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Non-Nuclear Method for Density Measurements

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NON-NUCLEAR METHOD FOR DENSITY MEASUREMENTS

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16. Abstract

Quality control (QC) and quality assurance (QA) are necessary to ensure fulfillment and compliance to specifications, guidelines, manuals, and programs which outline methods and requirements during construction. Density, an important part of quality control, can be used to evaluate the quality of Hot Mix Asphalt (HMA) and soil compaction. This study investigated new technologies used for QC and QA by comparing the Pavement Quality Indicator (PQI) model 301 with a nuclear gauge and core sample measurements for HMA. For soil QC and QA, non-nuclear technologies—the Electrical Density Gauge (EDG), the Moisture Density Indicator (MDI), and the Light Weight Deflectometer (LWD)—were also investigated against a nuclear gauge and traditional non-nuclear methods of measurement. Overall, the nuclear gauge shows higher accuracy and higher correlation with cores than the non-nuclear gauges tested in this study. A thorough investigation of calibration methods was also performed, both in the lab and on the field, to improve the accuracy of the PQI's results. Data analyses showed that the accuracies of the non-nuclear soil gauges are somewhat lower than that of the nuclear gauge. With an improved methodology to create soil models for the EDG and standardized ways to develop the LWD's target values, the EDG and LWD could have a similar or better accuracy than the nuclear gauge. With the EDG and the Soil Density Gauge (SDG), both recently ASTM approved, non-nuclear soil technology is the future. Furthermore, the non-nuclear gauges could be a better alternative to a nuclear gauge when the following benefits are considered: (1) economic savings; (2) faster data measurement (PQI); (3) elimination of intense federal regulations and safety concerns; (4) elimination of licensing and intense training.

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List of Abbreviations

Electrical Density Gauge (EDG)

Dynamic Cone Penetrator (DCP)

Hot Mix Asphalt (HMA)

Light Weight Deflectometer (LWD)

Moisture Density Indicator (MDI)

Pavement Quality Indicator (PQI)

Quality Assurance (QA)

Quality Control (QC)

Soil Density Gauge (SDG)

Time Domain Reflectometry (TDR)

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Abstract

Quality control (QC) and quality assurance (QA) are necessary to ensure fulfillment and compliance to specifications, guidelines, manuals, and programs which outline methods and requirements during construction. Density, an important part of quality control, can be used to evaluate the quality of Hot Mix Asphalt (HMA) and soil compaction. This study investigated new technologies used for QC and QA by comparing the Pavement Quality Indicator (PQI) model 301 with a nuclear gauge and core sample measurements for HMA. For soil QC and QA, non-nuclear technologies—the Electrical Density Gauge (EDG), the Moisture Density Indicator (MDI), and the Light Weight Deflectometer (LWD)—were also investigated against a nuclear gauge and traditional non-nuclear methods of measurement. Overall, the nuclear gauge shows higher accuracy and higher correlation with cores than the non-nuclear gauges tested in this study. A thorough investigation of calibration methods was also performed, both in the lab and on the field, to improve the accuracy of the PQI's results. Data analyses showed that the accuracies of the non-nuclear soil gauges are somewhat lower than that of the nuclear gauge. With an improved methodology to create soil models for the EDG and standardized ways to develop the LWD's target values, the EDG and LWD could have a similar or better accuracy than the nuclear gauge. With the EDG and the Soil Density Gauge (SDG), both recently ASTM approved, non-nuclear soil technology is the future. Furthermore, the non-nuclear gauges could be a better alternative to a nuclear gauge when the following benefits are considered: (1) economic savings; (2) faster data measurement (PQI); (3) elimination of intense federal regulations and safety concerns; (4) elimination of licensing and intense training.

Chapter 1 Introduction

Quality Assurance (QA) of Hot Mix Asphalts (HMA) pavements was first introduced in 1986 (Andrewski 2003) to validate selected variables' accuracy and conformity to standards and regulations. For HMA, density measurement is a general quality control (QC) and QA method which uses either nuclear gauge readings or core density measurements. Density is measured as part of the quality control process by paving contractors and for quality assurance by the Nebraska Department of Roads (NDOR). Core density measurement is done in accordance with the American Association of State Highway and Transportation Officials (AASHTO) procedure AASHTO T 166. However, the destructive coring process creates holes in the new pavement, though they are later patched. Nevertheless, this creates an imperfection in the pavements and could cause long-term issues such as cracks and potholes. Furthermore, measuring core density generally takes time. Core results are not typically available until the next day in order to allow for corrections to the paving process and compaction to be completed. The required use of some laboratory equipment adds an additional cost factor which must be considered. A minimum of one full-time lab technician is usually required to run all the tests. Only a small number of cores (usually less than ten) are used to gauge the values for several miles of pavement; therefore, the coring process does not always provide solid results as some loose particles can be lost and affect the density. This can lead to inefficient gathering of information which in turn can affect the quality of HMA pavements.

