as the results for EDG (with NDG soil model) when NDG is the reference device. Because the t-test results indicate a significant difference between the 1-point correlated SDG dry density values and the sand cone density values, Figure 67 shows only the

3-point correlated SDG density values plotted against the sand cone density values. The team correlated the SDG data using the sand cone density values. Similar to the EDG analysis results, the team observed a slope of near 1:1. However, the coefficient of determination (R^2 = 0.31) is lower than it is when NDG is the reference device.

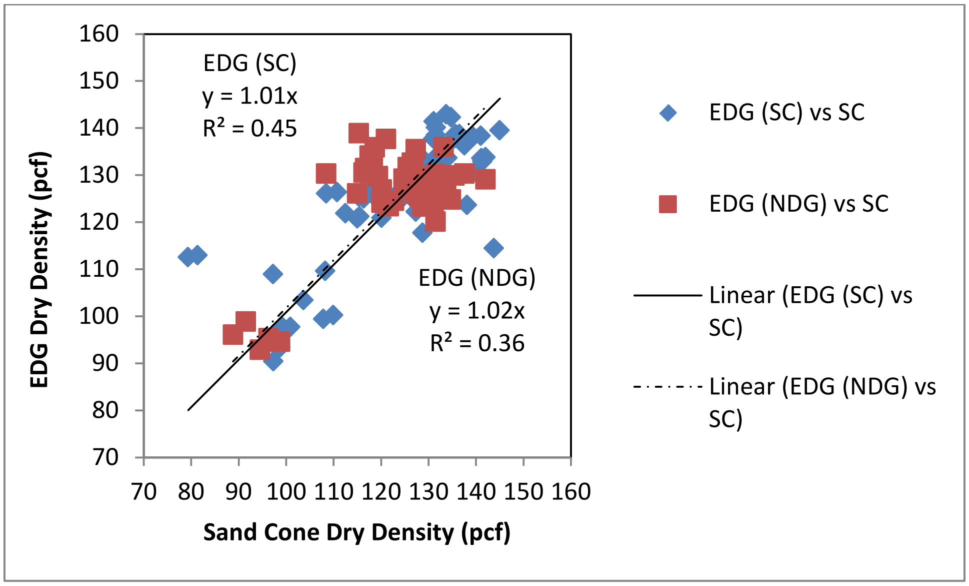

Figure 66. Dry Density Validation: EDG vs. Sand Cone

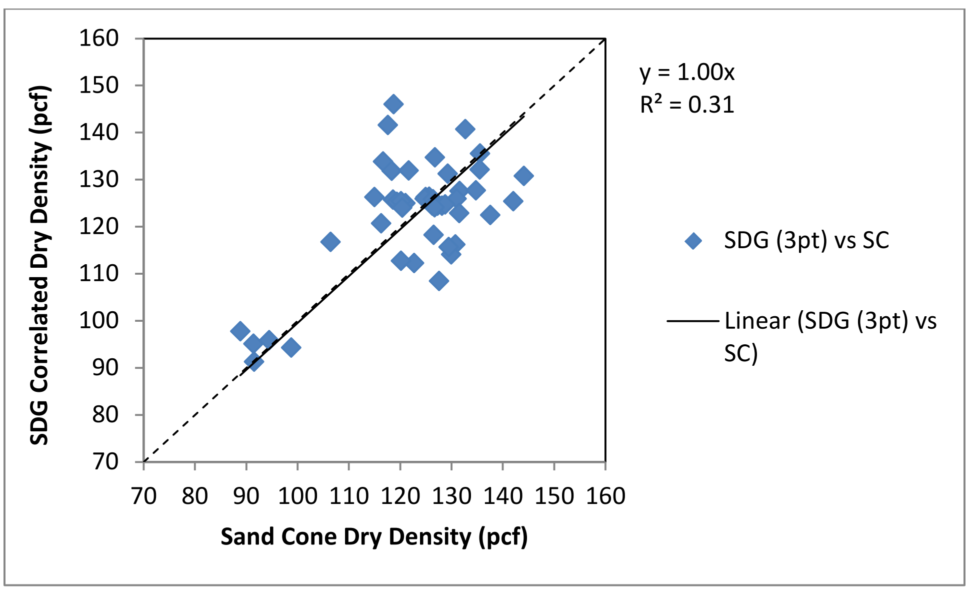

Figure 67. Dry Density Validation: SDG (3 pt.) vs. Sand Cone

Based on these results, the sand cone-based soil models and correlation for EDG and SDG provide poor to fair results with significant scatter, respectively. EDG with the soil model that is based on NDG and

3-point correlated SDG results (correlated by the NDG) provide significantly improved results when the NDG is used as the reference device.

Moisture Content

The team compared the moisture contents measured by NNDGs to moisture contents measured from the laboratory oven drying of soils used in the sand cone tests, which are considered to be the true moisture contents. The team correlated the SDG moisture content values with the oven values. Figure 68 shows that the EDG with NDG soil model data agree better with oven moisture content than the EDG with sand cone soil model data. The R^2 for EDG with sand cone 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). Figure 69 shows that the 3-point correlated SDG data also provide a very good agreement with the oven moisture content (R^2 = 0.93).

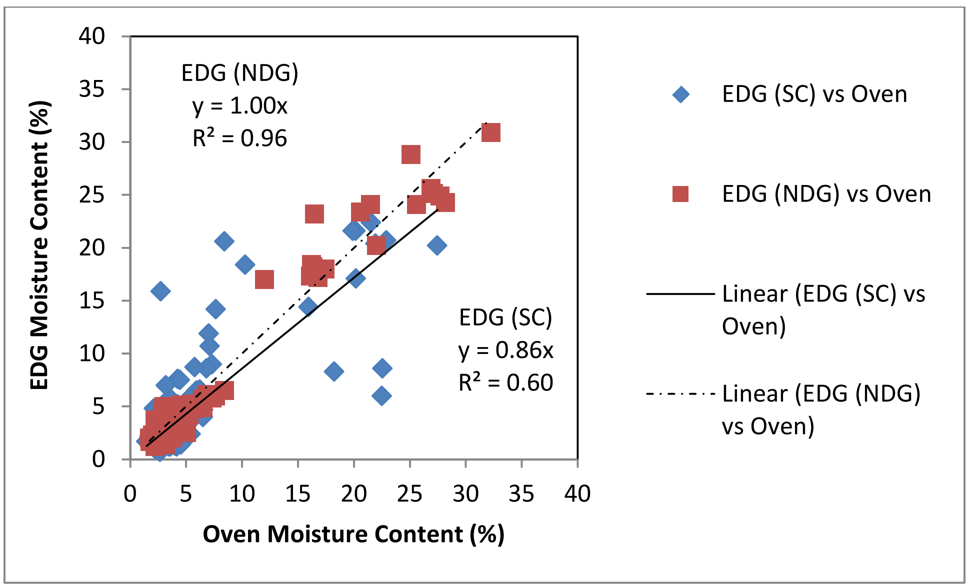

Figure 68. Moisture Content Validation: EDG vs. Oven

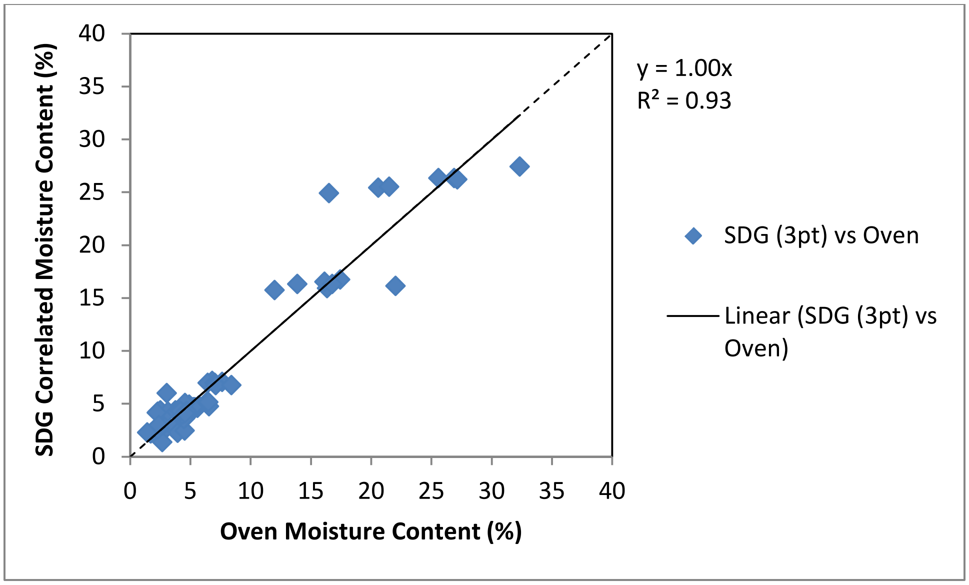

Figure 69. Moisture Content Validation: SDG (3 pt.) vs. Oven

Hence, and again similar to the case of the dry density results, the team split the data for each device into individual material subsets: fines, sands, and base (granular materials). Figures 70 and 71 present the subset validation plots for EDG and SDG, respectively.

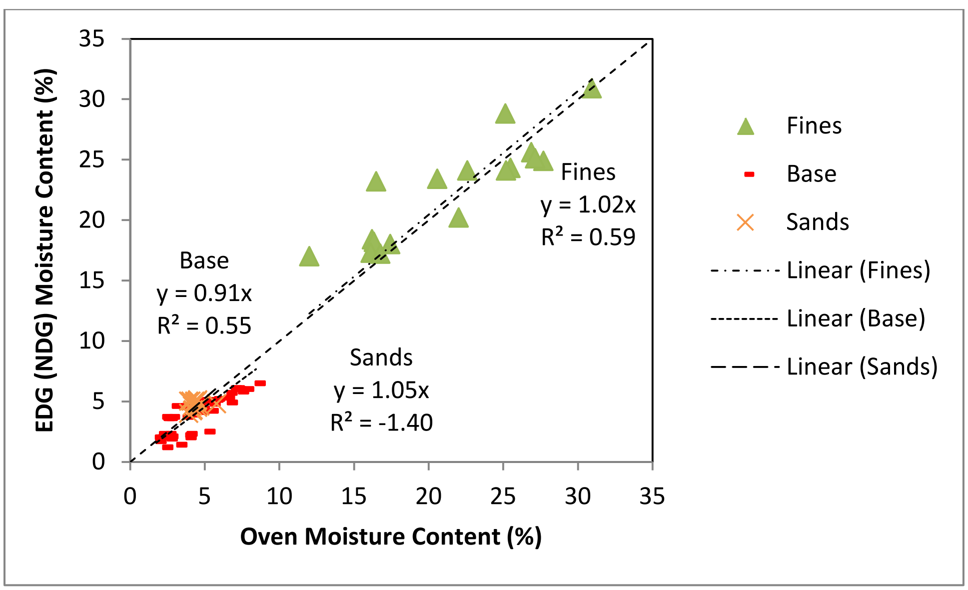

Figure 70. Moisture Content Validation: EDG (with NDG Soil Model) vs. Oven with Material Subsets

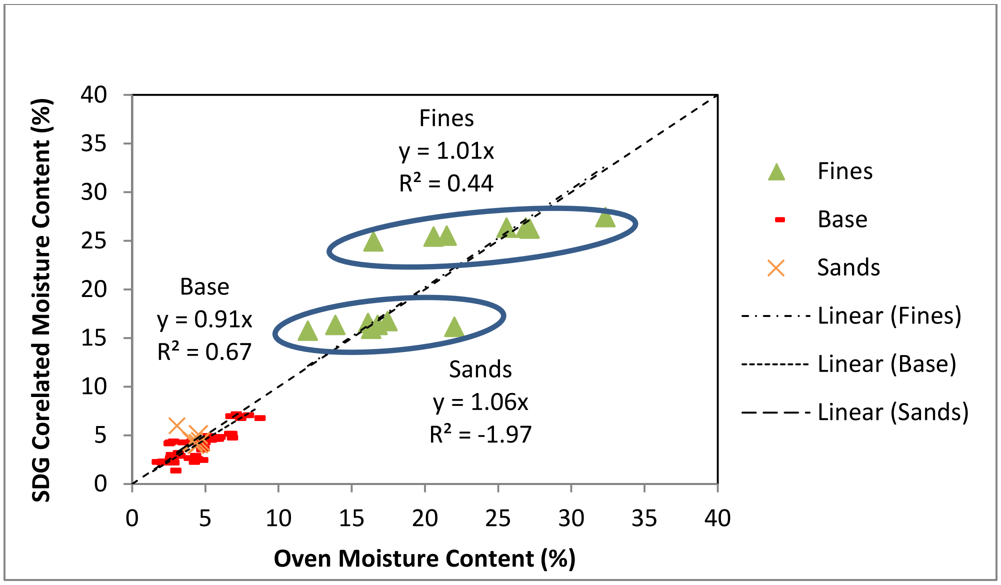

Figure 71. Moisture Content: SDG (3-Point Correlated by Oven) vs. Oven with Material Subsets

For the fines and base materials, the EDG data agree as "fair" ($0.4 < R^2 < 0.6$) with the oven data, and the SDG data agree "well" ($0.6 < R^2 < 0.8$) with the oven data for base material and "fair" for fine material. Sands data for both EDG and SDG agree poorly ($R^2 = -1.97$) with sands data for the oven. The negative R^2 indicates an inverse relationship between SDG moisture content and oven moisture in the sands data. Although the SDG R^2 is fair for the fines, a data banding effect is noticeable as 2 nearly horizontal lines of data points in the fines subset presented in Figure 71 (circled data). In the fines subset, the oven moisture content varies significantly, whereas the SDG moisture contents vary very little. Other researchers have observed this banding effect in other SDG research.[(27)] The banding effect is less prominent with EDG.

Like the dry density results, the moisture results indicate that the devices report a very good overall moisture content trend compared to laboratory oven values. However, when the team analyzed the material subsets, it observed a decrease in the values of R^2 and other problems, such as SDG data banding for fines. The 3-point correlated SDG data for the base and coarse materials produced the most promising results. Good values of R^2 indicate that SDG is applicable for base for QC purposes. However, poorer results for the fines and sands limit the types of material suitable for the moisture QC applicability of SDG. EDG produced "fair" values of R^2 for all material subsets except sands, but did not show the consistent accuracy that are needed for QC applications.

Wet Density Validation

Although dry density is often the desired parameter when comparing field density to maximum density determined in the laboratory, wet density is of key interest here because both types of device directly compute this parameter based on measured electrical relationships. Wet density, along with moisture content, can be used to calculate dry density values. Comparing NNDG wet density values to wet density data from reference devices can provide insight into how well NNDGs measure wet density. For instance, NNDGs may be able to measure wet density accurately, but due to the poor measurement of the moisture content, the resultant dry density values may also be poor. As with the dry density analysis, the team compared the EDG and SDG wet density values to the NDG and sand cone wet density values.

<u>*NNDG vs. NDG*</u>

Figure 72 presents the relationship between the EDG and NDG wet density values and shows the EDG data established using both NDG and sand cone soil models. A "very good" R^2 is evident (R^2 = 0.9) with a near 1:1 slope for the EDG with NDG soil model. The EDG data with the sand cone model agreed very poorly (R^2 = -0.44) with NDG.

Figure 73 displays the relationships between the correlated SDG and NDG wet density values. The 1-point correlated SDG density values correlate well (R^2 = 0.63) with the NDG density values. When the team applied the 3-point correlation method, the SDG wet density values still agreed well with the NDG values (R^2 = 0.76). The slopes of all the trend-lines for both devices are very close to 1:1 in the figures.

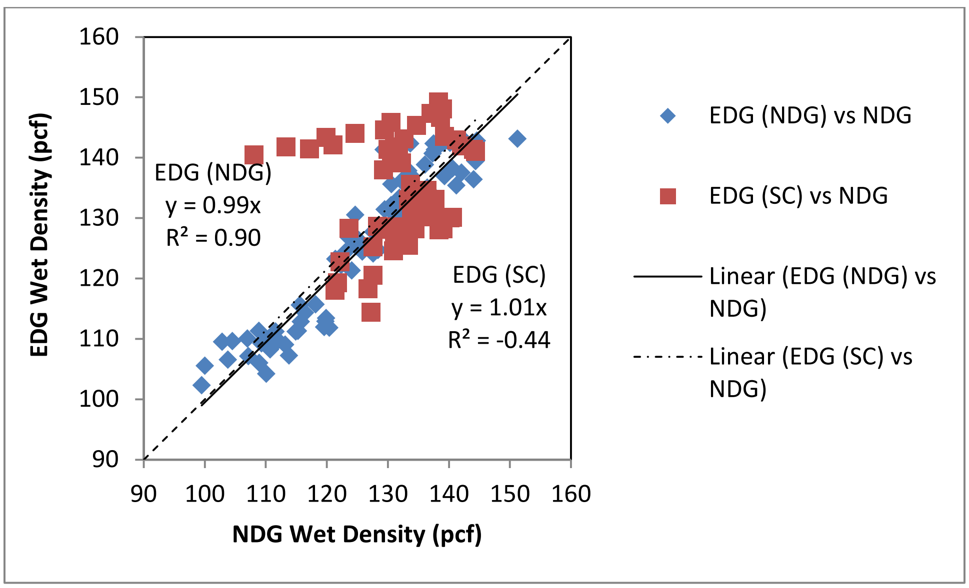

Figure 72. Wet Density Validation: EDG vs. NDG

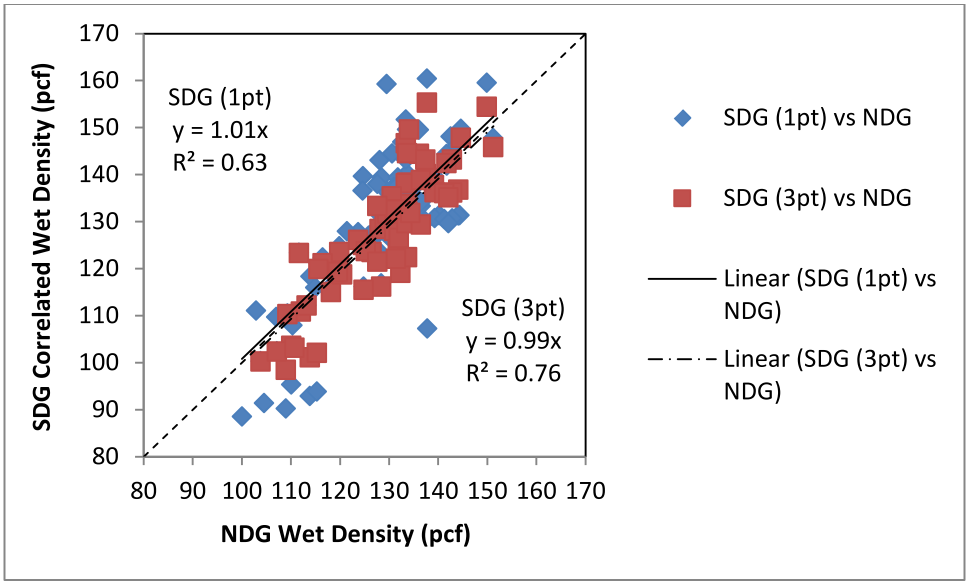

Figure 73. Wet Density Validation: SDG vs. NDG

Similar to the dry density results, the EDG with NDG soil model and 3-point correlated SDG data have the strongest agreement with NDG density of the data sets analyzed. As was the case with the dry density results, the research team split the data for each device into individual material subsets: fines, base, and sands. Figure 74 shows the separated density sets for the EDG data, and Figure 75 shows the separated sets for the 3-point correlated SDG data. The slopes stay very close to 1:1, but the values of R^2 decrease for each subset compared to the overall set. The EDG data agree very well with the NDG data for sands (R^2 = 0.82). The EDG results agree fairly well with the NDG results for the base material (R^2 = 0.54) and very poorly with the NDG results for fines (R^2 = - 0.66). The SDG results agree 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 fairly well with the NDG results for the base materials (R^2 = 0.44).

