COMPARISON OF NUCLEAR AND NON-NUCLEAR DENSITY GAUGES FOR DETERMINING IN-PLACE DENSITY OF HOT MIX ASPHALT

By

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A thesis submitted in partial fulfillment of

the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

WASHINGTON STATE UNIVERSITY
Department of Civil and Environmental Engineering

August 2012

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ACKNOWLEDGMENT

First, I would like to thank my advisor, Dr. Haifang Wen for all of his support. I would like to thank you so much for supporting me financially throughout this whole process. I would not be where I am today without the opportunity to work on this project.

I would also like to thank Dr. Shihui Shen for her knowledge and encouragement. I learned a lot from you through the classes we had together. Thank you for always being there to help me in any way you could.

Additionally, I would like to thank Dr. Sunil Sharma for helping to co-author this study and offering his expertise throughout this process. Lastly, I would like to thank Dr. Balasingam Muhunthan for agreeing to serve on my thesis committee.

A special thanks to the Idaho Department of Transportation as well for their support with this project.

Thank you everyone.

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Abstract

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August 2012

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Ensuring that an HMA mat is compacted uniformly to an adequate density is very important to the performance of the pavement structure over the project life. Nuclear density gauges (NDGs) have been used for many years in pavement construction as a method of non-destructive density testing. Non-nuclear density gauges (NNDGs) perform the same function as NDGs. However because NNDGs are not powered by a nuclear source material, they are not subject to the same extensive fees and regulations as NDGs. Field and laboratory testing results for two NNDGs, the Troxler PaveTracker and Transtech PQI, were analyzed in order to determine if the NNDGs could serve as viable replacements to NDGs. A number of potential factors that could affect the accuracy of NNDGs were studied. Ability of the NNDGs to establish a roller pattern and take readings at longitudinal pavement joints was also analyzed. Global factors of aggregate mineralogy, nominal maximum aggregate size, HMA class, and aggregate absorption were shown not to significantly affect the NNDGs. Local factors of surface fines and surface markings were also shown to have no significant affect on NNDG readings. Temperature and moisture were shown to affect NNDG readings. The NNDGs in general showed stronger correlations with core densities than the NDGs did. Further study on moisture, longitudinal joints, and roller patterns are suggested. Additional data is also needed to examine interactions between global factors for the PaveTracker.

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Dedication

This thesis is dedicated to my parents, grandparents and all of the rest of my family and friends who supported me in so many ways. None of this would have been possible without all of you. Thank you.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Density is a factor used in many pavement design methods, including AASHTO. Current methods of determining in-place density of hot mix asphalt (HMA) with cores are destructive. Because of this many agencies make use of nuclear density gauges for rapid, non-destructive density readings in the field. Lenz (2011) cites numerous studies indicating that “compaction is the greatest determining factor in dense graded pavement performance.”

Nuclear density gauges (NDGs) operate by measuring scatter of gamma radiation. Nuclear material is heavily regulated and requires extensive training and permits in order to operate. Storage and transportation are also inconvenient and expensive. The gauges may be unable to be brought onto Federal and/or military property as well. Non-nuclear density gauges (NNDGs) are not subject to these heavy regulations and are often smaller and more easily handled than NDGs.

NNDGs determine HMA density by measuring the electrical impedance at a chosen frequency of alternating current (Allen, 2003). The ability of the HMA to store electrostatic energy per unit volume is called the dielectric constant, and is determined from the electrical impedance. The dielectric constant of air is 1, while that of HMA (aggregate and binder) is 5-6. overall constant of the entire HMA mat is a weighted (by volume) average of the air and HMA constants (Allen, 2003). Figure 1.1 (Allen, 2003) shows a schematic of the operation of the PQI.

The PaveTracker is operates on the same principles as the PQI (Williams, 2008).

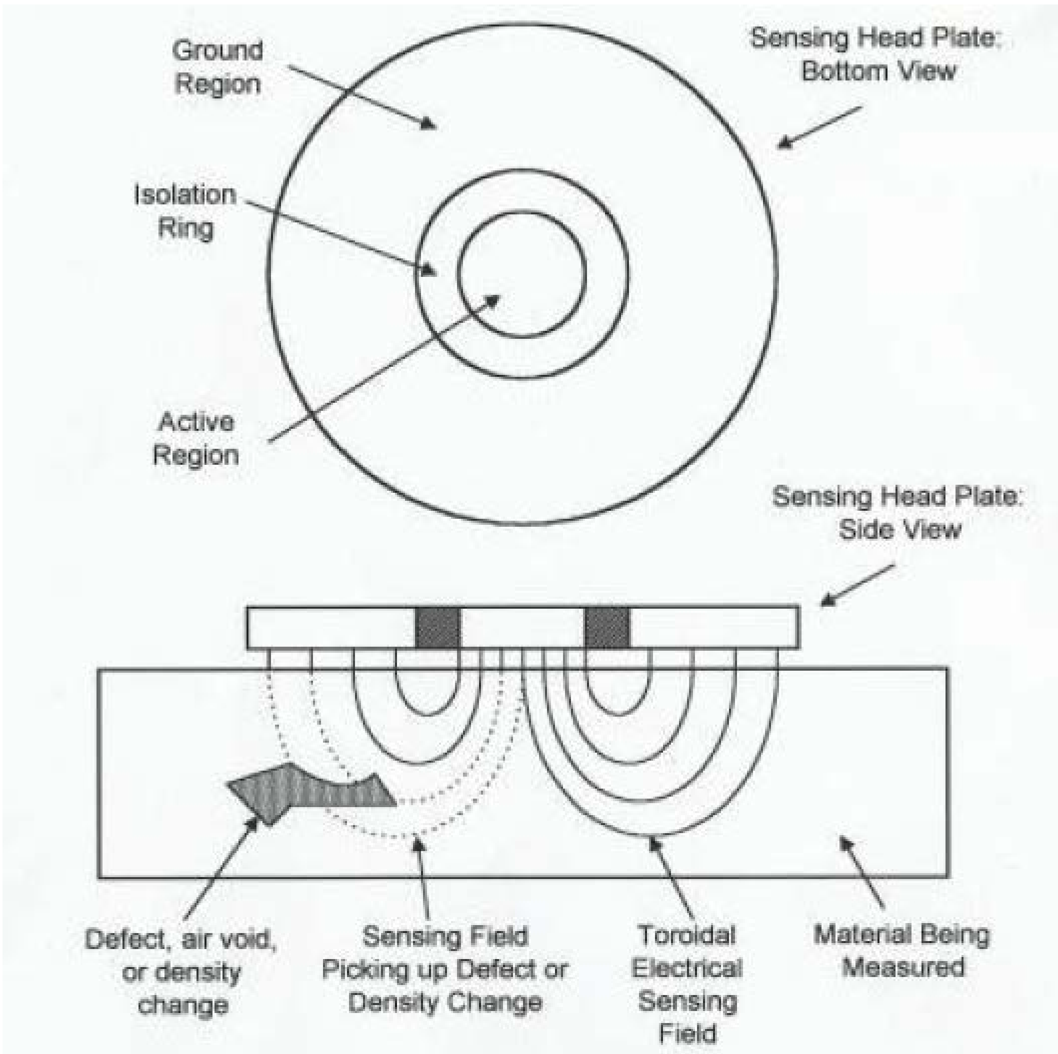

Figure 1.1. Operation of PQI.

In addition to density, many NNDGs also measure other parameters such as temperature and water content which may affect the readings provided by the NNDGs.

1.2 ORGANIZATION OF THESIS

This thesis is organized into chapters, which consist of sections and subsections. Chapter 1 provides an introduction to the project and gives some background on NNDGs. Chapter 2 is the literature review and survey of DOTs, which summarizes current research into NNDGs as well as responses received from a survey administered to DOTs around the country. Chapter 3 is the project background, which provides an introduction to the testing performed as well as the methodology and reasoning behind the testing. It also provides more detailed information about each project. Chapter 4 details the results and analysis of both field and lab testing. Chapter 5 contains the conclusions and recommendations reached from this study. Chapter 6 provides a list of references and Appendix A contains detailed survey information. Appendix B contains recommended procedures for PQI and PaveTracker testing.

CHAPTER 2: LITERATURE REVIEW AND SURVEY

2.1 DESIGN CONSIDERATIONS

Air voids is an important parameter for asphalt design. Density measurements in the field are performed to achieve designed air voids and consistency within the pavement. If areas of the asphalt pavement have lower density than the surrounding pavement, early failure is likely to occur at these locations. Identifying these locations during construction allows corrective actions to be performed, resulting in more uniform pavements. Density gauges can be used to determine the overall density of a pavement and also “are considered ideal to locate spots with or sections with low density” (Romero, 2002). Traditionally, NDGs, as well as field cores, are used to determine the density of hot mix asphalt in the field. Considering the complications with traditional NDGs, NNDGs are studied to replace nuclear gauges. A few non-nuclear gauges were reviewed, and described in the following sections.

2.2 PAVEMENT QUALITY INDICATOR (PQI)

The PQI is developed by TransTech; there are 2 Models, the 300 and 301. The 301+ is the 301 with improved software in order to improve gauge accuracy. The PQI used by WSU for this study was SN 897, shown in Figure 2.1. It is significantly smaller (12 pounds) than most NDGs and requires no warm up time as well as taking much shorter measurements (around 3 seconds) than NDGs. The gauges need to be calibrated in order to correct for their bias and measure true density, or can be used right out of the case for relative density (e.g. finding locations of lower density than surrounding material) (Sully-Miller, 2000).

Figure 2.1. PQI Non-Nuclear Density Gauge.

PQI readings have been shown to be affected by changes in gradation of HMA aggregate, aggregate source, and temperature between the reference material used to calibrate the gauge and the field material (Romero, 2002). The Romero (2002) study also indicated that high internal moisture contents can cause problems with the PQI readings, and concluded that an H_20 index reading of less than 5 was necessary to obtain meaningful density measurements. Sargand (2005) agrees, concluding that with increased surface moisture gauge readings decreased appreciably, and with internal moisture without surface moisture, gauges read far larger than core densities. They found that the max surface moisture level at which moisture is not a significant factor is 0.05 pounds per square foot (psf). Williams (2008) reported that moisture, surface debris, and presence of paint markings on the surface of the material can significantly affect PQI accuracy as well. Schmitt (2006) reports that air voids, asphalt content, pavement thickness and aggregate specific gravity can all affect the differences between NDG and NNDG readings. Mason (2009) found that traffic and binder content were all statistically significant factors affecting adjusted PQI readings. All of the literature agrees that it is critical to calibrate the gauge with the specific mixture being used in the field in order to obtain accurate readings.

Sully-Miller (2000) concludes that “PQI 300 is a reliable and accurate instrument to measure in-place density of compacted asphalt concrete.” Romero (2002) concludes that the PQI 300 is suitable for quality control (QC) to measure relative changes in density; however difficulty in calibrating the device daily in the field makes it unsuitable for quality acceptance (QA) work. Allen (2003) used two PQI 300’s operated by two different teams; one gauge's results most closely matched the lab cores, one least closely matched, with the NDG in the middle. This shows how important experience in operating the machine is as the more experienced group obtained the better results. Due to the inconsistencies between two PQI 300s Allen (2003) concludes that PQI is suitable for QC, more research and development of the device are needed before the PQI can be used for QA. Williams (2008) concludes that when properly calibrated, PQI be used for QC purposes, but not for QA.

Sebesta (2003) concluded that the PQI, PaveTracker, and Troxler 3450 NDG are all affected by mix temperature and moisture, though as long as site was not excessively wet, the PQI provided stable readings. The lift thickness input was found to make only 0.3 pounds per cubic food (pcf) difference in device reading when thickness input was varied from 1-8 inches. The PQI had a smaller standard deviation than the NDG in laboratory testing (0.5 pcf vs 1 pcf for NDG), however both gauges were found to be very repeatable. Field results concluded that the PQI results matched core results for mainline and joint density profiles whether calibrated or not, thus making it an acceptable alternative to NDGs. It was additionally concluded that in general the PQI provides a more accurate estimate of density differentials than the NDG (Sebesta, 2003).

Schmitt (2006) points out that as of the time of that study NDGs were the only feasible way for calibrating NNDGs other than cores, and thus an NDG was still required in the field. This would appear to eliminate the point of using the NNDG.

Apeagyei (2011) concluded that the PQI 301 results did not correlate well with core density or NDG measurements and thus was not suitable for measuring asphalt concrete density for acceptance purposes. Cho et al. (2011) found that while NDG has slightly higher correlation than the PQI with cores, the average difference between the NDG and PQI were not significant and the PQI delivered more consistent results and had a smaller standard deviation than the NDG. Additionally, when cores have a density higher than 90% of maximum theoretical density (MTD), the PQI is statistically more accurate and has a much better coefficient of correlation than the NDG (Cho et al, 2011). Cho et al. further conclude that only cores that fall between 89-

93% of MTD should be used to calibrate the PQI, and that eight such cores should be used in order to achieve optimum performance.

Ziari (2010) found that measurements at the edges of asphalt pavements were lower than at the medium of segments. Ziari (2010) asserts that calibration of the PQI is highly critical and their results indicated that PQI measurements were not significantly different with a probability of 95%. It was determined that PQI 301 was sufficient for both QC and QA. Larsen (2006) concludes that the PQI 301 was not useful for detecting non-uniformity in pavement. The PQI 301 showed a greater range of density in the more uniform sample, and vice versa.

Sargand et. al (2005) contend that many studies on NNDG effectiveness are flawed. They contend many studies contain questionable statistical analysis, do not combine enough data to make an adequate sample size, and following the manufacturer recommendations for calibrating NDGs but not calibrating NNDGs daily as recommended, thereby biasing results towards NDGs. Without daily calibration, results differed from both core densities and NDG results with statistical significance. After applying daily mix-specific offset to gauge results as recommended by manufacturers the PQI results had higher P-values than NDG results, indicating that PQI results agreed better with laboratory core results than did the NDG results. Thus, provided daily calibration is followed, the PQI is recommended for both QC and QA work.

2.3 PAVETRACKER

The PaveTracker, seen in Figure 2.2, is developed by Troxler. It is comparable in size to the PQI (11 pounds), takes readings in 2 seconds, and also requires no warm up time. Like the PQI, the PaveTracker calculates the density of an asphalt pavement by measuring the impedance of the pavement to an alternating current. The PaveTracker used in this study was a Troxler PaveTracker Plus, Serial Number (SN) 64454.

Figure 2.2. PaveTracker Non-Nuclear Density Gauge.

Apeagyei's (2011) lab study concluded that the PaveTracker Plus measurements did not correlate well with core density or NDG measurements and were less sensitive than the NDG tested. The PaveTracker performed better than the PQI 301 in terms of correlation with measured core density, relative bias, and relative errors. Neither NNDG in this study was deemed acceptable for density acceptance measurements in Virginia.

Romero (2002) concludes that the PaveTracker is not suitable for QA purposes or determining pay factors but was accurate for QC applications. PaveTracker measurements were found to be statistically different than core density in 82% of 38 total projects, and had a high correlation with core density in 55% of projects and a low correlation in 14% of projects. It was concluded that proper calibration is critical for NNDGs and that difficulty keeping the

PaveTracker accurately calibrated in the field made it unsuitable for QA. Mason (2009) agrees, finding that the PaveTracker correlates well with core densities but must be correlated each day with cores in order to remain accurate, thus is unsuitable to QA work but can be used for QC.

Williams (2008) concludes that moisture, surface debris, presence of paint, and gauge orientation significantly impacted PaveTracker accuracy. The PaveTracker was the most variable with the weakest relationship to core densities when compared to the PQI 300 and NDG. The PaveTracker was deemed inadequate for use as a QA tool. Schmitt (2006) found that PaveTracker consistently read lower than the NDG. NNDG biases were showed to change between mixture types or paving days within the same project. Daily calibration was recommended for each project. Larsen (2006) concludes that PaveTracker does not appear useful for measuring non-uniformity in pavement.

Sargand (2005) determined that the PaveTracker performance was not significantly influenced by surface temperature, and performed better with fine mixtures than coarse. Both surface and internal moisture were determined to significantly affect gauge readings. Area of laboratory specimen used to evaluate the device affected the accuracy of PaveTracker, with larger specimens resulting in larger density readings. It was also determined to be critical that the specimen to be measured was thicker than the measuring depth of the PaveTracker, approximately 1.75 inches. The PaveTracker was determined to be suitable for QC purposes, but not recommended for QA testing.

2.4 DEVELOPING TECHNOLOGIES

NNDGs are a continually developing field, with new technologies being developed every day. The current trend is towards developing "full coverage" non-nuclear technology, not necessarily measuring density. The belief is 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 construction. Two such developing technologies are the infrared imaging system and the instrumented roller, both of which attach directly to the rollers at the job site.

2.4.1 INFRARED IMAGING SYSTEM

The infrared imaging system involves a bar attached to a rolling compactor which uses infrared sensors to measure the temperature of the pavement as its being compacted. "Substantial research indicates that temperature differences in excess of 25°F indicate potential segregation in the HMA mat" according to Scullion (2006). By measuring the temperature of 100% of the HMA mat as it's being compacted, areas with significantly different temperature could be examined for segregation. The system is part of an effort to quality control 100% of pavement surface, rather than testing a few spots throughout.

2.5 SUMMARY OF LITERATURE

There has been an increasing demand for moving away from using nuclear density gauges for in-situ pavement measurements. NDGs are expensive to transport and maintain, as well as train people to use correctly. They are also not allowed on certain federal properties and military bases.

The research shows that when attention is paid to the calibration process, NNDGs are capable of measuring in situ density of various paving materials as accurately, or even more accurately in some cases, than the NDGs currently used on many paving projects. NNDG measurements are also affected by a variety or surface conditions with HMA, but these conditions can mainly be easily avoided by keeping the surface clean.

The NNDGs for measuring pavement density are mostly regarded as suitable for quality control but not for quality acceptance or determining pay factors. Their fast rate of measurement and portability make them suitable for finding low density spots in pavement during compaction. The NNDGs can measure relative changes in density without calibration, making them a valuable option for quality control work. Proper calibration of all gauges according to manufacturer's suggestions is recommended for all gauges regardless of intended use, in order to maintain accuracy and precision in measurements.

2.6 SURVEY OF DOTs

A survey regarding Non-Nuclear Density Gauge (NNDG) use was sent out to various departments of transportation all over the country inquiring about their experience with and opinions of currently available NNDG technology. Detailed survey response information can be found in Appendix A. Of the 40 respondents, 37% had experience with NNDGs. When asked if they had performed research or established standards for NNDGs, 52.5% reported having conducted some sort of research or experiment, but only 15% had established standards for any type of NNDG technology.

The NNDG that most were experienced with was the Pavement Quality Indicator (PQI), with 69% of the agencies having some experience with the device. The majority of agencies indicated that one or more of the NNDGs they had experience with required further study before judgment was made on its applicability to replace current NDGs.

When asked what their agency would deem acceptable accuracy for an NNDG to replace current NDGs, the majority of agencies preferred a minimum correlation with a current test such as NDG, sand cone, or cores. For unbound materials, the minimum R^2 value for these correlations varied by agency between 0.8~0.99, and the maximum deviation from true density ranged from 1~3 pcf. For HMA, the minimum R^2 values ranged from 0.7~0.99, with the maximum deviation from true density (which is essentially the same requirement as a minimum correlation with cores) ranged from 1~2 pcf. Some agencies expressed that they intended to stay with NDGs, or that for the non-nuclear stiffness gauges that new standards would have to be developed which relied on stiffness instead of density for pass/fail criteria. In addition, these agencies indicated that the gauges had to be accurate enough for the agencies current standards, as accurate as the NDGs, or that gauges were currently only acceptable by the agency for use in quality control.

Agencies were also asked to rank from 1-5 (5 being the most impotant), the most important criteria of NNDGs to them among accuracy, cost, ease of use, speed, and other. Accuracy was easily the number one criteria, with ease of use and cost a virtual tie for second, and speed fourth. Other agencies were mostly concerned with repeatability of results, and a few expressed that the NNDGs would have to be accepted by industry and provide similar or better results than current NDGs.

CHAPTER 3: PROJECT BACKGROUND

This study was performed in conjunction with the Idaho Transportation Department (ITD). Testing of the NNDGs was conducted at field projects around Idaho, as well as in the laboratory at Washington State University. The effects of both global (i.e. aggregate size, HMA class) and local (i.e. debris, moisture) factors were studied. The primary goal of this project is to determine the suitability of the Troxler PaveTracker and Transtech PQI as replacements for the NDGs.

3.1 FIELD TESTING

HMA field testing was conducted with the PQI and the PaveTracker NNDGs, as well as contractor and ITD NDGs and occasionally ITD PQIs. Testing was conducted at all spots cored for calibration by ITD or the contractor, usually 5~7 spots. When it was possible, additional cores (up to 7) were taken for joint tests. All spots tested with the NNDGs were also tested with NDGs.

Field testing procedures were conducted as follows:

- Input mix design and pavement mix data as specified in manufacturers manual
- Determine roller pattern with devices in continuous mode
- Test calibration locations in average mode
- Obtain NDG readings at calibration locations

- Re-test calibration locations
- Core calibration locations
- Perform local factor testing at research locations in average mode
    - Bare HMA
    - Surface fines
    - Surface moisture
    - Surface paint
- Core research locations

Testing was conducted at all calibration locations without surface fines, and again after fines had been added for the NDG readings. NNDG readings were conducted alongside NDG readings between every roller pass of the pavement test strip until the NDG found a “break over point.” The break over point is the point at which the density reading stops increasing with each roller pass and the subsequent reading decreases. The number of roller passes at which the density reading stops increasing is the number of passes used to compact the pavement during the project. Testing of this proved difficult to record in time, after waiting for the NDG, to move out of the way of the roller.

In average mode, five PQI readings were taken with the average result recorded. Figure 3.1 (Sebesta, 2003) shows the PQI measurement pattern for average mode. Two PaveTracker readings, with the gauge rotated 180° between readings, were averaged.

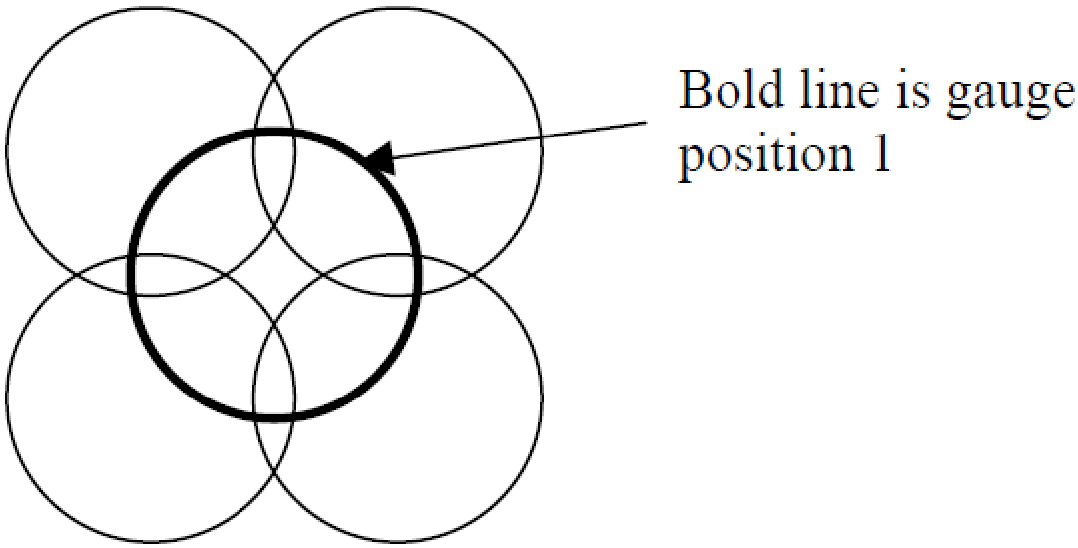

Figure 3.1. PQI Measurement Pattern

For local factor testing at research locations, readings were first taken on bare HMA. Fines were then applied to the surface to fill in surface voids. The fines were then brushed off as much as possible and the surface was sprayed with water and measurements repeated. As soon as the water had evaporated, the surface was sprayed with spray paint and readings were taken. Test location stationing was recorded along with any other test location information available.