Nuclear gauge technology offers a faster method of determining in-place HMA density, and has been used successfully to replace and/or complement most coring in many states. Depending on the specifications, Nebraska uses the coring method solely, or a combination of the coring system with nuclear gauges. With nuclear gauges, come many advantages and disadvantages. Nuclear gauges operate with the use of radioactive materials that may be hazardous to the health and well-being of the operators. Therefore, proper precautions and care need to be taken during operation. All users must have received radiation safety training and be aware of the applicable safety procedures and regulations. The use of dosimeters or film badges is also required for personal monitoring during use. Along with operation guidelines, routine procedures such as source leak tests and annual calibration are recommended to properly maintain the gauges. Strict licensing and re-licensing, record-keeping, and storage of the gauges are all added to the complications of nuclear gauge technology. Finally, transporting radioactive materials also requires rules and regulations. Consequently, there is a high demand for a device that is accurate, easy to use, quick, non-destructive, and non-radioactive. The PQI seems one of the gauges to overcome many or all of the problems posed by the core method and nuclear gauges.

The quality of pavement foundation is affected by the properties of its sub-grade and compaction conditions (Hancher et al. 2003). To ensure appropriate backfill, soil is compacted to achieve its minimum physical properties. The foundation materials are therefore usually compacted at different moisture conditions to identify moisture and density maximum values (ASTM D 698/AASHTO T99) that will be used later for quality assurance. For those reasons, density and moisture content are the common factors used to evaluate soil compaction. The density in-place or in situ density is the general method used for QA. Like HMA, nuclear gauges can measure in-place soil density and moisture content (ASTM D6938- 10, the Standard Test Method for In-place Density and Water Content of Soil and Soil-aggregate by Nuclear Methods.) which can be compared to the soil's maximum dry density and optimum moisture content for quality control purposes. Other means of obtaining in situ density are the Standard Test Method for Density and Unit Weight of Soil In-Place by the Sand-Cone Method (ASTM D1556-07), the Standard Test Method for Density and Unit Weight of Soil In-Place by the Rubber Balloon Method (ASTM D2167-08), or Standard Test Method for Density of Soil In-Place by the Drive-Cylinder Method (ASTM D2937-10). When these lengthy and destructive traditional methods are combined with the high costs, intense regulations, safety concerns (to just name few problems with nuclear gauges), non-nuclear technology standardization for QA and QC seems logical. To do so, the efficiency of these non-nuclear devices needs to be proven.

The main goal of this study is to assist the Nebraska Department of Roads (NDOR) with supporting data in order to adopt non-nuclear gauges as a test modality to assess HMA pavement and in-place soil. As a step towards this goal, the objectives of this research are:

(1) To assess the effects of a considerable number of factors potentially affecting the density and moisture measurements generated by non-nuclear gauges on HMA compared to the nuclear gauge and core samples through intensive field and lab tests; and
(2) To find the most effective method to assess soil compaction through field and lab tests; and
(3) To conduct economic analyses for the best alternative.

To be adopted for all QC and QA purposes, the performance of non-nuclear technology must initially be proven adequate. Although a number of studies have showed non-nuclear devices' capability, there has been disagreement in test results and recommendations for their uses. In order to be accepted and adopted as standards, the accuracy and repeatability of non-nuclear methods should be equivalent or better than the nuclear and other traditional methods. In order to evaluate this claim, the PQI model 301 was tested against the nuclear gauge and core samples for HMA QC. Similarly, the EDG, MDI, and LWD were all tested and compared against the nuclear gauge as well as a selected traditional method for soil QC and QA.

Chapter 2 Hot-Mix Asphalt

2.1 Methodology

The first objective of this research is to measure the effectiveness of the PQI model 301 which was compared to a nuclear gauge in terms of accuracy. The project examined the determination of field density of HMA mixtures, and first examined the PQI as a possible new way to gather real-time quality control data. After that part was established, a strategy for the evaluation of the PQI was developed. The traditional core sampling method was selected as standard, and both the nuclear gauge and PQI density measurements were compared against it. The next step was then to find innovative ways to improve the data accuracy by coming up with various calibration methods along with different techniques of measurement.

2.2 Literature Reviews

Different studies have been done to measure the effectiveness of nuclear and non-nuclear gauges. In 1999, a Humboldt nuclear gauge was compared to the first model of the PQI for variation in compaction and density variables (Rogge and Jackson 1999). Both gauges were tested at forty-five different locations for six site visits. Both gauges were compared to cores that were taken at each test area, and findings revealed that neither density values correlated well with core densities (Rogge and Jackson 1999).