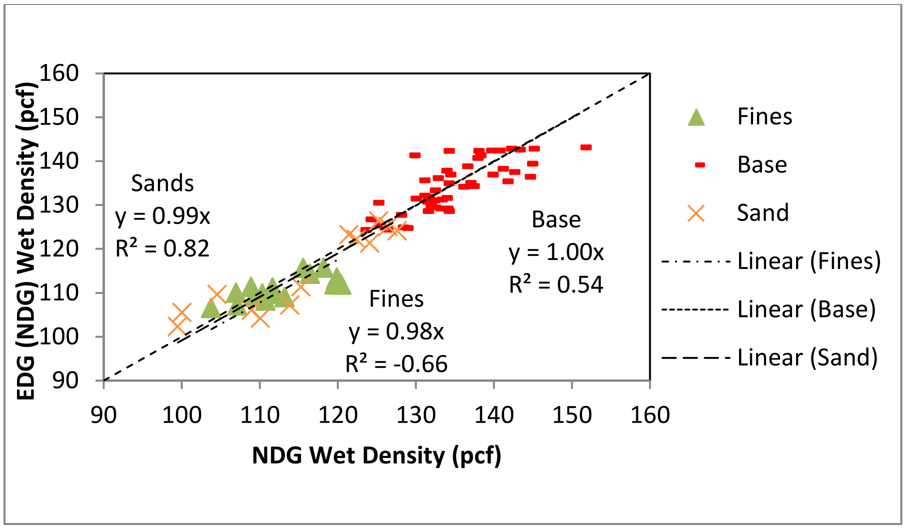

Figure 74. Wet Density Validation: EDG (NDG Soil Model) vs. NDG with Material Subsets

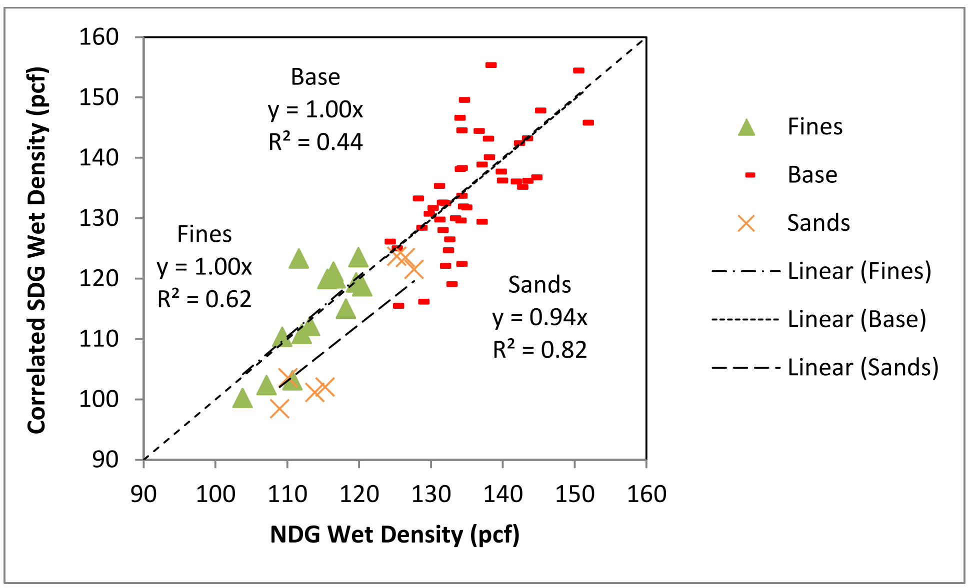

Figure 75. Wet Density Validation: SDG (3-Point Correlated by NDG) vs. NDG with Material Subsets

NNDG vs. Sand Cone

Figure 76 compares the wet density values for the EDG with sand cone soil model to the sand cone wet density values. The coefficient of determination is poor (R^2 = 0.20). Figure 77 presents the 3-point correlated SDG density values plotted against the SC density values. The research team correlated the SDG data using the sand cone density values. Similar to the EDG analysis case, the team observed a near 1:1 slope, but the R^2 is lower compared to the NDG results (R^2 = 0.05). Similar to the dry density results, the wet density validation of the NNDG data with the sand cone data are not as favorable as the NNDG data correlated with the NDG data.

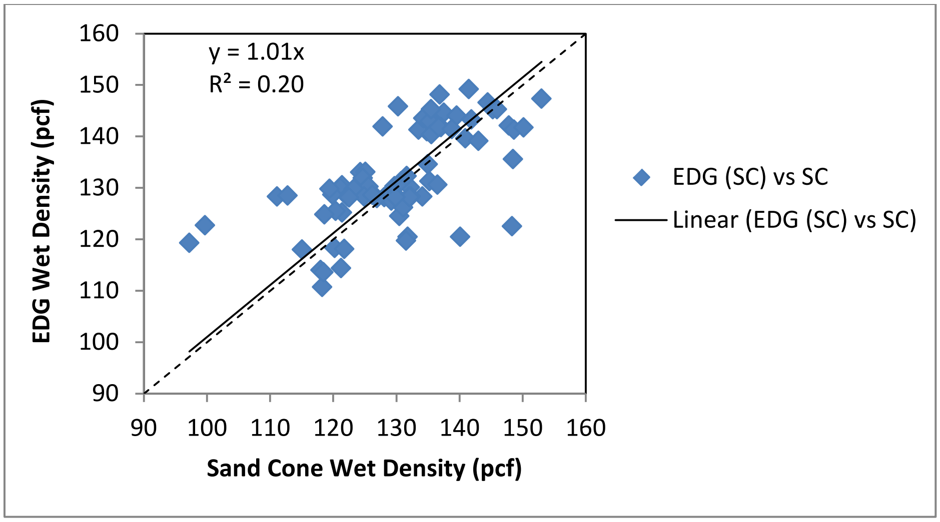

Figure 76. Wet Density Validation: EDG vs. Sand Cone

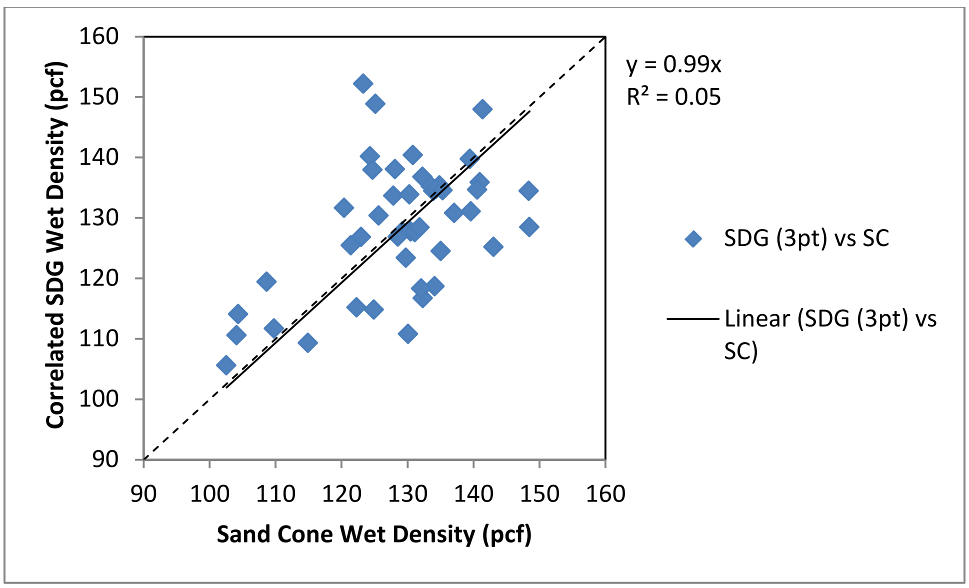

Figure 77. Wet Density Validation: SDG (3 pt.) vs. Sand Cone

EDG Experiments on Soil Model Size

The EDG data acquired for the t-test and validation analysis were all based on 3-point soil models. The team conducted further experiments 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 the soil models that are based on more than 3 data points can produce more accurate EDG outputs than the soil models that are based on only 3 data points. The team conducted soil model size experiments and analysis only on Year 3 (2013) materials (maintenance stockpiles).

The team altered the setup of the EDG soil models from the soil model procedure it usually used. Rather than establishing the soil model at only three locations, the team established a soil model at all the test locations. The EDG allows users to remove locations from the soil model as long as a minimum of three locations are in the soil model. After the team took soil model readings at all locations for a given soil, it established three soil model sizes:

- A typical 3-point model whereby the operator removes all soil model locations except the 3 locations that can provide (in the operator's best judgment) the best range of material density values and moisture properties.

- A 5-point soil model that has a procedure similar to the establishment of the 3-point soil model, except that 5 locations remain in the soil model rather than 3.

- An all-point soil model that uses all of the locations tested.

The team hypothesizes that increasing the soil model size increases the accuracy of the results. Using an "all-point" soil model (that is, using all tested locations for correlation) is not realistic for construction practice. However, it can verify the accuracy of the soil model size (3-points) used in this study. Meehan and Hertz had previously conducted experiments using "all-point-like" soil models in their evaluation of the EDG.(21)

Immediately after conducting the tests to establish the soil model, the team took "job site" measurements. Typically, these measurements produce density values and moisture contents once the soil model is established. In this testing, however, the job site measurements did not produce readings because the team had not completely established the soil model. Rather, EDG stored the electrical parameters from the job site measurements. After the establishment of the three soil models (3-point, 5-point, or all-point) following the field tests, the job site measurements produced density values and moisture contents at each location for each soil model. The team used only NDG to establish the soil models.

Figure 78 shows the wet density correlations for the EDG and NDG data for the 3-point, 5-point, and all-point soil models. Very little change is evident in the trend-lines for the different soil models. The coefficient of determination (R^2 = 0.86) for the 3-point soil model is actually slightly higher than for the 5-point soil model (R^2 = 0.82). However, the values of R^2 for the 3-point and all-point models are identical (R^2 = 0.86 for both). Figure 79 shows the dry density validation for the 3-point, 5-point, and all-point soil models. Similar to the wet density results, the values of R^2 for dry density change very little between each validation (R^2 = 0.93 or 0.92 for all validations).

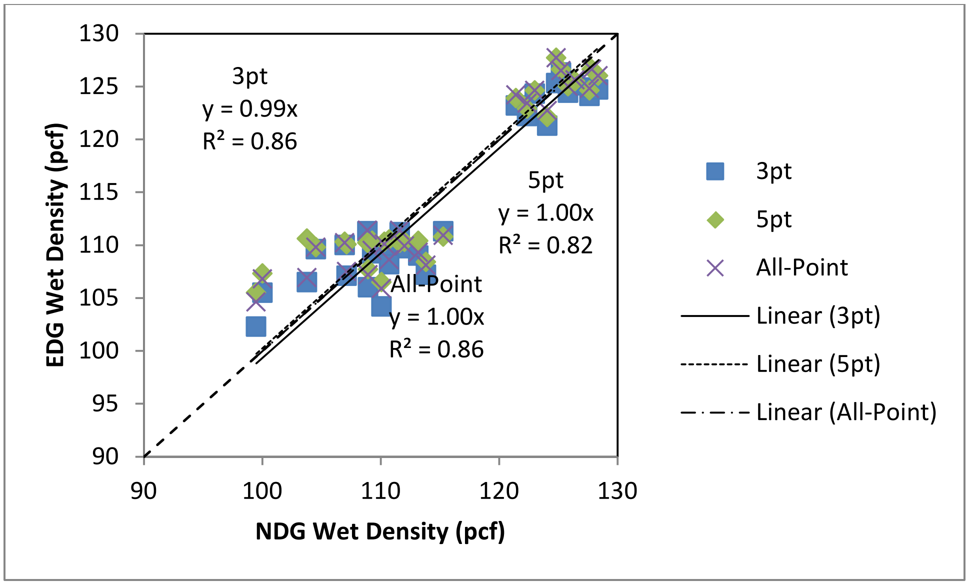

Figure 78. EDG Wet Density vs. NDG Wet Density for 3-Point, 5-Point, and All-Point Soil Models

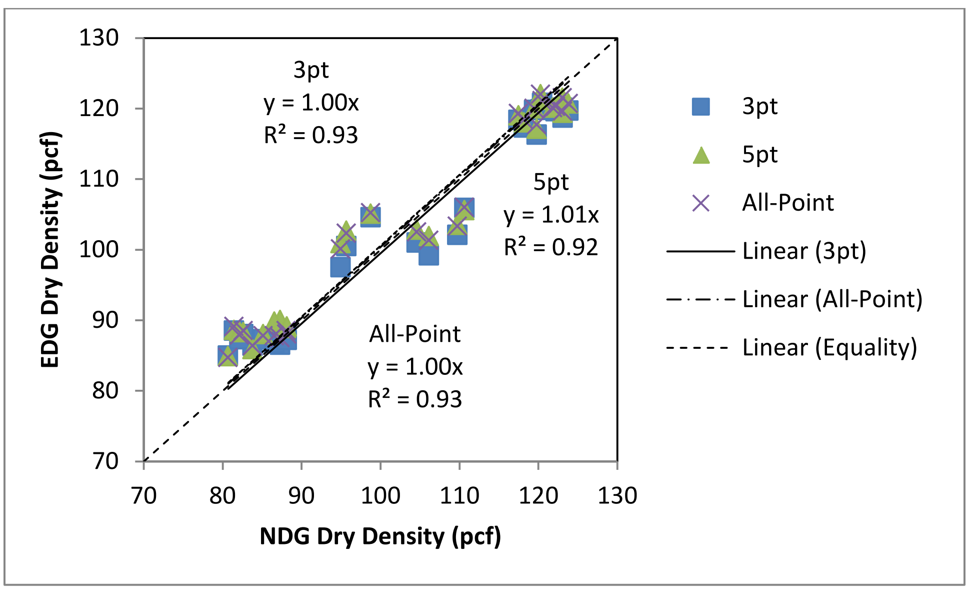

Figure 79. EDG Dry Density vs. NDG Dry Density for 3-Point, 5-Point, and All-Point Soil Models

Figure 80 shows the moisture validations between the NDG moisture contents and the moisture contents obtained using EDG with 3-point, 5-point, and all-point soil models. Similar to the wet density results, very little change is evident between the three soil model sizes (R^2 = 0.97 for all validations). The slopes and values of R^2 are nearly the same for each plot.

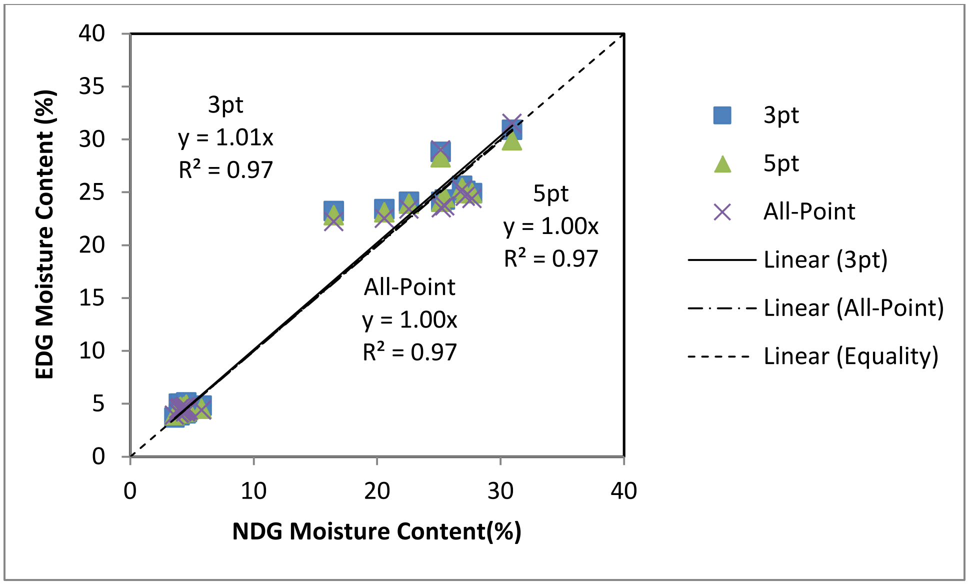

Figure 80. EDG Moisture Content vs. NDG Moisture Content for 3-Point, 5-Point, and All-Point Soil Models

These results suggest that soil model size does not have a significant impact on the accuracy of EDG. In some cases, the 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 set up in accordance with ASTM D7698-11 to incorporate a large variation of moisture contents and density values.[54]

Evaluation of an Alternative Prototype to Replace EDG Dart Measurements

For the 2013 soil testing, Electrical Density Gauge Company, LLC provided the research team with a prototype device that was designed to replace EDG darts for density and moisture content measurements. Figure 81 shows a picture of the "plate" prototype device. The Electrical Density Gauge Company is considering the plate device as a possible method to replace the current dart method, shown in Figure 82. The plate device is minimally destructive and requires less time to set up than the dart method. The plate does require a minimal amount of pushing into the surface in order to establish good contact between the metal rods and the soil.

The plate device features 2 parallel metal rods connected by a square piece of hard plastic. Metal screws connect the rods to the plastic. The screws also provide a clamping point for the EDG's alligator clamps. All the other EDG components can be used with the plate prototype. The plate device was originally intended to be used with a newer EDG H-4114SD.3F model. Due to a problem with the newer model's battery, the research team used the older EDG C model to take both the dart and plate measurements. Due to the late arrival of the new EDG prototype, the team evaluated this device using only the 2013 test soils (ITD maintenance stockpile).

Figure 81. EDG Plate Prototype Device

Figure 82. EDG Dart Setup

Dry Density

The research team compared the calculated dry density results obtained using the plate and dart methods to the calculated NDG dry density values. Figure 83, 84, and 85 show the dry density comparisons for the 3-point, 5-point, and all-point soil model data, respectively. The plate method compared very favorably to the dart method for the 5-point and all-point soil model data.