Testing was also performed at seven locations along the longitudinal joints of the pavement, when additional coring was available. Test locations were to be equal to the lift thickness or a minimum of two inches from the pavement joint, but given the size of the machines' testing surfaces, it sometimes wasn't possible to get that close and maintain continuous gauge contact. Testing was instead performed as close to the joint as possible while maintaining complete contact with the pavement with the NNDGs test plate. If two lanes were being paved, seven readings were to be taken when the joint was unconfined, then at the same location when the other lane was paved and the joint became confined. If one lane was being paved, the seven locations were only tested once as the joint would never be unconfined.

Initially an additional five spots were to be tested every 1~1.5 hours as the HMA cooled, however all of this testing proved difficult to accomplish in one day, so data was often sporadically timed while testing occurred at other locations. Temperature effects were also tested in the laboratory. After testing was concluded the model of each contractor and ITD gauge was recorded. ITD was contacted after project conclusion in order to obtain core density information.

Field testing was conducted at paving projects throughout Idaho. The PQI and PaveTracker provided to WSU were taken to all field projects for which they were functional, the PaveTracker malfunctioned for part of the paving season. Field testing data from previous ITD testing of the PQI was also included in the analysis of the PQI. HMA mix properties for all projects are shown in Table 3.1. Further details regarding specific projects are given in the subsections below.

Table 3.1. Field Project Mix Properties.

Project Mix Properties					
Project	**HMA Class**	**Lift Thickness (in)**	**NMAS (in)**	**Aggregate Source**	**Aggregate Absorption (%)**
SH-51	3	1.8	0.5	Gravel	1.4
I-84	6	2.7	0.75	Granite	1.3
SH-8	4	1.8	0.5	Basalt	2.6
I-90	5	2	0.5	Gravel	0.1
US-12	2	2.4	0.75	Basalt	2.2
US-95 Frontage	3	1.2	0.5	Gravel	0.9
US-95 Lewiston	5	1.92	0.75	Basalt	1.5
Beaver Creek Rd	3	3	0.75	Gravel	1.3
US-95 Wilder	4	1.9	0.5	Granite	0.34
SH-37	2	1.8	0.5	Gravel	1.17

Table 3.2. Data Obtained at Projects.

Data Obtained at Project						
Project	**PQI**	**PaveTracker**	**Local Factors**	**Longitudinal Joints**	**Temperature**	**Roller Pattern**
SH-51	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	Yes	Yes*	Yes	No	No	Yes
US-95 Frontage	Yes	No	Yes	No	No	No
US-95 Lewiston	Yes	No	No	No	No	No
Beaver Creek Rd	Yes	No	Yes	No	No	No
US-95 Wilder	Yes	Yes	Yes	Yes	No	Yes
SH-37	Yes	Yes	Yes	Yes	Yes	Yes

3.1.1 SH-51, MP 60, Grandview, ID. Project A011(575)

Project A011(575) was located on State Highway 51, from Milepost 60 to Snake River Bridge, in Grandview, ID. Testing was performed July 18-19, 2011. Mix design was performed by Strata, dated June 23rd, 2011.

Testing was performed with the PaveTracker, three PQIs, and one Troxler 4640B NDG (SN:2307). The WSU PQI as well as ITD PQIs #753 and #896 were used. The NDG belonged to the contractor on the project. The NDG was only tested with fines on the surface. Seven cores were taken with all local factors applied, these locations were also used for gauge calibration. The ITD PQIs were only used on bare HMA, while both WSU NNDGs tested all local factors. Seven additional cores were taken on the unconfined joint at the midline of the road after the first lane was paved. Readings were also taken at the confined joint the next day in the other lane, however cores were unable to be obtained. Readings were taken at six additional locations 2-3 hours apart to test for temperature effects. Readings were attempted at the same location as the NDG while the contractor was establishing their roller pattern, however it proved too time consuming to test with three gauges in the time it took the roller to come back to that location.

3.1.2 I-84, Nampa, ID. Project A010(916)

Project A010(916) was located on Interstate 84, from Franklin Blvd to 11th Ave, in Nampa, ID. Testing was performed July 28, 2011. Mix design was performed by Central Paving Co., dated September 27th, 2010.

Five cores were taken of the HMA mat, which was only a short stretch underneath of an overpass. These five locations were tested with all local factors with both the PQI and PaveTracker, as well as a contractor NDG. The NDG was only tested with fines on the surface. Testing was additionally performed on the confined joint that was present, however additional coring for this site could not be obtained.

3.1.3 SH-8, Moscow, ID. Project A012(001)

Project A012(001) was located on State Highway 8, from White Place to South Fork Palouse River Bridge in Moscow, ID. Testing took place on August 9th, 2011. Mix Design was performed by Allwest Testing & Engineering, dated June 24th, 2011.

The WSU PQI and Pavetracker were used in this project in addition to two NDGs, a Troxler 3440 belonging to the contractor, and a Troxler 4640B (SN:2331) belonging to ITD. Roller pattern testing was performed, with density readings being recorded for nine roller passes. Readings were taken with the NNDGs with and without fines at the five locations being tested with the NDG and cored for QA by the contractor. The NDG was only used with fines on the surface. An additional four locations were tested with both NNDGs with all local factors and cored. Five additional readings were taken at the confined and unconfined joint. Temperature tests were also attempted at four locations, however were only able to be tested twice each due to time constraints.

3.1.4 I-90, Pinehurst ID. Project A010(498)

Project A010(498) was located on Interstate 90 from Pinehurst to Elizabeth Park Rd overpass, in Pinehurst, ID. Mix design was performed by Knife River, dated August 16, 2011. Both WSU NNDGs were used on this project, along with a two ITD and two contractor's NDGs. ITD used Troxler 3440 and Troxler 4640-B NDGs, and the contractor used MC-1-DR-P and MC-1-D2-D NDGs. Readings were taken after each roller pass with both the PQI and PaveTracker. Five locations were tested by ITD and the contractor for calibration of gauges. These locations were tested with the PQI, PaveTracker, and all four NDGs. Five additional locations were tested with both the PQI and PaveTracker for local factors with cores obtained.

3.1.5 US-12, Kooskia, ID. Project A012(007)

Project A012(007) was located on US-12 from Post Office Cr to Warm Springs in Kooskia, ID. The WSU PQI and PaveTracker were brought to this project. Additionally two ITD PQIs (#817 and #818) as well as an ITD Troxler 3440 (#23589) were used. Roller pass data was obtained for five passes. Six locations were tested for calibration of gauges by ITD, and five additional locations were tested for local factors. The PaveTracker malfunctioned during local factor testing, and was unavailable for the rest of the project. As a result, the six ITD locations were only tested with the three PQIs and the NDG. All but the first local factor location were only tested with the PQI.

3.1.6 US-95 Frontage Rd, Coeur D'Alene, ID. Project A011(978)

Project A011(978) was located on US-95 Frontage Rd, from Boekel to Ohio Match Rd, in Coeur D'Alene, ID. Mix Design was reviewed and approved by ITD on September 22, 2011.

The WSU PQI and an ITD NDG were used for this project. Five locations were tested with and without fines for gauge calibration by ITD. An additional five locations were tested with and without fines with the PQI and contractor NDG for research purposes. However due to time constraints, no additional factors (water, paint) were able to be tested.

3.1.7 US-95 Lewiston Hill, Lewiston, ID. Projects A011(485) and A011(029)

Projects A011(485) and A011(029) were companion projects constructed at the same time. Project A011(029) was located on US-95, Lewiston Hill southbound lanes, and Project A011(485) was also located on US-95, from Poe to the top of Lewiston Hill. Both projects were located near Lewiston, ID. Mix design was performed by Strata, dated August 19^{th}, 2008.

The data for Projects A011(485) and A011(209) were provided by ITD. An ITD PQI Model 301, as well as three NDGs: Troxler 4640-B, CPN MC3-DRP, and Troxer 3440, were used on this project. Readings were taken on HMA without fines only, with a total of 10 locations being tested with all four gauges. All 10 locations were then cored to determine density.

3.1.8 Project STP-5758(102)

Project STP-5758(102) was located on Beaver Creek Rd, between the city of Wallace and the Coeur d'Alene national forest in Shoshone County, ID. ITD also performed all testing for this project, a PQI and Troxler 4640B NDG were used. Testing was performed at seven locations, both with and without fines for the PQI (NDG was only used with fines) on September 16th, 2009. Cores were taken at all seven locations to determine true density.

3.1.9 Projects A011(566) and A013(103)

Projects A011(566) and A013(103) were located on US-95, from Wilder SCL to Parma SCL & Parma NCL to Jct. I-84, in Wilder, Idaho. Testing was performed on May 22nd, 2012 and June 2nd, 2012, respectively. Mix design was reviewed and approved by ITD on May 11th, 2012.

The WSU PQI and PaveTracker, a PQI 301 from ITD and an ITD Troxler 4640-B NDG were used on this project. The contractor also used their own NDG. Seven test locations from each project phase were used for calibration of gauges by ITD, and an additional seven locations were used to test local factors. Additionally, roller pass data was taken for six roller passes. Cores were taken for all fourteen testing locations.

3.1.10 Project A011(6229)

Project A011(6229) was located on SH-37 near Rockland, Idaho, from Lowery Lane to Portage Canyon. Mix design was performed by Reliance Testing & Inspection, dated June 17th, 2010. Testing was performed on June 7th, 2012. Two test strips were constructed for this project. The materials for the two test strips were identical, except that one had 5.8% AC, and the other had 6.0% AC. The WSU PQI and PaveTracker, as well as Troxler 3440 and Troxler 4640-B NDGs were used. Five cores were taken from each test strip for calibration of gauges by ITD. Five additional cores from each strip were taken from local factor test locations. Additionally, Roller pass data was also obtained for both test strips and temperature testing was performed.

Readings were also taken with both NNDGs and an NDG at three longitudinal joint locations on each test strip, however no cores were obtained.

3.2 LABORATORY TESTING

Laboratory testing was conducted in order to observe the effects of temperature as well as both surface and internal moisture on the performance of the NNDGs. The mold used to compact the HMA sample was made of four bolted together “C” shaped steel sections, with the final mold measuring 21.625 x 23.875 inches, and a slab thickness of 2 inches. The steel pieces are 8 inches in height. A 6-inch tall wooden block topped with a metal plate was placed inside of the mold to achieve the desired slab thickness. This resulted in a compacted slab volume of 0.623 ft^3. A total of five laboratory samples were compacted using a vibratory plate compactor as shown in Figure 3.1. Slabs were targeted to 7% air voids.

The mold was first sprayed 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 plate compactor was removed and the steel sides were unbolted from around the sample. This was done in order to eliminate any potential interference with the gauges from the steel pieces.

Figure 3.1. Laboratory compaction using vibratory plate compactor.

One HMA batch was prepared using a mix design provided by POE Asphalt company, while the other four were compacted using loose mix taken from field projects and compacted in the laboratory. Loose mix was separated into 10 equal mass pans and heated for 2 hours in a 160°C oven. Mix was then poured into the mold and compacted using the vibratory compactor. Laboratory Slabs # 3, 4, 5, and 6 used loose mix from I-90 Pinehurst, US-95 Frontage, US-12, and US-95 Wilder, respectively.

Due to difficulties obtaining a smooth, evenly compacted surface when using the vibratory compactor (vs. rollers used for field projects), fines were added to the surface during temperature testing to help ensure continuous contact between the gauge and paving surface.

NNDGs were immediately placed on the slab and temperature and density readings were taken as the slab cooled without moving the gauge. The sample was then placed into the oven still atop the wooden block and reheated at 120°C for approximately two hours before being tested (at the same location) with the second gauge.

Once temperature testing was concluded, the effects of moisture were tested. The fines would have soaked up water and created a “mud” on the surface of the specimen. Therefore, the HMA slabs were flipped over and no fines were used. The bottom of the sample was compacted against a smooth metal plate at the bottom of the mold, resulting in a smooth even surface without the need for added fines. Water was applied to the specimen from a small 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, gauge location was marked in order to replace it as close as possible to the original location and orientation to minimize procedural error.

Once the surface was completely flooded, the gauge was placed on the surface and not moved; readings were taken every few minutes as water drained down into the HMA in order to test the effects of internal water on gauge readings. Once readings were taken the specimen was allowed to dry for several days and moisture testing was conducted with the second gauge. The slab was then cored at each test location using an electric drill and coring bit, and readings were compared to the measured core density.

CHAPTER 4: RESULTS OF FIELD AND LABORATORY TESTING

4.1 FIELD TESTING RESULTS

Once all of the readings and core densities were obtained for each location, the device results were calibrated to each individual mix. This was done by finding the difference between the gauge readings and the density of cores taken for calibration purposes. The differences for the first 3, 4, or 5 readings (for 3, 4, and 5 point calibrations), were averaged, and this became the calibration factor for the machines. This number was then added to each remaining reading from the site to obtain calibrated readings. These calibrated readings were then compared to the measured core densities for their respective locations. NDG and NNDG data were compared to core densities in order to compare the accuracy of the NDGs and NNDGs. The effects of fines, paint, and moisture on the HMA surface (local factors) were also examined.

For local factors, Student t-test was also performed on the results for each gauge. The t-test was a two-tailed, paired value test comparing the calibrated gauge (whether NDG or NNDG) readings with the core density from that location. The data both with and without fines was compared with core density for the PQI and PaveTracker. The NDG is only used with fines on the surface. Therefore, only one NDG reading, per NDG at each project, was compared with core density. Finally, a General Linear Model (GLM) statistical analysis was performed for each NNDG to determine whether any global factors had a statistically significant effect on the results of the NNDG testing. Further details regarding the GLM model and statistical analysis are found in Section 4.5.

4.1.1 PQI Correlation Results

The PQI was used on every field project, with some projects having multiple PQIs if ITD supplied their own gauge on that project. Difference between core density and gauge reading was calculated and averaged in order to obtain a calibration factor which was then added to all gauge results in order to calibrate the gauge readings for an individual HMA mix. This offset can then be programmed into the gauge for continued readings of the same mix. PQI calibration factors for each project, along with minimum, maximum, and range between maximum and minimum values are shown in Table 4.1.

Table 4.1. PQI Calibration Factors.

		PQI Calibration Factors					
		3 point		4 Point		5 Point	
Project	Gauge	HMA Without Fines	HMA With Fines	HMA Without Fines	HMA With Fines	HMA Without Fines	HMA With Fines
I-84	WSU	22.40	22.20	22.85	22.63	x	x
SH-51	WSU	22.80	22.67	22.30	21.95	22.34	22.06
	ITD #753	22.37	x	21.85	x	21.94	x
	ITD #896	22.43	x	21.93	x	22.02	x
I-90	WSU	26.97	26.17	26.85	26.05	26.57	26.14
SH-8	WSU	1.80	3.20	2.13	3.53	2.16	3.40
US-12	WSU	18.07	x	17.38	x	16.92	x
	ITD #817	17.33	x	17.50	x	17.28	x
	ITD #818	17.10	x	17.30	x	17.12	x
US-95 Frontage	WSU	22.07	x	22.35	x	22.46	x
US-95 Lewiston Hill	ITD	0.60	x	0.38	x	0.10	x
Beaver Creek	ITD	27.27	27.27	27.18	27.13	26.64	26.54
US-95 Wilder Phase 1	WSU	17.16667	x	17.8	x	17.94	x
	ITD #819	18.93333	x	19.5	x	19.58	x
US-95 Wilder 2	WSU	20.0	x	20.0	x	20.0	x
SH-37	WSU	23.0	x	23.75	x	x	x
	Maximum Value:	27.27	27.27	27.18	27.13	26.64	26.54
	Minimum Value:	0.60	3.20	0.38	3.53	0.10	3.40
	Range:	26.67	24.07	26.80	23.60	26.54	23.14

Calibration factors vary significantly from project to project, with a maximum range between factors of 26.67, 26.80, and 26.54 pcf for the three, four, and five point calibrations, respectively. The maximum calibration factor observed for any mix was 27.27 pcf for the three point calibration at the Beaver Creek project, while the minimum factor of 0.10 pcf was observed for the five point calibration at the Lewiston Hill project. This shows the critical nature of mix specific calibration for the PQI, as uncalibrated results can range from negligible error (0.10 pcf lower), to 27 pcf lower than core density depending on the project mix. The results stay fairly constant regardless of number of calibration points chosen or presence of fines on the surface, with the range of factors only varying 3.66 pcf across the entire spectrum of calibration factors calculated.

Calibrated readings for both PQI and NDGs were plotted against the core density values in order to assess how closely the gauges measure the actual in-place density of the HMA mat. The results are shown in Figures 4.1 through 4.3 for 3-point, 4-point, and 5-point calibration, respectively. Trendlines were forced to intercept at the origin, as the ideal relationship between gauge readings and core density would overlap with the line of equality

The PQI without fines and NDG readings correlate very well with core densities for the 3-point correlation. Slopes of all three trendlines are 0.99. The R^2 value of the PQI without fines (0.82) is greater than that of the NDG (0.77). The PQI with fines had the lowest value at 0.55.

The PQI without fines and NDG readings also correlate very well with core densities for the four point correlation. Slopes of all three trendlines are again close to one. The R^2 values of the PQI without fines (0.82) again exceed that of the NDG (0.70), with the PQI with fines having the lowest value at 0.62.

The PQI without fines and NDG readings again correlate very well with core densities for the five point correlation. Slopes of all three trendlines are 0.99. The R^2 values of PQI without fines (0.79) is greater than that of the NDG (0.70), with the PQI with fines having the lowest value at 0.60. A summary of the correlation data is shown in Table 4.2.

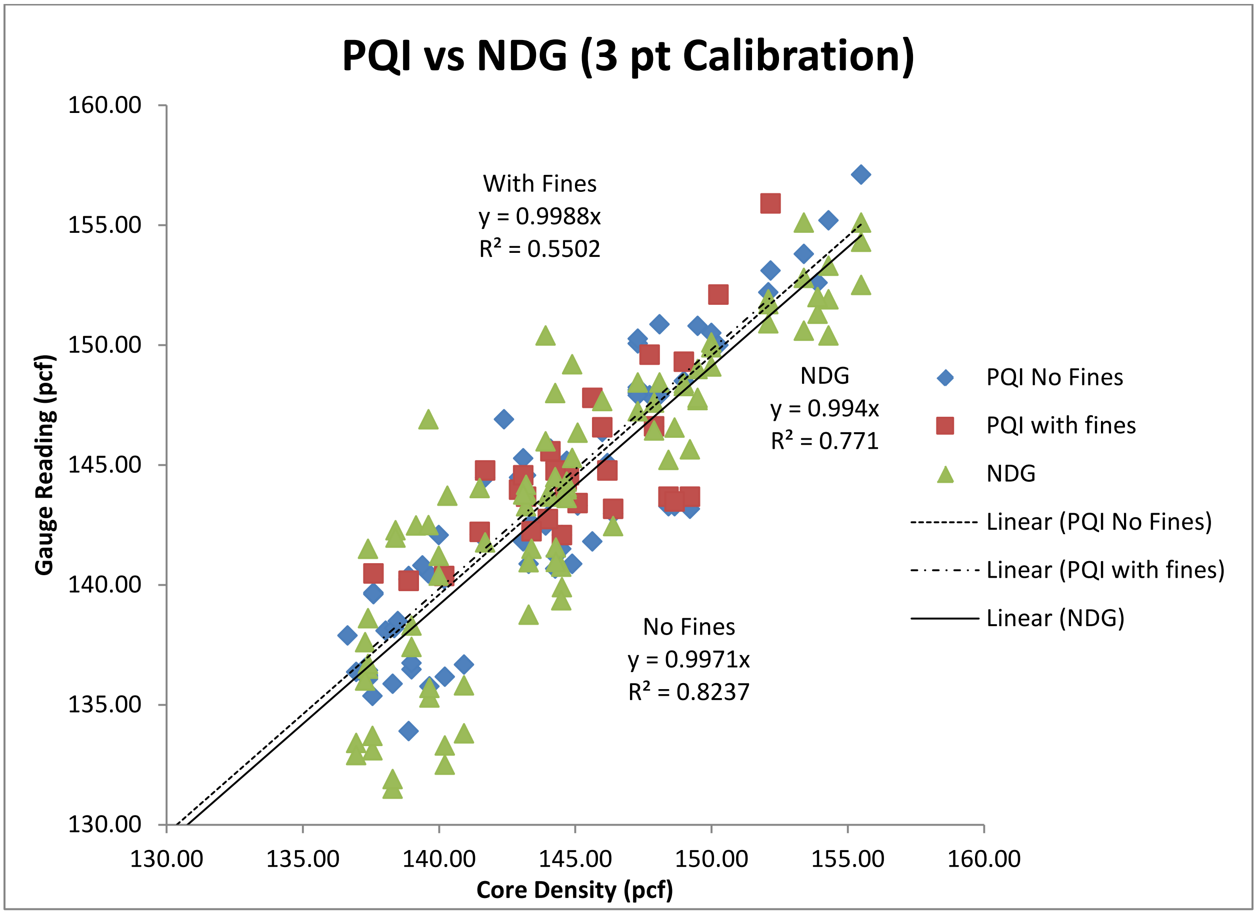

Figure 4.1. PQI vs NDG 3-point Calibration Correlation Results.