Sully-Miller Contracting Company also compared a nuclear gauge to the PQI in order to study variance (Miller and Sully 2000). Standard deviations of the PQI were much lower and different as compared to the nuclear gauge’s standard deviations. The difference in surface texture caused the nuclear gauge to show bigger variations, which appeared to have no impact on the PQI. It was concluded that the PQI was accurate for HMA density measurements (Miller and Sully 2000).

Conversely, Henault evaluated the effectiveness of the PQI model 300 for quality assurance testing in his study (Henault 2001). The calibration method of five core offset was used on the ten different sites tested. The nuclear gauge results were much more correlated than that of the PQI and, consequently, it was not recommended for quality assurance tests (Henault 2001).

Prowell and Dudley conducted a similar study in 2002 and reported that the nuclear gauge showed better correlations with cores than the PQI (Prowell and Dudley 2002). Allen, Schultz, and Willet also compared a nuclear gauge's density measurements to that of a non-nuclear gauge. The five core average offset calibration method was used to improve the PQI's density values. Findings validated the use of the PQI for quality control, but not quality assurance (Allen and al. 2003). After improvements have been made to better non-nuclear gauges, Hurley, Prowell and Cooley compared the newer PQI in 2004 to the nuclear gauge. A total of twenty site visits were made and while the PQI had improved, it was still inferior to the nuclear gauge for density measurements (Hurley et al. 2004). Schmitt, Rao, and Von Quitos did a study in 2006 to compare the PQI model 300, model 301, and Pave Tracker 2701-B to the nuclear gauge. To start, no calibration was made to the gauges to observe the results, and data revealed that nuclear gauges' values were much greater than the non-nuclear gauges' values. They also reported that the difference in nuclear and non-nuclear densities increased when the pavement thickness increased. A mandatory calibration on each site test was then recommended before measurements could be taken. A ten-core calibration was used and showed improvements in the data. However, PQI's practicality was questioned (Schmitt et al. 2006).

In 2007, Kvasnak (et al. 2007) and a group of researchers) also compared the PQI and Pave Tracker to the nuclear gauge to study factors that affect non-nuclear gauges. It was found that roller pass, pavement moisture condition, and aggregate were among some of the factors that affected density measurements. Another important finding was the need to study a test strip or bed for calibration purposes (Kvasnak et al 2007).

2.3 Testing Methods

2.3.1 Core Method

Cores need to be extracted from the area where the nuclear gauge and PQI have been used. Cores are taken soon after the pavement has been laid down and the roller passes. The cores are usually very hot and therefore not easily drilled out. To facilitate the coring process, the research team used dry ice (CO2) as a method to cool down the asphalt, as shown below in Figure 2.1. Dry ice cools down the surface and leaves no trace of water, which helps with the density measurements done on site for calibration purposes. Important care needs to be taken when drilling to ensure underlying layers are not included in the sample. Drilling depth is usually dictated by the bituminous layers. The results could be affected if the cores are tested with excessive layers. After the cores have been drilled out, their bulk specific gravity measurements are computed using the saturated surface dry method as specified in AASHTO 166 or by similar guidelines. This measure of density has been adopted as the standard for such research. Nuclear gauge density and PQI density are both compared to this density to measure accuracy. However, biases occur in taking core density measurements because this method is not totally accurate and can be offset by human errors, core debris left in holes, and many other factors including mix types and hot weather temperatures.

Figure 2.1. Dry ice cools the hot pavement

2.3.2 Nuclear Method

Nuclear gauges emit gamma rays from a radioactive source to measure density. The emitted rays go through the compacted materials and use a count system that, combined with other variables, are used to read the density. The research team performed nuclear readings on HMA pavements using the American Society for Testing and Materials (ASTM) standard D 2950. The first five cores taken were used to calibrate both the nuclear and non-nuclear gauges. Furthermore, the difference between the average of the first five nuclear gauge density measurements and the average of the first five core measurements was used to offset the nuclear gauge for the remaining measurements, as advised by Troxler 3440 operating manuals and specifications. Figure 2.2 shows the Troxler 3440 nuclear gauge used for this study. The results are then compared to the PQI’s and documented for later analyses.

Figure 2.2. Nuclear Gauge is shown measuring density

2.3.3 Non-Nuclear Method (PQI)

The PQI model 301, manufactured by Transtech Systems Inc., was used as a non-nuclear alternative to measure density for the project. The PQI estimates density by measuring the change in an electromagnetic field when a current is sent through the compacted material. A dielectric constant proportional to the pavement's density is measured when the electrical current is transmitted. The PQI model 301 is shown in Figure 2.3. The PQI is also calibrated and offset using the average of the first 5 core density measurements, and by also following the manual and operation specifications. Different measurement modes can also be used to improve the accuracy of the results. The average mode, for example, automatically calculates an average of all the densities at the measured spot, as long as they are within close proximity to each other (about 1 ft).