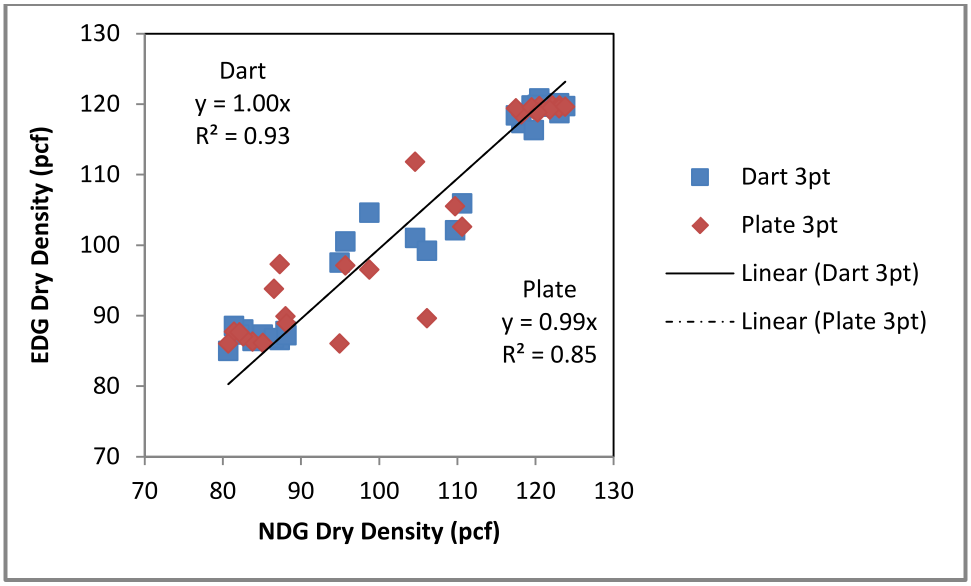

Figure 83. EDG Dart and Plate Dry Density Validation with 3-Point Soil Model Data

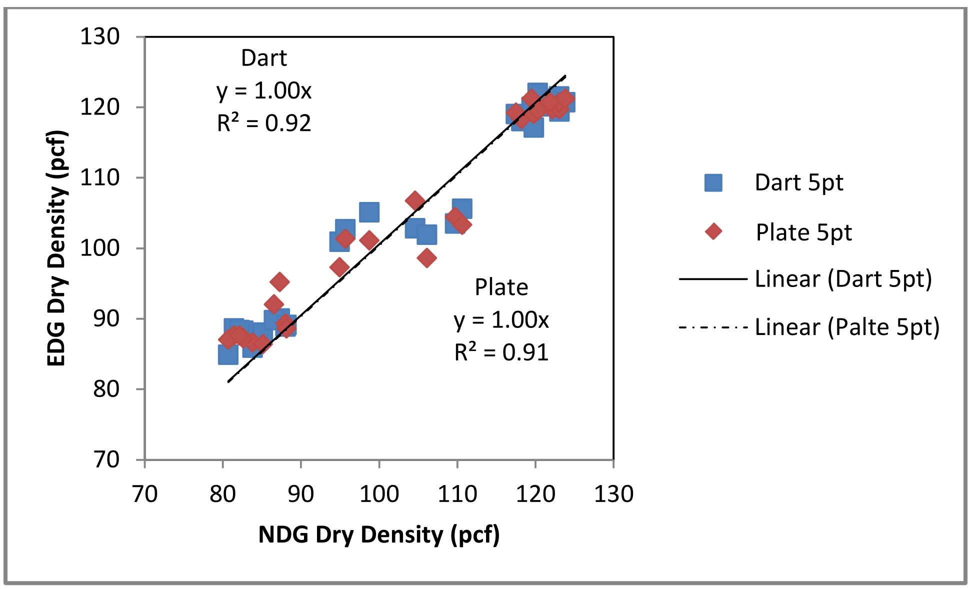

Figure 84. EDG Dart and Plate Dry Density Validations with 5-Point Soil Model Data

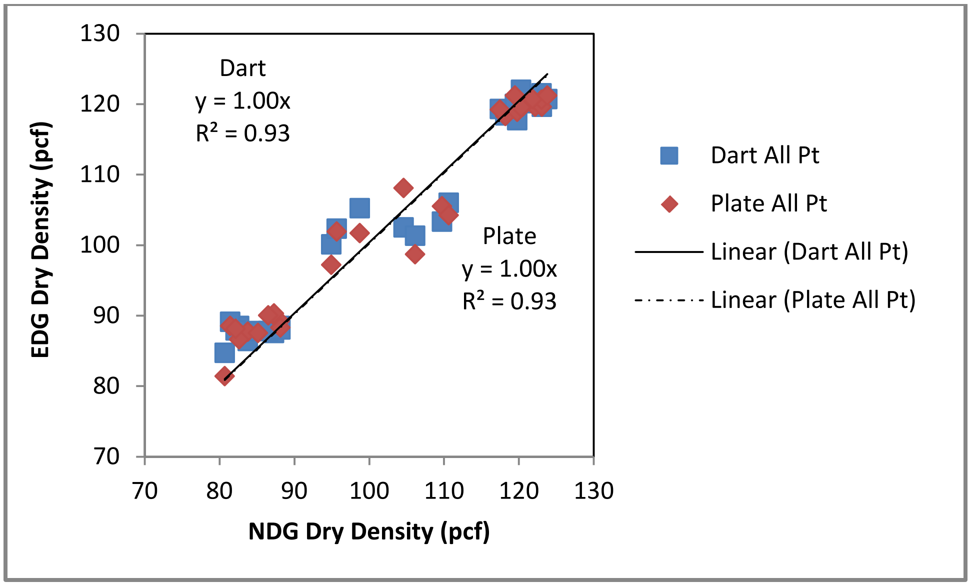

Figure 85. EDG Dart and Plate Dry Density Validation with All Tested Points in the Soil Model

Moisture Content

The team compared the EDG plate and dart moisture content measurements to the NDG moisture content measurements. Again, the team analyzed the results for both the plate and dart methods using the 3-point, 5-point, and all-point soil models. Figures 86, 87, and 88 show the moisture content comparison for the 3-point, 5-point, and all-point soil model data, respectively. Since the team did not take oven moisture samples at all the locations, the NDG moisture contents were used as reference values. These figures also include oven moisture contents whenever available. The values of R^2 for the dart and plate methods are very good and very close to one another. It seems that the plate-based EDG device can eliminate the banding issues related to the dart-based device, which is a significant improvement. In addition, the NDG moisture contents are very close to the oven moisture contents.

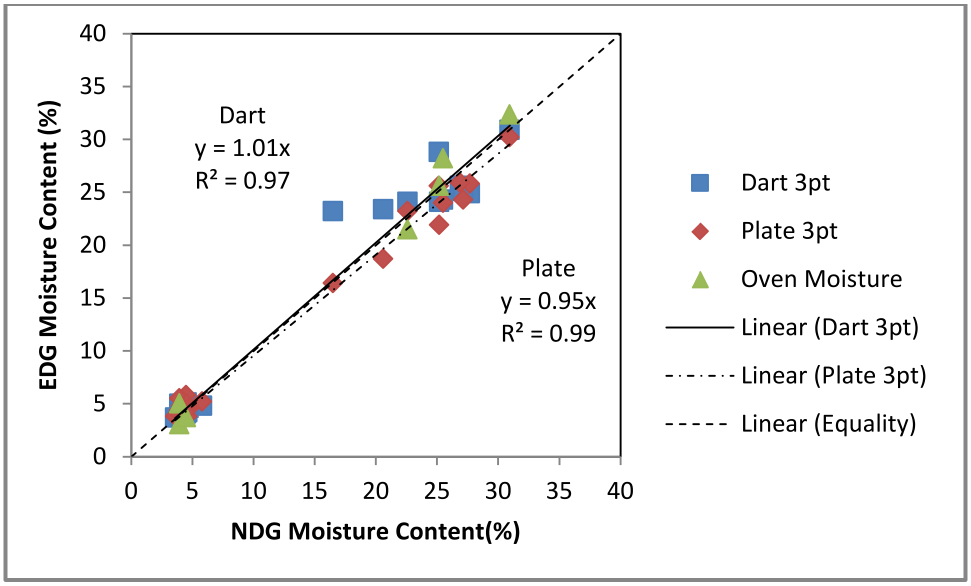

Figure 86. EDG Dart and Plate Moisture Content Comparison with 3-Point Soil Model Data

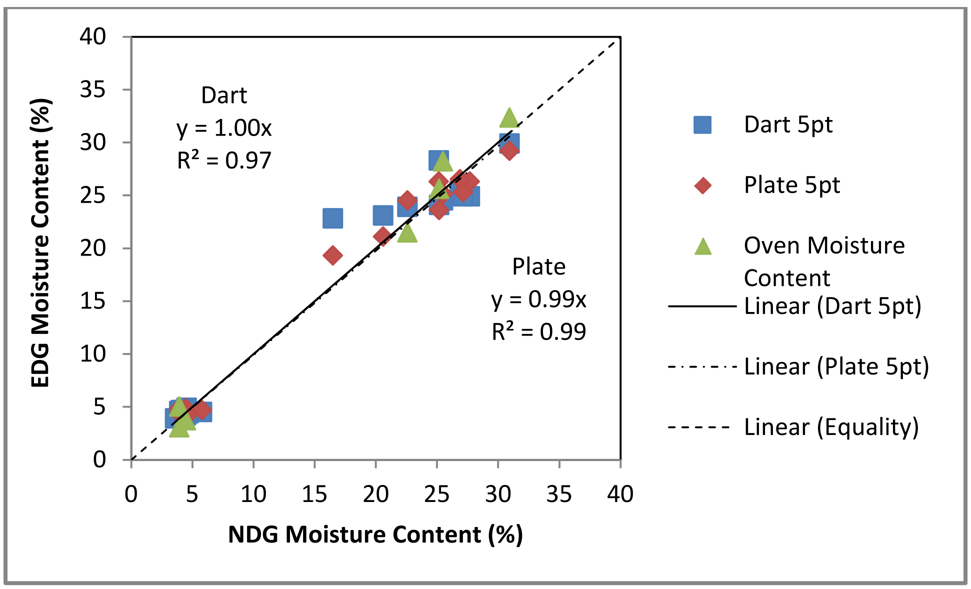

Figure 87. EDG Dart and Plate Moisture Content Comparison with 5-Point Soil Model Data

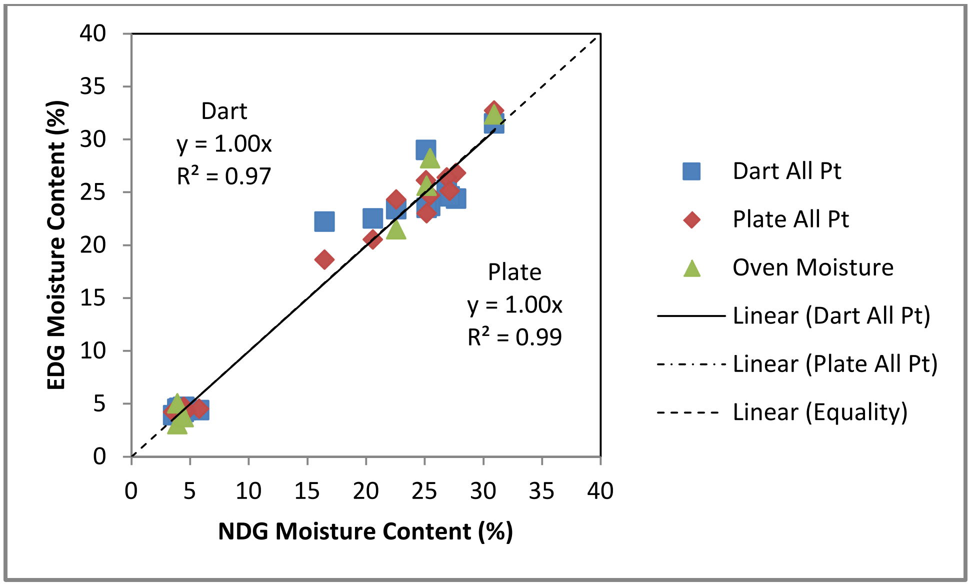

Figure 88. EDG Dart and Plate Moisture Content Comparison with All Tested Points in the Soil Model

Wet Density

The team compared the EDG plate and dart wet density measurements to the NDG wet density measurements. The team analyzed the results for both the plate and dart methods using the 3-point, 5-point, and all-point soil models. Figures 89, 90, and 91 show the wet density comparison for the 3-point, 5-point, and all-point soil model data, respectively.

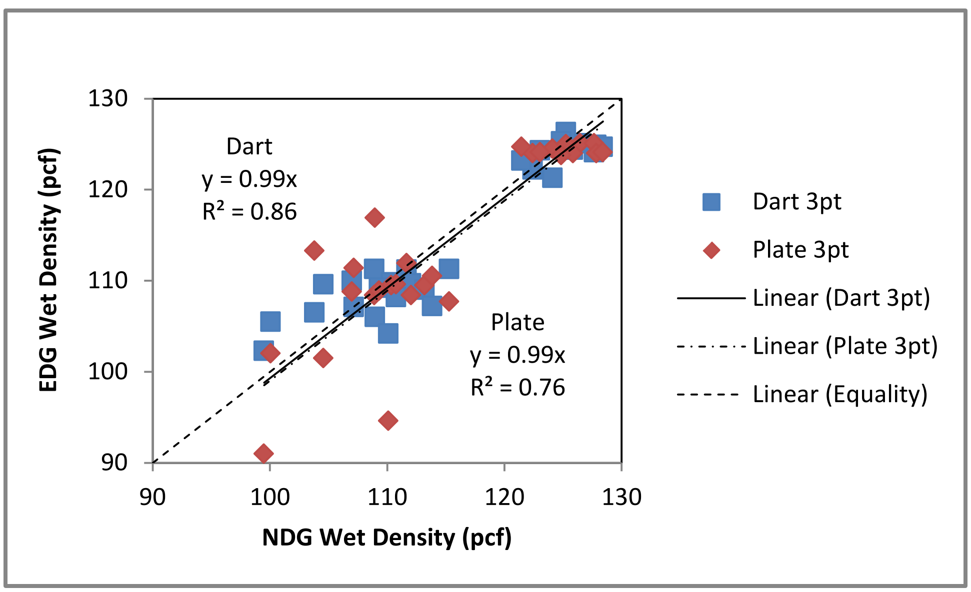

Figure 89. EDG Dart and Plate Wet Density Validation with 3-Point Soil Model Data

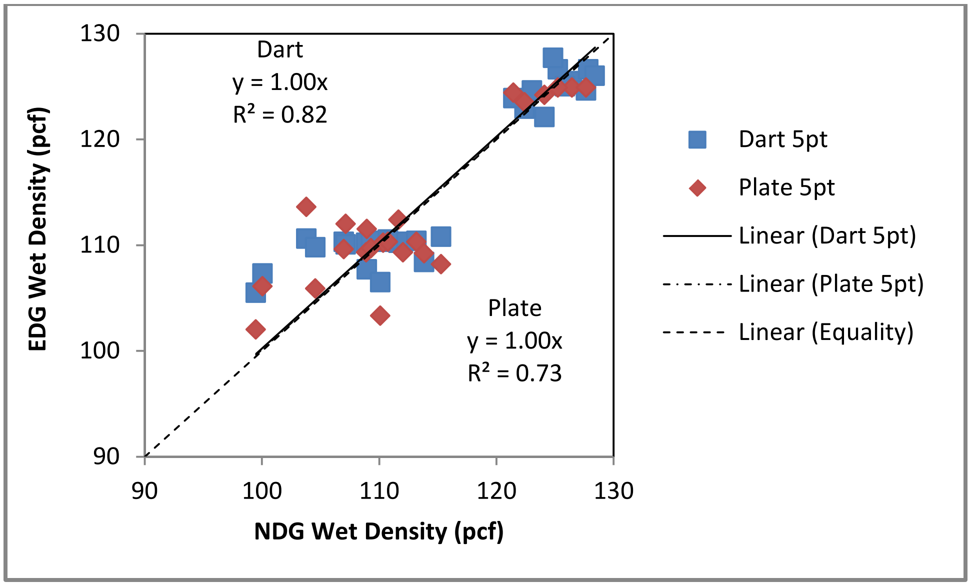

Figure 90. EDG Dart and Plate Wet Density Validation with 5-Point Soil Model Data

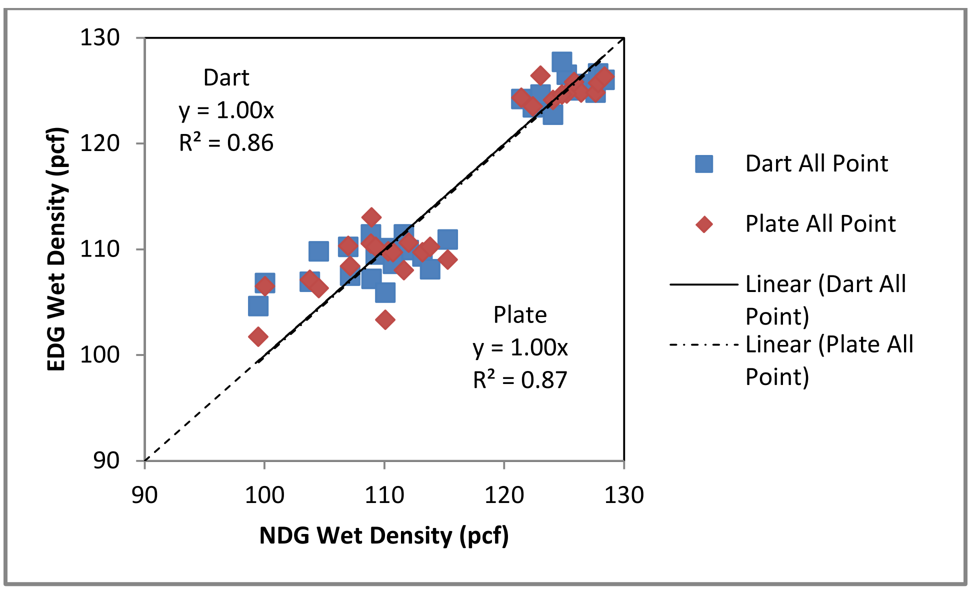

Figure 91. EDG Dart and Plate Wet Density Validation with All Tested Points in the Soil Model

The values of R^2 for the dart data tend to be higher than for the plate data, except when all points were used in the soil model. In the all-point case (Figure 91), the values of R^2 for the dart and plate data are nearly equal. It is also noted that the EDG dry density results correlate with NDG dry density results better than the wet density correlation between the EDG and NDG results.

The plate prototype is a promising device to replace darts for taking EDG measurements. The moisture content measurements were nearly equal to oven results, with the plate performing slightly better than the dart method. The dry density results also were very similar between the two methods. However, the plate-based EDG eliminated the moisture banding issue that is associated with the dart-based EDG, which makes the plate-based EDG very promising and warrants further study.

EDG and SDG Data Analysis Summary

After completing the t-test and correlation analysis of EDG and SDG for dry density values and moisture contents, we found the following results and drew the following conclusions:

- The EDG with NDG soil model and 3-point correlated SDG have the strongest agreement with NDG density and oven moisture content of all the correlation methods used for each gauge.
- Neither gauge type is suitable for the QC determination of density values and moisture content in fine-grained materials, which mirrors the results of other recent studies.(21,27)
- SDG determined base material moisture content well when compared to the oven. However, the SDG density values agreed poorly with the NDG density values for base materials. The EDG results showed a fair agreement with the NDG results for base density values and to the oven for base moisture content.
- If used for coarse materials, the team recommends that NNDGs should be correlated via NDG (for density) and laboratory oven (for moisture content). The sand cone is not suitable for NNDG density correlation. The use of NDG in NNDG correlations defeats the purpose of NNDGs fully replacing NDGs; however, the use of NDGs can be limited.
- Due to the lack of "good" values of R^2 in fines and inconsistent and less than "good" correlations for the base material, the team does not recommend either the EDG or SDG to replace NDGs for field compaction QC.
- The 3-point soil model is sufficient for the EDG device. The research team recommends developing the EDG soil model based on the procedures stated in ASTM D7698.
- The plate-based new EDG model shows high potential to accurately measure the dry density and moisture contents of soils and warrants further study.