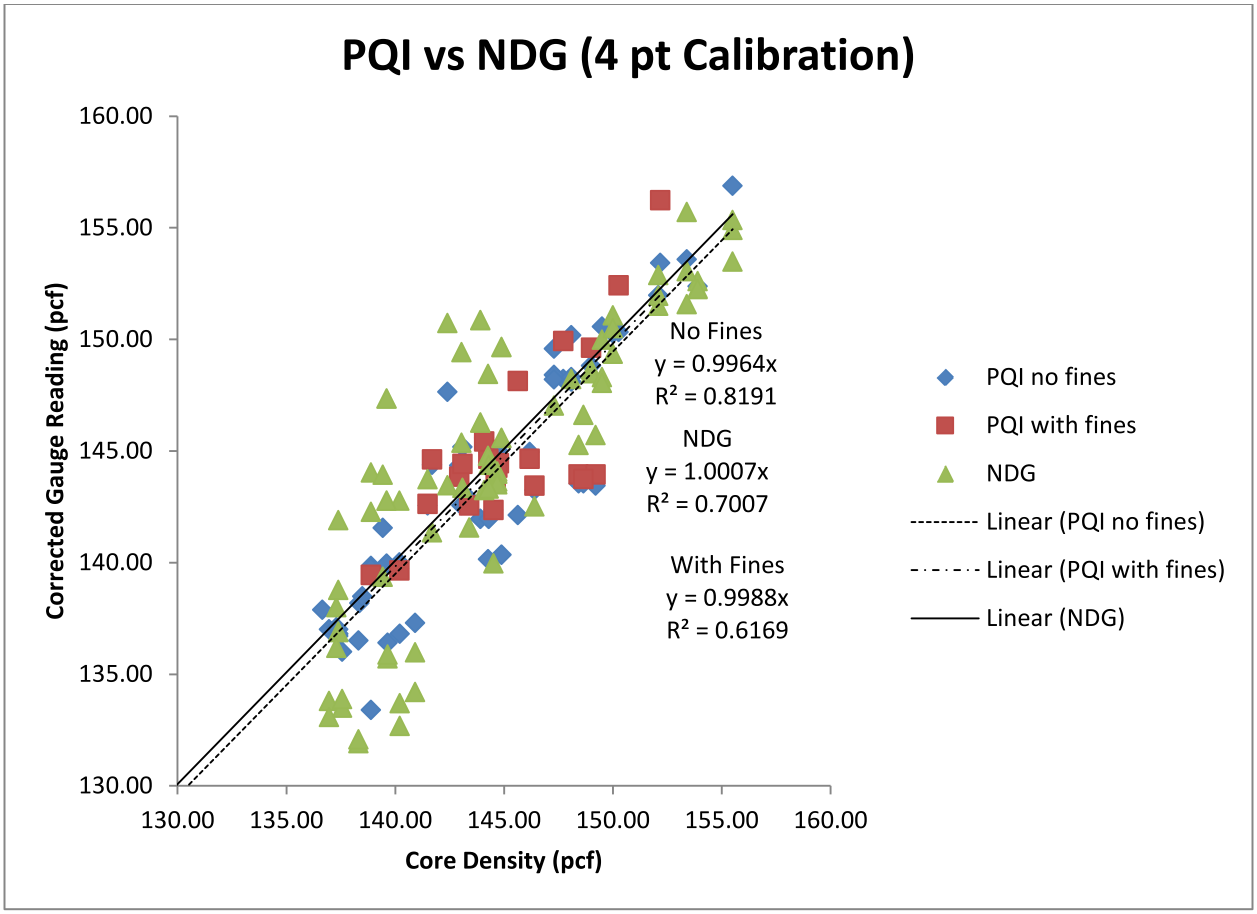

Figure 4.2. PQI vs NDG 4-point Calibration Correlation Results

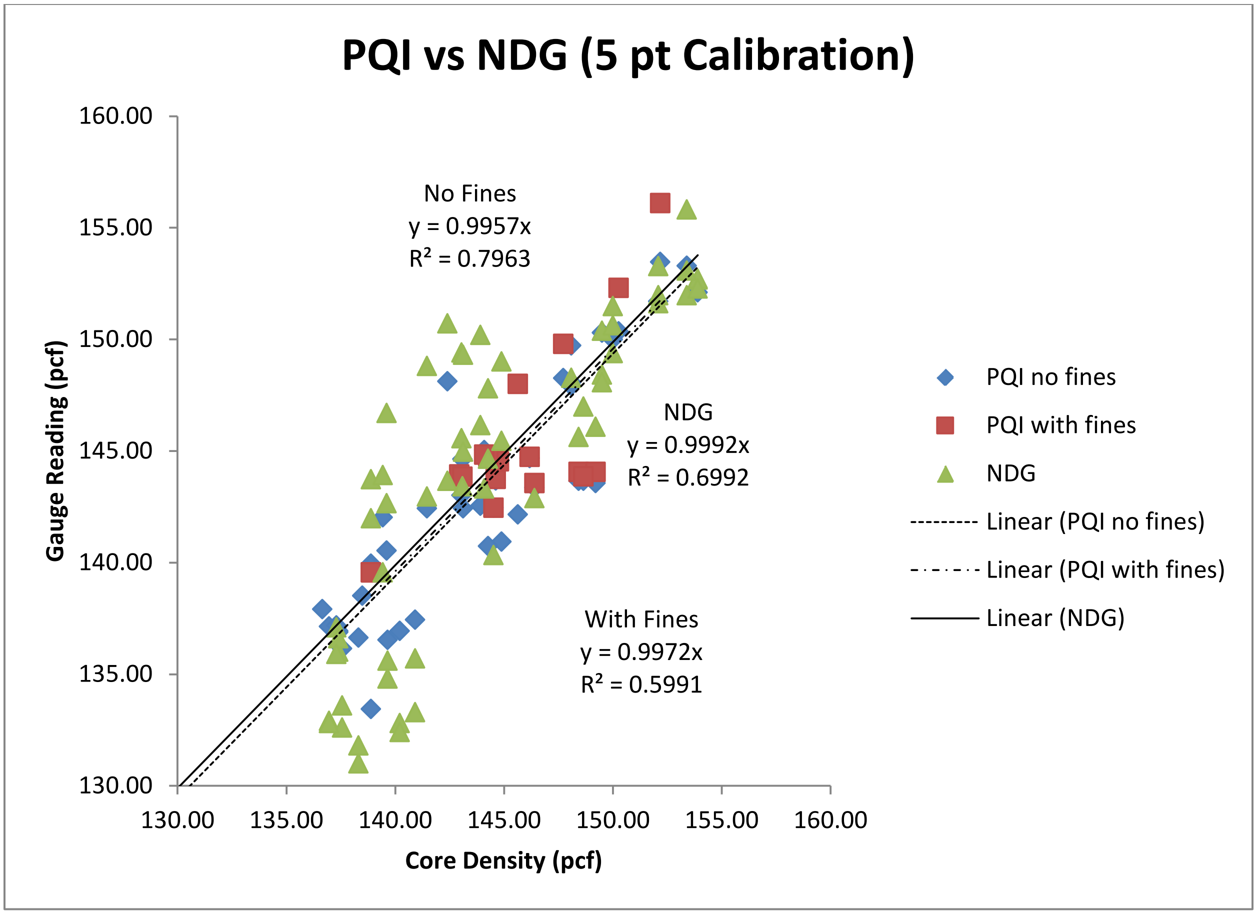

Figure 4.3. PQI vs NDG 5-point Calibration Correlation Results

Table 4.2. PQI Correlation Results.

	PQI Correlation Results					
	3 point Calibration		4 point calibration		5 point calibration	
	Slope	R^2	Slope	R^2	Slope	R^2
PQI No Fines	0.99	0.82	0.99	0.82	0.99	0.79
PQI With Fines	0.99	0.55	1.00	0.62	0.99	0.60
NDG	0.99	0.77	0.99	0.70	0.99	0.70

ITD uses 5-7 field cores to obtain correction factors. Based on the 3-point, 4-point, or 5-point calibration, the PQI without fines can be used to replace NDGs without compromising accuracy.

4.1.2 PaveTracker Correlation Results

The PaveTracker has considerably less data than the PQI, due primarily to it malfunctioning and being sent in for repair for a good part of the paving season. Difference between core density and gauge reading was again calculated and averaged in order to obtain a calibration factor which was then added to all gauge results in order to calibrate the gauge readings for an individual HMA mix. This offset can then be programmed into the gauge for continued readings of the same mix. PaveTracker calibration factors for each project, along with minimum, maximum, and range of the values are shown in Table 4.3.

Table 4.3. PaveTracker Correlation Factors.

	PaveTracker Calibration Factors					
	3 point		4 Point		5 Point	
Project	**HMA Without Fines**	**HMA With Fines**	**HMA**	**HMA w fines**	**HMA**	**HMA w fines**
I-84	13.58	12.20	13.94	12.48	x	x
SH-51	15.73	16.87	16.05	16.67	16.18	16.91
I-90	20.25	18.85	19.90	18.50	20.32	18.51
SH-8	-19.88	-21.30	-18.90	-20.71	-18.47	-20.68
US-95 Wilder 1	13	x	13.45	x	13.42	x
US-95 Wilder 2	15.5	x	15.6	x	15.8	x
SH-37	18.6	x	19.25	x	x	x
Maximum Value:	20.25	18.85	19.90	18.50	20.32	18.51
Minimum Value:	-19.88	-21.30	-18.90	-20.71	-18.47	-20.68
Range:	40.13	40.15	38.80	39.21	38.79	39.19

Calibration factors very significantly from project to project, with a maximum range between factors of 40.15, 39.21, and 39.19 pcf for the three, four, and five point calibrations, respectively. The maximum calibration factor observed for any mix was 20.32 pcf for the five point calibration at the Pinehurst project, while the minimum factor of -21.30 pcf was observed for the three point calibration at the SH-8 project. This shows that mix specific calibrations are also critical with the PaveTracker. Uncalibrated results can range from 20.32 pcf higher to 21.30 pcf lower than core density, depending on the project mix. The results stay fairly constant regardless of number of calibration points chosen or presence of fines on the surface, with the range of factors only varying 1.36 pcf across the entire spectrum of calibration factors calculated.

Calibrated readings for both PaveTracker and NDGs were plotted against the core density values in order to assess how closely the gauges measure the actual in-place density of the HMA mat. The results are shown in Figures 4.4 through 4.6 for 3-point, 4-point, and 5-point calibration, respectively. Trendlines were again forced to intercept at the origin, as the ideal relationship between gauge readings and core density would overlap with the line of equality.

The PaveTracker (with and without fines) and NDG readings correlate well with core densities for the three point correlation. As seen in Figure 4.4, slopes of all three trendlines are essentially one. The R^2 value of the PaveTracker with fines (0.81) is greater than that of the NDG (0.77), which is the same as the PaveTracker (0.77).

Figure 4.5 shows that for the four point calibration, slopes of all three trendlines are essentially one. The R^2 value of the NDG data set (0.70) is less than that of both PaveTracker data sets. The PaveTracker with fines has a higher R^2 value (0.82) than the PaveTracker without fines (0.76).

Figure 4.6 shows that for the five point calibration, slopes of all three trendlines are again essentially one. The R^2 value of the PaveTracker with fines (0.81) is the highest, followed by the PaveTracker without fines (0.78). The NDG has the lowest R^2 value (0.70). A summary of correlation data for the PaveTracker is shown in Table 4.4.

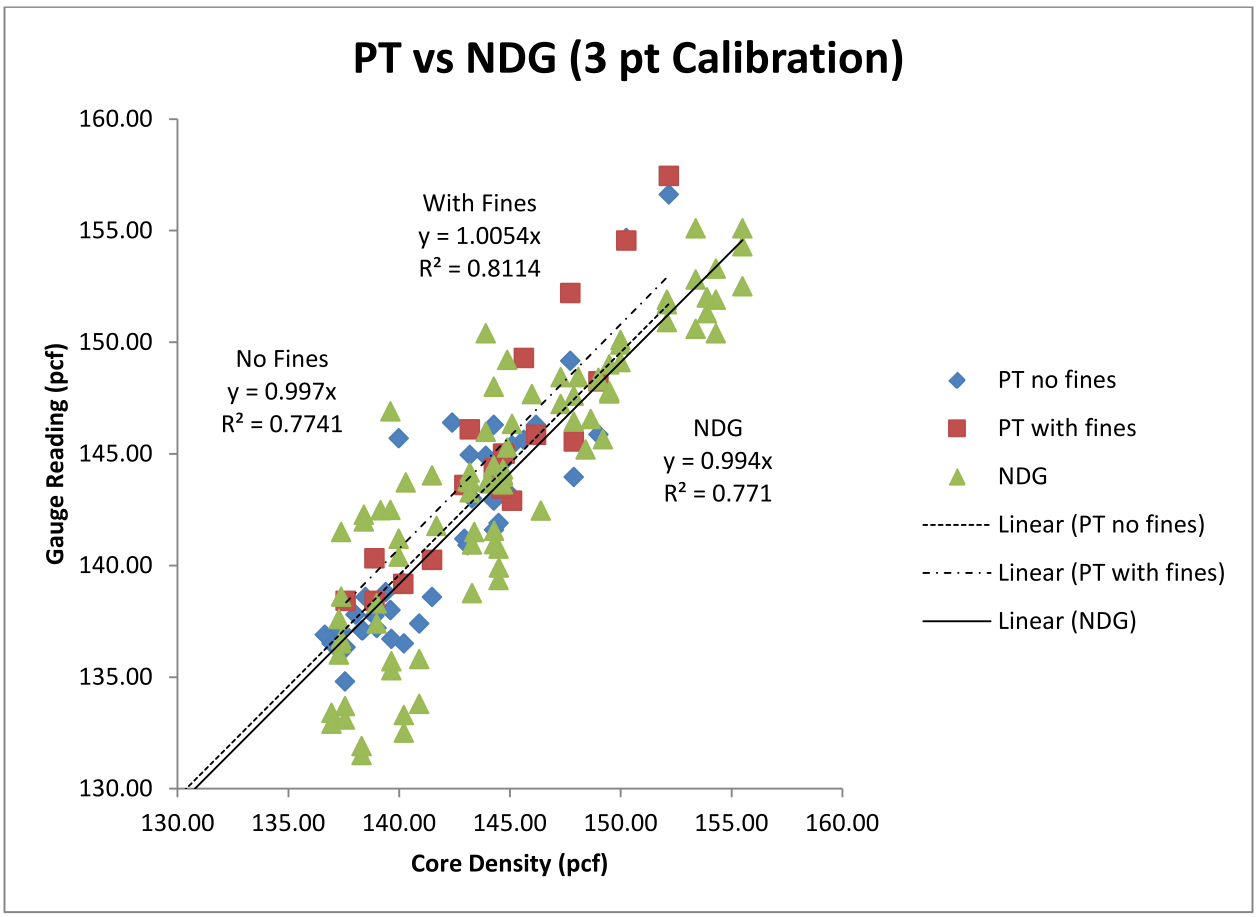

Figure 4.4. PaveTracker vs NDG 3-point Calibration Correlation Results.

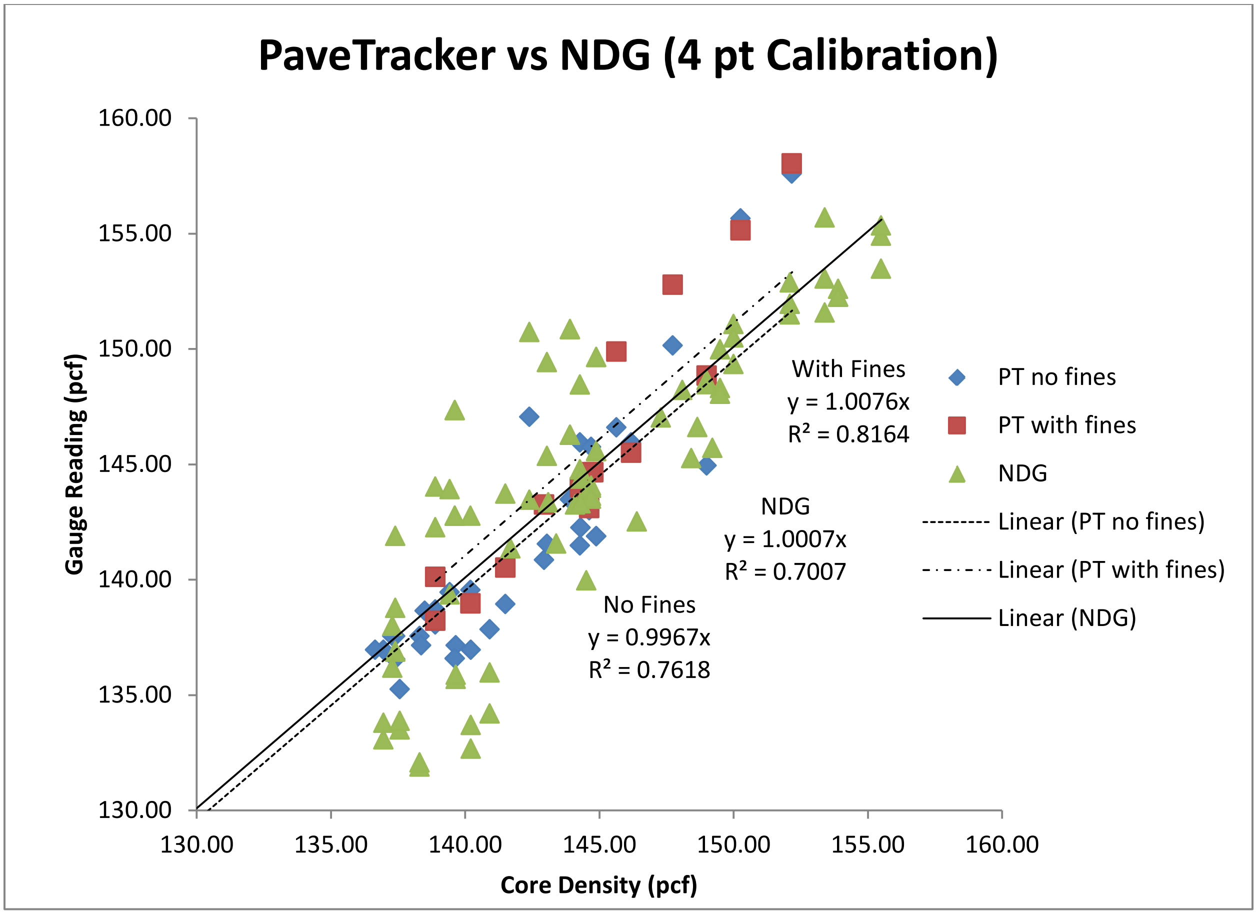

Figure 4.5. PaveTracker vs NDG 4-point Calibration Correlation Results

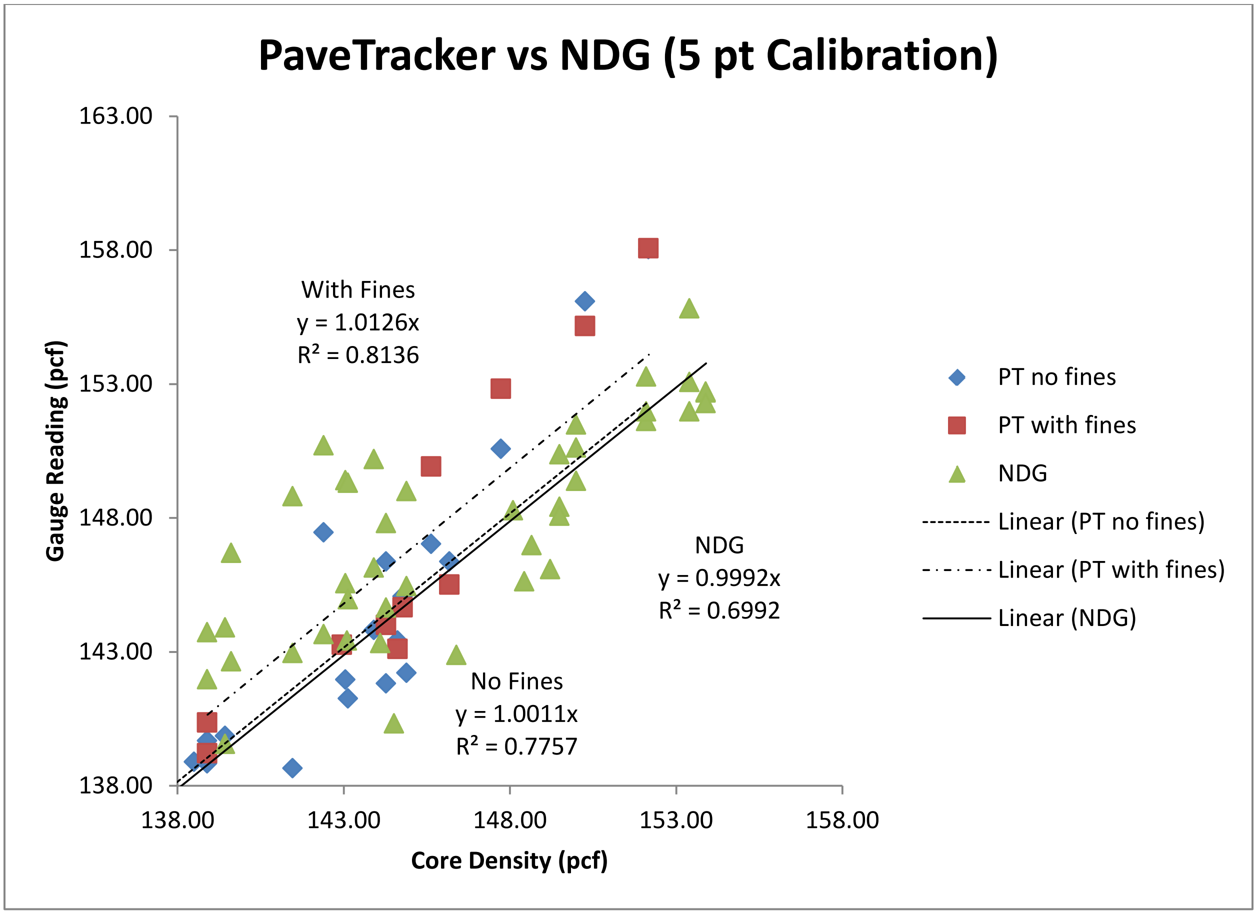

Figure 4.6. PaveTracker vs NDG 5-point Calibration Correlation Results

Table 4.4. PaveTracker Correlation Results.

	PaveTracker Correlation Results					
	3 point Calibration		4 point calibration		5 point calibration	
	Slope	R^2	Slope	R^2	Slope	R^2
PT No Fines	0.99	0.77	0.99	0.76	1.00	0.78
PT With Fines	1.01	0.81	1.01	0.82	1.01	0.81
NDG	0.99	0.77	1.00	0.70	0.99	0.70

ITD uses field cores for calibration of gauges. Based on the 3-point, 4-point, or 5-point calibration results, the PaveTracker without fines can be used to replace NDGs without compromising accuracy.

4.1.3 Roller Pattern Testing

Testing was also conducted to determine if the NNDGs could accurately establish a roller pattern for field compaction. Figures 4.7 and 4.8 show the PQI and PaveTracker density readings, respectively, after each roller pass.

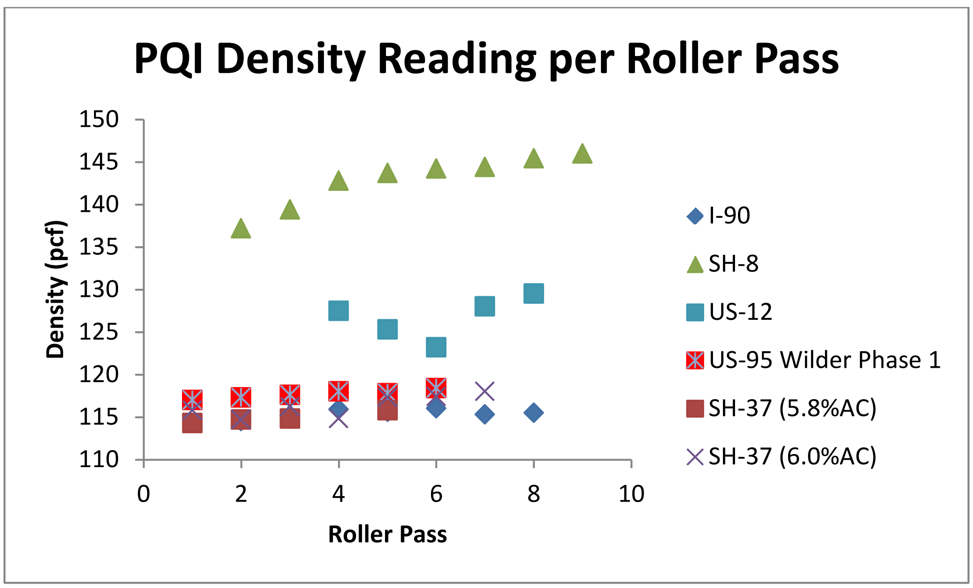

Figure 4.7. PQI Density Reading at each Roller Pass.

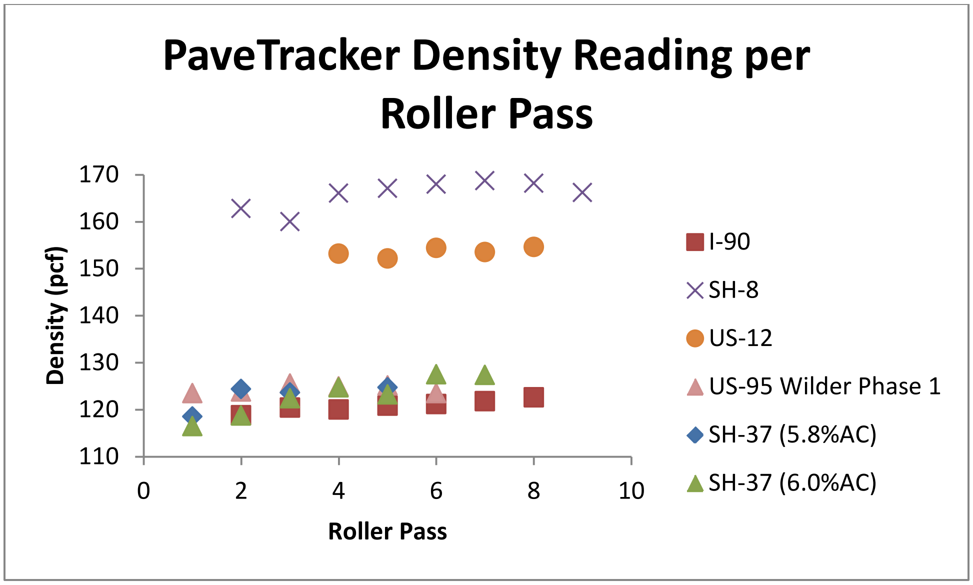

Figure 4.8. PaveTracker Density Reading at each Roller Pass.