Figure 2.3. PQI model 301shown taking measurements

2.3.4 Calibration

To improve the accuracy of the results, the gauges need to be properly calibrated. Density measurements are relative measures of compaction, and are adjusted to be very close to the core measurement. Several methods can be used for calibration. The AASHTO TP 68 standard advises the users to record density measurements after each series of rollers pass through. Once the density no longer increases, it is accepted and used to calibrate the devices. The AASHTO TP 68 also recommends using the average of up to five core calibration densities to offset the gauges. ASTM has also recommended similar methods of calibration. TransTech suggests a core calibration using a minimum of five gauge readings at each location. ASTM has also published numerous standards to recommend how electromagnetic devices should be calibrated (Kvasnak et al. 2007). The research team started to calibrate the PQI by taking five single measurements at a location, averaging the densities, and adjusting the results with the core measurements. To improve the results, the readings are taken using an average mode of five to read a single location.

The nuclear gauge reading is also done in both directions (parallel and perpendicular to the pavement), and the average is computed for calibration. Dry ice, as introduced earlier, served as a method to quickly cool down the pavement before coring. Dry ice also allowed the research team to take cores without using water—allowing the cores to be measured right on site. All cores are also measured later in the laboratory after a drying period of at least 24 hours. Both measurements are compared, and adjustments were made to improve the results' accuracy. Figures 2.4 and 2.5 show the cores while being measured both on-site and later in the lab. The calibration method adopted by the research team conforms to the recommendations of both manufacturers as well as those recommendations in the AASHTO TP 68 "Standard Method of Test for Density of In-Place Hot-Mix Asphalt (HMA) Pavement by Electronic Surface Contact Devices." Ideally, a calibration method will reconcile the differences between dissimilar measures of the same property. However, in this case due to the unpredictability of the gauges and other biases, perfect agreements are not always present, and regressions are used in analyses to adjust one method to the others.

Figure 2.4. On-site set up for core measurements

Figure 2.5. Lab set up for core measurements

2.4 Data Analysis

As noted earlier, this study has set out to compare measured differences obtained in the field from both nuclear and non-nuclear density gauges. Both gauges were compared separately against the study's control density measurement: laboratory tested core samples from the same location. The underlying hypothesis of this study is that a proportional increase in measured core density should linearly equate to a proportional increase in non-destructive density gauge readings in the field. Unfortunately, due to external variables inherent to the paving and coring process, data collected onsite does not follow an easily identifiable trend. Due to the external variables, each data point was accepted or rejected based on a few key criteria.

2.4.1 Outliers

Generally, an outlier is identified as all values above the mean, plus or minus three standard deviations (Los Alamos 2000). Initially, PQI density and core density correlation was found to be extremely low at 4.21% for site number five (Figure 2.6). However, as Figure 2.7 illustrates, when outliers are excluded from the dataset, the correlation between readings from the PQI and tested core samples increases dramatically to 56%. Outliners were taken out of the data pool to improve the results for this study.

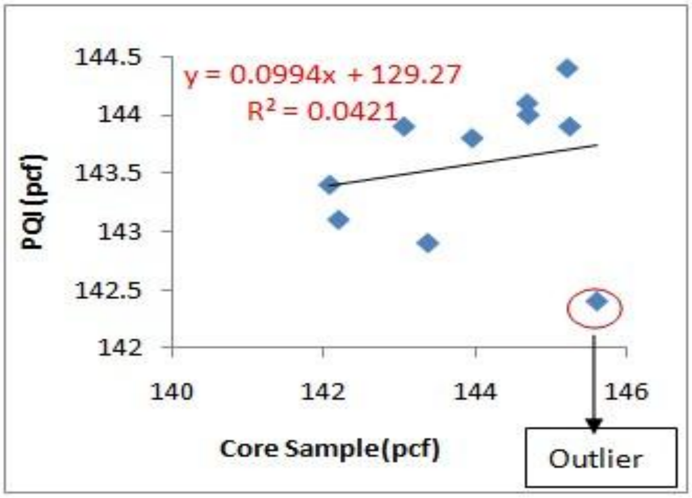


Figure 2.6. PQI's relationship with core samples before removing the outliers

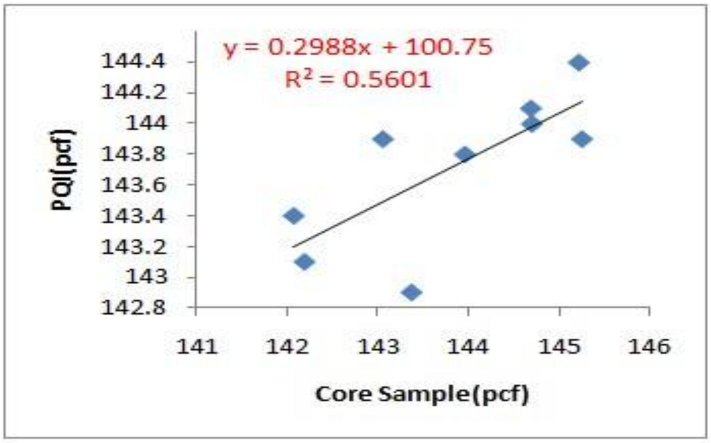


Figure 2.7. PQI's relationship with core samples after removing the outliers

2.4.2 Poor Core Samples

Extreme care should be taken to avoid altering and damaging cores during and after coring. In this study, core samples that exhibited qualities of a poor specimen according to AASHTO T166-05 were not included within the data pool for analysis. Figures 2.8 and 2.9 illustrate the kinds of cores that were accepted and rejected.