GeoGauge Results

Figures 92 - 94 show the GeoGauge stiffness results for all the tested projects plotted against the NDG dry density values, sand cone dry density values and moisture contents, respectively. Figures 95 - 97 show the GeoGauge modulus results plotted against the NDG dry density values, sand cone dry density values, and moisture contents, respectively. No consistent trends are evident in any of the comparisons. The lack of correlation between the stiffness/modulus parameters and moisture content or density values is consistent with findings from previous research.(22,23) No trends between stiffness/modulus values and moisture contents or density values are evident on a project-level basis. Until modulus and stiffness specifications are established, GeoGauge is unable to provide relevant information to ITD and contractor personnel. GeoGauge can provide some insight into the uniformity of the unbound layer, but the uniformity that it reports may not match the uniformity that a moisture/density measuring device reports.

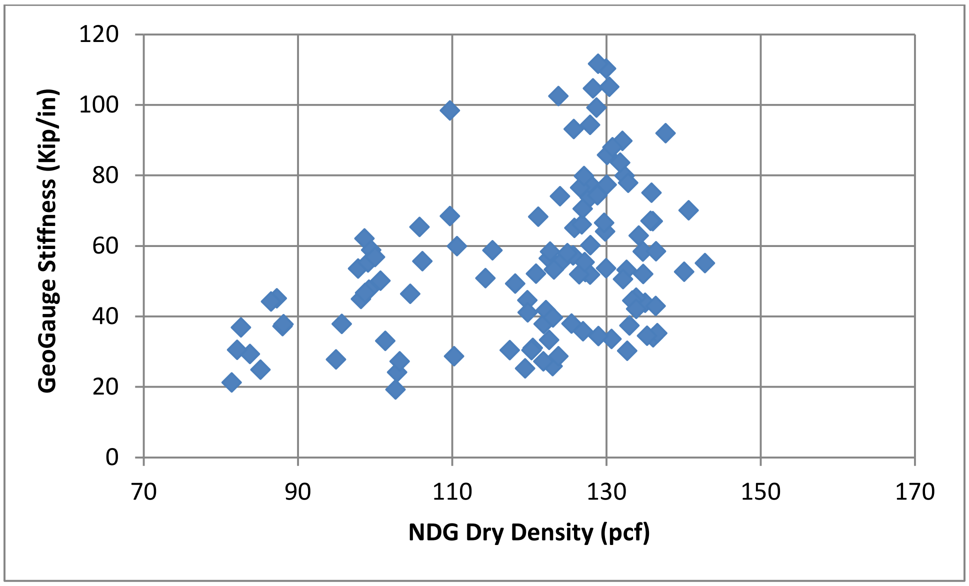

Figure 92. GeoGauge Stiffness vs. NDG Dry Density

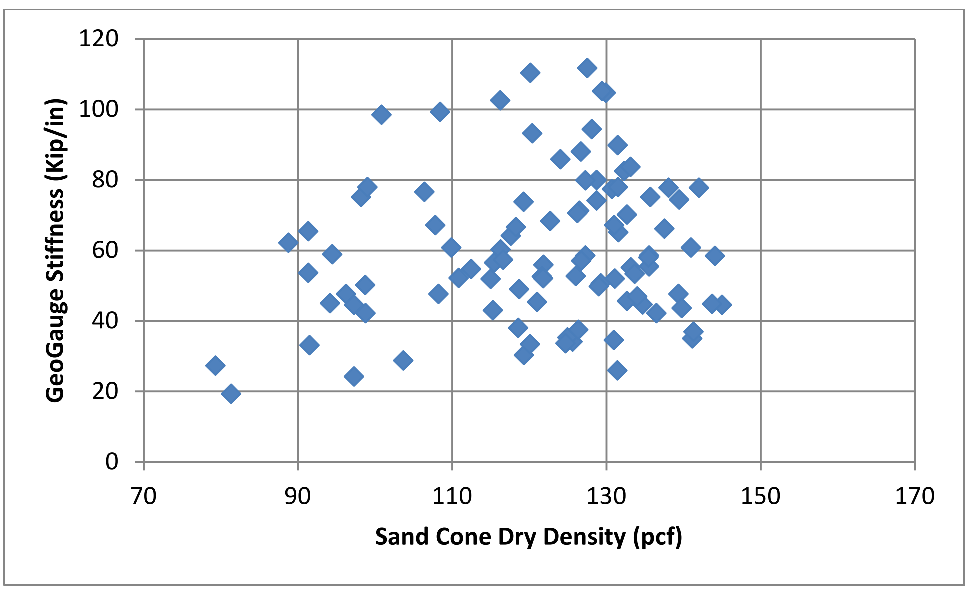

Figure 93. GeoGauge Stiffness vs. Sand Cone Dry Density

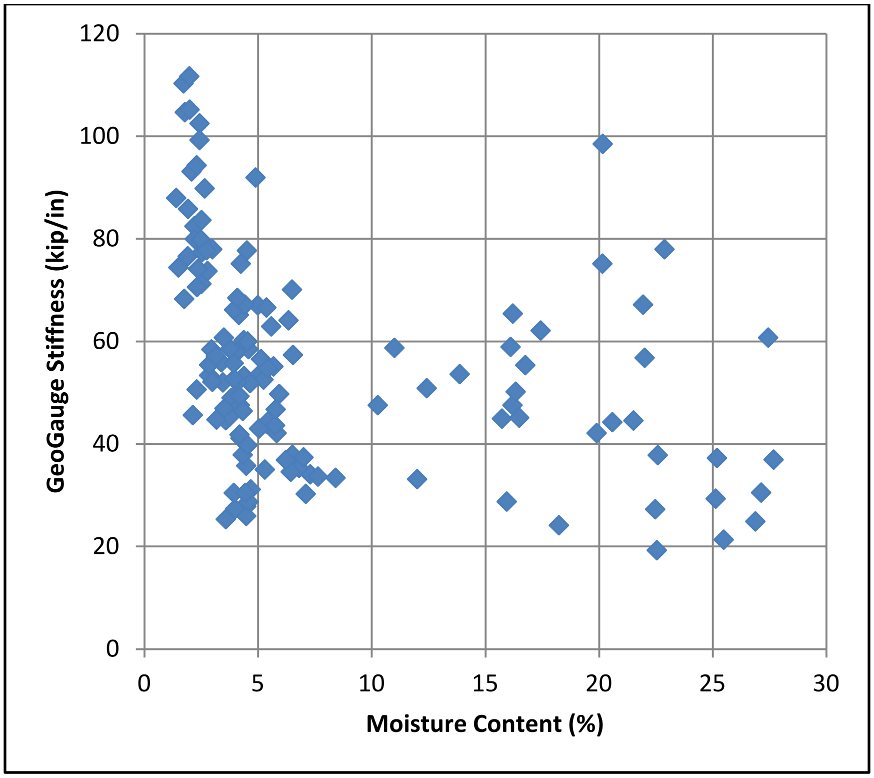

Figure 94. GeoGauge Stiffness vs. Oven Moisture Content

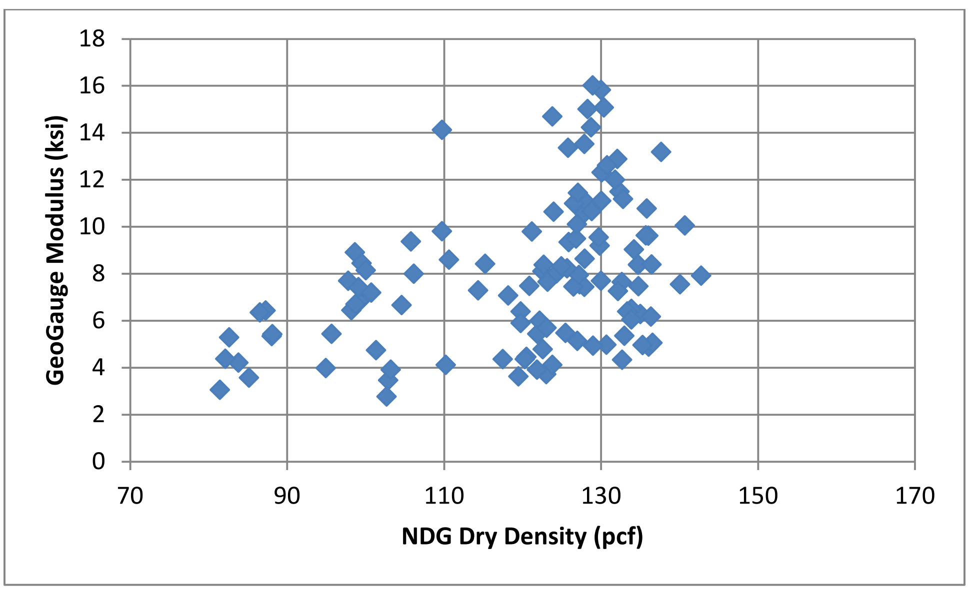

Figure 95. GeoGauge Modulus vs. NDG Dry Density

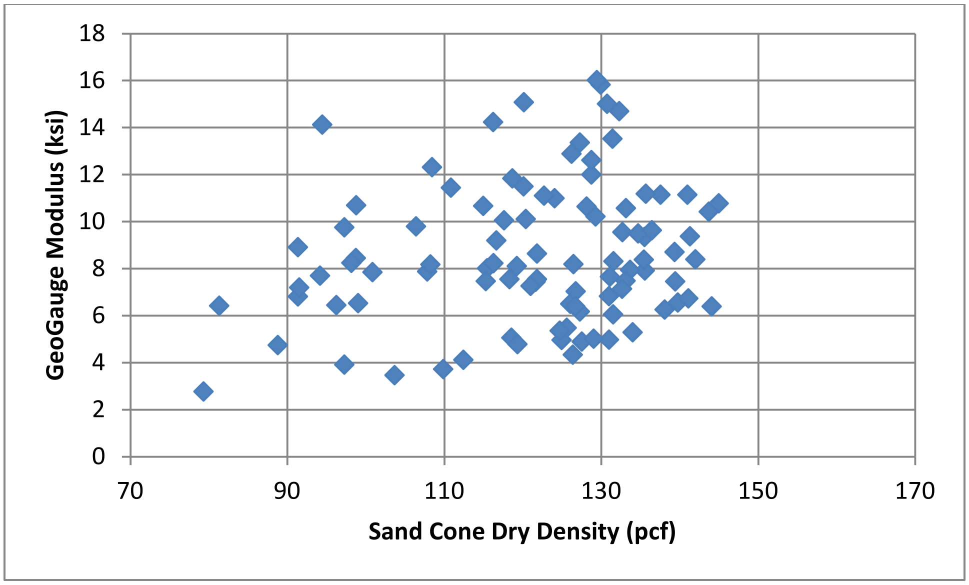

Figure 96. GeoGauge Modulus vs. Sand Cone Dry Density

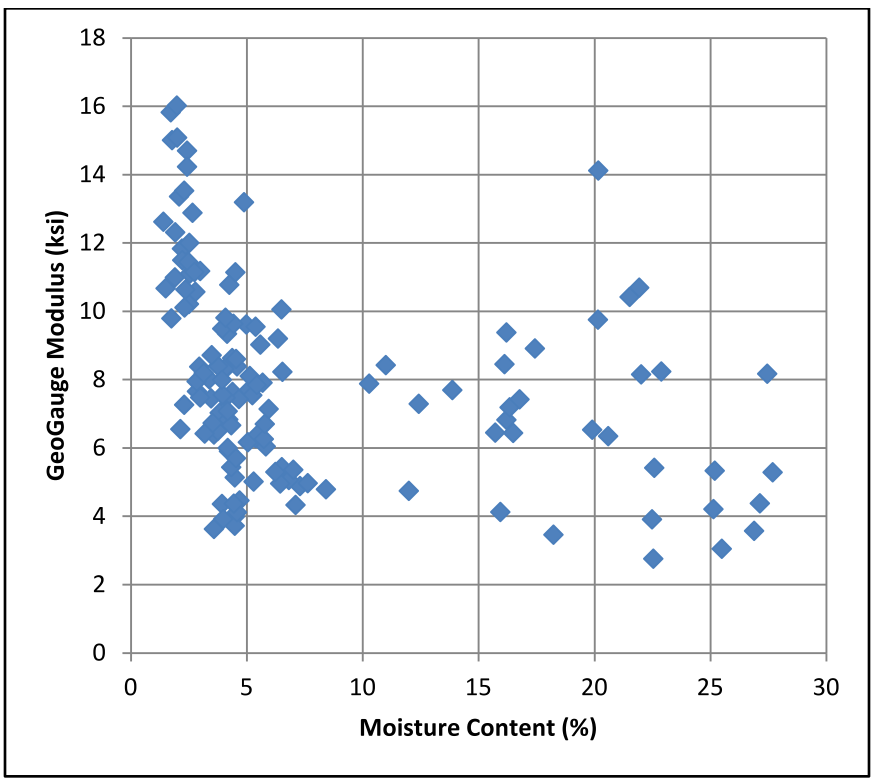

Figure 97. GeoGauge Modulus vs. Oven Moisture Content

CRABS and FDR Base Test Results

For the CRABS and FDR projects, the research team compared the SDG density and GeoGauge stiffness values to the NDG density values to determine if either non-nuclear device could adequately determine the maximum roller pass density when compared to NDGs. The maximum roller pass density is the roller pass during compaction where subsequent passes do not significantly increase (or reduce) the pavement density. 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.[62] Based on instruction from ITD field personnel, the roller passes for this study were a combination of static and vibratory. ITD personnel re-establish the roller pattern periodically (usually every 1,000 feet) to adjust for changes in the maximum density of the base material. The FDR base density roller patterns are very similar to the CRABS roller patterns, except that the contractor personnel establish the number of roller passes.

CRABS Project – US-95 Wilder

Figures 98, 99, and 100 show the density trends per roller pass obtained from SDG and NDG for 3 roller pattern setups on US-95 Wilder, which is a CRABS project site. Figures 101, 102 and 103 show the corresponding GeoGauge stiffness values per roller pass for the same 3 roller setups. These figures show that SDG and GeoGauge could not precisely match the pattern of NDG.

NDG had difficulty measuring precisely to specifications in a reasonable number of passes and meeting the 0.5 pcf requirement. In all 3 roller setups, NDG predicted that the density value was highest on the 11th or 12th roller pass. Except for the evidence shown in Figure 100, SDG could not detect a peak density or the number of passes that indicate sufficient compaction, which is no more than 0.5 pcf more than the previous density measurement.

The GeoGauge also did not match the density pattern of NDG. The overall stiffness trend was unpredictable. Figure 101 shows that the stiffness value slowly increases as the number of roller passes increases. However, Figure 102 GeoGauge Roller Pattern Setup 2 at US-95 Wilder Site shows that the stiffness value decreases, and then begins to increase after 7 roller passes. Figure 103 indicates that the overall trend-line remains fairly flat, although stiffness jumps are evident. Although the density values of SDG and NDG vary significantly, the overall density trend increases in these figures. In comparison, the GeoGauge results are more sporadic than those of the other devices, and the data suggest that the GeoGauge is not precise enough to establish a consistent roller pattern.

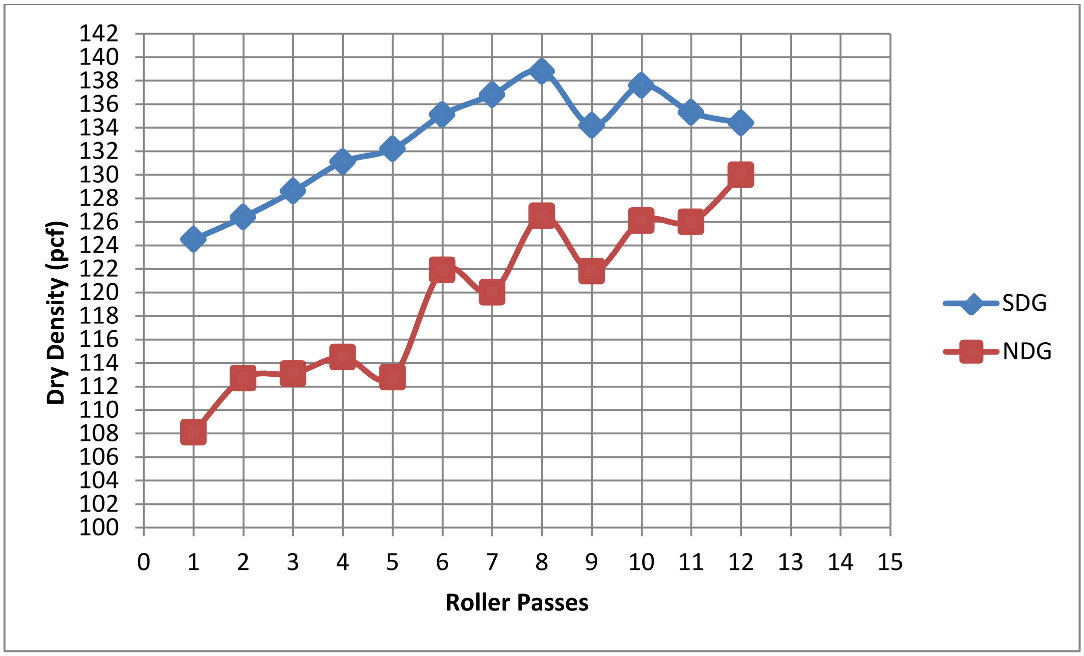

Figure 98. Comparison of NDG and SDG Density Values for Roller Pattern Setup 1 at US-95 Wilder Site