Uncalibrated density readings varied more than 30 pcf between some projects, so the initial density reading was subtracted from each subsequent density reading in order to find the relative change in density readings and make break-points easier to see in the plots. Figures 4.9 and 4.10 show the change in density readings after each roller pass for the PQI and PaveTracker, respectively.

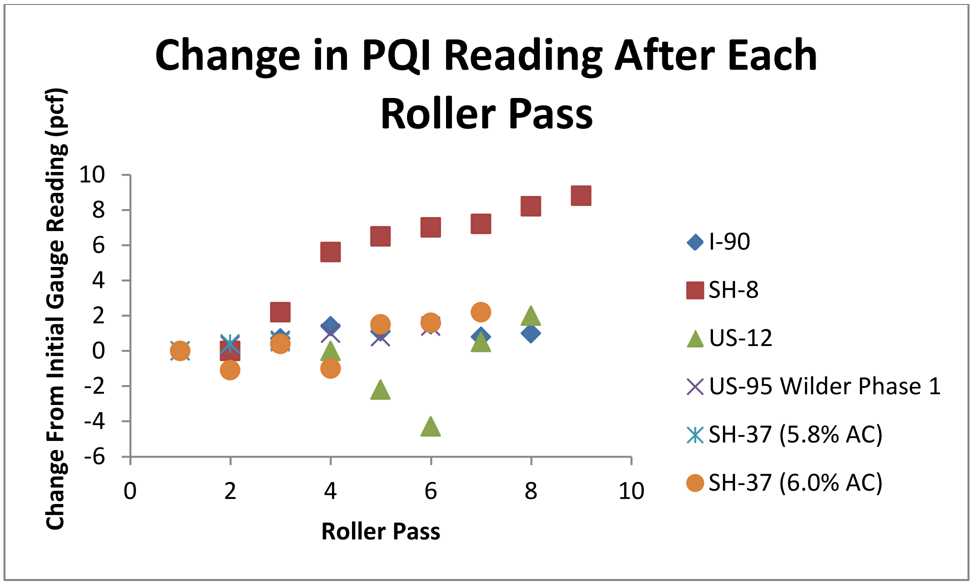

Figure 4.9. Change in PQI Reading After Each Roller Pass.

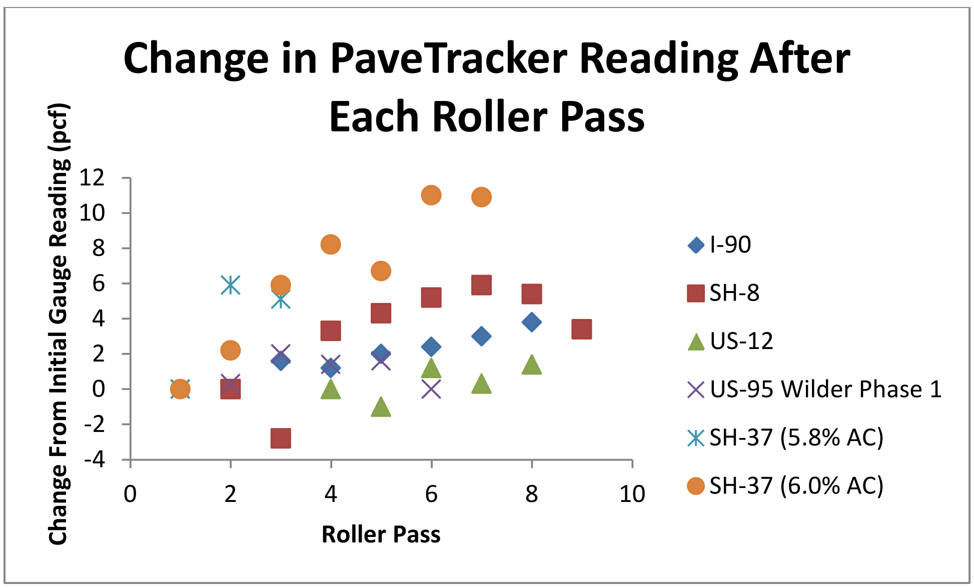

Figure 4.10. Change in PaveTracker Reading After Each Roller Pass.

It seems that the identification of break-points are project specific. Break-points were identified in some, but not all, projects.

4.1.4 Local Factor Results

The local factors of surface fines, presence of paint, and moisture were tested in the field. The intent of the local factor testing is to determine which factors affect gauge readings.

Surface Fines/Debris

The first local factor tested was the presence of surface fines or debris. Fines were placed on the surface and spread into a thin layer filling in surface gaps, which is a standard testing procedure for NDGs. Figure 4.7 shows a test location with fines on the surface. Tables 4.6 and 4.7 show the gauge readings with and without surface fines, as well as the percent error vs core density for both sets of readings. The P-value obtained from a two-tailed, paired t-test is also shown. A P-value is less than 0.05 indicates that the local factor causes a significant difference in percent error with 95% confidence.

Figure 4.11. Test Location with Surface Fines.

Table 4.5. 3-Point Calibrated PQI Readings With and Without Surface Fines.

PQI Readings With and Without Surface Fines					
Project	Without Fines (pcf)	With Fines (pcf)	Core Density (pcf)	percent error Without Fines	percent error With Fines
I-84	143.30	143.60	145.10	1.24	1.03
	142.10	142.40	141.50	0.42	0.64
SH-51	139.60	140.60	137.60	1.45	2.18
	140.50	140.50	140.20	0.21	0.21
	133.90	140.30	138.90	3.60	1.01
	140.20	140.30	138.90	0.94	1.01
I-90	145.17	145.17	144.70	0.32	0.32
	144.47	144.77	142.95	1.06	1.27
	144.07	144.57	144.62	0.38	0.04
	144.67	145.37	144.78	0.08	0.41
	145.07	145.57	146.18	0.76	0.42
	145.07	145.57	144.28	0.54	0.89
SH-8	146.60	145.20	147.90	0.88	1.83
	148.50	147.90	149.00	0.34	0.74
	153.10	154.50	152.18	0.61	1.53
	150.00	150.70	150.26	0.18	0.29
	147.90	148.20	147.73	0.11	0.32
	141.80	146.40	145.64	2.64	0.52
US-95 Wilder Phase 1	135.87	135.97	138.31	1.77	1.70
	136.67	136.67	140.92	3.02	3.02
	136.37	136.57	136.97	0.44	0.29
	136.17	136.27	140.22	2.89	2.82
	135.77	136.07	139.66	2.79	2.57
	135.37	135.77	137.57	1.60	1.31
	133.87	135.87	129.53	3.34	4.89
Beaver Creek	146.37	146.57	146.00	0.25	0.39
	144.47	144.77	141.70	1.95	2.16
	145.67	145.57	144.10	1.09	1.02
	145.27	144.57	143.10	1.51	1.02
			Average	1.26	1.24
			T-Test	0.89	

Table 4.6. 3-Point Calibrated PaveTracker Readings With and Without Surface Fines.

PaveTracker Readings With and Without Surface Fines					
Project	Without Fines (pcf)	With Fines (pcf)	Core Density (pcf)	percent error Without Fines	percent error With Fines
I-84	145.38	144.28	145.10	0.20	0.57
	138.58	141.63	141.50	2.06	0.09
SH-51	136.33	137.28	137.60	0.92	0.23
	139.23	138.03	140.20	0.69	1.55
	137.73	137.28	138.90	0.84	1.17
	138.38	139.18	138.90	0.37	0.20
I-90	146.10	146.40	144.70	0.97	1.17
	141.20	145.00	142.95	1.22	1.43
	143.35	144.85	144.62	0.88	0.16
	145.00	146.40	144.78	0.15	1.12
	146.30	147.25	146.18	0.08	0.73
	146.30	145.75	144.28	1.40	1.02
SH-8	143.97	146.97	147.90	2.66	0.63
	145.87	149.67	149.00	2.10	0.45
	156.62	158.87	152.18	2.92	4.40
	154.67	155.97	150.26	2.93	3.79
	149.17	153.62	147.73	0.97	3.98
	145.62	150.72	145.64	0.02	3.49
US-95 Wilder Phase 1	137.10	137.20	138.31	0.88	0.80
	137.40	138.70	140.92	2.50	1.58
	136.50	137.50	136.97	0.34	0.39
	136.50	138.00	140.22	2.65	1.58
	136.70	137.40	139.66	2.12	1.62
	134.80	135.70	137.57	2.02	1.36
	135.50	136.70	129.53	4.61	5.53
			Average	1.46	1.56
			T-Test	0.70	

The P-values for the PQI and PaveTracker are 0.89 and 0.70, respectively. These are both significantly greater than 0.05, indicating that surface fines/debris do not significantly affect gauge accuracy with 95% confidence. The average percent error for the PaveTracker is slightly higher (1.56%) with fines than without fines (1.46%). The average percent error for the PQI without fines (1.26%) is very close to the average percent error for the PQI with fines (1.24%).

<u>Surface Markings (Paint)</u>

Presence of pavement markings such as paint could potentially affect NNDG readings. Therefore testing was performed with spray paint applied to the pavement surface, as seen in Figure 4.12. Results of gauge readings with and without paint on the surface are shown in Tables 4.7 and 4.8 for the PQI and PaveTracker, respectively.

Figure 4.12. Applying Paint to HMA Surface.

Table 4.7. PQI With and Without Surface Paint.

PQI With and Without Paint					
Project	**Without Paint (pcf)**	**With Paint (pcf)**	**Core Density (pcf)**	**percent error Without Paint**	**percent error With Paint**
I-84	143.60	143.70	141.30	1.63	1.70
	143.30	143.50	145.10	1.24	1.10
SH-51	139.60	140.30	137.60	1.45	1.96
	140.50	140.60	140.20	0.21	0.29
	140.30	140.30	138.90	1.01	1.01
	140.20	140.50	138.90	0.94	1.15
I-90	144.47	144.77	142.95	1.06	1.27
	144.07	144.77	144.62	0.38	0.10
	144.67	144.87	144.78	0.08	0.06
	145.07	145.37	146.18	0.76	0.56
	145.07	145.37	144.28	0.55	0.75
SH-8	153.10	152.70	152.18	0.60	0.34
	150.00	152.50	150.26	0.17	1.49
	147.90	147.80	147.73	0.12	0.05
	141.80	141.80	145.64	2.64	2.64
US-95 Wilder Phase 1	135.87	135.57	138.31	1.77	1.99
	136.67	136.47	140.92	3.02	3.16
	136.37	136.47	136.97	0.44	0.37
	136.17	134.97	140.22	2.89	3.75
	135.77	136.17	139.66	2.79	2.50
			T-Test:	0.17	

Table 4.8. PaveTracker with and without surface paint.

PaveTracker With and Without Paint					
Project	**Without Paint (pcf)**	**With Paint (pcf)**	**Core Density (pcf)**	**percent error Without Paint**	**percent error With Paint**
I-84	144.73	144.18	141.30	2.43	2.04
	143.68	144.28	145.10	0.98	0.57
SH-51	136.33	137.13	137.60	0.92	0.34
	139.23	138.53	140.20	0.69	1.19
	137.73	135.93	138.90	0.84	2.14
	138.38	138.23	138.90	0.37	0.48
I-90	141.20	143.25	142.95	1.22	0.21
	143.35	142.75	144.62	0.88	1.29
	145.00	143.40	144.78	0.15	0.95
	146.30	147.55	146.18	0.08	0.94
	146.30	147.55	144.28	1.40	2.27
SH-8	156.62	157.72	152.18	2.92	3.64
	154.67	153.97	150.26	2.93	2.47
	149.17	151.72	147.73	0.97	2.70
	145.62	138.32	145.64	0.02	5.03
US-95 Wilder Phase 1	137.10	137.60	138.31	0.88	0.52
	137.40	138.60	140.92	2.50	1.65
	136.50	138.90	136.97	0.34	1.41
	136.50	138.30	140.22	2.65	1.37
	136.70	136.50	139.66	2.12	2.26
			T-Test:	0.20	

Tables 4.7 and 4.8 show that the P-values of the paired student t-tests of the percent error of the PQI and PaveTracker with and without surface paint are 0.17 and 0.20, respectively. Both values are greater than 0.05, indicating that surface paint has no significant effect on gauge accuracy with 95% confidence.

Surface Moisture

Presence of moisture has been shown to affect NNDG readings, therefore testing was performed with water applied to testing surface with a small spray bottle, as shown in Figure 4.13. Change in H_2O index was plotted vs. both change in gauge reading and change in gauge percent error as seen in figures 4.14 through 4.17.

Figure 4.13. Water Being Applied to Testing Surface.

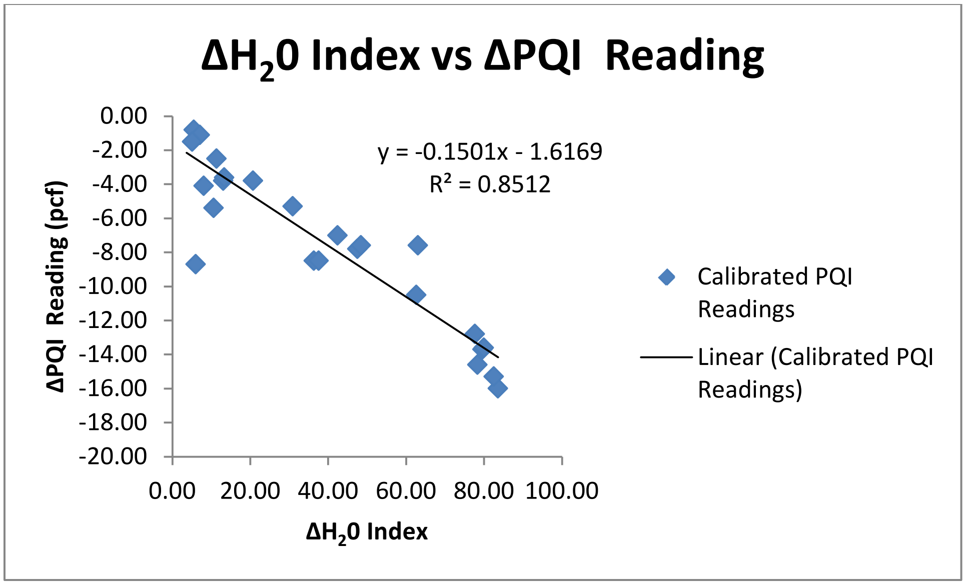

Figure 4.14. Change in H_2O Index vs Change in PQI Reading.

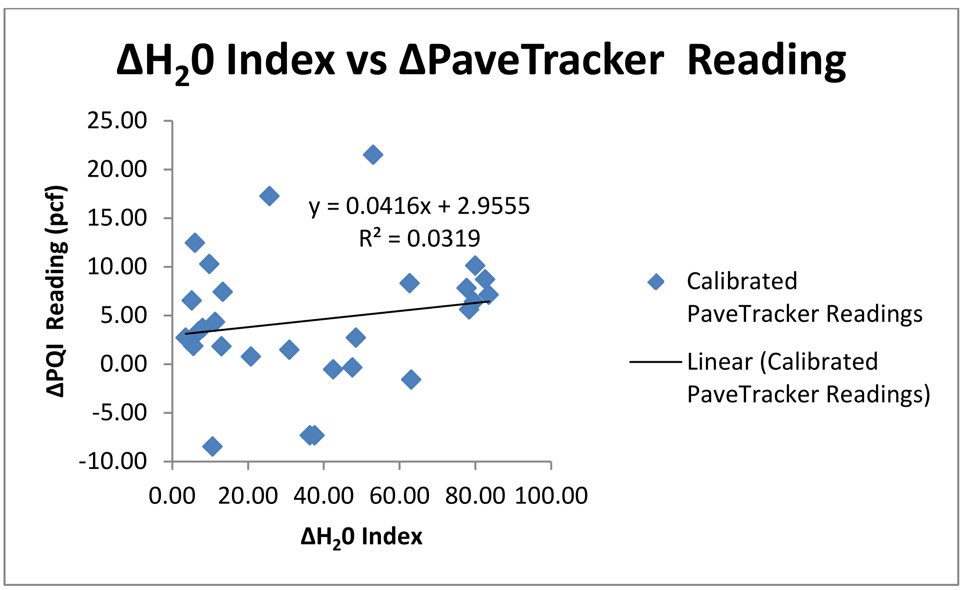

Figure 4.15. Change in H_2O Index vs Change in PaveTracker Reading.

Figure 4.14 shows that calibrated PQI readings exhibit a decreasing trend with increased H_2O index. PQI Readings will drop approximately 1.5 pcf for each 10 point increase in H_2O

index. Figure 4.15 shows that there is no trend in the PaveTracker data, the trendline is nearly flat with a slope of 0.04, and has a very low R2 value of 0.03.

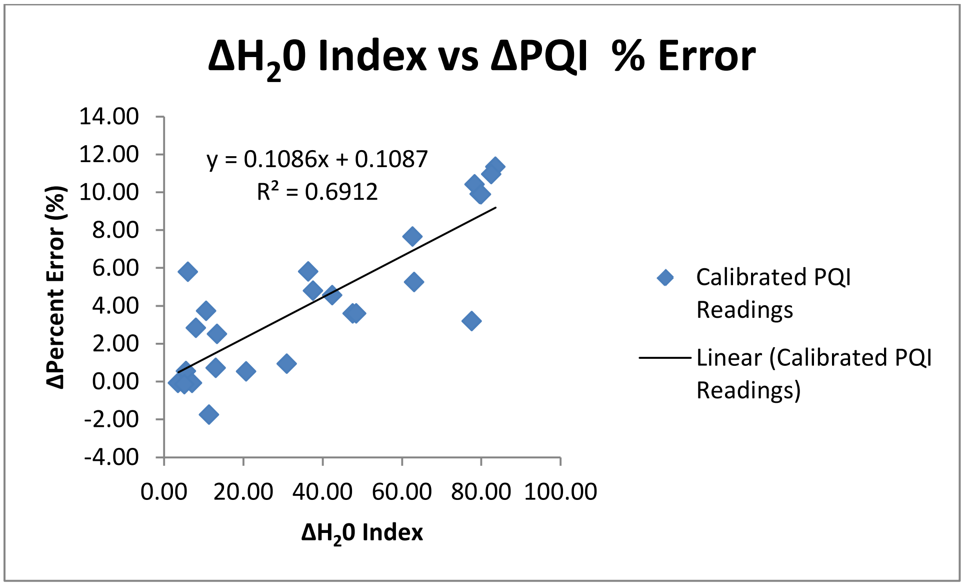

Figure 4.16. Change in H_2O Index vs Change in PQI Percent Error.

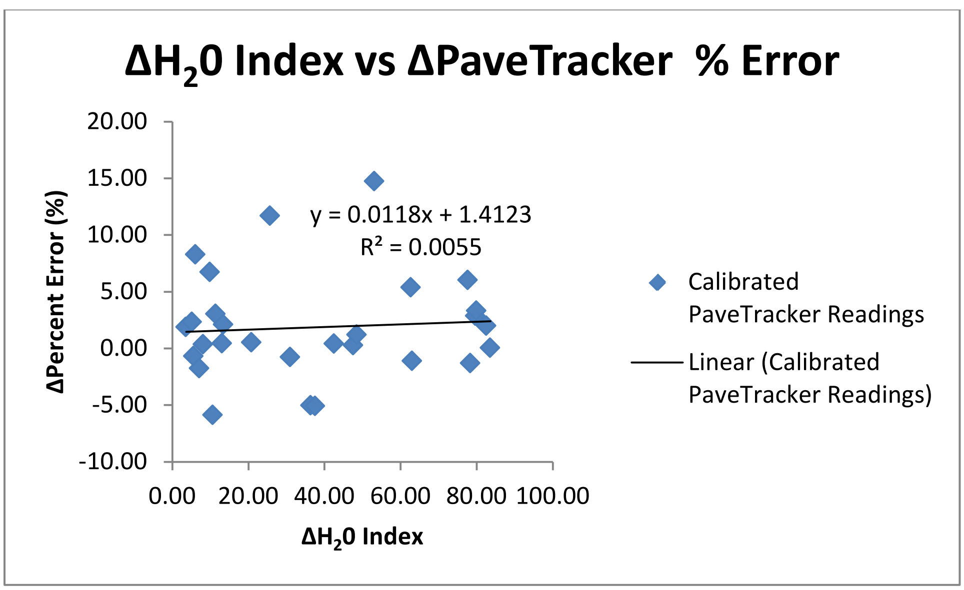

Figure 4.17. Change in H_2O Index vs Change in PaveTracker Percent Error.

Figures 4.16 and 4.17 show the change in percent error vs. the change in H_2O index for the PQI and PaveTracker, respectively. The percent error of the PQI increases with increasing H_2O index. The trendline of the PQI data indicates that the percent error will increase approximately 1.09% for each 10 point increase in H_2O index. The PaveTracker data once again shows no trend, with a trendline slope of 0.01 and an R^2 value of 0.01.

4.1.5 Longitudinal Joint Testing Results

NNDG readings were also taken at pavement joints when possible at field projects. Readings were taken at both confined and unconfined joints, as close as possible to the edge of the pavement while maintaining constant contact between the gauge and pavement. Cores were only able to be obtained for the unconfined joint of the SH-51, MP 60 project. Because of the lack of cores for test locations, gauge readings were compared to the average of all cores taken at the project, in order to compare readings at joints to an "average" density in the middle of the pavement.

The exceptions to this are the joint readings from the SH-51, MP 60 project; because cores were obtained for the unconfined joint locations. Gauge readings from unconfined joints are compared to core density of that location, while confined joint readings are compared to the average of the unconfined core densities. As the confined joint readings were performed the following day after the second lane was paved, and testing occurred directly adjacent to the unconfined joint tests. Tables 4.9 and 4.10 show the density testing results for the confined and unconfined joints, respectively.

Table 4.9. Confined Joint Density Testing Results.

Confined Joints					
Project	**PQI**	**PaveTracker**	**Average Density**	**%Error (PQI)**	**%Error (PT)**
SH-51	141	141.23	130.62	7.95	8.13
	140.9	138.33	130.62	7.87	5.91
	140.5	136.83	130.62	7.57	4.76
	140	137.28	130.62	7.19	5.10
	139.9	136.98	130.62	7.11	4.87
	139.6	137.83	130.62	6.88	5.52
	140.3	137.43	130.62	7.41	5.22
I-84	140.2	132.43	143.32	2.18	7.60
	141.3	137.58	143.32	1.41	4.01
	140.7	133.68	143.32	1.83	6.73
	141.1	134.78	143.32	1.55	5.96
	140.8	134.73	143.32	1.76	5.99
SH-8	149.7	151.52	148.55	0.77	2.00
	144.5	144.32	148.55	2.73	2.85
	142.6	141.87	148.55	4.01	4.50
	140	133.92	148.55	5.76	9.85
	140.8	139.97	148.55	5.22	5.78
US-95 Wilder 1	134.47	130.2	136.94	1.80	4.92
	134.27	129.6	136.94	1.95	5.36
	134.27	130	136.94	1.95	5.07
	134.07	129.5	136.94	2.10	5.43
	134.47	130.5	136.94	1.80	4.70
			Average:	4.04	5.47

The average percent error between the confined joint readings and the average core densities for each project (except SH-51 data as previously noted), along with the average percent errors for all data, are shown in Table 4.9. The PQI and PaveTracker have an average percent error of 4.04% and 5.47%, respectively. The average percent error of the PQI and PaveTracker readings in the middle of the HMA mat, without surface fines, are 1.26% and 1.46%, respectively, as shown in Tables 4.5 and 4.6. The average percent error of both gauges was higher for the confined joints than for standard readings of the pavement mat. This is to be expected because the readings are not being compared to cores taken at that exact spot but rather to an average of cores taken from the pavement project.