Figure 2.8. Example of rejected cores

Figure 2.9. Example of an accepted core

2.4.3 Average Difference

After the appropriate filters were applied to the data pool, the average difference between the core density and gauge density was found to be the most understandable method of assessment to observe the differences among each gauge (Romero 2002). However, the average difference or the t-test cannot assume that the gauge 'trend' changes in the core density. To highlight this point, Table 2.1 and Figure 2.10 describe data trends that were discovered through an analysis of data collected onsite. When the difference is calculated, the PQI is 1.89 lb/ft^3 lower than the cores, while the nuclear gauge's difference is 1.07 lb/ft^3 higher than the cores. However, Figure 2.10 shows that both gauges follow trends similar to that of the core sample densities. If these gauges were evaluated based on the difference, the nuclear gauge would result in closer values to core samples than the PQI's.

2.4.4 Student T-Test

To test for statistically significant differences between core samples and pavement gauges, student T-tests are a sound analysis. In this analysis, the hypothesis is that the difference between the core and gauge density readings is zero. In other words, if the t-test value is greater than the t-value (95% confidence interval) using a probability t-value table, it can be concluded that there is a statistical difference between gauge density and the core density (Romero 2002).

Table 2.1. Average difference and T-test results between both gauges and core values

Site	*Number of cores*	*Difference(**lb/ft^3**)*		*T-test*	
		PQI	*Nuclear*	*PQI*	*Nuclear*
1	*9*	*3.972*	*0.6609*	*Reject*	*Accept*
2	*10*	*3.2428*	*0.6428*	*Reject*	*Accept*
3	*10*	*0.4195*	*1.4555*	*Accept*	*Accept*
4	*9*	*1.074*	*1.331*	*Accept*	*Reject*
5	*9*	*0.9281*	*0.7169*	*Reject*	*Reject*
6	*9*	*2.098*	*0.1467*	*Reject*	*Accept*
7	*9*	*1.608*	*2.058*	*Reject*	*Accept*
8	*10*	*2.752*	*0.873*	*Reject*	*Accept*
9	*9*	*1.3477*	*0.181*	*Reject*	*Accept*
10	*15*	*1.784*	*0.45*	*Reject*	*Accept*
11	*9*	*0.9613*	*2.3992*	*Accept*	*Accept*
12	*20*	*2.3858*	*2.781*	*Reject*	*Reject*
13	*10*	*2.0013*	*0.2137*	*Accept*	*Accept*
Average		*1.89*	*1.07*		

For sites 3, 11, and 13, the statistical difference between each gauge and the cores is greater than 95%. Both gauges therefore displayed density values that are very close to that of the core. For the majority of the remaining sites, the nuclear gauge shows closer values to the core's according to the student t-test analysis.

2.4.5 Coefficient of Correlation

The coefficient of correlation analysis is another method of evaluating the applicability of a new gauge to measure density (Romero 2002). This analysis is used to decide if a statistically significant linear relationship exists between the gauges when compared against core samples (TransTech Systems 2004). The values of the coefficient of correlation range between +1 and -1. If the value is close to +1, it indicates that there is significant correlation between gauge density and core density.

Coefficients of correlations values for the nuclear gauges were higher than the PQI's for most of the sites. This shows that the cores are better explained by the nuclear gauge, compared to the PQI. It should be noted that there were few instances when the PQI's showed better correlation (sites 2, 7, 9).

Table 2.2. Coefficient of Correlation and R-squared between

both gauge densities vs. Core density

Site	Coefficient of Correlation(R)		Coefficient of Determination(R^2)	
	PQI	Nuclear Gauge	PQI	Nuclear Gauge
1	0.198	0.6128	0.0392	0.3755
2	0.5046	0.064	0.2546	0.0041
3	0.2052	0.8211	0.0421	0.6742
4	0.7356	0.8901	0.5411	0.7922
5	0.7235	0.8295	0.5235	0.6881
6	0.746	0.9577	0.5565	0.9172
7	0.6476	0	0.4194	0.0025
8	0	0	0.2351	0.0082
9	0.7922	0.7185	0.6275	0.5163
10	0.138	0	0.019	0
11	0	0	0.1232	0.0006
12	0	0	0.0297	0.0006
13	0	0.5877	0.1681	0.3454
Average	0.252	0.407	0.275	0.333

2.4.6 Coefficient of Determination

Figure 2.10 indicates a weak correlation between both gauges individual densities as compared to core density results—this is indicated by the low R^2 values for both gauges.