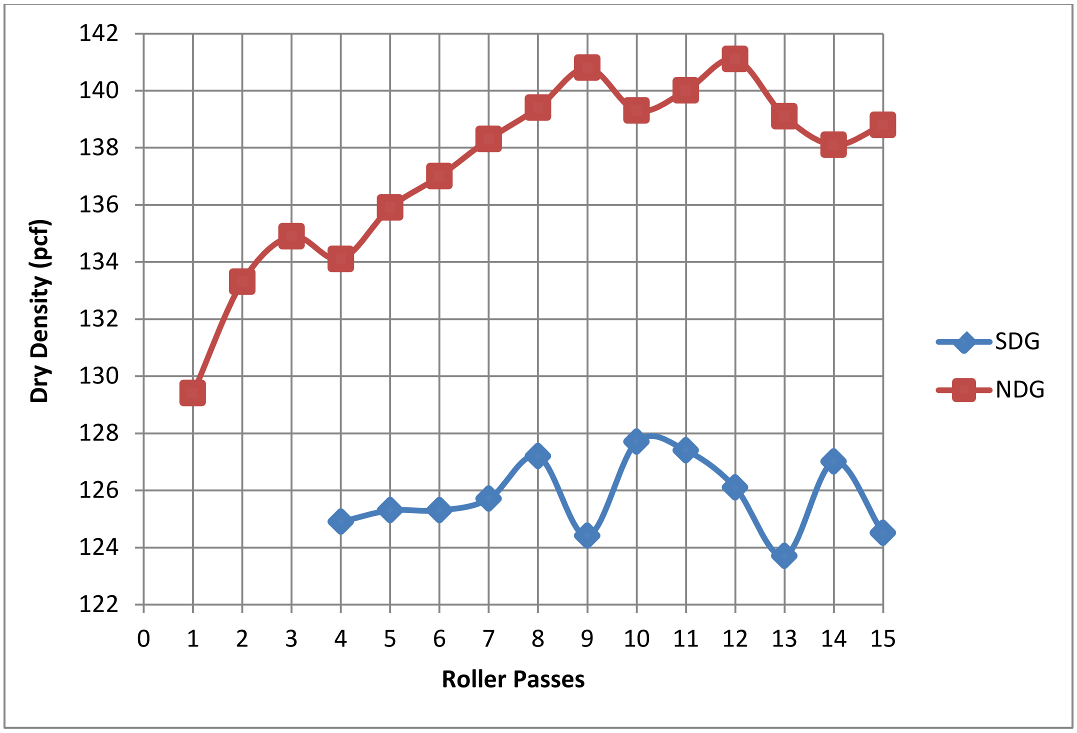

Figure 99. Comparison of NDG and SDG Density Values for Roller Pattern Setup 2 at US-95 Wilder Site

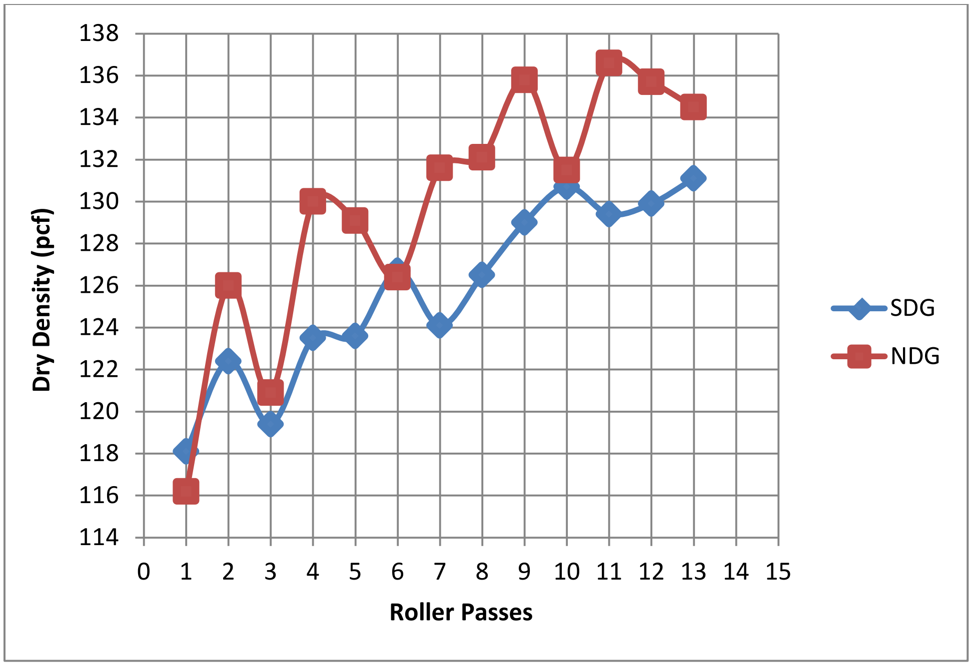

Figure 100. Comparison of NDG and SDG Density Values for Roller Pattern Setup 3 at US-95 Wilder Site

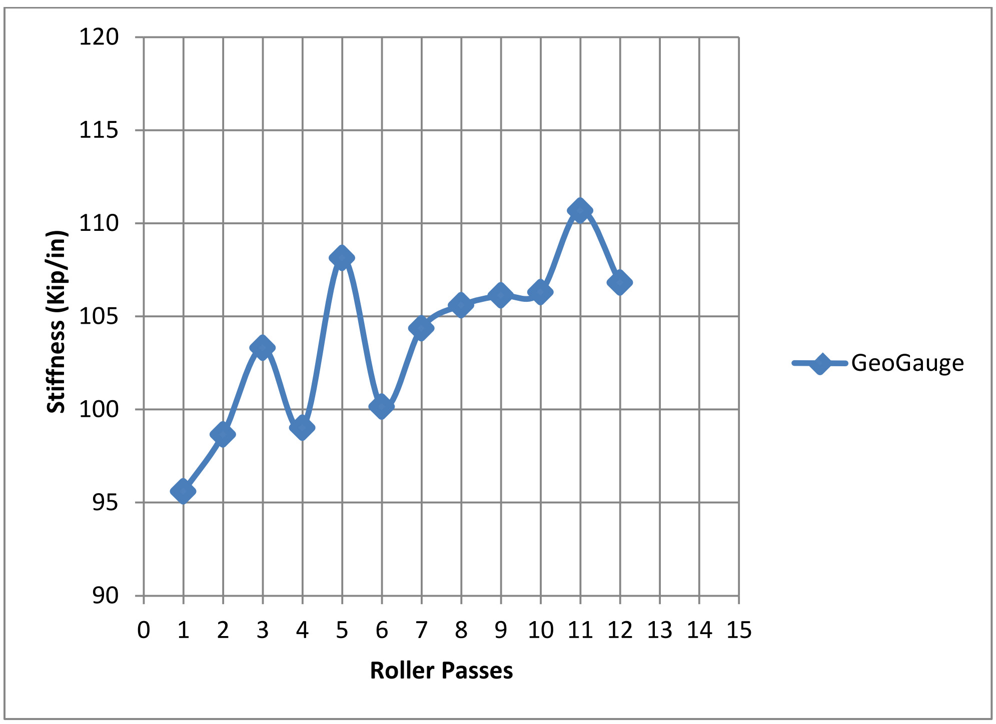

Figure 101. GeoGauge Stiffness Values for Roller Pattern Setup 1 at US-95 Wilder Site

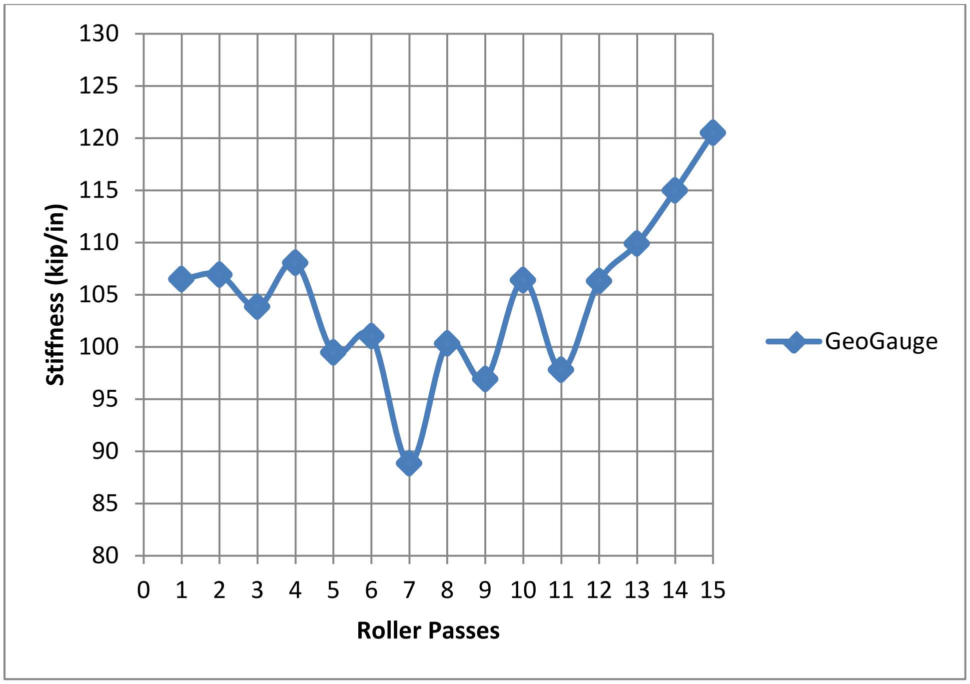

Figure 102. GeoGauge Stiffness Values for Roller Pattern Setup 2 at US-95 Wilder Site

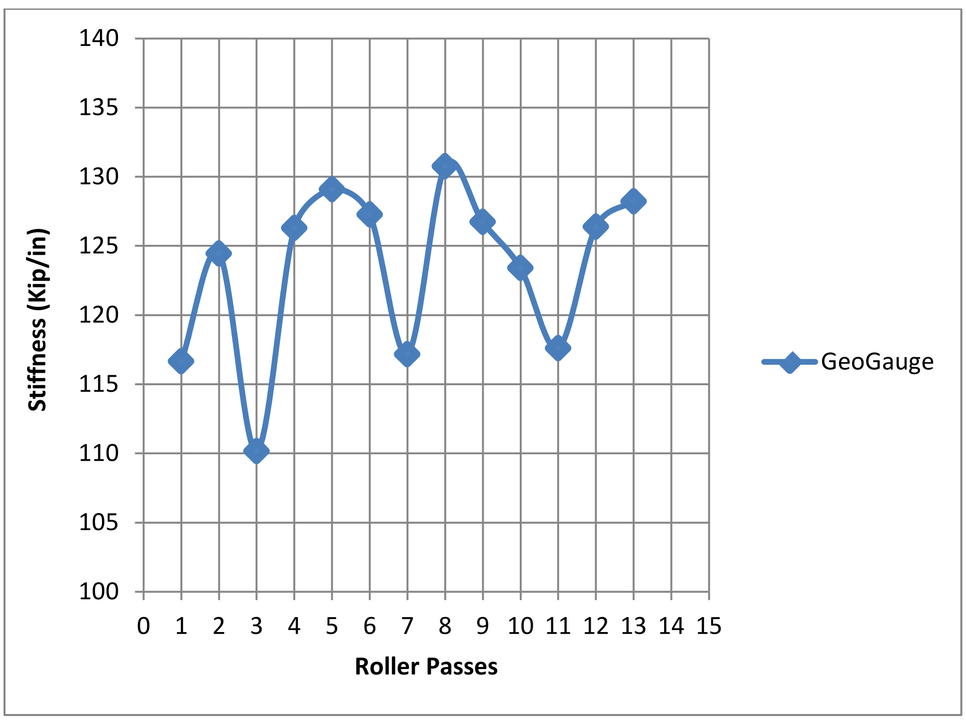

Figure 103. GeoGauge Stiffness Values for Roller Pattern Setup 3 at US-95 Wilder Site

FDR Testing at US-95 Cottonwood

The team also used SDG and GeoGauge to set up roller patterns on US-95 Cottonwood, an FDR project site. The contractor personnel established the break-over point, based on the NDG measurements. Figure 104 shows the SDG and NDG wet density values. SDG experienced a false break on the fourth pass and then its readings continued to increase even after the NDG testing was completed. The GeoGauge trend-line, shown in Figure 105, remained inconsistent, with large variations in stiffness values.

Based on these observations, neither SDG nor GeoGauge could identify the maximum roller pass density and were not effective in establishing a roller pattern. Note that the number of roller passes and total increase in density values for this project were much lower than the number of passes and total density increases for the roller pattern setups at the US-95 Wilder site.

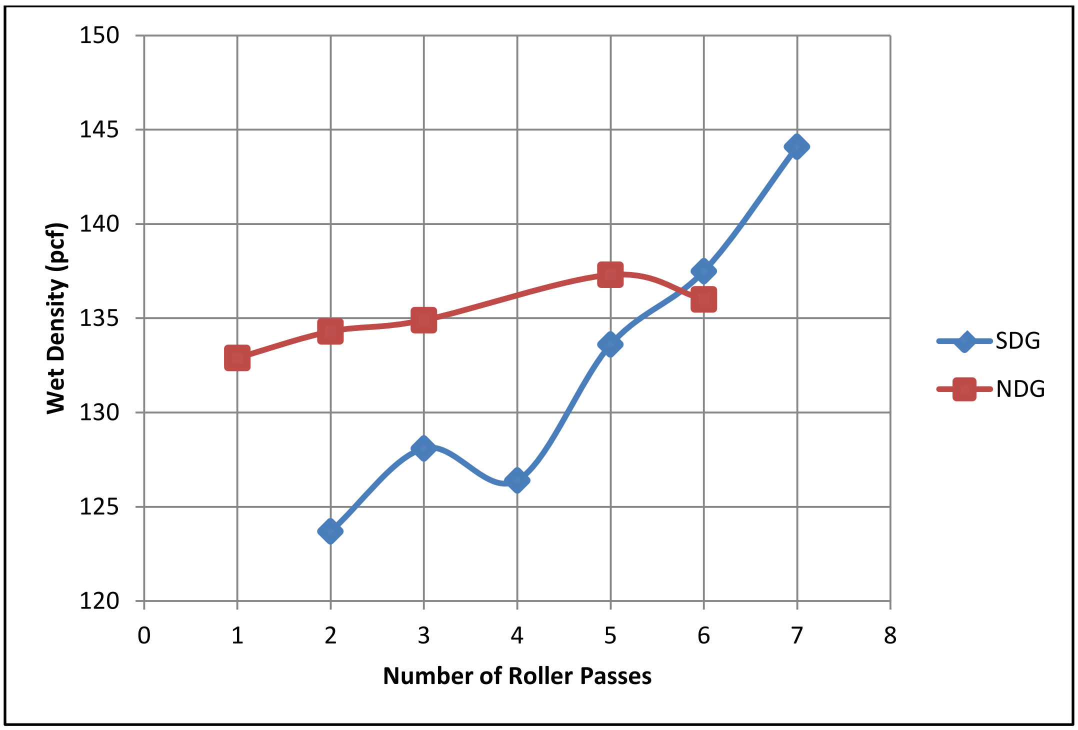

Figure 104. Comparison of NDG and SDG Wet Density Values for Roller Pattern Setup at US-95 Cottonwood Site

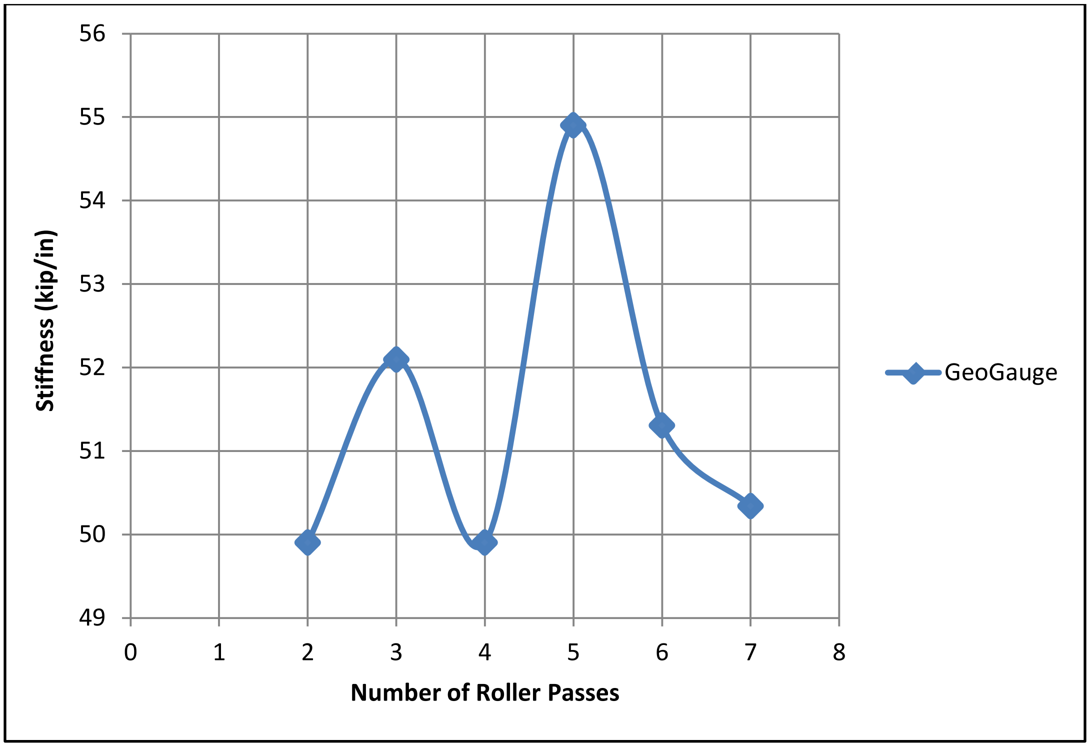

Figure 105. GeoGauge Stiffness Values for Roller Pattern Setup at US-95 Cottonwood Site

For the FDR projects in Idaho, contractor personnel established the roller patterns and ITD personnel verified the density of the FDR base using the backscatter NDG method later the same day. For the US-95 Cottonwood project, the research team tested SDG and GeoGauge at the roller setup location at 2- and 4-hour intervals after the last roller pass. Table 21 presents the SDG density values and moisture contents and GeoGauge stiffness and modulus results. SDG reported significant decreases in wet density, dry density and moisture content values. The loss of moisture was expected (due to the evaporation in the case of emulsified asphalt). The decrease in dry density values, however, was not expected. The GeoGauge stiffness and modulus values increased, indicating that the material was gaining strength as time elapsed, which was an expected outcome.

The change in results (density/moisture values for the SDG and stiffness/modulus values for the GeoGauge) indicates that neither device was able to predict the density immediately after the roller pattern when ITD personnel took the measurements at a "later time" after compaction. For NDG, the "later time" density measurements were comparable to the peak density values established during the roller pattern setup. However, the SDG and GeoGauge "later time" (2 hours and 4 hours, respectively) results differ significantly compared to the results obtained immediately after compaction. Hence, neither device was able to produce accurate results in "later time" testing and replace NDG in this manner of testing.

The FDR results indicate that the GeoGauge can accurately report an increase in material stiffness value with time. However, the GeoGauge cannot be used in the same testing manner as a NDG. Dry density remains constant with time, whereas stiffness does not. SDG reported a decrease in wet density, dry density, and moisture content values with time. However, because the dry density value is expected to remain constant, SDG cannot properly measure the dry density of a soil.

Table 21. SDG and GeoGauge Measurements Over Time for FDR Base at US-95 Cottonwood Site

		Time		
		Last Roller Pass		
		0 HR	**2 HR**	**4 HR**
SDG (Same Spot)	Wet Density (pcf)	144.10	131.40	124.60
	Dry Density (pcf)	135.40	124.10	118.00
	Moisture Content (%)	6.40	5.90	5.60
SDG Clover	Wet Density (pcf)	-	132.20	130.30
	Dry Density (pcf)	-	124.70	122.80
	Moisture Content (%)	-	6.10	6.10
GeoGauge (Average)	Stiffness (kip/in.)	50.34	68.01	73.62
	Modulus (ksi)	7.22	9.76	10.56

Note: "-" indicates that the research team did not take SDG cloverleaf measurements during the roller pattern setup.