Table 4.10. Unconfined Joint Density Testing Results.

Unconfined Joints					
Project	**PQI (pcf)**	**PaveTracker (pcf)**	**Project Average Density (pcf)**	**%Error (PQI)**	**%Error (PaveTracker)**
SH 78 MP 60	138.8	129.13	134.79	2.97	4.20
	139	131.88	133.55	4.08	1.25
	138.5	131.93	130.59	6.06	1.03
	137.4	125.78	130.24	5.50	3.42
	137.5	127.78	130.81	5.12	2.31
	137.2	125.18	127.28	7.79	1.65
	137.8	128.73	127.04	8.47	1.33
SH 8	142.3	140.52	148.55	4.21	5.41
	147	151.02	148.55	1.04	1.66
	146.8	149.72	148.55	1.18	0.79
	149	154.42	148.55	0.30	3.95
	147.8	153.22	148.55	0.50	3.14
US 95 Wilder	134.27	130	136.94	1.95	5.07
	134.17	130.8	136.94	2.02	4.48
	133.07	128.4	136.94	2.83	6.24
	134.07	130.2	136.94	2.10	4.92
	133.97	129.4	136.94	2.17	5.51
SH-37 5.8%AC	139.5	135.9	140.84	0.95	3.51
	140.4	139.4	140.84	0.31	1.02
	139.9	137.8	140.84	0.67	2.16
SH-37 6.0%AC	141.1	141.2	140.84	0.18	0.26
	139.4	133.8	140.84	1.02	5.00
	139	131.9	140.84	1.31	6.35
			Average:	2.73	3.25

The average percent error between the unconfined joint readings and the average core densities for each project (except SH-78 data as previously noted), along with the average percent error for all data, are shown in Table 4.10. The PQI and PaveTracker had an average percent error of 2.73% and 3.25%, respectively. The average percent error of the PQI and PaveTracker readings in the middle of the HMA mat, without surface fines, are 1.26% and 1.46%, respectively, as shown in Tables 4.5 and 4.6. The average percent error of both NNDGs was higher for the unconfined joints than for standard readings of the pavement mat.

The unconfined joint readings show a lower percent error than the confined joint readings. This is likely largely influenced by the use of the exact core densities for the SH-51 readings.

4.2 LABORATORY TESTING RESULTS

Laboratory testing included testing of the effects of temperature, surface moisture, and internal moisture. HMA loose mix was taken from field project sites and calibration constants from the corresponding field projects may be used. As the PaveTracker malfunctioned for most of the paving projects, only uncalibrated PaveTracker data is shown.

4.2.1 PQI Laboratory Temperature Testing

Laboratory temperature testing was conducted with fines filling in surface voids of the test specimen. Gauges were set on the specimen without moving, and readings were taken as the specimen cooled. This procedure was later modified at the suggestion of a Troxler Representative who cautioned that leaving the gauge to sit on hot HMA could overheat the internal electronics and provide unreliable readings. Both percent error and gauge density reading were compared with temperature.

Figure 4.18 shows the percent error of the uncalibrated data plotted against the temperature for each slab. There is no visible trend in the plot, and there is very little variation within each sample. Lab 2 slab has the largest variation, with a 2.11% range of percent error, all other slabs vary less than 1%. This indicates that the error of the gauge does not vary more than roughly 2% with change in temperature. Figure 4.19 is the same plot with the calibrated data. There is again no clear trend and when calibrated to the individual mix, all data points fall between 1-2 percent error. The average percent error for the corrected data is 1.55%, which is shown as a line on the plot. Paired, two-tailed t-test shows P-values of 0.028 and 5.37E-10 for the calibrated and uncalibrated PQI data, respectively. This indicates that temperature significantly affects PQI readings with 95% confidence.

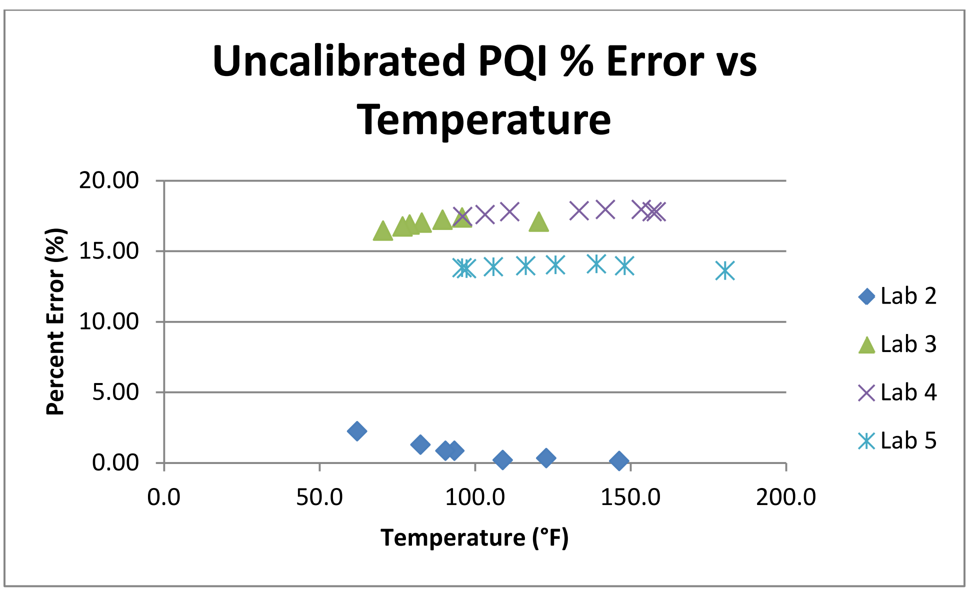

Figure 4.18. Uncalibrated PQI Percent Error vs Temperature.

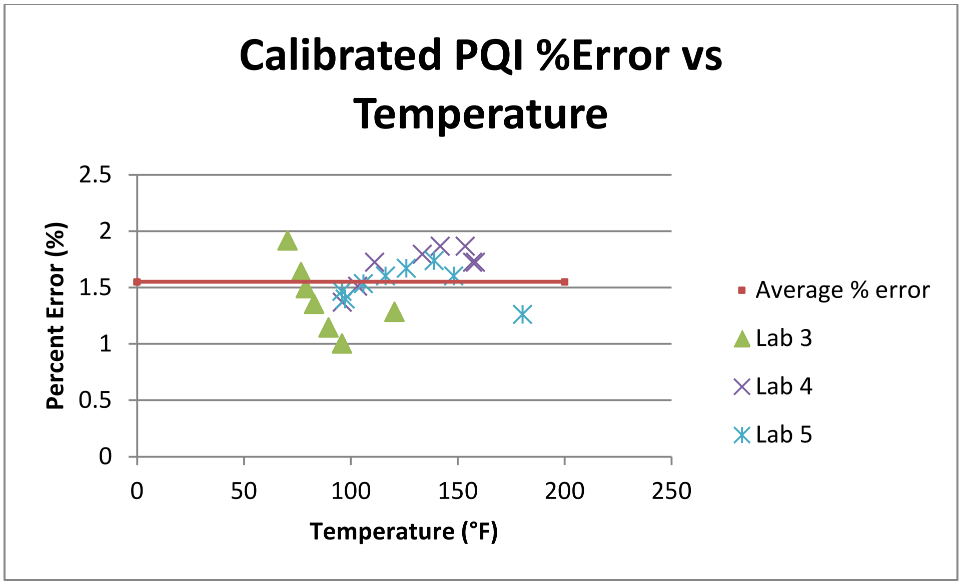

Figure 4.19. Calibrated PQI Percent Error vs Temperature.

PQI density readings were also analyzed to determine any potential changes in density readings at different temperatures. Figure 4.20 shows uncalibrated PQI density readings plotted against temperature for each lab sample. There is little variation within lab samples, with laboratory slab 2 varying the most, with a 3.7 pcf difference between minimum and maximum readings. The overall data also shows no trend. Figure 4.21 is the same plot with the calibrated PQI data, and shows the same overall results. Laboratory slab 3 has the most variation with 1.3 pcf between minimum and maximum readings, there is no overall trend in the data.

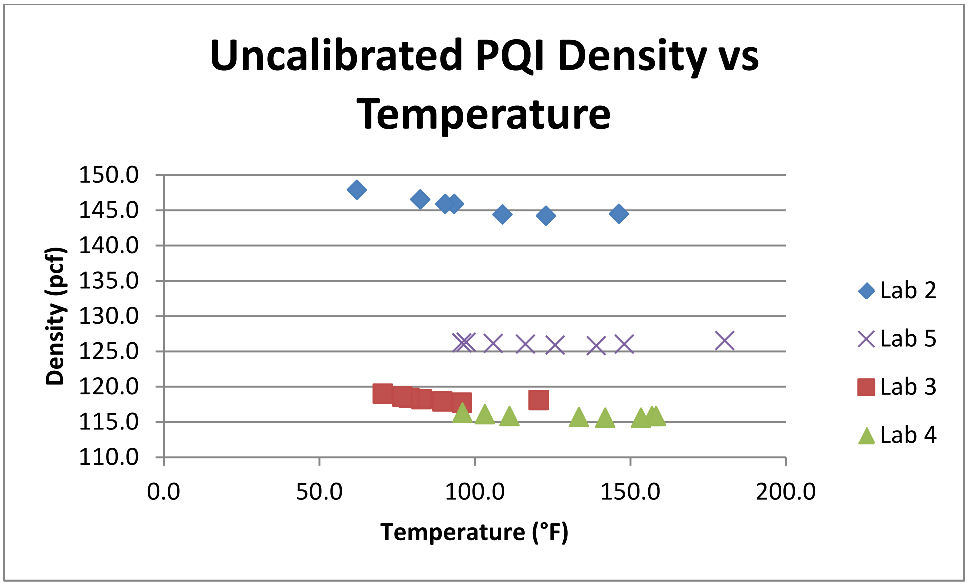

Figure 4.20. Uncalibrated PQI Density vs Temperature.

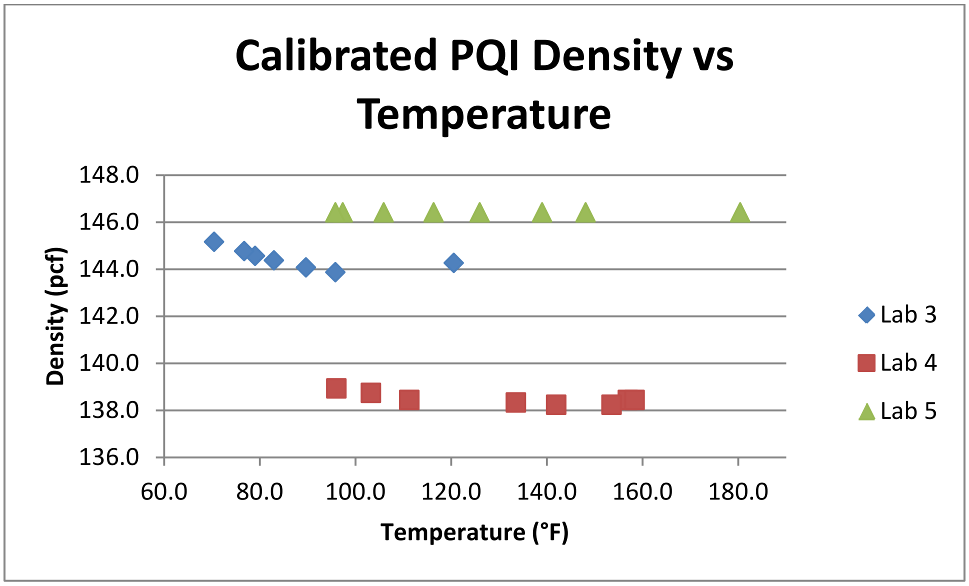

Figure 4.21. Calibrated PQI Density vs Temperature.

Tables 4.11 and 4.12 show summaries of the calibrated and uncalibrated lab temperature testing data, respectively. Core density as well as minimum and maximum temperature, density reading, and percent error are shown.

Table 4.11. Calibrated PQI Laboratory Temperature Testing Data Summary.

	Calibrated PQI Laboratory Temperature Data Summary					
	Lab 3		Lab 4		Lab 5	
	Min	Max	Min	Max	Min	Max
Temp (°F)	70.50	120.60	96.10	158.40	95.90	180.50
Density (pcf)	143.87	145.17	138.23	138.93	143.87	144.57
Percent Error (%)	1.00	1.91	1.37	1.87	1.26	1.74
Core Density (pcf)	142.44		140.86		146.42	

Table 4.12. Uncalibrated PQI Laboratory Temperature Testing Data Summary.

	Uncalibrated PQI Laboratory Temperature Data Summary							
	Lab 2		Lab 3		Lab 4		Lab 5	
	Min	Max	Min	Max	Min	Max	Min	Max
Temp (°F)	62.20	146.50	70.50	120.60	96.10	158.40	95.90	180.50
Density (pcf)	144.20	147.90	117.70	119.00	115.60	116.30	125.80	126.50
Percent Error (%)	0.12	2.23	16.46	17.37	17.44	17.93	13.60	14.08
Core Density (pcf)	144.67		142.44		140.86		146.41	

4.2.2 PaveTracker Laboratory Temperature Testing

Figure 4.22 shows the percent error of the PaveTracker data plotted against temperature for each lab sample. There is no visible trend in the plot, and there is little variation within each sample. Lab 3 has the largest variation, with a 3.10% range of percent error, all other lab samples had percent error less than 1.5%. This indicates that the error of the gauge does not vary more than roughly 3% with change in temperature. The average percent error for the corrected data is 11.16%, which is shown as a line on the plot. Data is spread uniformly around the average, further indicating no trend in the results.

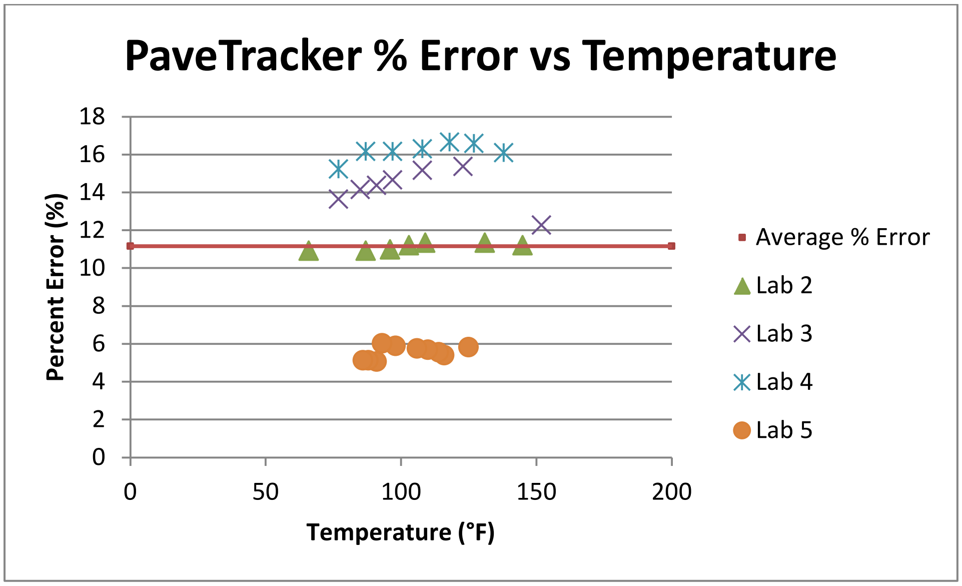

Figure 4.22. PaveTracker percent error vs Temperature.

PaveTracker density readings were also analyzed to determine any potential changes in density readings at different temperatures. Figure 4.23 shows PaveTracker density readings plotted against temperature for each lab sample. There is little variation within lab samples, with laboratory slab 3 varying the most, with a 4.3 pcf difference between minimum and maximum readings. All other slabs vary less than 2 pcf . The overall data also shows no trend. Table 4.13 shows a summary of the temperature testing data for each lab sample. Core density as well as minimum and maximum temperature, density reading, and percent error are shown. The P-value obtained from a paired student t-test was 0.0025, indicating that uncalibrated PaveTracker readings at different temperatures differ significantly from core density with 95% confidence.

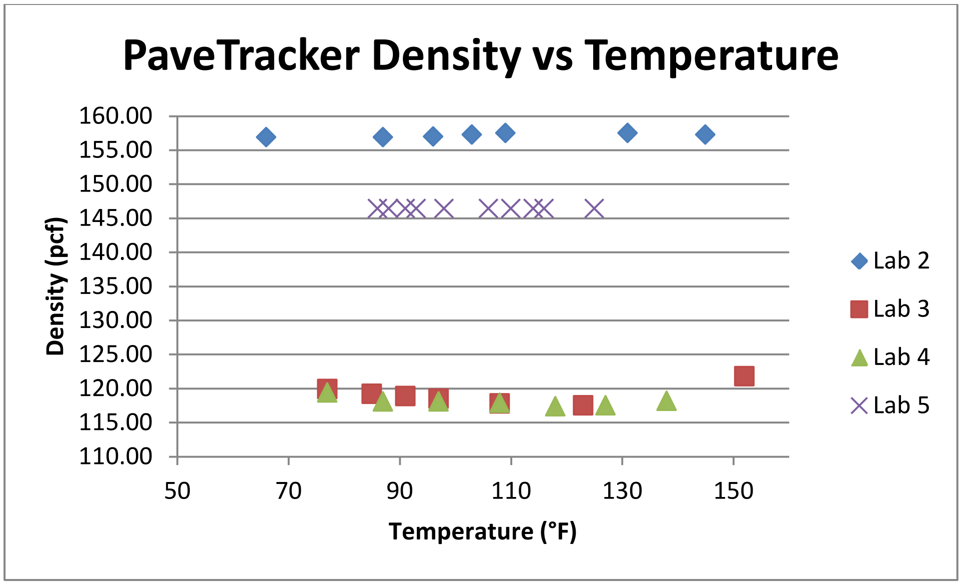

Figure 4.23. PaveTracker Density vs Temperature.

Table 4.13. PaveTracker Laboratory Temperature Testing Data Summary.

	PaveTracker Laboratory Temperature Data Summary							
	Lab 2		Lab 3		Lab 4		Lab 5	
	Min	Max	Min	Max	Min	Max	Min	Max
Temp (°F)	66.00	145.00	77.00	152.00	77.00	138.00	86.00	125.00
Density (pcf)	156.90	157.50	117.50	121.80	117.40	119.40	137.60	139.00
Percent Error (%)	10.91	11.34	12.27	15.37	15.24	16.66	5.06	6.02
Core Density (pcf)	141.46		138.84		140.86		146.41	

4.2.3 PQI Laboratory Moisture Testing

Effects of moisture on the surface of the test specimen as well as water inside of the specimen were tested. Figure 4.24 shows the PQI density reading vs the H2O index for both surface and internal moisture. Surface and internal moisture have similar affects on the PQI readings. Trendlines for both sets of data show decreased readings with increased H_2O index.

Internal moisture causes a 0.9 pcf decrease in PQI readings for each 10 point increase in H_2O index, while surface moisture causes a 1.3 pcf decrease for each 10 point increase in H_2O index.

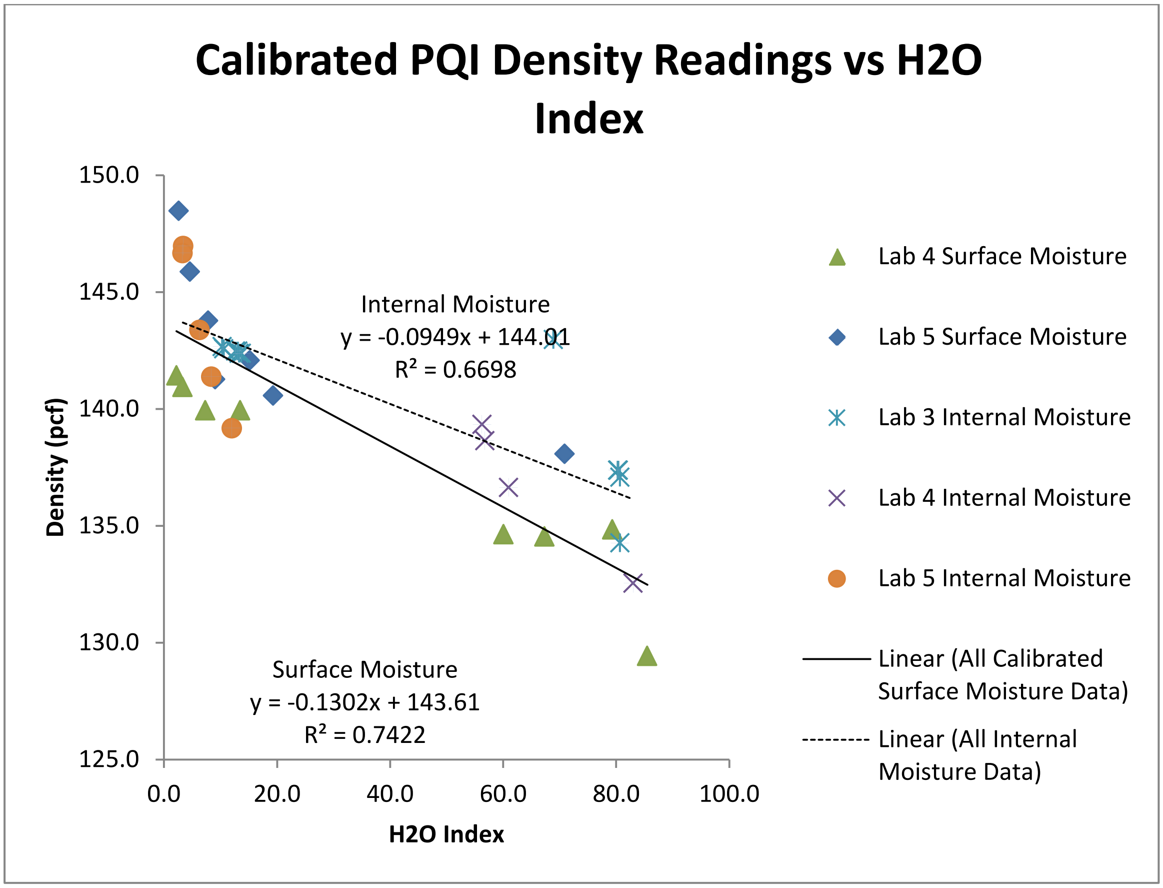

Figure 4.24. PQI Density Reading vs H2O Index.

Figure 4.25 shows the PQI percent error plotted against the H2O index for both surface and internal moisture. Surface moisture causes increased percent error with increased H2O index, with the trendline indicating that for every 10 point increase in H2O index, percent error will increase 0.63%. The internal moisture data shows no trend, with a nearly flat trendline and a nearly zero R^2 value.