Nonetheless, as shown in Table 2.2, four sites out of thirteen show a 50%+ relationship between PQI density and core density. Additionally, five out of thirteen sites indicated that there is a 50%+ relationship between nuclear gauge densities and core densities.

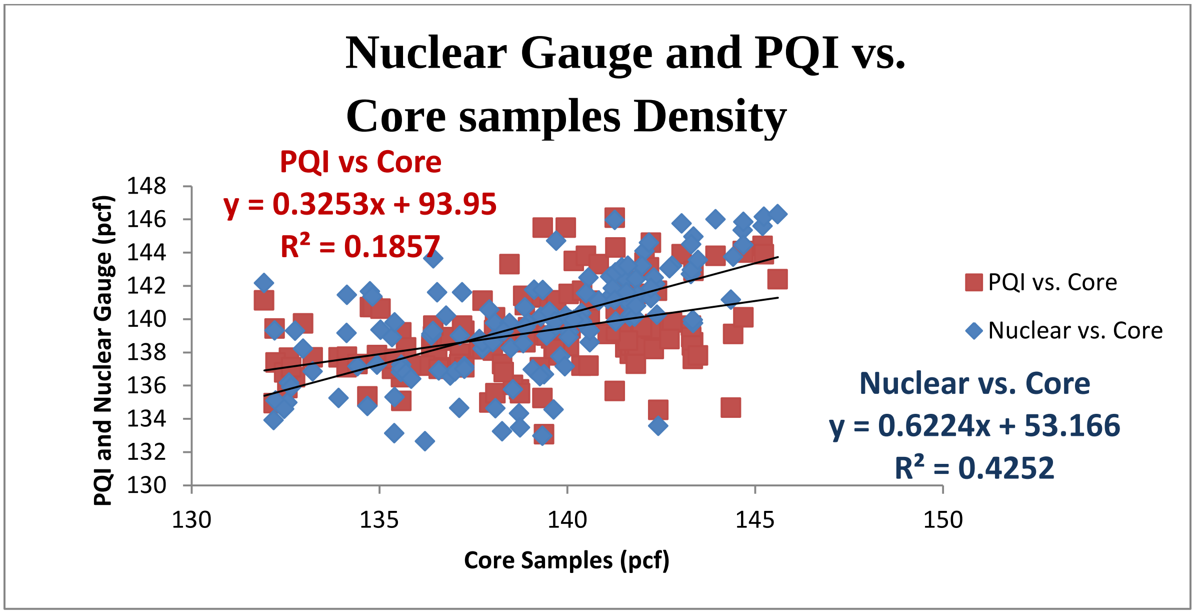


Figure 2.10. PQI & Nuclear Gauge relationship vs. Core Samples

2.4.7 Coefficient of Determination based on average density from each site

Table 2.3 shows a correlation between both gauges densities compared against individual core locations and the site averages overall. Analysis results indicated that the measurements are better explained by both gauges when considering site averages rather than individual locations.

Table 2.3. Correlation between Nuclear Gauge and Cores

	Individual Samples		Site Averages	
R Squared	PQI	Nuclear Gauge	PQI	Nuclear Gauge
	0.19	0.43	0.40	0.78