Chapter 5
Cost and Implementation Review

The accuracy of NNDGs are the most important factors in determining their suitability to replace NDGs. However, the cost and ease of implementing NNDGs are also key factors for ITD, contractors, and other agencies to consider when comparing NDGs and NNDGs. This chapter focuses on the implementation concerns and costs associated with NNDGs and compare these factors to current NDG use. This section presents a review of PQI 301, PQI 380, PT Plus, SDG 200, and EDG. This chapter does not review the GeoGauge because implementation of the GeoGauge would require the development and acceptance of new modulus and stiffness specifications, which are not feasible at this time.

Implementation

Along with performance, additional implementation concerns for NNDGs include:

- Possible Need for New Standards.
- Size and Weight of the Devices.
- Frequency of Factory Correlation.
- Battery Life.
- Amount of Operator Training Needed.
- Possible Need for Field Correlation.
- Speed of Devices in the Field.
- Special Storage and Handling Concerns.
- Ease of Use for Operators.
- Costs.

Table 22 summarizes the above implementation details for each NNDG. As a reference, the table also presents details for a new Troxler 3430 NDG. Current ASTM standards are available for all NNDGs included in this evaluation. HMA NNDGs also have an applicable standard, AASHTO T 343, *Density of In-Place Hot Mix Asphalt (HMA) Pavement by Electronic Surface Contact Devices*, which is the basis for current ITD field procedures.[47] NNDGs weigh about half as much as a typical NDG. Each device requires annual factory calibration and also has the ability to export data to a computer, although this study does not evaluate the software programs for each device. Battery life can vary between gauges and depends greatly on the number of measurements taken in a given time period. Hence, the battery life values presented in Table 22 are estimations based on the manufacturers' predictions and the authors' experience. Each device features at least 25 hours of battery life for a new battery under normal test conditions (about every five to ten minutes per density measurement). PQI 301 tends to go into power-save mode after five minutes if no new readings are taken. With this feature, PQI 301s tend to have a long duration of battery. The life to replace battery for PT, PQI 380, and SDG is comparable to that of PQI 301. SDG takes measurements at multiple electromagnetic frequencies, which requires slightly more battery power to perform compared to PQI. Once the soil model is established, EDG can have a long battery life (up to 60 hours).

Table 22. Summary of Implementation Details for NNDGs and NDG

	Nuclear Gauge	PQI 301	PQI 380	PT Plus	SDG	EDG
Manufacturer	Troxler	Trans Tech	Trans Tech	Troxler	Trans Tech	Humboldt
Model Number	3430	301	380	2701-B	200	H-4114SD.3F
ASTM Standard	D 6938 (soils) D 2950 (HMA)	D 7113	D 7113	D 7113	D 7830	D 7698
AASHTO Standard	T310 (Soils)[1]	T343	T343	T343	None	None
Package Weight	29 lb	16 lb	14.2 lb	10.5 lb	14.2 lb	15 lb
Package Dimensions (in.)	14.8 × 9.1 × 7.2	10.75 × 10.75 × 11	11 × 11 × 12	16 × 9 × 7.5	11 × 11 × 12	21 × 17 × 8
Equipment Correlation	Annual	Annual	Annual	Annual	Annual	Annual[2]
Reported Test Parameters	Density & Moisture Content	Density	Density	Density	Density & Moisture Content	Density & Moisture Content
Battery Type	NiCad	NiMH	NiMH	NiMH	NiMH	Li-ION
Battery Life on Full Charge	30 hours	50 hours	35 hours	32 hours	25 hours	60 hours
Requires Field Correlation	No for QC, No for Soils QA, Yes for HMA QA	Suggested	Suggested	Suggested	Suggested	Yes
Time to Complete Single Test (Minutes)	2 - 3	< 1	< 1	< 1	2	1 - 4
Data Storage for Download	Yes	Yes	Yes	Yes	Yes	Yes
Handling in the Field	Moderate	Easy	Easy	Easy	Easy	Moderate
Storage	Very Secure	Moderate	Moderate	Moderate	Moderate	Moderate
Operator Training	Extensive	Easy	Easy	Easy	Moderate	Difficult
Ease of Use	Moderate	Easy	Easy	Easy	Moderate	Difficult
Initial Cost of Unit	$8,000	$8,200	$8,900	$8,800	$8,900	$8,835

[1] ITD follows WAQTC TM-8 to measure the density of asphalt pavement mixes using nuclear methods.
[2] The owner can perform EDG calibration using a master correlation unit.

EDG requires a soil model correlation in order to operate in the field. If necessary, a soil model from another soil could be applicable for a different material; however, the research team strongly recommends a soil-specific model for each material and project site. Each NNDG requires a field block correlation in order to produce good QC and QA measurements. NDGs generally do not require field correlation to another method, except for QA purposes for HMA paving projects.

In most cases, NNDGs can take measurements in a shorter amount of time than NDGs. HMA NNDGs can take a single measurement within seconds. The time to perform a 5-shot average for each device is about 30 seconds. Each SDG measurement takes about 20 seconds to complete, and a 5-shot average measurement can take up to two minutes to complete. The measurement time for EDG is only a few seconds, and thus, a two-shot average can take less than 10 seconds. However, hammering the metal darts into the ground and connecting the equipment is time-consuming. Hammering darts can be quick and easy in soft clays and sands, but much more difficult in other materials, including gravels and stiff clays. NDGs can take QC readings in as few as 15 seconds. For QA purposes and improved accuracy, however, WAQTC TM-8 requires one-minute interval readings.[48] Because two NDG shots are necessary for both pavement and soil applications, at least two minutes are necessary in order to obtain data. Unless the team uses a backscatter measurement method, NDGs require more time for unbound materials than NNDGs due to the time required to drive a pinhole.

Most of the devices are easy to handle in the field. PQIs, PT, and SDG are easy to carry and do not require any special attachments other than handle extensions. Compared to the other devices, EDG has more discrete equipment components, including darts, a dart template, temperature probe, electrical cables, and the gauge itself. These pieces of equipment make transporting the gauge to and in the field more difficult than for other NNDGs. NDGs are heavier than NNDGs, and the operator must take special care to know the location of NDG at all times. NDGs also require special overnight storage locations and special provisions for storage during transport. NNDGs do not have requirements for storage when they are not in use.

Operator training is substantial for NDGs due in large part to extensive nuclear safety training that is required for each operator. The actual density measuring operation of NDGs is not particularly difficult. PQI 301, PQI 380, and PT are fairly easy to learn and operate. SDG is likewise easy to use when the material inputs are known. Once the soil model is established, EDG is likewise very easy to learn and operate. However, setting up a good soil model requires a fair amount of practice and experience.

Cost Analysis

The initial and lifetime costs of the devices are also important factors in selecting NDGs and NNDGs. This section presents information regarding the operational costs associated with the density devices used for compaction control. This analysis includes the five NNDGs discussed in the implementation review (PQI 301 and 380, PT, SDG, and EDG) and the Troxler 3430 NDG.

The research team contacted the device manufacturers to obtain the initial costs of their devices, costs for additional accessories, and other lifetime costs, such as device calibration. ITD personnel (District 2 Materials Engineer) provided the team with additional data regarding the operating costs of NDGs.

Nuclear Gauge Costs

Table 23 presents a summary of the data regarding NDG costs that the manufacturers and ITD provided to the team. This summary includes the initial costs, annual calibration and repair to the gauges, annual and periodic operator training, radioactive licensing fees, and other costs. Most of the costs shown are for a single gauge or operator, and some costs, such as the Nuclear Regulatory Commission (NRC) radioactive materials license, are district-wide costs. The table does not show the expenses involved for the storage facility to accommodate the radioactive materials securely.

In order to analyze lifetime NDG costs on a district-wide scale, the team developed a scenario that assumes a district owns 10 NDGs and that 20 technicians are likely to use the devices. This scenario also assumes a 10-year gauge life. Table 24 presents the annual cost of operations under this scenario. The estimated annual cost per district per year for NDGs under this scenario is $16,523. The analysis does not consider the potential annual costs for an approved storage facility or the disposal costs at the end of the gauge's life.

Non-Nuclear Gauge Costs

A key benefit of electromagnetic NNDGs is that they are not subject to the strict safety regulations of NDGs. This advantage eliminates a number of the cost items associated with NDG ownership and operation. Table 25 and 26 respectively present summaries of the initial and annual costs for HMA and unbound NNDGs. With an initial price of NDG at about $8000, NNDGs tend to be slightly more expensive initially than their nuclear counterparts. For most NNDGs, however, the difference between a new NDG and a new NNDG device is less than $1,000. The lone exception is PQI 301 with a recommended verification (standardization) block, which totals $9,150. The initial device costs for all the other NDG and NNDG devices include standardization plates and blocks. The research team assumes that the annual calibration costs ($400) are approximately the same for all the devices. NNDGs do have other associated costs, including battery replacement (typically required every two years), periodic PT sensor cover replacement, and EDG accessory replacement.

Table 23. Purchase and Operating Costs of Nuclear Density Gauges

	Item	Cost
1.	Initial cost of a new Troxler Model 3430	$8,000
2.	Calibration costs (annual)	$400
3.	Leak tests (semi-annual)	$40
4.	Average cost of repairs (annual)	$60
5.	NRC[1] radioactive material license (annual)	$3,400
6.	RSO[2] training (annual) – per district	$395
7.	Online radiation safety training (annual)	$129
8.	Hazmat training (every 3 years)	$49
9.	TLD[3] nuclear badge per person (annual)	$140
10.	Radiation monitoring fee (annual)	$75
11.	Radiation survey meter	$500
12.	Calibration of radiation survey meter (annual)	$75
13.	Disposal costs (includes shipping) – waived with purchase of replacement unit.	$1,040
14.	Approved storage facilities	*unknown*

[1] *Nuclear Regulatory Commission*
[2] *Radiation Safety Officer*
[3] *Thermoluminescent Dosimeter*

Table 24. Annual Cost for NDG Operations: 10 Gauges, 20 Technicians, 10-Year Equipment Life

	Item	Unit Cost	Annual Cost for 10 Units
1.	Calibration Costs	$400	$4,000
2.	Leak Tests	$40	$800
3.	Average Cost of Repairs	$60	$600
4.	NRC Radioactive Material License	$3,400	$3,400
5.	RSO Training (annual) – per District	$395	$350
6.	Online Radiation Safety Training (annual)	$130	$2,600
7.	Hazmat Training (every 3 years)	$50	$333
8.	TLD Nuclear Badge per Person (annual)	$140	$2,800
9.	Radiation Monitoring Fee (annual)	$75	$1,500
10.	Calibration of Radiation Survey Meter (annual)	$75	$75
11.	Annualized Cost of Radiation Survey Meter (1)	$65	$65
		Total	$16,523

Table 25. Purchase and Operating Costs of HMA Non-Nuclear Density Gauges

	Item	Cost		
		PQI 301	**PQI 380**	**PT Plus**
1.	Purchase Price for a Single, Fully-Equipped Device (excludes shipping)	$8,200	$8,900	$8,800
2.	Annual Calibration	$400	$400	$400
3.	Additional Recommended Accessories	$950 (Verification Block)	None	None
4.	Replacement Cost of Batteries	$174	$298	$172
5.	Other Expendable Items	None	None	$53.70 (Sensor Cover)
6.	Technical Phone/Email Support	Yes	Yes	Yes
7.	On-Site Operator Training	Available	Available	Available
8.	Discounts for Multiple Purchases	Yes	Yes	Yes
9.	Duration of Warranties	12 Months	12 Months	18 Months

Table 26. Purchase and Operating Costs of Non-Nuclear Density Gauges for Unbound Materials

	Item	Cost	
		EDG	SDG
1.	Purchase Price for a Single, Fully-Equipped Device (excludes shipping)	$8,835	$8,900
2.	Additional Optional Accessories	$2,250 (master calibration unit)	None
3.	Replacement Cost of Batteries	$435	$298
4.	Expendable Items for EDG • Probes 4-in. to 12-in. (set of 4) • Spike template • Temperature sensor • AC charger • Soil test cables	 $128 - $272 $35 $120 $120 $50	None
5.	Device Calibration	$400	$400
6.	Technical Phone/Email Support	Yes	Yes
7.	On-Site Operator Training	Provided at no cost	Available
8.	Discounts for Multiple Purchases	Yes	Yes
9.	Duration of Warranties	12 months	12 months

Tables 27 and 28 present the annual NNDG operating cost analyses for HMA NNDGs and unbound NNDGs, respectively. The NNDG analyses use the same scenario as the NDG analysis, which assumes 10 gauges, 20 technicians, and a 10-year equipment life. NNDG annual costs are very comparable for each device. PQI had the lowest annual cost, at $475 per unit per year, followed by PT at $500 per unit per year.

For the unbound devices, EDG had lower annual costs than SDG. The lower expense of EDG is attributable primarily to its calibration costs. Humboldt offers EDG owners the opportunity to purchase their own master calibration unit (MCU), which allows owners to perform their own annual calibrations. The MCU has a high initial cost (approximately $2,250), but saves money on annual manufacturer calibration costs, especially if an owner were to own multiple EDGs. Each SDG has an approximate $400 annual calibration cost. Other EDG expenses include the replacement of required external equipment, which includes metal darts, temperature probes, and testing cables that connect the darts to the EDG device. These added EDG costs are highly variable and dependent on the frequency of testing, the types of material being tested (stiffer material will put more wear and tear on the metal darts), and the care the technician takes when handling the equipment.

Table 27. Annual Costs for HMA NNDG Operations: 10 Gauges, 20 Technicians, 10-Year Equipment Life

	Item	Cost					
		PQI 301		PQI 380		PT Plus	
		Unit	Annual (10 units)	Unit	Annual (10 units)	Unit	Annual (10 units)
1.	Device Calibration	$400	$4,000	$400	$4,000	$400	$4,000
2.	Additional Optional Accessories	None		None		$25 (4 x sensor cover)	$250
3.	4 × Battery Replacement (every 2 years)	$75	$750	$125	$1,250	$75	$750
	Total	$475	$4,750	$525	$5,250	$500	$5,000

Table 28. Annual Costs for Unbound NNDG Operations: 10 Gauges, 20 Technicians, 10-Year Equipment Life

	Item	Cost			
		EDG		SDG	
		Unit	Annual (10 units)	Unit	Annual (10 units)
1.	Device Calibration	None[1]		$400	$4,000
2.	Additional Optional Accessories	None		None	
3.	4 × Battery Replacement (every 2 years)	$180	$1,800	$125	$1,250
4.	Expendable Items for EDG • 1 × Probes 12 in. • 4 × Probes 6 in. • 4 × Temp. Sensors • 1 × Soil Test Cables	 • $40 • $35 • $50 • $10	 • $400 • $350 • $500 • $100		
	Total	$315	$3,150	$525	$5,250

[1]*Assumes that the owner purchases the master calibration unit (MCU).*

Life-Cycle Cost Comparison

The research team calculated the life-cycle costs for a single NDG and each of the 5 NNDGs (PQI 301, PQI 380, PT, EDG, and SDG). The parameters used in the previous cost scenarios (10 gauges, 20 technicians, and 10-year life) are the same, except that the team examined the life-cycle costs associated with a single device. The team determined the life cycle cost for a single device by finding the life costs of 10 devices (per district) and dividing that number by 10 to produce a cost per gauge. Table 29 presents the life-cycle cost comparison. The initial costs of the devices include the unit device cost and recommended accessories. The cost of the verification block for PQI 301 was included in the initial cost. For EDG, the team divided the cost of the MCU by 10 to obtain a per-gauge estimate of cost for the unit (the MCU can be used for multiple EDGs). The team then applied the divided MCU cost to the initial cost of the EDG device.

Clearly, the life-time cost of each NNDG is less than the cost of NDG. The life-time cost savings of NNDGs is at least $9,700 compared to NDG, which results in a district-wide savings (assuming 10 devices) of $97,000 over the lifetime considered in this study.

However, a true life-cycle cost comparison will certainly vary from this estimate. Recall that 2 NNDGs, one for HMA and one for unbound materials, are required to replace the functions of a single Troxler 3430 NDG. The least expensive HMA NNDG (PT) paired with the least expensive unbound NNDG (EDG) results in a lifetime cost of $26,010, and together have a higher lifetime cost than the lifetime cost of the NDG ($24,523). However, a district is not likely to replace 10 NDGs with 10 HMA NNDGs and 10 unbound NNDGs. Some appropriate combination of HMA and unbound devices could be purchased to suit the needs of the district. Districts could also share devices as needed, depending on the number, type, and size of construction projects statewide.

Table 29. Life-Cycle Cost Comparison of NDG and NNDGs

	Device	**Initial Cost**	**Annual Cost**	**Lifetime (10 years) Cost**
1.	NDG (Troxler 3430)	$8,000	$1,652.30	**$24,523**
2.	PQI 301	$9,150	$475.00	**$13,900**
3.	PQI 380	$8,900	$525.00	**$14,150**
4.	PT	$8,800	$500.00	**$13,800**
5.	EDG	$9,060	$315.00	**$12,210**
6.	SDG	$8,900	$525.00	**$14,800**

In terms of device performance, neither of the unbound NNDGs is appropriate for QA purposes at this time. Thus, NDGs are still necessary for QA purposes for unbound materials. The introduction of HMA NNDGs alone would reduce at least some NDG dependence. With fewer NDGs, fewer operators will need NDG training, and therefore, some costs savings are possible.

Chapter 6
Conclusions and Recommendations

Conclusions

Density is one of the most important factors that affect the performance of HMA pavement. Proper density in the pavement, base, embankment, and subgrade layers helps to ensure that a roadway will be long-lasting and perform well. ITD currently uses NDGs to measure the *in situ* density of pavements, bases, sub-bases, and subgrades. Due to the costs associated with NDGs, various researchers have performed extensive studies on NNDGs over the last two decades to measure density and compaction. ITD has begun using NNDGs, and this report reviews five devices that have the potential to replace NDGs for density and moisture measurements.

This study evaluated PQI 301 and PT Plus as devices for HMA, and EDG, SDG, and GeoGauge as devices for unbound materials. The objectives of this research were to compare NNDGs to existing NDGs in Idaho in terms of accuracy and to evaluate each device based on their unique capabilities, features, and costs of operation.

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

HMA Devices

- Based on data analysis of individual projects, PQI and PT performed as well as the current ITD NDG practice, in terms of percentage of field projects for which the PQI readings have no statistically significant difference from the core densities.
- After correlation, the global factors, including HMA class, lift thickness, HMA NMAS, aggregate mineralogy, and binder absorption did not statistically affect the correlated devices.
- PQI and PT were unable to consistently determine the same roller pattern as NDG.
- The effects of fines and surface paint had no statistically significant impact on density measurements.
- Moisture had a significant impact on NNDG density measurements. In the case of a damp HMA surface, the team recommends drying the surface with a paper towel or waiting for the location to dry, without the use of fines underneath the device.
- The temperature effects on the NNDG readings were not statistically significant.
- The use of six-inch cores for correction reduced the error measurements more than the use of four-inch cores.