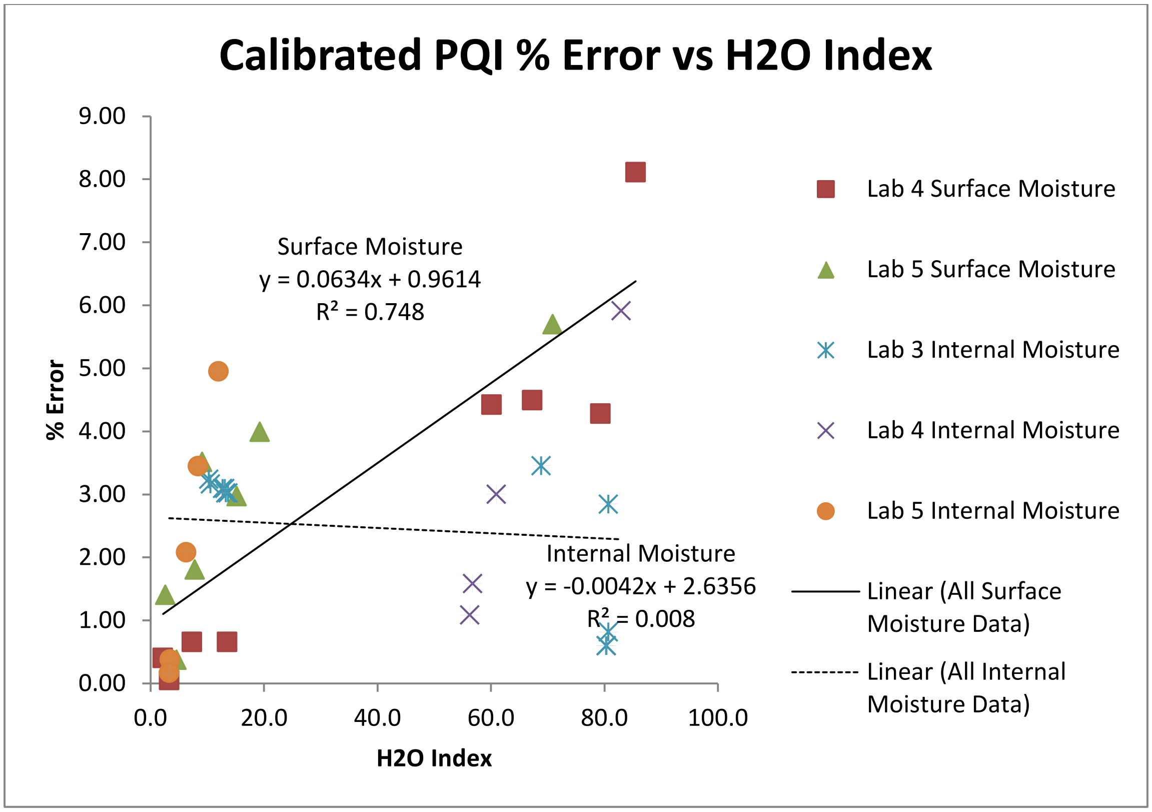

Figure 4.25. PQI percent error vs H2O Index.

4.2.4 PaveTracker Laboratory Moisture Testing

Surface and Internal moisture were tested with the PaveTracker as well. As the PaveTracker does not have a moisture measurement function, the PQI H2O index was used. Figure 4.26 shows the PaveTracker density reading vs the H2O index for both surface and internal moisture. Neither data set shows a trend, with both trendlines having a very low R^2 value. Data is spread out across a range of over 60 pcf of density, with only an 8.7 pcf difference between core densities. Additional testing is recommended.

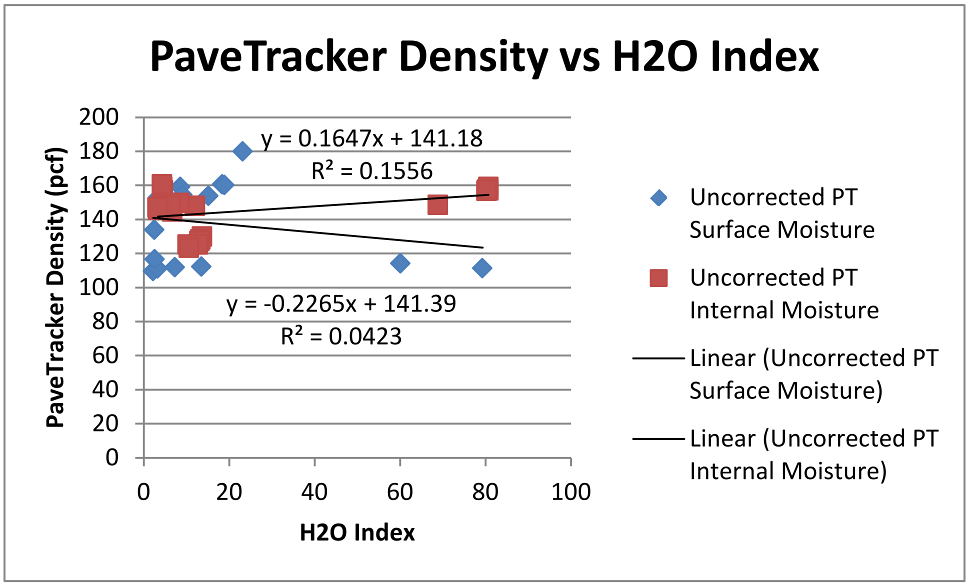

Figure 4.26. PaveTracker Density Reading vs H2O Index.

Figure 4.27 shows the PaveTracker percent error vs H2O index for both surface and internal moisture. Trendlines for both data sets have similar slopes, however the R^2 value for surface moisture is four times less than that for internal moisture. Trendlines from both data sets indicate that for every 10 point increase in H2O index, percent error will rise roughly 1%. Additional testing is again recommended in order to improve correlations, especially in the surface moisture data.

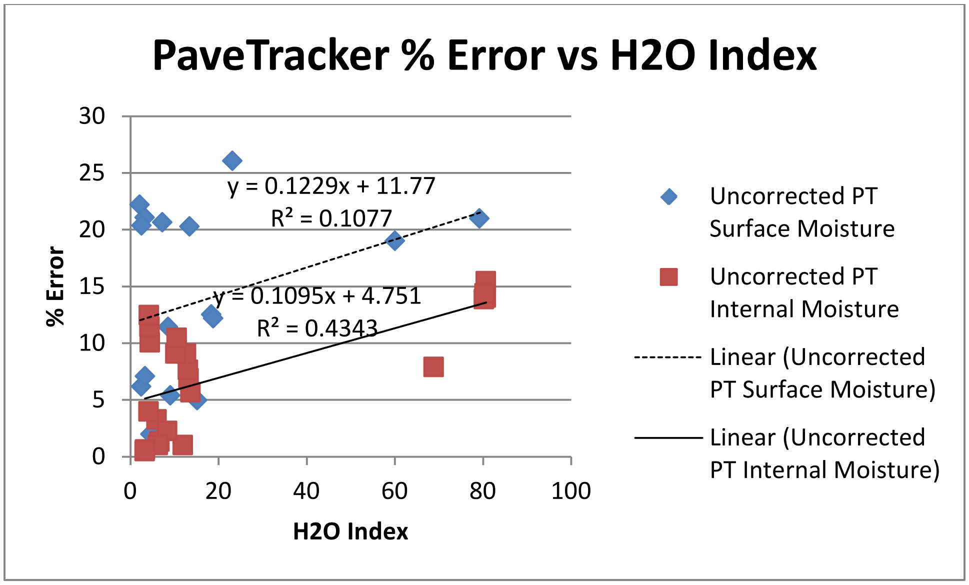

Figure 4.27. PaveTracker percent error vs H2O Index.

4.3 LOCAL FACTOR ANALYSIS

Local factors of surface fines and surface markings (paint) were tested. Fines had miniscule effects on the percent error of the NNDGs, changing the percent error of the PQI only 0.35%, and the PaveTracker percent error 0.22%. Paint likewise had no apparent effect, changing the PQI percent error 0.08%, and the PaveTracker percent error 0.17%. Both factors were also insignificant at 95% confidence by the student t-test.

Testing also revealed that while the gauges have approximately the same percent error regardless of whether testing is occurring at a joint or in the body of the mat. Additionally, the NNDGs show promise in being able to establish a roller pattern, although definitive results are still lacking due to the testing being terminated whenever the contractor's NDG detects the break over point.

4.4 LABORATORY TESTING ANALYSIS

Testing on the effect of specimen temperature on gauge performance was performed on laboratory compacted slabs. The largest range in PQI percent error among all lab samples was 2.11%, with all other lab samples varying less than 1 percent error, data is also evenly distributed around the average percent error (Figure 4.19), and does not have any discernible trend, either as a whole or among a single lab sample. PQI density readings also showed little variation, with a maximum variation of 3.7 pcf (uncalibrated) or 1.3 pcf (calibrated). There is no overall trend to the data.

Results are similar for the PaveTracker, with a maximum 3.1% range in percent error in one sample, all other samples having less than 1.5% range in percent error. Data is again spread uniformly about the mean and shows no trends. Uncalibrated Density readings varied 4.3 pcf in one lab sample, and less than 2 pcf in all other samples.

The effect of both surface and internal moisture was also examined. Internal moisture caused a decrease in of 0.095 pcf in PQI readings for each 10 point increase in H2O index. Surface Moisture caused a decrease in PQI readings of 1.3 pcf for each 10 point increase in H2O index.

The PaveTracker showed no trend between Density and the H2O Index provided by the PQI (Figure 4.21). There is a weak correlation between the PaveTracker percent error and H2O Index. The trendlines indicate that percent error will rise roughly 1% for each 10 point increase in H2O index. This is roughly the same result as the PQI.

4.5 GENERAL LINEAR MODEL ANALYSIS

A multiple regression model was analyzed using Minitab 16 software to determine the effects of the global factors, including pavement thickness, aggregate mineralogy, aggregate absorption, HMA class, and nominal maximum aggregate size.. Three aggregate types, granite(W_1), gravel (W_2), and basalt were present within the data set and were used as categorical indicator variables within the model. Aggregate size, X_1 (in), lift thickness, X_2 (in), HMA class X_3 (1-6), and aggregate absorption, X_4 (%), are quantitative rather than categorical variables. Due to the limited number of field projects, the only possible two-way interactions are W_i*X_3 and W_i*X_4, which are included in the statistical model.

The model used is:

$$Y= \beta_0 + \beta_1 W_1 + \beta_2 W_2 + \beta_3 X_1 + \beta_4 X_2 + \beta_5 X_3 + \beta_6 X_4 + \beta_7 W_1 X_3 + \beta_8 W_2 X_3 + \beta_9 W_1 X_4 + \beta_{10} W_2 X_4 + \epsilon$$

Where:

W_1={1 if aggregate 1, else 0}

W_2 = {1 if aggregate 2, else 0}

The model is based on the assumptions that the data is normally distributed, has constant variance, and has X_1 and X_2 interact with aggregate type, and $X_{(1,2,3,4)}$ do not interact. The basalt response was used as a baseline for the other aggregate responses. Thus, if W_3 =1 (i.e. the aggregate type for this response is basalt), then:

$$Y(3) = \beta_0 + \beta_3 X_1 + \beta_4 X_2 + \beta_5 X_3 + \beta_6 X_4 + \epsilon$$

If W_2=1 (aggregate is gravel), then:

$$Y = Y(3) + \beta_2 W_2 + \beta_8 W_2 X_3 + \beta_{10} W_2 X_4 + \epsilon$$

Where:

If $W_2 = 1$ has an effect, then $\beta_2 \neq 0$

If the aggregate type interacts with X_3, $\beta_{(7 \text{ or } 8)}$ then $\neq 0$

If the aggregate type interacts with X_4, then $\beta_{(9 \text{ or } 10)} \neq 0$

In order to assess the appropriateness of the model assumptions, graphical analysis of normal probability plots of the residuals as well as residuals versus fitted values were performed. The data was analyzed at 95% confidence, with two-sided confidence intervals. The data was fit without the intercept, and hypothesis tests of H_0:$\{\beta_i=0\}$ Vs Ha: $\{\beta_i \neq 0\}$. The non-intercept approach was chosen because if all X_i's are 0, then the gauge response would also be 0, which is unreasonable.

4.5.1 PQI General Linear Model Analysis

Normal probability plots of both the residual and standardized residual are roughly linear as shown in Figures 4.28 and 4.29, indicating normal distribution of data as expected. Both the residual versus fit plot (Figure 4.30) and standardized residual versus fit plot (Figure 4.31) show a roughly uniform spread of the residuals around zero, indicating constant variance as assumed.

The fit of the model to the data was analyzed numerically via the standard and adjusted R^2 values of 65.19% and 60.89%, respectively, which is a reasonably good fit of the data.

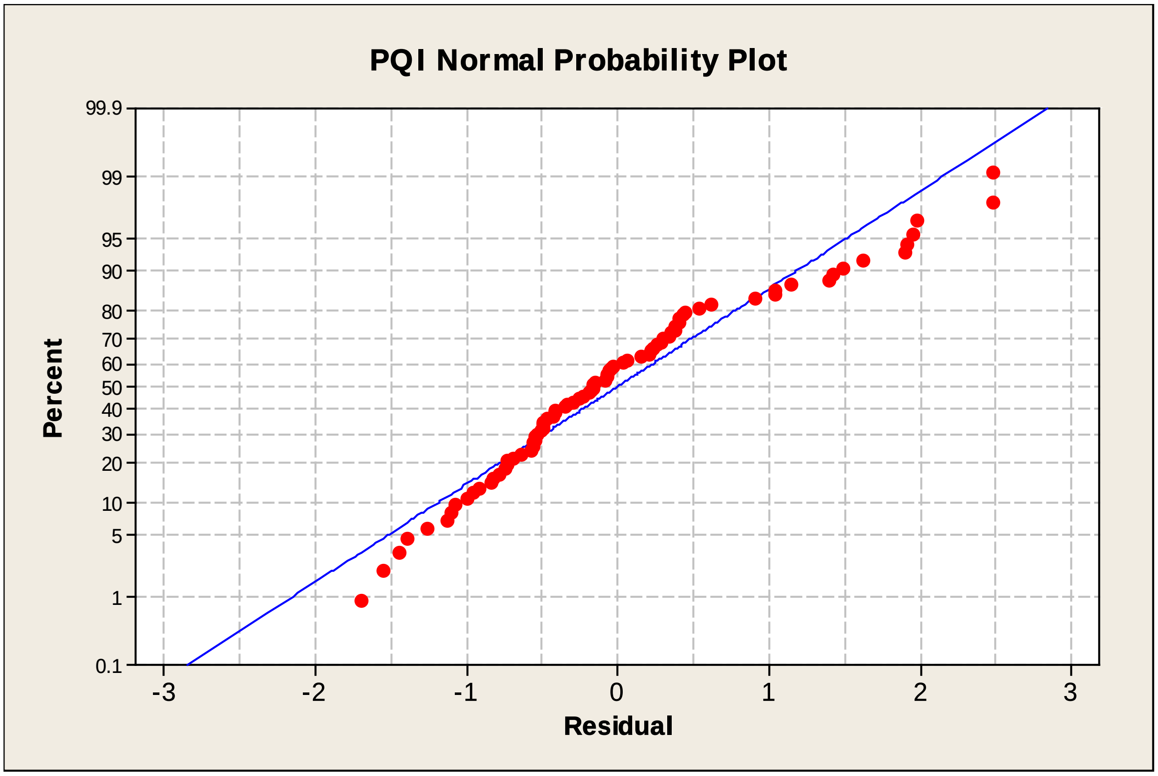

Figure 4.28. Normal Probability Plot of PQI Residuals

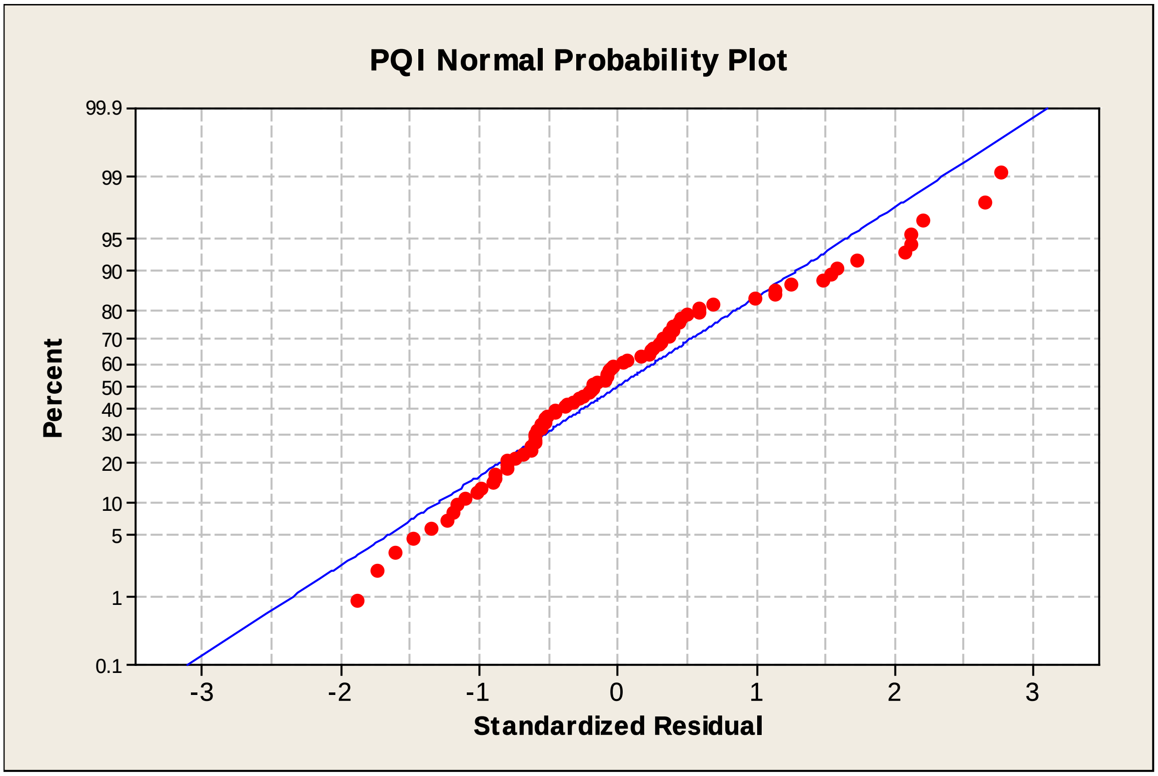

Figure 4.29. Normal Probability Plot of PQI Standardized Residuals

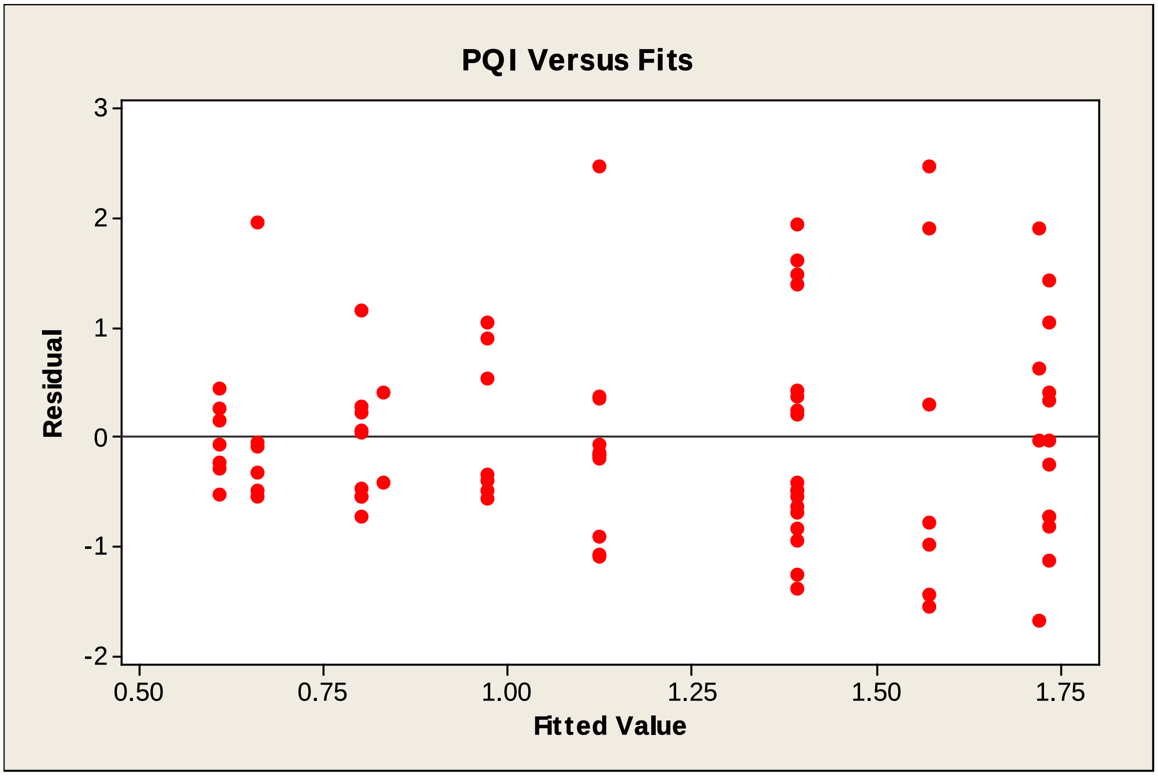

Figure 4.30. PQI Fitted Values vs. Residuals

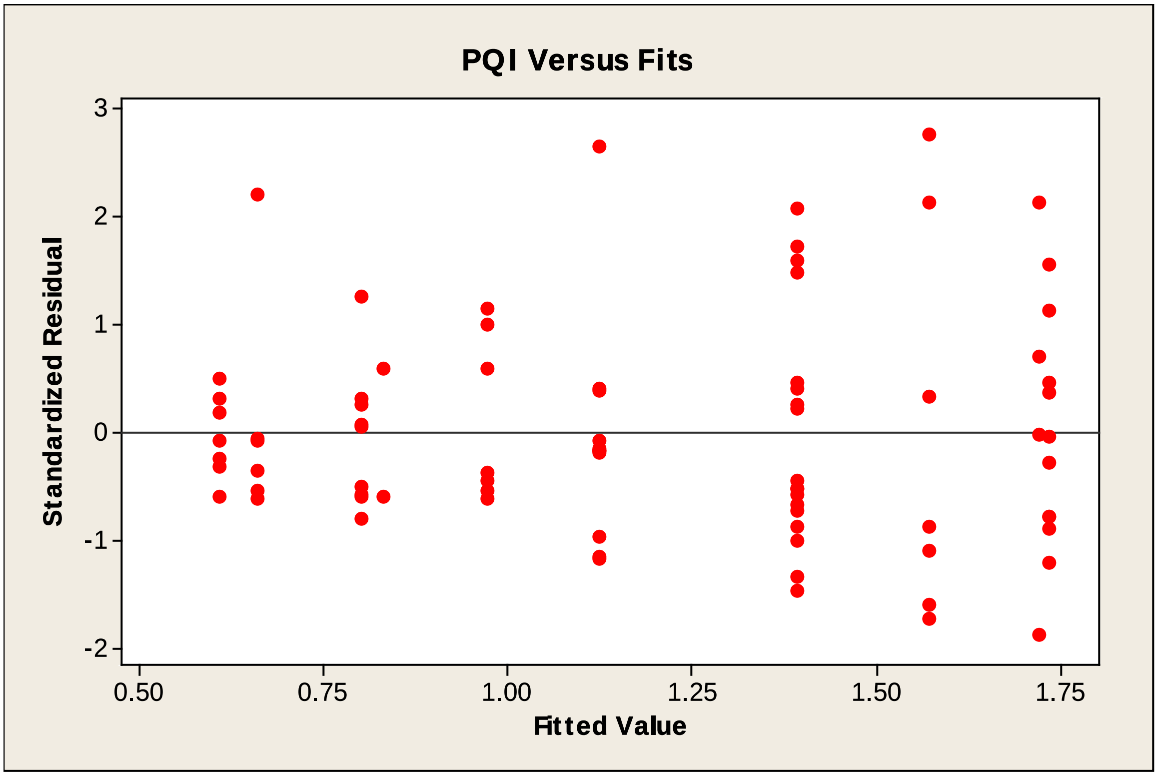

Figure 4.31. PQI Fitted Values vs. Standardized Residuals

Analysis of Variance (ANOVA) was conducted and tests are table is shown in Table 4.14.