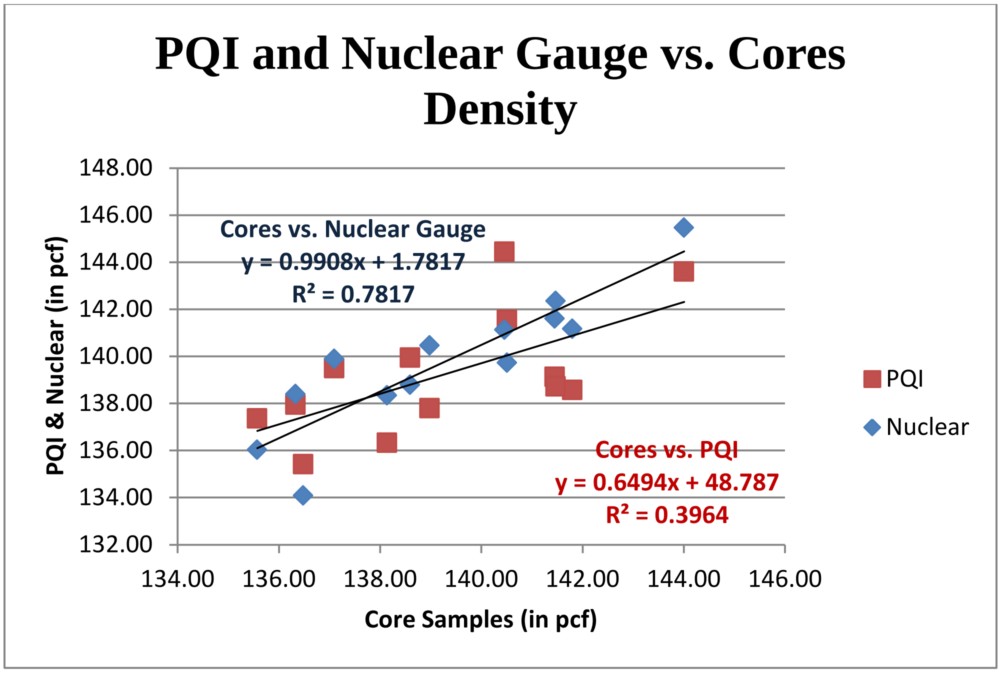
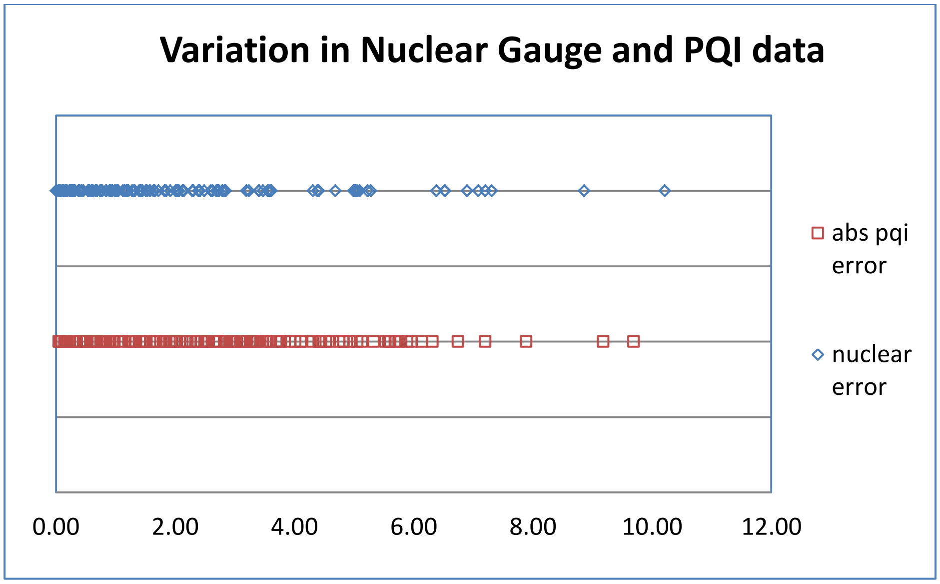


Figure 2.11. Relationship between each gauge and core samples

2.4.8 Error of the Standard deviation

Figure 2.12 illustrates the absolute density differential variation for both gauges. When taken as a whole, the average difference between both gauges is very similar, varying by only 0.04 lb/ft^3.



Nuclear SD: 2.00

PQI SD: 1.96

Figure 2.12. Absolute Density Differential Variation for both gauges

2.4.9 Data Reliability

When comparing both gauges, it is important not to look only at how each gauge trends as compared to the project's benchmark points (core samples), but to also look at an overall tolerance. A clear grouping of PQI readings can be seen in Figure 2.13 where the nuclear gauge data are spread more evenly throughout the plus or minus one and two standard deviation boundaries. Table 2.4 demonstrates that 80% of the time the PQI data typically fall within 1 standard deviation of a core sample, as compared to 67% of the time for the nuclear gauge. Results are even better, 99% of the time, for the PQI when using the 2 standard deviation range.