Unbound Devices

- The EDG with NDG soil model and 3-point correlated SDG produced the most favorable t-test and agreements with NDG density values and oven moisture content for the entire data set. Uncorrelated and 1-point correlated SDG data were less favorable. The EDG with sand cone soil model did not agree well with the sand cone, NDG, and oven data. The SDG measurements correlated by the sand cone also did not agree well with the sand cone, NDG, and oven data.

- The EDG with NDG soil model and the 3-point correlated SDG generally provided good to fair estimates of dry density and moisture content compared to the NDG and oven results. However, the gauges were often imprecise, especially in fine soil, and sometimes produced results that were significantly different from those obtained using the NDG and oven. Because of these differences and inconsistencies, the research team does not recommend EDG and SDG for QC/QA purposes at this time.

- The sand cone density values were highly variable and inconsistent. When the team correlated NNDGs with sand cone density values, the NNDGs did not agree well with the sand cone data.

- Testing a larger number of test spots in the soil model did not significantly change the EDG job site results. Soil models with 3, 5 and all (5 to 10) points did not have significant differences in the accuracy of readings.

- A minimally destructive prototype device designed to replace the metal dart for EDG electrical measurements showed very good potential. The research team encourages the continued evaluation of the prototype.

- The GeoGauge modulus and stiffness values showed no correlation with density values and moisture contents, which was as expected based on previous research.

Implementation of HMA NNDGs

HMA Devices

- The research team recommends the use of NNDG to replace current ITD NDG practice, because NNDGs perform as well as the current ITD NDG practice, when compared to the core results, but offer lower life-cycle cost.

- The research team recommends that wet pavement surfaces should be towel-dried or allowed to air-dry before taking measurements and no fines should be used underneath the device after towel-drying, if NNDG is used to measure the HMA density.

- Although fines and paint did not have a significant effect on the measurements, the team recommends that surface conditions must be consistent. If fines are used to correlate the gauges, they should be used on all subsequent measurements. Markings to outline NNDG footprints should have a minimal impact on NNDG measurements.

- The research team recommends the use of six-inch cores to correct HMA NNDGs.

- The recommended procedures, based on this study, are included in the revised ITD Field Operating Procedure (FOP) for AASHTO T 343 (Appendix C).

Recommended Further Studies

HMA Devices

- The research team recommends further studies to develop procedures to use HMA NDG and NNDGs to measure density values at the longitudinal joints.

- The research team recommends further studies to examine the accuracy of HMA NNDGs during production paving (any paving that occurs after the establishment of the test strip).

Devices for Unbound Materials

- The research team recommends further examination of SDG 200 for establishing roller patterns in CRABs and FDR projects. This study did not evaluate NNDG use on CRABS and FDR projects extensively. However, a few tested roller setups showed that SDG was reasonably capable of establishing break-over points. The team does not recommend either SDG or the GeoGauge for post-compaction pattern density measurements on CRABS and FDR bases.

- Due to late arrival of the plate-based EDG, only limited tests were conducted. However, it has high potential to be used to measure the dry density and moisture contents of unbound soils and is recommended to be further evaluated.

- The research team recommends further studies to evaluate the stiffness-based devices.

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Appendix A
Survey Results

This survey was intended to collect feedback on the use of current Non-Nuclear Density Gauge technology by state DOTs, for both HMA and unbound materials. We appreciate your timely response on this survey.

1. Has your agency used non-nuclear testing devices for measuring density and moisture content of unbound (soils and granular) and/or bound (HMA) materials?

   [15 of 40 responses to this question] Yes
   [25 of 40 responses] No

   If you answered no, please explain why not then skip to Question 3.

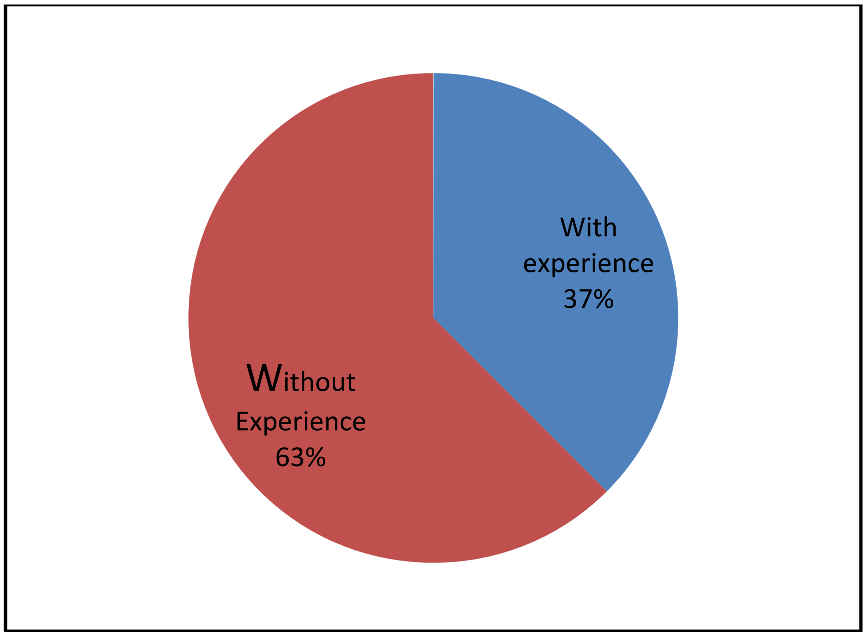


Figure 106. Agency Experience with NNDGs

2. What brands of non-nuclear gauges has your Department used?

   [12 of 23] Humboldt GeoGauge
   [8 of 23] Humboldt Electrical Density Gauge (EDG)
   [4 of 23] Trans Tech Soil Density Gauge (SDG)
   [2 of 23] Durham Moisture + Density Indicator
   [16 of 23] Pavement Quality Indicator (PQI) Model __________
   [10 of 23] PaveTracker
   [7 of 23] Other: ____

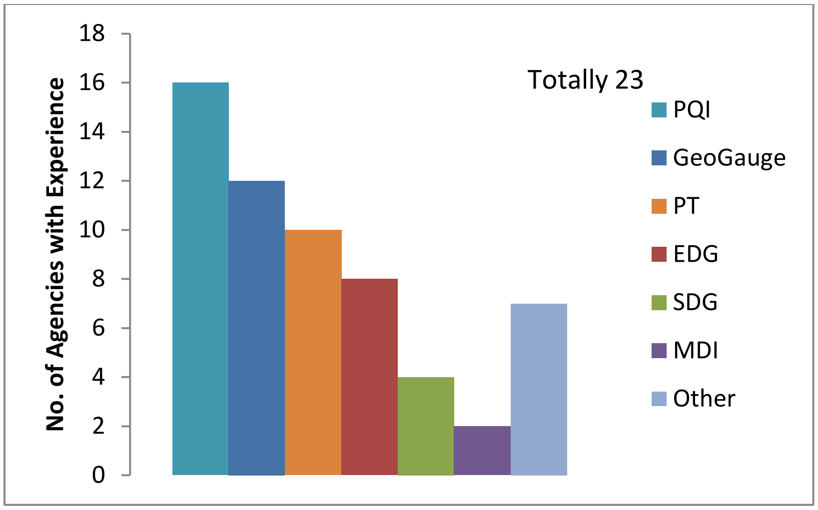


Figure 107. NNDGs Used by Agencies

2. What is your agency's current assessment of non-nuclear density gauges as a tool for measuring density and moisture content of unbound (soils and granular) and bound (HMA) materials? Please include comments as needed to explain why you answered as you did.

[10 of 27]	Device Acceptable Replacement to Nuclear Gauges
[16 of 27]	Further Study Is Needed Before Adoption
[6 of 27]	Device Modifications Needed Before Adoption
[9 of 27]	Not Acceptable as Replacement to Nuclear Gauges

*Note: Respondents can have multiple answers if experience with multiple NNDGs exists

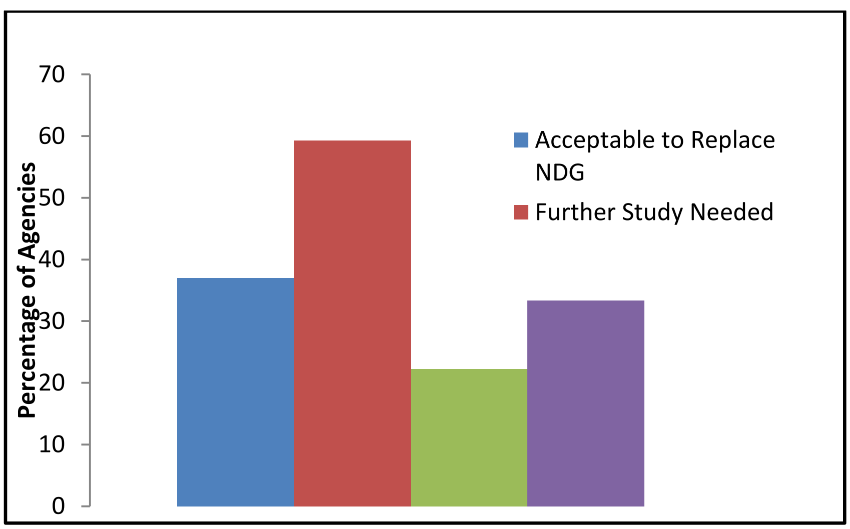


Figure 108. Agency View of Current NNDG Technologies

3. What would your agency consider to be an acceptable level of accuracy for these non-nuclear gauges to be accepted for use?

a. Unbound:

[10 of 25] Correlation with nuclear gauges: min. $R^2 > 0.85$
[8 of 25] Correlation with sand cone: min. $R^2 > 0.85$
[13 of 25] Deviation from true density < 0.5 - 3pcf values given
[5 of 25] Others: modulus based specs needed to replace NDG

b. HMA:

[5 of 29] Correlation with nuclear gauges: R^2 >0.7 - 0.99 values given
[17 of 29] Correlation with cores: $R^2 > 0.7$ - 0.99 values given
[11 of 29] Deviation from true density < 0.5 - 2pcf values given
[9 of 29] Other: ____

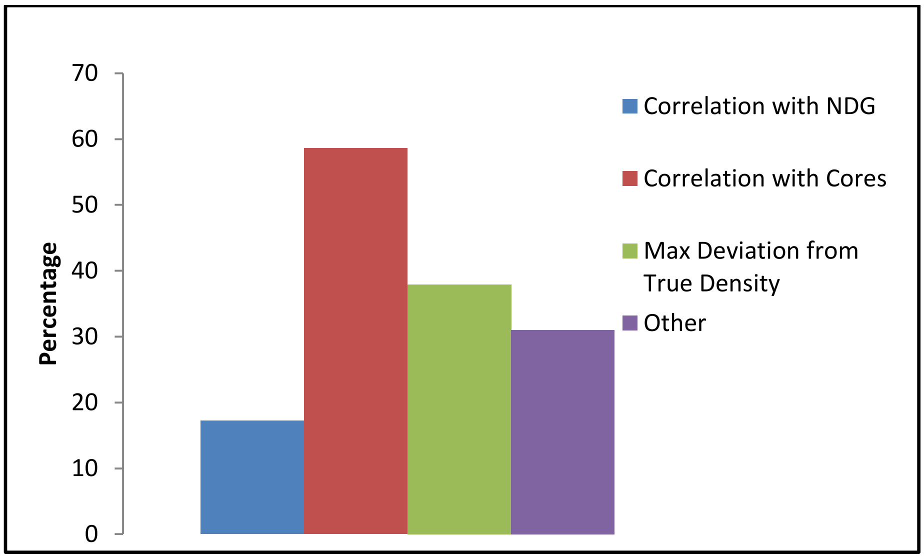


Figure 109. Agency Preferred Measure of Accuracy for HMA Devices

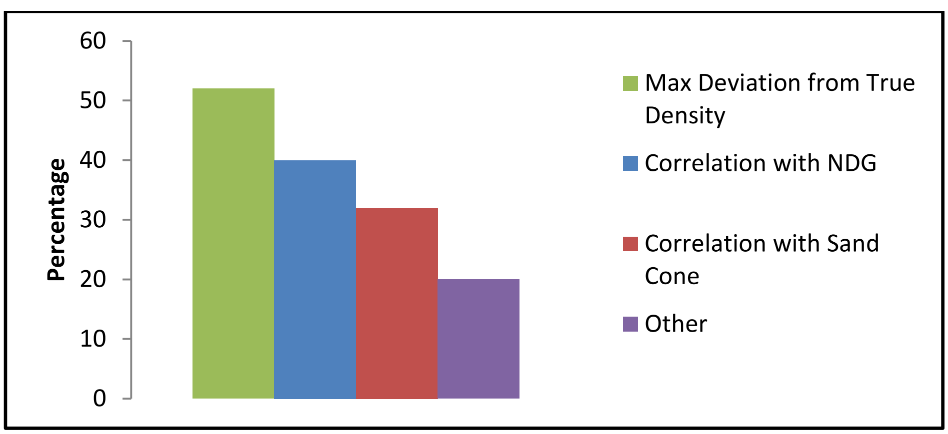


Figure 110. Agency Preferred Measure of Accuracy for Unbound Devices

4. What are the most critical factors to consider before adopting non-nuclear gauges (rank all that apply using 1 for the most important factor)?

   [1.15] Accuracy
   [2.86] Cost
   [2.77] Ease of Use
   [3.25] Speed
   [2.20] Other

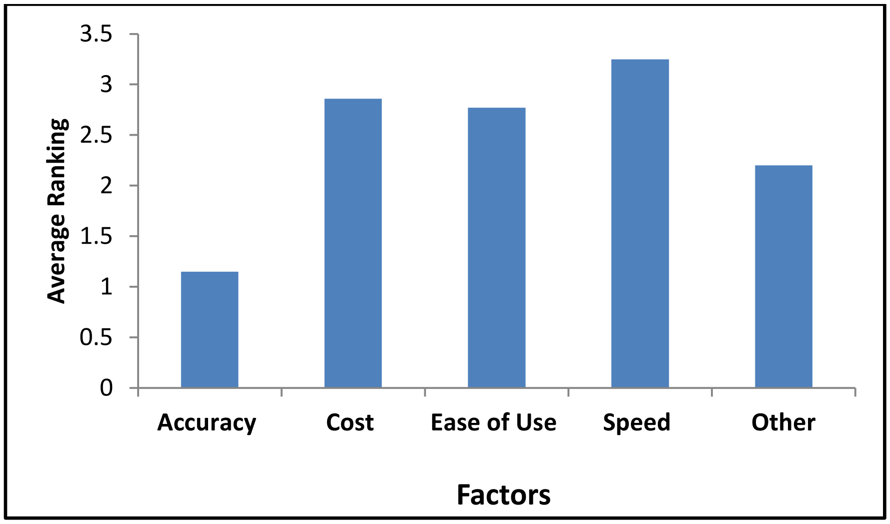


Figure 111. Critical Factors for NNDG Adoption by Agencies

5. Has your agency conducted or are you conducting any research, field studies, correlations studies, and/or experiments on non-nuclear testing devices?

   [21 of 40] Yes
   [19 of 40] No

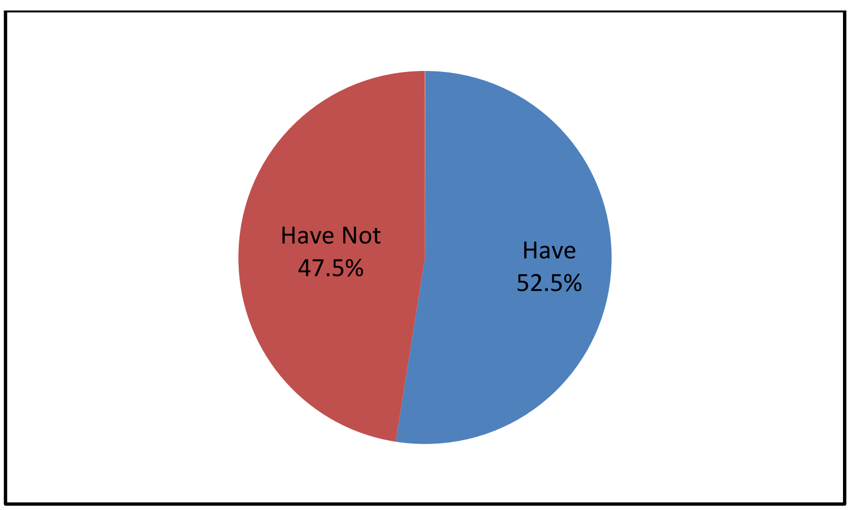


Figure 112. Percentage of Agencies that Have Performed NNDG Research

7. Does your Department have standards established for Non-Nuclear density devices?

[6 of 40] Yes
[34 of 40] No

Appendix B
HMA Project Data

Table 30. HMA Project: SH-78

		Correlation Locations					Validation Locations	
		1	2	3	4	5	6	7
PQI (Avg.)	H_2O Index	4.2	4.7	4.5	4.1	4.8	4.4	4.4
	Density (pcf)	117.8	118.0	118.5	116.8	117.7	117.5	117.4
	Temp. (°F)	160.7	153.0	157.2	165.5	168.4	170.2	163.5
PT (Avg.)	Density (pcf)	125.4	125.2	124.1	120.1	123.5	122.2	122.8
	Temp (°F)	154.0	150.0	154.0	161.0	163.0	165.0	159.0
NDG (4640)	Density (pcf)	140.4	143.1	143.7	139.9	140.9	139.6	141.7
Core Density (pcf)		139.3	140.5	142.9	137.6	140.2	138.9	138.9

Table 31. HMA Project: SH 8

		Correlation Locations					Validation Locations			
		1	2	3	4	5	6	7	8	9
PQI (Avg.)	H_2O Index	5.8	6.2	6.90	5.30	5.8	7.8	6.2	5.9	5.0
	Density (pcf)	144.5	144.8	149.50	144.80	146.7	151.3	148.2	146.1	140.0
	Temp. (°F)	149.4	135.7	140.70	164.50	168.6	134.1	150.1	144.0	142.0
PT (Avg.)	Density (pcf)	163.9	167.7	172.50	164.40	165.7	177.5	174.7	169.1	166.7
	Temp (°F)	145.0	141.0	145.00	167.00	164.0	135.0	143.0	139.0	139.0
NDG (4640)	Density (pcf)	151.4	150.8	151.95	149.75	151.6	-	-	-	-
Core Density (pcf)		145.7	147.6	150.90	147.90	149.0	152.2	150.3	147.7	145.6

Table 32. HMA Project: I-90 Pinehurst

		Correlation Locations					Validation Locations			
		1	2	3	4	5	6	7	8	9
PQI (Avg.)	H_2O Index	3.9	2.6	3.9	3.3	4.0	3.4	2.9	3.7	2.5
	Density (pcf)	117.3	118.2	118.5	117.5	118.2	117.1	117.7	118.1	118.1
	Temp. (°F)	106.2	110.7	107.0	106.0	114.1	140.2	132.7	117.4	117.4
PT (Avg.)	Density (pcf)	123.1	125.2	126.0	125.7	125.7	123.0	124.9	125.5	125.5
	Temp (°F)	106.0	112.0	112.0	112.0	115.0	136.0	130.0	117.0	117.0
NDG (4640)	Density (pcf)	142.2	140.4	145.0	143.0	142.6	-	-	-	-
Core Density (pcf)		141.3	144.5	146.7	143.2	144.7	144.6	144.8	146.2	144.3