Table 4.14. PQI GLM Model Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	128.33	128.33	14.26	15.19	0.00
W1	1	35.76	0.76	0.76	0.81	0.37
W2	1	59.52	2.49	2.49	2.66	0.11
x1	1	23.30	0.02	0.02	0.03	0.87
x2	1	0.34	0.92	0.92	0.98	0.32
x3	1	1.49	2.26	2.26	2.41	0.13
x4	1	0.01	2.56	2.56	2.72	0.10
W2*x3	1	5.97	4.91	4.91	5.23	0.025
W2*x4	1	0.10	0.10	0.10	0.11	0.74
W1*x3	1	1.82	1.82	1.82	1.94	0.17
Error	73	68.54	68.54	0.94		
Lack-of-Fit	1	0.38	0.38	0.38	0.40	0.53
Pure Error	72	68.16	68.16	0.95		
Total	82	196.87				

The only H_0 rejected was H_0:{ β_8=0}, indicating that aggregate type 2 (gravel) interacts with X_3, pavement class. The other null hypotheses being retained indicate that none of the global factors affects the response with statistical significance at 95% confidence. The regression equation is:

$$E1 = 1.49W_1+2.39W_2-0.32X_1+0.54X_2+0.32X_3-0.55X_4-0.51W_1*X_3-0.85W_2*X_3+0.21W_2*X_4$$

Based on R^2 values and the diagnostics run on the data, including normal probability plots and plots of residuals, the model appears to be an appropriate estimate of the effects of global factors on PQI readings. The only factor resulting in a statistically significant difference in the response was the interaction of the gravel aggregate type and pavement class. However, there was no significant interaction between W_1 (granite) and X_3. Additionally, the model was unable to estimate the interaction of W_1 and X_4. Because there are only two projects with granite-based aggregate, limiting the predictive power of the model, additional data may be needed to draw conclusions on this combination. This is expected because the device has been corrected with field core density.

4.5.2 PaveTracker General Linear Model Analysis

Normal probability plots of both the residual and standardized residual are roughly linear as shown in Figures 4.32 and 4.33, indicating normal distribution of data. Both the residual versus fit plot (Figure 4.34) and standardized residual versus fit plot (Figure 4.35) show a roughly uniform spread of the residuals around zero, indicating constant variance. The fit of the model to the data was analyzed numerically via the standard and adjusted R^2 values of 62.94% and 58.19%, respectively, which is a reasonably good fit of the data.

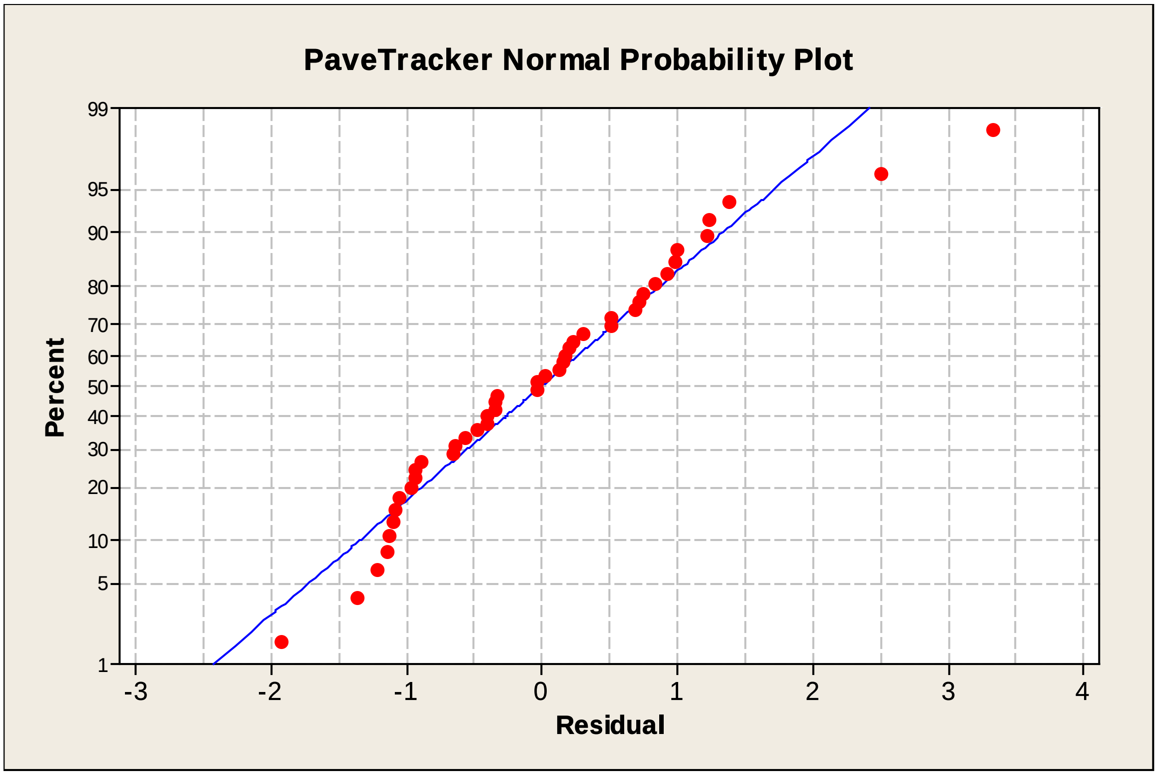

Figure 4.32. Normal Probability Plot of PQI Residuals

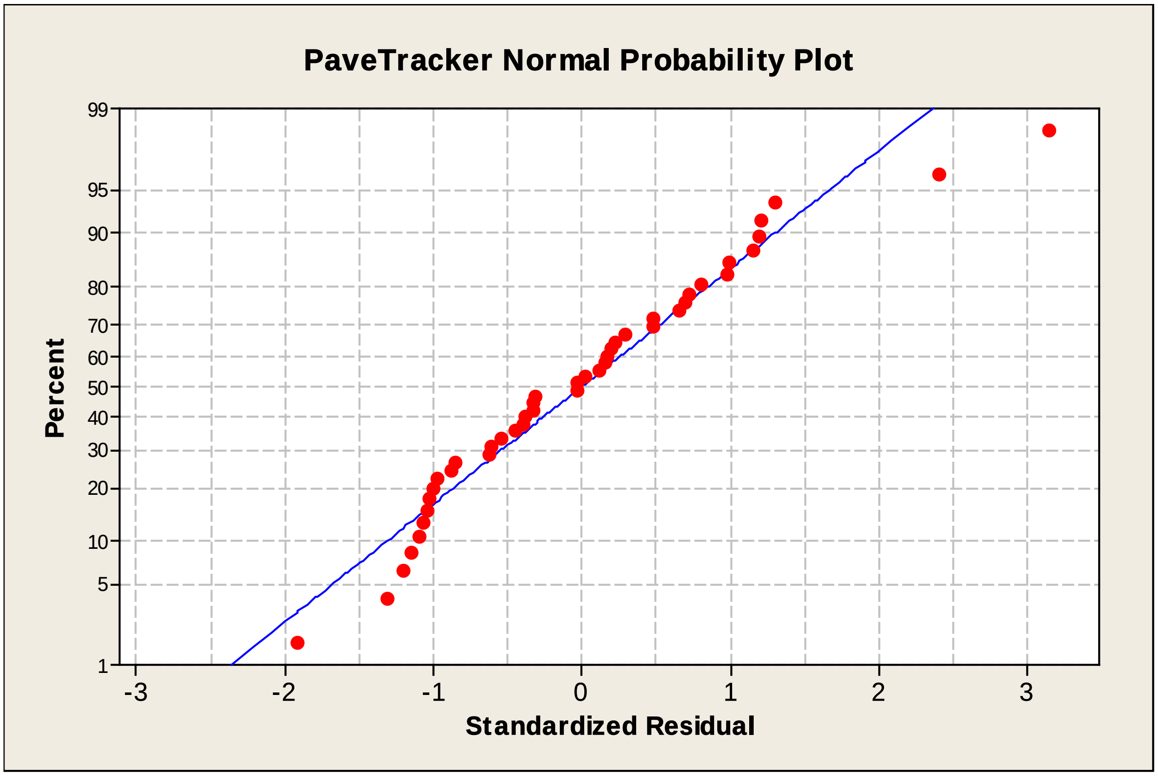

Figure 4.33. Normal Probability Plot of PQI Standardized Residuals

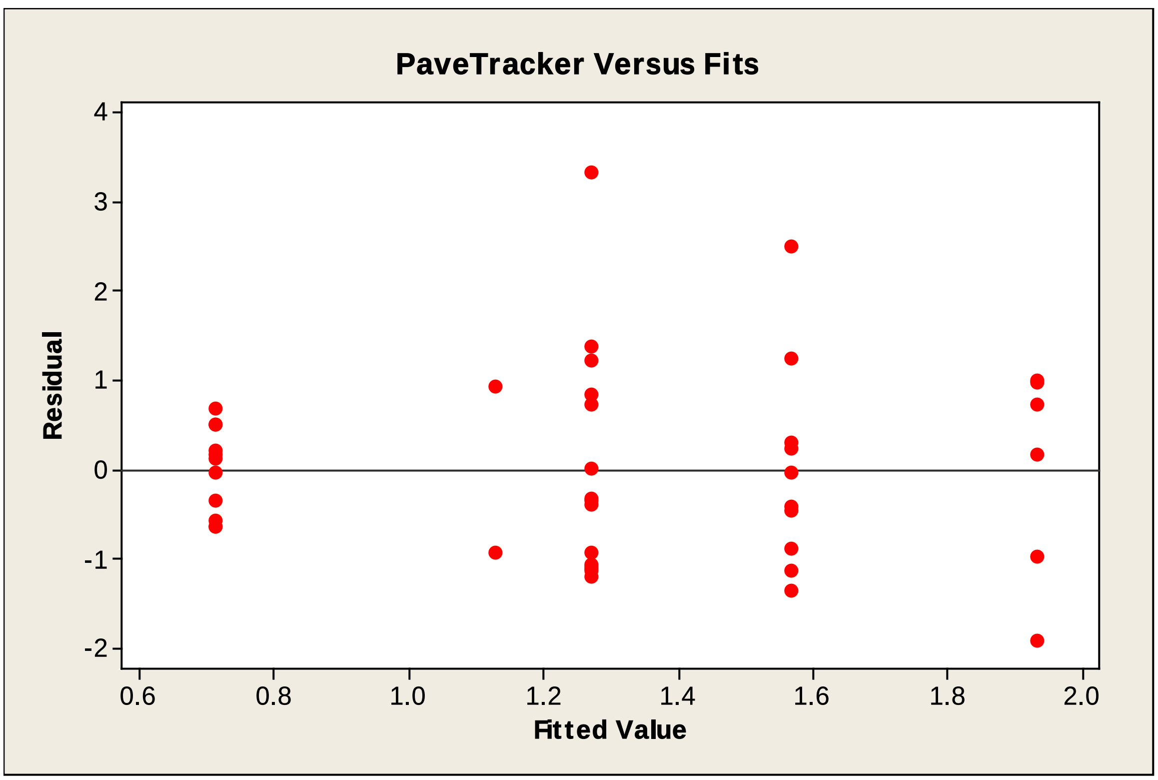

Figure 4.34. PQI Fitted Values vs. Residuals

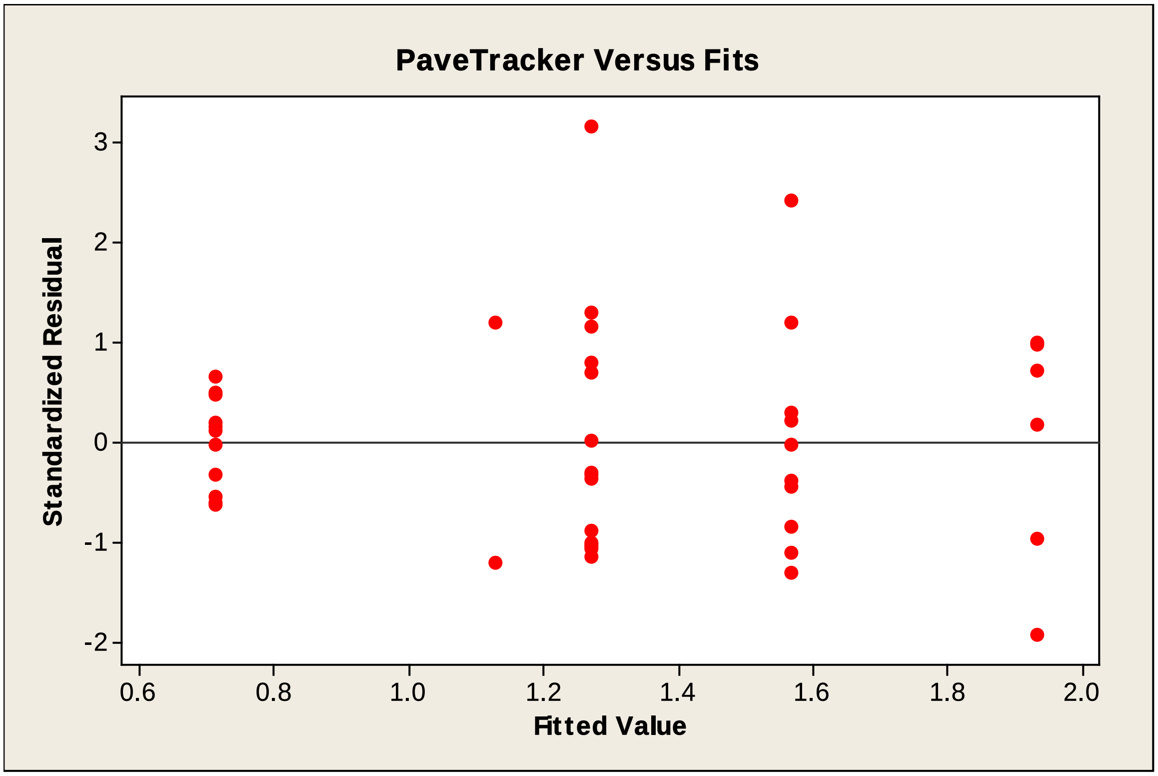

Figure 4.35. PQI Fitted Values vs. Standardized Residuals

ANOVA was conducted to perform statistical analysis. The results are shown in Table 4.15.

Table 4.15. PaveTracker GLM Model Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	79.34	79.34	15.87	13.25	0.00
W2	1	52.91	1.22	1.22	1.02	0.32
x1	1	20.59	0.01	0.01	0.01	0.92
x2	1	1.21	0.26	0.26	0.22	0.64
x3	1	3.78	4.63	4.63	3.87	0.058
x4	1	0.85	0.85	0.85	0.71	0.40
Error	39	46.72	46.72	1.20		
Total	44	126.06				

Due to a lack of data caused by the malfunctioned PaveTracker for several projects, only the main factors were included in the model. The basalt response was used as a baseline, and other aggregates are "non-basalt." All null hypotheses were retained indicating that none of the global factors affects the response with statistical significance at 95% confidence. The regression equation is:

$$E1 = -0.78W_2 - 3.09X_1 + 3.44X_2 - 0.66X_3 - 0.83X_4$$

The model appears to be a reasonably fit. No global factors were found to significantly affect the PaveTracker. This is expected, as the results for each project have been calibrated with field cores. The results again indicate that the calibration process is critical.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

Asphalt pavement service life is greatly affected by the density of the HMA layer which is often inspected by the use of a nuclear density gauge. However, nuclear density gauges have strict regulations, license, storage, and transportation requirements. This study evaluated the effectiveness of non-nuclear density gauges to replace nuclear density gauges. Two non-nuclear density gauges were evaluated in the field and laboratory.

Global Factors

The effects of global factors nominal maximum aggregate size, aggregate mineralogy, HMA class, and aggregate absorption were analyzed using a General Linear Model and ANOVA analysis. For the PQI, interactions between aggregate mineralogy and both HMA class and aggregate absorption were also analyzed.

- PQI
    - Statistical model predicts PQI percent error with 65% R^2
    - No global factors significantly affect gauge accuracy with 95% confidence
        - Interaction between aggregate mineralogy and HMA class is statistically significant with 95% confidence
- PaveTracker
    - Statistical model predicts PaveTracker percent error with 63% R^2
    - No global factors significantly affect gauge accuracy with 95% confidence

<u>*Local Factors*</u>

Local factors of surface fines/debris, surface paint, moisture, and temperature were tested. Testing was conducted both in the field and on slabs compacted in the laboratory.

- <u>PQI</u>
  - Surface fines/debris changed percent error 0.35%
    - Found statistically insignificant with 95% confidence with student t-test.
  - Surface markings (paint) changed percent error 0.08%
    - Found statistically insignificant with 95% confidence with student t-test.
  - Temperature caused < 1.3 pcf variation in readings
    - < 1% variation in percent error
  - Field (surface) moisture:
    - 1.5 pcf decrease in density reading for each 10 point increase in H_2O index
    - 1.09% increase in percent error for each 10 point increase in H_2O index
  - Laboratory surface moisture:
    - 1.3 pcf decrease in density reading for each 10 point increase in H_2O index
    - 0.63% increase in percent error for each 10 point increase in H_2O index
  - Laboratory internal moisture:
    - 0.9 pcf decrease in density reading for each 10 point increase in H_2O index
    - No trend in percent error with change in H_2O index
- <u>PaveTracker</u>
  - Surface fines/debris changed percent error 0.22%

        - Found statistically insignificant with 95% confidence with student t-test.
    - Surface markings (paint) changed percent error 0.17%
        - Found statistically insignificant with 95% confidence with student t-test.
    - Temperature typically caused < 2 pcf variance in readings
        - < 1.5% range in percent error
    - Field Surface moisture:
        - No trend in either density reading or percent error
    - Laboratory moisture:
        - No trend in density reading for either surface or internal moisture
        - Weak positive trends in percent error
            - 1.23% increase for each 10 point increase in H_2O index (surface moisture)
            - 1.09% increase for each 10 point increase in H_2O index(internal moisture)

<u>Longitudinal Joint Testing</u>

- <u>PQI</u>
    - Neither confined or unconfined joint readings differed significantly from average core density with 95% confidence

- <u>PaveTracker</u>
  - Unconfined joint readings were found to be statistically different from average core density of mat by student t-test
  - Confined joint readings were not found to differ significantly from average core density with 95% confidence.

<u>Comparison with NDGs</u>

- <u>PQI</u>
  - R^2 with core density exceeds NDG for 3-point, 4-point, and 5-point calibration
    - $R^2 > 0.83$ for all calibrations
    - 0.99 slope with core density
    - Can replace NDGs without compromising accuracy based on all calibrations
  - Lighter than NDGs
  - Faster readings than NDGs
- <u>PaveTracker</u>
  - R^2 close to or exceeding NDG for 3-, 4-, and 5-point calibrations
    - $R^2 > 0.77$ for all calibrations
    - 0.99-1.00 slope with core density
    - Can replace NDGs without compromising accuracy based on 5-point calibration
  - Lighter than NDGs
  - Faster readings than NDGs

Based on the lab and field testing performed with the two gauges, it is our conclusion that both the PaveTracker and PQI appear to be valid replacements for NDGs. Both NNDGs correlate with core density as well or better than NDGs. Additionally, neither gauge is significantly affected by global or local factors (other than moisture). While variability due to moisture is a concern, literature suggests keeping the H2O index under 10 (Schmitt, 2006) to avoid possible problems with the device. The H2O index of freshly laid asphalt is almost always less than that. Therefore, care should be taken to keep surfaces as dry as possible, and technicians should be cautious of the moisture conditions on site, both gauges appear to have the ability to take density as accurately as the NDG.

Further research is needed on the effects of moisture on the readings of the NNDGs. Additional testing should also be performed on longitudinal joints (with cores), as well as on establishing a roller pattern. Additional testing is also needed in order to examine the affect of interactions between global factors on PaveTracker readings.

CHAPTER 6 REFERENCES

Allen, D., Schultz, D., Willett, D. *Evaluation of Non-Nuclear Density Gauges*. Kentucky Transportation Center, August, 2003.

Apeagyei, A., Diefenderfer, B. *An Evaluation of the Potential Use of Non-Nuclear Density Gauges for Asphalt Concrete Acceptance*. Virginia Center for Transportation Innovation and Research, February, 2011.

Cho, Y., et al. *Non-Nuclear Method for Density Measurements*. Publication SPR1 (10) P335, The Charles W. Durham School of Architectural Engineering & Construction, June, 2011.

Larsen, D., Henauld, J. *Quantifying Segregation in HMA pavements using Non-nuclear Density Devices: Data Collection Report for Connecticut*. Publication CT-2238-F-06-2; SPR # 2238, Connecticut Dept. of Transportation, November, 2006.

Lenz, Russel. Texas *Department of Transportation Pavement Design Guide*. http://onlinemanuals.txdot.gov/txdotmanuals/pdm/manual_notice.htm. Updated January 1, 2011. Accessed July 11, 2012.

Mason, M., Williams, R. *Investigation of Electromagnetic Gauges for Determination of In PlaceDensity of HMA Pavements*. IHRB Project TR-576, Iowa State University Institute for Transportation, May, 2009.

Romero, P. *Evaluation of Non-Nuclear Gauges to Measure density of Hot-Mix Asphalt Pavements.* University of Utah, Department of Civil and Environmental Engineering, July, 2002.

Sargand, S. Sang-Soo, K. Farrington, S. *A working Review of Available Non-Nuclear Equipment for Determining In-Place Density of Asphalt*. Ohio Research Institute for Transportation and the Environment, December, 2005.

Schmitt, R.L., Rao, C., and Von Quintas, H.L. *Non-Nuclear Density Testing Devices and Systems to Evaluate In-Place Asphalt Pavement Density*. Publication 06-12; SPR# 0092-05-10, Wisconsin Department of Transportation, May, 2006.

Sebesta, S., Zeig, M., Scullion, T. *Evaluation of Non-Nuclear Density Gagues for HMAC: Year 1 Report*. Publication FHWA/TX-04/0-4577-1, Texas Transportation Institute, October 2003.

Sully-Miller (2000). *A Summary of Operational Differences between Nuclear and Non-Nuclear density instruments*. Sully-Miller Contracting Company, October, 2000.

William, S., (2008), *Non-Nuclear Methods for HMA Density Measurements*, Publication MBTC 2075, Final Report, University of Arkansas.

Ziari, H., Behbahani, H., Izadi, A. and Divandary, H. *Field evaluation of nondestructive tests in measuring the pavement layers density*. Journal of Applied Science, Volume 10, 2010, pp. 3091-3097.

APPENDIX A: SURVEY RESULTS

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] Yes

[25 of 40] No

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

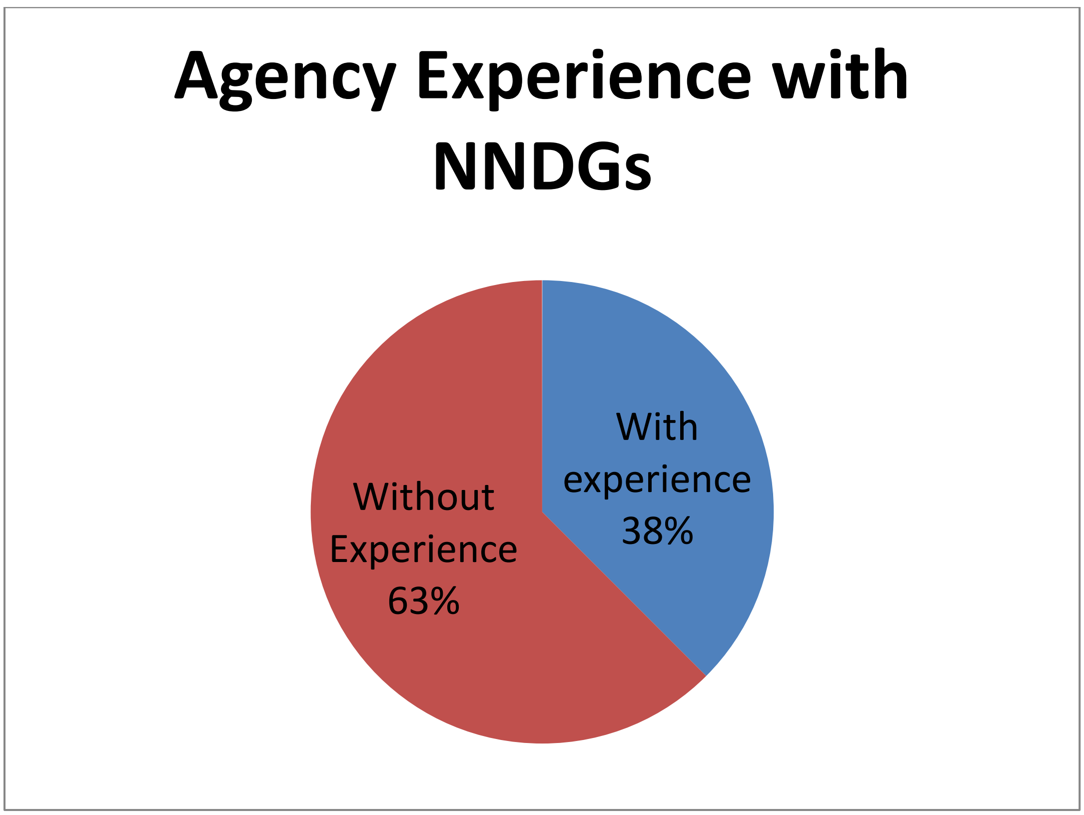

Figure 1. DOT Experience with NNDGs.

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: ____

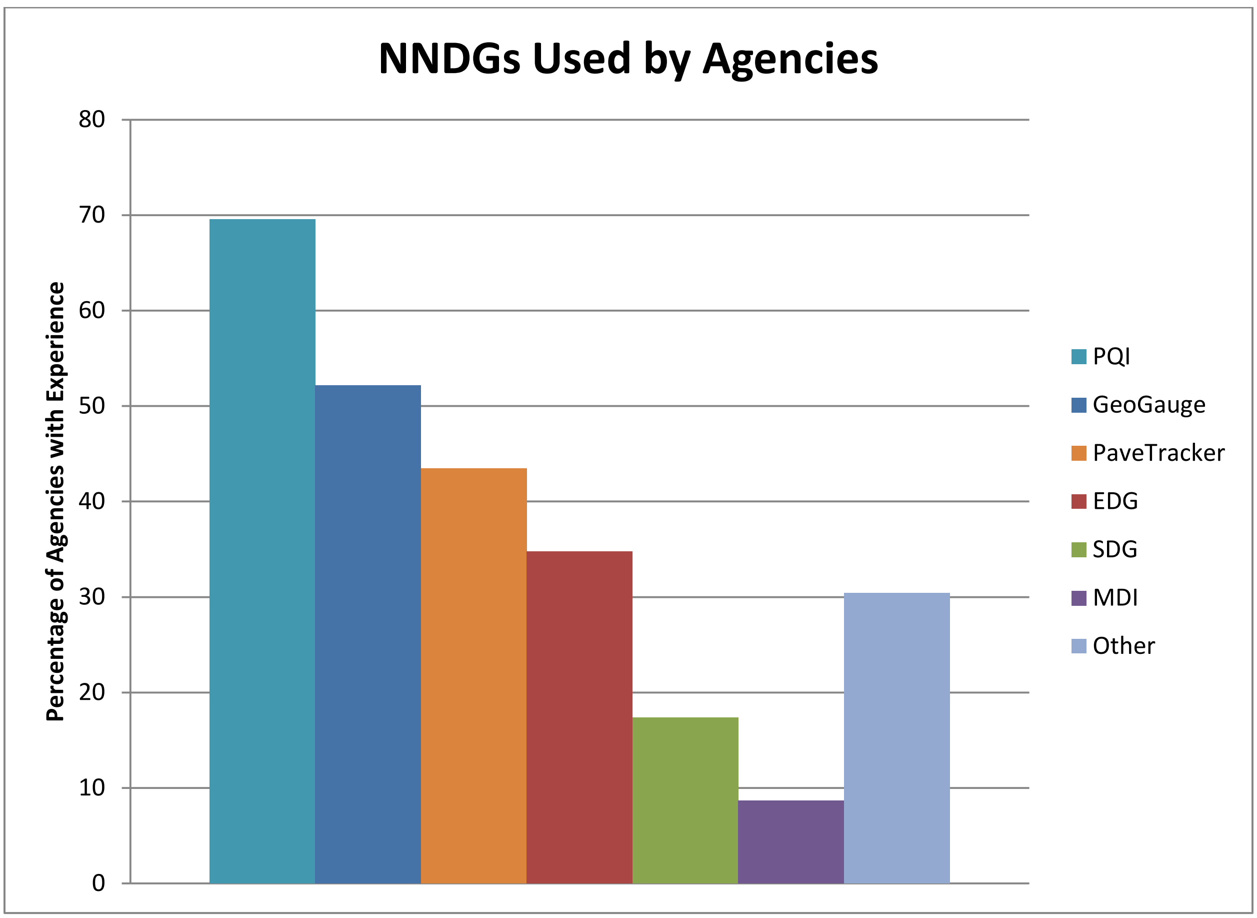

Figure 2. NNDGs Used by DOTs.

3. 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.

Device Acceptable Replacement to Nuclear Gauges [10 of 27]

Further Study Is Needed Before Adoption [16 of 27]

Device Modifications Needed Before Adoption [6 of 27]

Not Acceptable as Replacement to Nuclear Gauges [9 of 27]

*note, respondents can have multiple answers if experience with multiple NNDGs exists

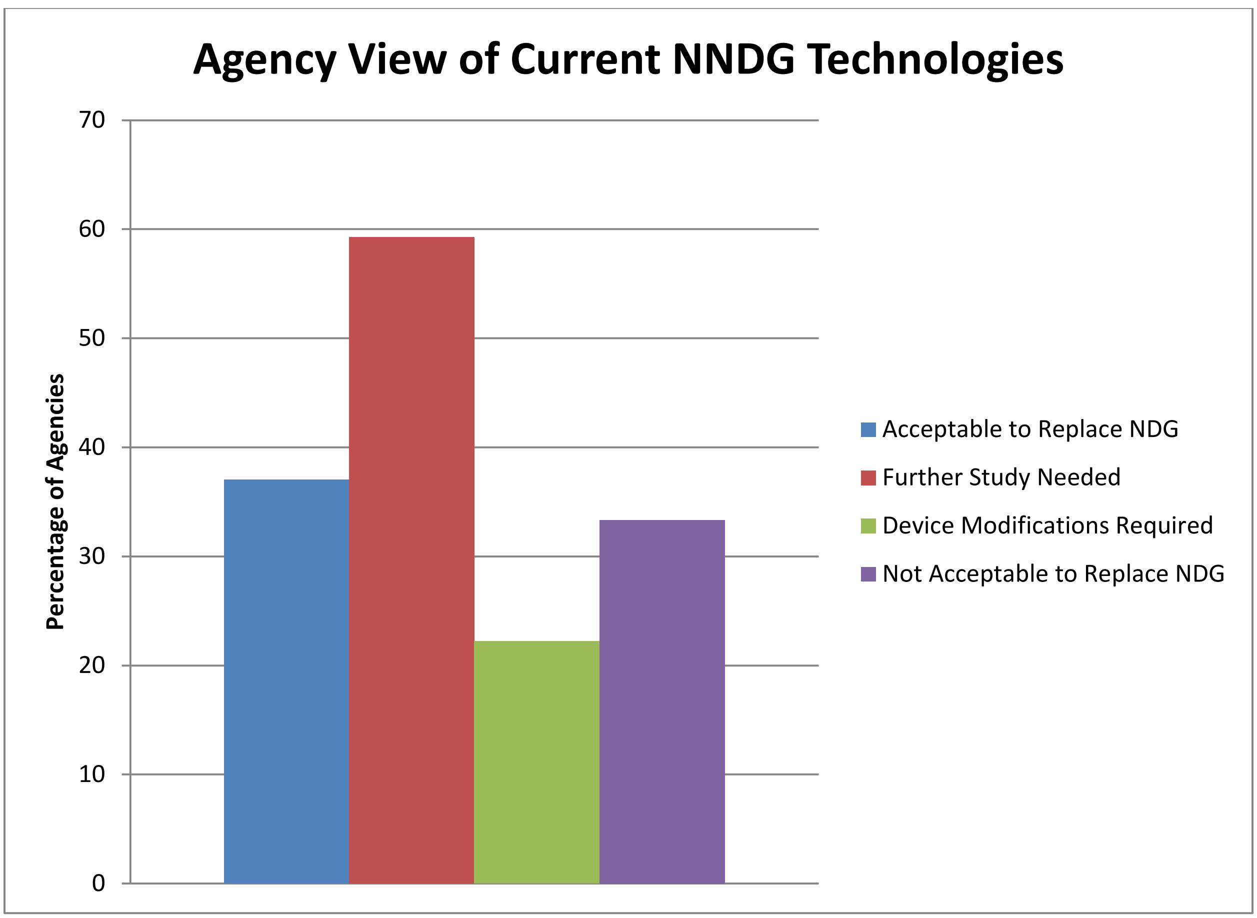

Figure 3. DOT View of Current NNDG Technologies.

4. 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. R2 0.85 + values given

[8 of 25] Correlation with sand cone, min. R2 0.85 + values given

[13 of 25] Deviation from true density: max= 0.5-3 pcf values given

[5 of 25] Other: most say modulus based specs needed to replace NDG

b. HMA :

[5 of 29] Correlation with nuclear gauges, min. R2 0.7-0.99 values given

[17 of 29] Correlation with cores, min. R2 0.7-0.99 values given

[11 of 29] Deviation from true density: max 0.5-2 pcf values given

[9 of 29] Other: ____

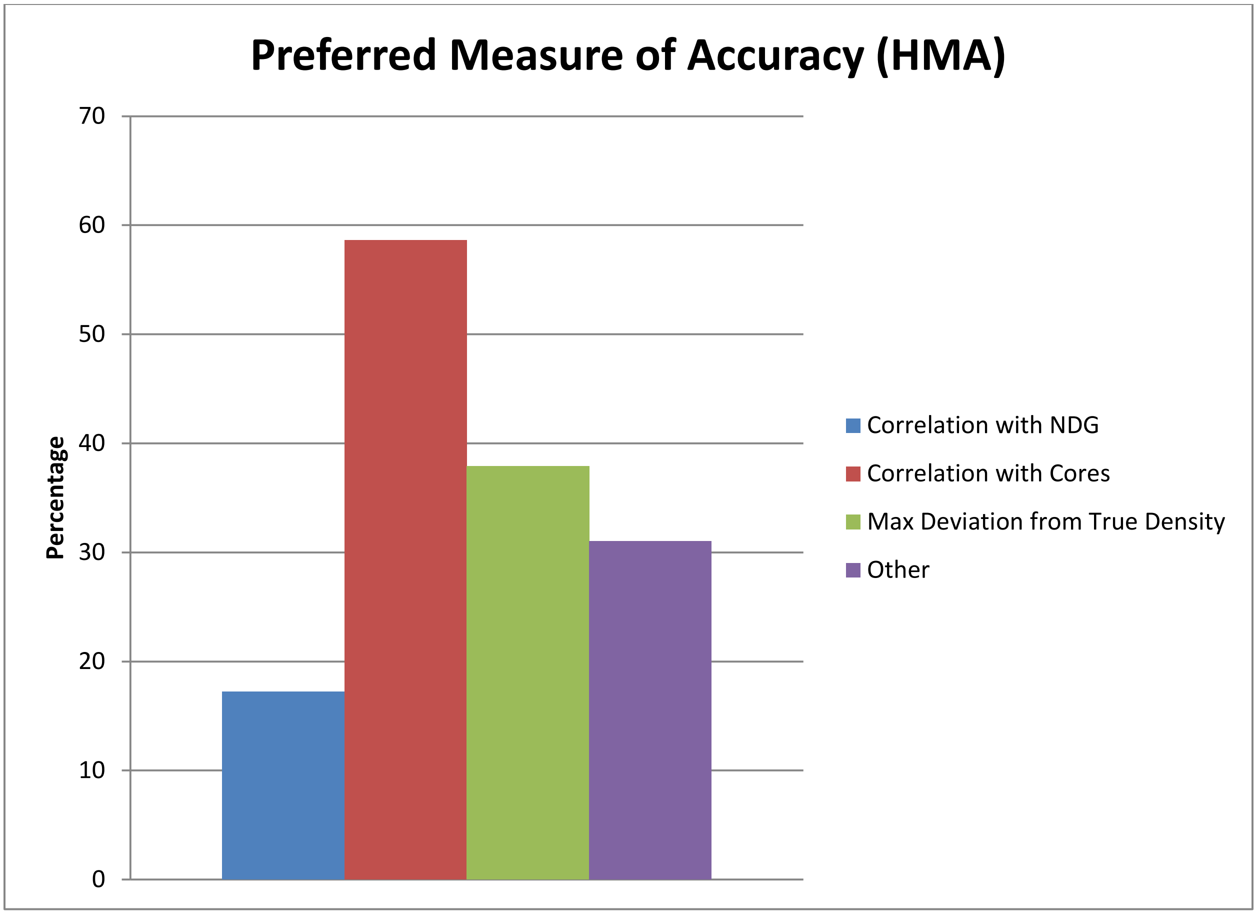

Figure 4. Preferred Measure of Accuracy for HMA NNDGs.

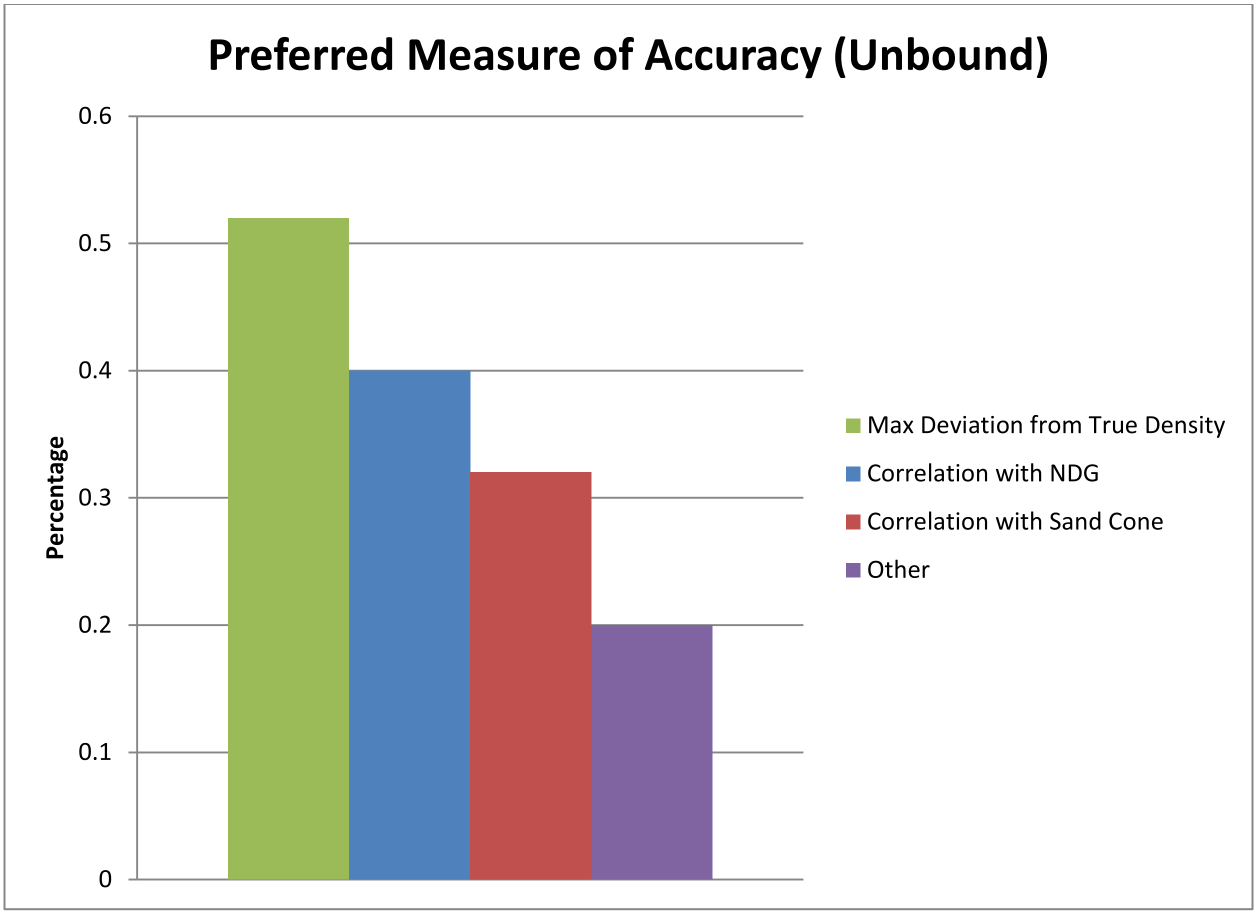

Figure 5. Preferred Measure of Accuracy for Unbound Material NNDGs.

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

____ Accuracy [Average Importance = 1.15 (33 of 35 respondents ranked)]

____ Cost [Average Importance = 2.86 (30 of 35 respondents ranked)]

____ Ease of Use [Average Importance = 2.77 (31 of 35 respondents ranked)]

____ Speed [Average Importance = 3.25 (28 of 35 respondents ranked)]

____ Other: [Average Importance = 2.2 (10 of 35 respondents ranked)]

6. 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

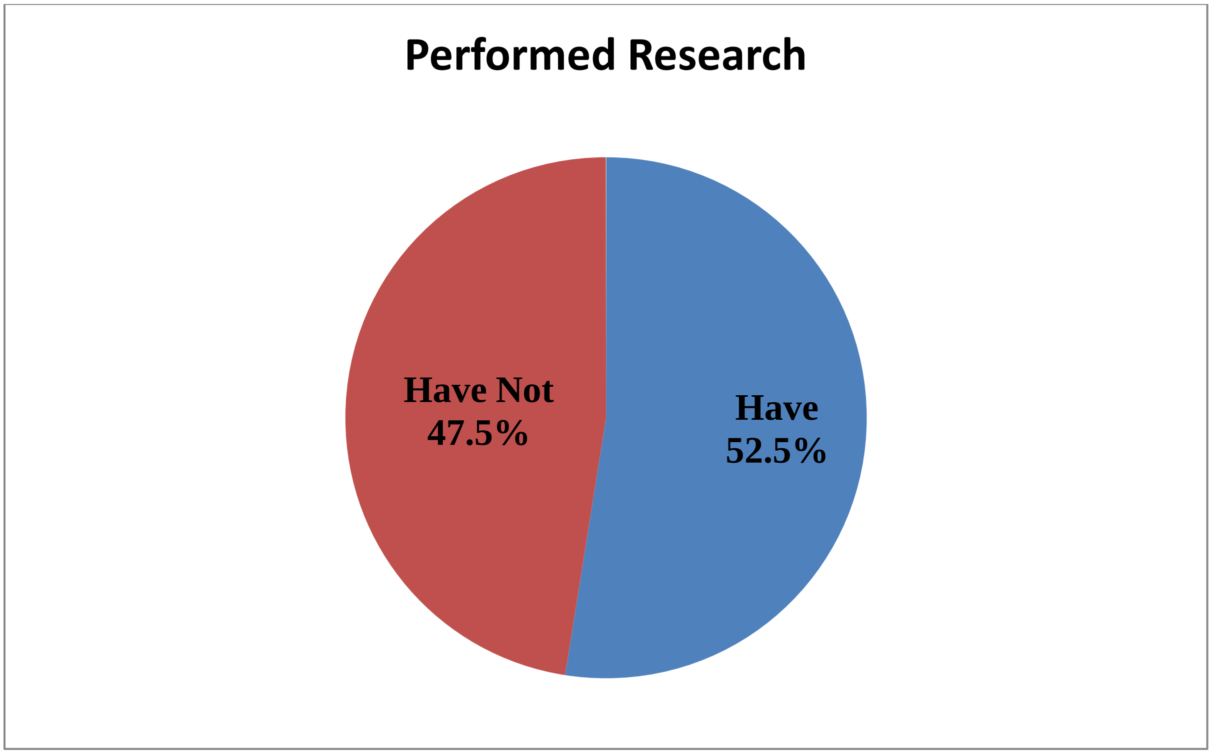

Figure 6. NNDG Research Conducted by DOTs.

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

[6 of 40] Yes

[34 of 40] No

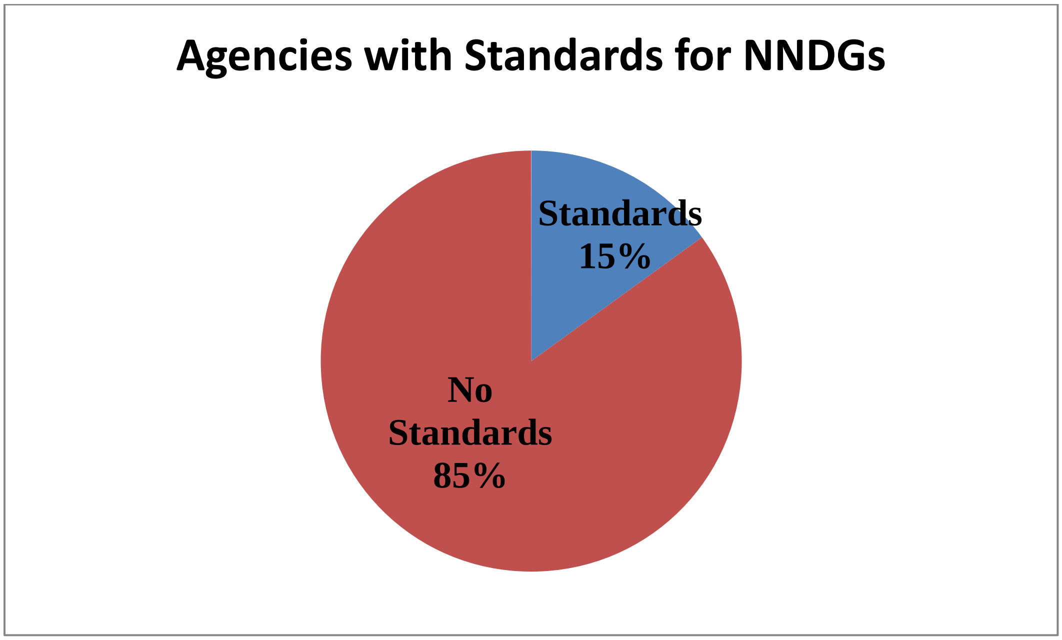

Figure 7. Percent of DOTs with Existing NNDG Standards.

APPENDIX B: PROCEDURE FOR DETERMINING IN-PLACE DENSITY OF HMA WITH NNDGS

1.0 Introduction and Scope

1.1 This test method describes the procedures for determining the in-place density of hot mix asphalt by electrical impedance measuring devices.

2.0 Interferences

2.1 The composition of the HMA may significantly affect measurements. The instrument should be calibrated to the specific mix design being used on each project.

2.2 The average of 5 readings at different points around the location of interest are averaged to determine the gauge reading, in order to avoid interference from irregularities in compacted HMA.

3.0 Apparatus

3.1 Density gauges shall use alternating frequency circuits, combined with an impedance sensing mechanism.

3.2 Gauges shall provide density readouts immediately to operator.

3.3 Gauges shall automatically average a number of individual measurements to obtain a mean reading.

3.4 Gauge shall include continuous reading mode of operation.

4.0 Calibration

4.1 Calibrate gauge for each mix design according to manufacturer's recommended procedures prior to testing materials. The following general guidelines are also applicable.

4.2 Density gauges should be calibrated on the HMA mat when temperature is in the same range that subsequent readings will be taken during paving. Gauge calibration using core samples is performed as follows.

- Identify a minimum of 5 test locations on asphalt mat
- Place gauge at test location and draw outline of gauge location on mat
- Perform 5 readings, one in the middle of outline, other 4 at 2, 4, 8, and 10 o'clock around outside of outline
- Average readings, record average
- Cut 6" core from center of outline
- Repeat with each additional test location
- In laboratory, perform density measurements on 6" cores using appropriate test methods
- Calculate difference between average of 5 gauge readings and actual core density
- Average differences from all test locations
- Program difference into gauge as offset, in order to change all subsequent readings by average difference.

5.0 Test Site Preparation

5.1 Optimum condition for testing is a completely dry, smooth surface with total contact between gauge testing surface and HMA

5.2 Dry test location with cloth to remove any standing moisture and brush surface clear of debris

6.0 Procedure

6.1 Calibrate unit according to section 4.0 of this specification for mix being used

6.2 Prepare test location according to section 5.0 of this specification

6.3 Place gauge on testing surface and take average of 5 readings as described in section 4.0 of this specification

6.4 Record average of 5 density readings