Table 33. HMA Project: Beaver Creek (by ITD)

		Correlation Locations					Validation Locations	
		1	2	3	4	5	6	7
PQI (Avg.)	H_2O Index	-	-	-	-	-	-	-
	Density (pcf)	118.4	117.7	118.4	119.1	117.2	118.4	118.0
	Temp. (°F)	-	-	-	-	-	-	-
NDG (4640)	Density (pcf)	142.6	139.0	144.0	144.1	138.2	140.1	140.2
Core Density (pcf)		145.3	144.1	146.9	146.0	141.7	144.1	143.1

Table 34. HMA Project: US-95, Lewiston Hill (by ITD)

		Correlation Locations					Validation Locations				
		1	2	3	4	5	6	7	8	9	10
PQI (Avg.)	H_2O Index	-	-	-	-	-	-	-	-		-
	Density (pcf)	144.5	152.8	150.4	154.6	156.5	153.2	150.2	152.0	149.9	151.6
	Temp. (°F)	-	-	-	-	-	-	-	-	-	-
NDG (4640)	Density (pcf)	148.4	154.5	156.8	153.8	155.9	154.0	152.4	154.7	153.5	155.3
Core Density (pcf)		144.2	152.1	153.2	154.3	155.5	153.4	149.5	153.9	150.0	152.1

Table 35. HMA Project: US-95, Wilder Phase 1

		Correlation Locations					Validation Locations								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
PQI (Avg.)	H_2O Index	5.1	4.4	6.6	5.6	5.5	4.8	6.1	5.2	4.3	6.2	5.6	4.7	5.6	8.6
	Density (pcf)	118.7	118.4	118.9	119.3	118.9	119.0	119.1	118.7	119.5	119.2	119	118.6	118.2	116.7
	Temp. (°F)	135.7	140.2	134.0	139.9	135.6	141.0	133.0	145.0	138.8	127.1	132.1	13.06	130.8	131.5
PT (Avg.)	Density (pcf)	123.6	122.0	122.9	124.2	124.1	123.1	124.1	124.1	124.4	123.5	123.5	123.7	121.8	122.5
	Temp (°F)	136.0	144.0	129.0	134.0	135.0	143.0	130.0	133.0	134.0	124.0	131.0	131.0	130.0	131.0
NDG (4640)	Density (pcf)	138.8	135.5	140.4	139.8	143.9	138.9	140.0	133.9	136.2	135.8	135.7	137.7	135.5	136.2
Core Density (pcf)		137.2	136.4	133.9	139.0	137.4	137.4	137.3	138.3	140.9	137.0	140.2	139.7	137.6	138.1

Table 36. HMA Project: US-95, Wilder Phase 2

		Correlation Locations					Validation Locations	
		1	2	3	4	5	6	7
PQI (Avg.)	H_2O Index	4.8	4.9	4.7	4.5	4.8	4.8	4.5
	Density (pcf)	118.2	118.5	118.7	118.1	118.2	117.9	118.5
	Temp. (°F)	137.6	145.4	142.6	139.5	136.3	140.7	132.2
PT (Avg.)	Density (pcf)	121.8	123.2	123.9	122.3	121.6	121.4	123.1
	Temp (°F)	145.0	141.0	143.0	138.0	134.0	121.4	128.0
NDG (4640)	Density (pcf)	118.2	118.4	118.6	118.0	118.0	117.8	118.3
Core Density (pcf)		137.2	139.1	139.0	138.0	138.4	136.7	138.5

Table 37. HMA Project: US-95, Wilder Phase 3

		Correlation Locations					Validation Locations	
		1	2	3	4	5	6	7
PQI (Avg.)	H_2O Index	4.1	4.5	4.3	4.3	3.9	3.4	3.6
	Density (pcf)	119.0	117.3	116.8	117.7	118.4	116.4	117.7
	Temp. (°F)	133.3	129.9	129.9	123.2	132.8	136.0	142.3
PT (Avg.)	Density (pcf)	125.6	120.2	117.9	119.2	122.1	116.5	119.8
	Temp (°F)	135.0	132.0	124.0	121.0	133.0	130.0	139.0
NDG (4640)	Density (pcf)	142.3	137.3	139.0	134.4	136.1	136.4	134.1
Core Density (pcf)		141.1	132.2	132.2	133.6	137.1	131.3	136.6

Table 38. HMA Project: SH-37 Rockland 5.8 Asphalt Content

		Correlation Locations					Validation Locations			
		1	2	3	4	5	6	7	8	9
PQI (Avg.)	H_2O Index	7.0	4.4	5.2	9.9	6.4	9.0	5.2	5.9	5.3
	Density (pcf)	118.1	117.1	118.3	119.6	118.4	120.0	118.4	118.0	118.2
	Temp. (°F)	114.7	117.4	124.4	120.1	117.6	110.4	121.1	125.8	135.8
PT (Avg.)	Density (pcf)	120.5	117.1	123.0	125.6	122.9	124.8	123.2	117.9	122.8
	Temp (°F)	121.0	122.0	123.0	121.0	120.0	113.0	125.0	124.0	128.0
NDG (4640)	Density (pcf)	141.7	142.3	140.4	139.3	144.4	146.7	146.0	143.2	145.2
Core Density (pcf)		139.5	139.7	141.7	140.0	143.3	143.9	144.9	N/A	144.3

Table 39. HMA Project: SH-37 Rockland 6.0 Asphalt Content

		Correlation Locations					Validation Locations				
		1	2	3	4	5	6	7	8	9	10
PQI (Avg.)	H_2O Index	7.4	6.5	6.3	5.8	5.4	15.7	6.6	7.8	6.1	5.1
	Density (pcf)	118.5	118.5	119.1	118.5	118.2	123.9	117.8	118.8	118.2	118.2
	Temp. (°F)	138.9	126.2	108.3	121.7	137.1	134.8	128.5	120.7	127.8	136.2
PT (Avg.)	Density (pcf)	123.2	122.2	123.9	123.3	123.0	127.8	120.2	122.3	119.0	121.6
	Temp (°F)	130.0	123.0	113.0	114.0	141.0	128.0	129.0	121.0	123.0	131.0
NDG (4640)	Density (pcf)	140.8	143.1	144.7	144.3	144.3	144.4	140.3	146.3	143.7	145.7
Core Density (pcf)		140.8	139.8	144.5	144.5	144.3	142.4	139.4	143.1	141.5	144.3

Table 40. HMA Project: SH-55 Cascade

		Correlation Locations						Validation Locations					
		1	2	3	4	5	6	7	8	9	10	11	12
PQI (Avg.)	H_2O Index	3.1	3.0	3.3	3.7	3.3	3.6	3.3	4.2	4.2	4.1	3.7	3.6
	Density (pcf)	117.8	117.0	117.6	117.1	117.4	117.5	116.8	117.6	117.3	117.6	117.3	117.5
	Temp. (°F)	135.4	123.4	117.9	110.8	131.6	124.1	147.6	126.8	161.9	156	144.8	163.6
PT (Avg.)	Density (pcf)	118.8	117.5	117.8	116.3	117.6	118.6	116.9	119.4	120.4	117.6	117.6	119.1
	Temp (°F)	142.0	123.0	116.0	112.0	135.0	125.0	145.0	128.0	159.0	154.0	129.0	159.0
NDG (4640)	Density (pcf)	140.6	139.0	139.7	138.5	139.2	140.1	137.6	141.5	140.9	138.7	137.3	139.4
Core Density (pcf)		140.8	138.0	139.2	137.7	139.5	139.3	136.7	138.0	138.9	138.5	137.4	138.0

Table 41. HMA Project: SH-95 Athol

		Correlation Locations							Validation Locations						
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
PQI (Avg.)	H_2O Index	8.0	6.3	6.3	5.8	5.6	6.3	5.6	7.7	7.2	6.7	6.5	7.0	7.3	7.1
	Density (pcf)	119.4	118.9	118.5	118.2	118.0	119.2	118.3	119.1	118.8	119.7	119.4	118.6	118.4	118.2
	Temp. (°F)	113.8	106.8	108.4	107.6	113.9	97.4	112.5	124.3	126.9	130.6	129.9	128.5	128.2	130.8
PT (Avg.)	Density (pcf)	125.0	124.7	122.3	122.3	121.7	123.1	123.5	123.5	123.3	125.4	124.1	121.9	122.7	122.5
	Temp (°F)	104.0	110.0	103.0	98.0	108.0	97.0	116.0	128.0	114.0	132.0	128.0	128.0	127.0	118.0
NDG (4640)	Density (pcf)	144.2	144.8	144.2	141.2	140.6	143.5	142.0	137.8	141.4	146.0	145.0	142.7	140.2	139.9
Core Density (pcf)		147.7	146.6	145.0	143.9	144.8	147.0	144.8	144.4	144.2	149.8	148.3	145.9	144.2	144.6

Table 42. HMA Project: US-95 Smokey

		Correlation Locations					Validation Locations		
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
PQI (Avg.)	H_2O Index	4.4	4.8	4.9	4.3	4.5	4.6	5.1	4.6
	Density (pcf)	128.5	130.5	129.2	127.8	128.1	127.2	129.4	129.3
	Temp. (°F)	92.9	97.1	87.4	94.9	95.4	97.1	92.7	90.4
PT (Avg.)	Density (pcf)	145.9	146.6	145.2	142.5	143.8	141.6	146.1	145.8
	Temp (°F)	94.0	99.0	88.0	97.0	98.0	95.0	94.0	91.0
Core Density (pcf)		145.3	148.9	146.0	146.3	146.3	146.0	148.3	144.5

Table 43. HMA Project: US-12

		Correlation Locations					Validation Locations				
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
PQI (Avg.)	H_2O Index	4.3	4.6	4.4	4.6	4.4	3.9	4.0	4.2	4.2	4.3
	Density (pcf)	130.8	129.9	130.8	130.7	129.7	131.0	131.3	130.3	129.6	129.8
	Temp. (°F)	97.2	91.2	101.2	92.1	104.7	86.9	83.9	83.8	81.8	83.1
PT (Avg.)	Density (pcf)	146.7	145.5	148.4	148.3	145.5	145.2	146.9	144.2	144.0	143.5
	Temp (°F)	102.0	92.0	103.0	92.0	104.0	89.0	84.0	84.0	85.0	84.0
Core Density (pcf)		150.1	147.3	150.2	149.9	148.8	150.7	150.2	148.9	147.5	146.5

Appendix C
Recommended Changes to ITD FOP for AASHTO T-343

Changes are underlined {Comments are bracketed}

{Proposed Changes to}
Density of In-Place Hot Mix Asphalt (HMA) Pavement by Electronic Surface Contact Devices FOP for AASHTO T-343

Scope

This procedure covers the in-place density determination of Hot Mix Asphalt (HMA) in accordance with AASHTO T-343 using an electronic surface contact device/gauge. This field operating procedure is derived from AASHTO T-343. The gauge measures density and relative compaction of HMA pavements by measuring changes in the electromagnetic field resulting from the compaction process.

Apparatus

- Electronic surface contact gauge shall meet the following requirements:
  - Be housed in an enclosure of heavy-duty construction.
  - Function in the temperature and moisture levels experienced during the placement of HMA pavements.
  - Include the internal circuitry suitable for displaying individual measurements.
  - Include a continuous measurement mode of operation.
  - Provide power to the sensor which allows data acquisition, readout function, and calibration.

Calibration

Calibration of the gauge shall be performed as specified in the Idaho Transportation Department's Laboratory Operations Manual Section 200.

Standardization

Standardize the gauge daily per the manufacturer's instructions. Gauges are paired to specific standardization (reference) blocks. Use only the standardization block paired with the gauge. <u>Standardize gauges on the ground, at least three feet away from human, vehicles and other metallic objects</u>.

PQI 301. Establish initial reference reading with the standardization block after calibration. Calculate and record upper and lower limits. Record date. Record and compare daily readings to upper and lower limits. Remove gauge from service if values are not within limits

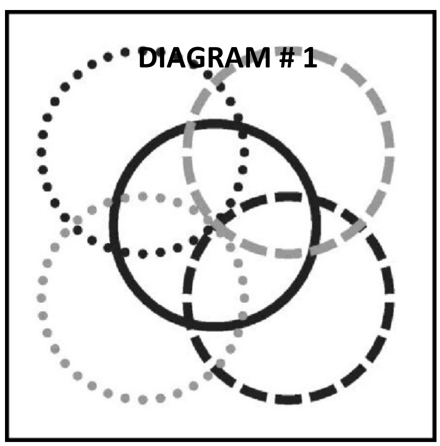
PQI 380. Record date. Record results (pass/fail). Remove failing gauge from service

Pavetracker. Record date. Remove gauge from service if it displays an error message. Verify the standardization by taking a continuous mode reading on the case standardization plate for 10 seconds. The reading shall stay within ± 0.5 lb/ft^3 of the reference value printed inside the gauge case. Remove gauge from service if requirement is not met {Suggested by Troxler representatives}.

Correlation with Cores

Correlate the gauge for each Job Mix Formula (JMF) and each pavement lift. These correlation measurements/readings should be taken at the same temperature range as the acceptance tests.

1. Determine the number of cores required for correlation. Cores shall be located on the first day's paving or on the test strip. For projects with test strips locate the test sites in accordance with the IT125. Test sites shall be determined using random sampling practices.
2. Clear any existing correlations from the gauge.
3. Place the gauge on the HMA mat at the test sites and draw an outline around the base of the gauge. The mat shall be flat, relatively smooth and clear of any loose particles. The mat shall have no noticeable moisture visible. If moisture is present, wait for the mat to dry or thoroughly dry location with a towel.
4. Perform and record five (5) measurements as shown in diagram #1. Determine and record the average test site measurement / reading.



5. Obtain a 6" core from of each test site in accordance with WAQTC TM 11. The core should be taken from approximately the center of the footprint.
6. Determine the density of the cores by the FOP for AASHTO T 166, Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface Dry Specimens.

7. Calculate the difference between the core density and the average gauge density at each test site to the nearest 0.1 lb/ft^3. Calculate the average difference and standard deviation of the differences for the entire data set to the nearest 0.1 lb/ft^3.

8. If the standard deviation of the differences is equal to or less than 2.5 lb/ft^3, the correlation factor applied to the gauge reading shall be the average difference calculated above in 7.

9. If the standard deviation of the differences is greater than 2.5 lb/ft^3, the test site with the greatest variation from the average difference shall be eliminated from the data set and the data set properties and correlation factor recalculated.

10. If the standard deviation of the modified data set still exceeds the maximum specified in 8, additional test sites will be eliminated from the data set and the data set properties and correlation factor recalculated. If the data set consists of less than five (5) test sites, additional test sites shall be established.

11. Adjust the gauge, following the manufacturer's procedures, to account for the average difference. This will calibrate the instrument to the HMA mat by adding (or subtracting) the average difference.

Core Correlation Example:

Core Density	**Avg. Test Site In-Place**	**Difference**:
T-166:	**T-343:**	
144.9 lb/ft^3	117.1 lb/ft^3	27.8 lb/ft^3
142.8 lb/ft^3	116.4 lb/ft^3	26.4 lb/ft^3
143.1 lb/ft^3	116.6 lb/ft^3	26.5 lb/ft^3
140.7 lb/ft^3	116.1 lb/ft^3	24.6 lb/ft^3
145.1 lb/ft^3	117.3 lb/ft^3	27.8 lb/ft^3
144.2 lb/ft^3	116.9 lb/ft^3	27.3 lb/ft^3
143.8 lb/ft^3	116.7 lb/ft^3	27.1 lb/ft^3
	Average Difference:	**+ 26.9 lb/ft^3**
	Standard Deviation (n – 1):	1.11 lb/ft^3

Procedure

1. Select a test location(s) randomly and in accordance with ITD requirements. Ensure that the device is correlated in accordance with "Correlation with Cores Section". Locate the measurement area away from any known sources of electromagnetic interference such as overhead high-tension power lines or large metal objects.

2. Brush the surface clear to remove any loose particles. It shall be flat, relatively smooth and clear of any loose particles. <u>The mat shall have no noticeable moisture visible. If moisture is present, wait for the mat to dry or thoroughly towel dry location prior to testing. No fines shall be used after towel-drying.</u>

3. Place the gauge firmly on the test surface and trace an outline around the probe (base) of the unit. <u>The gauge shall be at least three feet away from human, vehicles and other metallic objects</u>.
4. Perform and record five (5) measurements as shown in diagram #1. Determine and record the average test site measurement / reading

Calculation

<u>Density measurements / readings from gauge at single location: 117.1 lb/ft^3, 116.9 lb/ft^3, 117.3 lb/ft^3, 116.8 lb/ft^3, and 117.3 lb/ft^3</u>

<u>Offset Calibration</u>

<u>Avg. Density at single location: 117.1 lb/ft^3</u>
<u>Core Correction Offset: 26.9 lb/ft^3</u>
<u>Avg. Corrected Density: 144 lb/ft^3</u>

Percent Compaction

Percent compaction is determined by comparing the average corrected test site density as determined by this procedure to the maximum density from AASHTO T 209.
G_{mm} and maximum density from the FOP for AASHTO T 209: G_{mm} = 2.466 = 153.5 lb/ft^3

$$\frac{\text{Corrected Reading}}{\text{Maximum Density}} * 100 = \%\ \text{Compaction}$$

$$\frac{145.2}{153.5} * 100 = 94.6\%$$

Report

Results shall be reported on standard forms approved by ITD. Include the following information:

- Location of test and thickness of layer tested
- Visual description of material tested.
- Make, model and serial number of the density gauge.
- Individual Density readings to 0.1 lb/ft^3.
- Average Density readings to 0.1 lb/ft^3.
- <u>Average</u> Core Correction to 0.1 lb/ft^3.
- Maximum density to 0.1 lb/ft^3.
- Percent compaction to 0.1%.
- Name and signature and STQP / WAQTC qualification number of the tester.

Performance Exam Checklist

Density of In-Place Hot Mix Asphalt (HMA) Pavement by Electronic Surface Contact Devices

FOP for AASHTO T-343

Participant Name ______________________________ **Exam Date** ______________

Record the symbols "P" for passing or "F" for failing on each step of the checklist.

Procedure Element	**Trial 1**	**Trial 2**
1. Gauge turned on?	_____	_____
2. Test location selected away from any known sources of electromagnetic interference such as overhead high-tension power lines or large metal objects?	_____	_____
3. The HMA surface is free of moisture, relatively flat, and smooth?	_____	_____
4. Surface brushed clear of loose particles?	_____	_____
5. Gauge placed firmly on HMA surface?	_____	_____
6. Outline traced around base?	_____	_____
7. Five (5) measurements taken per diagram # 1 and recorded?	_____	_____
8. Average density and temperature calculated?	_____	_____
9. <u>Correction equation or average offset applied to obtain corrected density?</u>	_____	_____
10. Compaction calculated to 0.1%?	_____	_____

Comments: First attempt: Pass ☐ Fail ☐ Second attempt: Pass ☐ Fail ☐

____

____

Examiner Signature ______________________________WAQTC #:_______________

Examiner Signature ______________________________WAQTC #:_______________