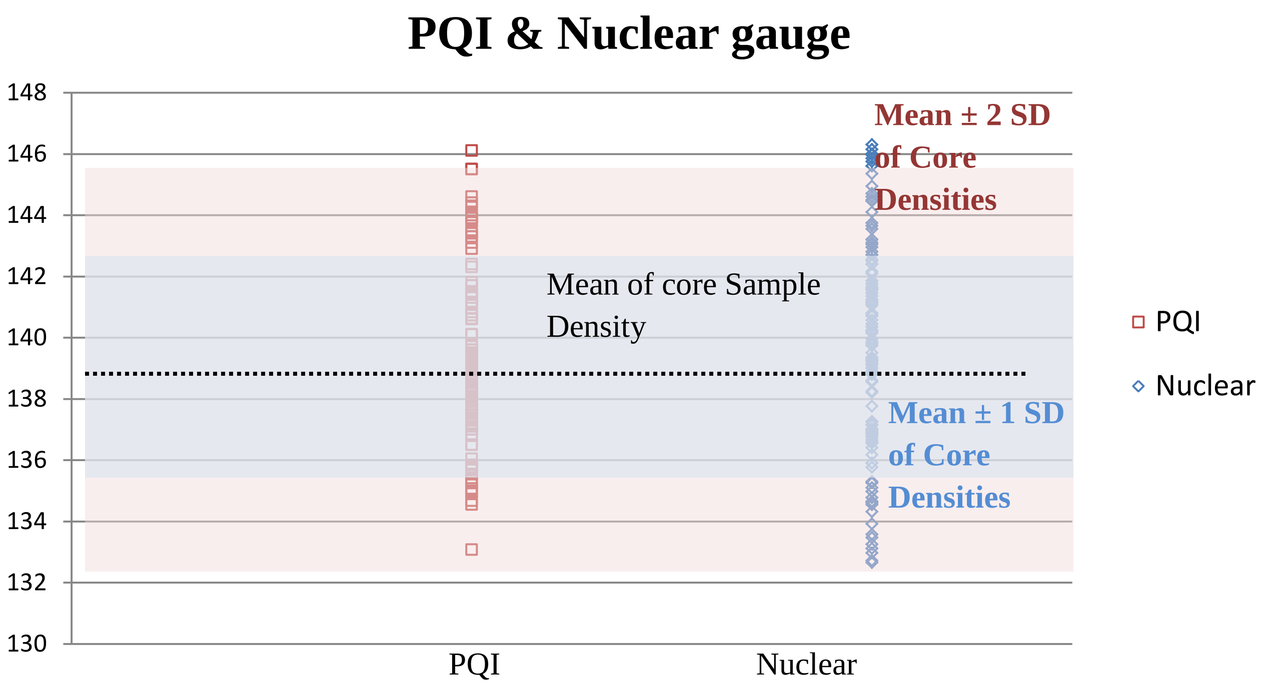


Figure 2.13. PQI & Nuclear Gauge Data reliability

Table 2.4. Range of data within ± 1 and ± 2 standard deviation

	± 1 SD	± 2 SD
PQI data within acceptable range (%)	79.86	99.28
Nuclear data within acceptable range (%)	66.91	96.40

Describing individual gauge readings as compared to a mean of all collected benchmark data is integral to creating and showcasing very simply how both gauges perform overall, but it does not directly express to what extent each gauge reading can be trusted when compared to their paired core samples.

Table 2.5 shows the distribution of when exactly it is appropriate to reasonably accept gauge readings. It was discovered that when core sample density results fall between 89% and 93% of the maximum theoretical density (MTD) value of the mix design, both gauges can be assumed to provide readings within the targeted 70% of a normally distributed bell curve. When applying this finding to the PQI's previously collected readings, an average density difference of 0.59 lb/ft^3 was found between the corresponding core samples and initial PQI readings. **Thus, it is recommended to select the core samples which range between 89% and 93% of MTD for the PQI calibration at site.**

Table 2.5. Core Sample Density vs. MTD values

Core sample density compared to the MTD (%)	Number of Samples	% of the cores	Difference =|gauge-core|	
			PQI	Nuclear
86%	4	3%	5.79	5.01
87%	8	6%	4.68	2.96
88%	11	8%	3.48	3.33
89%	11	8%	1.96	2.49
90%	16	12%	0.71	0.77
91%	26	19%	0.78	0.96
92%	21	15%	0.70	0.36
93%	24	17%	1.14	0.63
94%	14	10%	2.02	0.20
95%	4	3%	4.89	0.14

From Table 2.6 it can be concluded that when a core sample value falls between 90% and 94% of the maximum theoretical density, the PQI would give a very accurate comparison to the traditional coring method. In this mentioned range, 72% of all collected data can be found and considered accurate. Within the same accuracy range, the average difference between PQI readings and corresponding core densities was 0.13 lb/ft^3. The nuclear gauge, on the other hand, does not provide a convenient range using the MTD values. When applying the same concept, the nuclear gauge data would be deemed reliable when readings fall between 88% and 90%, and between 93% and 94% of the MTD values.

Table 2.6. PQI and Nuclear gauges Density vs. MTD values

PQI and Nuclear Gauge densities compared to the MTD value (%)	Number of Samples	Difference =|PQI-Core|	Number of samples	Difference =|Nuclear –Core|
86~87%	1	6.32	3	2.56
87~88%	2	8.79	7	4.36
88%~89%	12	0.65	8	0.09
89% ~90%	15	1.52	13	0.19
90~91	45	0.41	27	1.13
91~92%	27	0.67	19	0.41
92~93%	18	0.58	27	1.7
93%~94%	10	0.68	17	0.75
94%~100	9	0.02	18	1.79

Based on the results shown in Table 2.7, it is apparent that a tremendous improvement in the level of confidence is achieved when operating both devices within a range of 89% to 93% of the MTD value of the mix. Improvements are also significant when looking at the correlation coefficient within the stated range. What this illustrates is that when ignoring collected data not obtained within the recommended MTD range, the correlation improved by17%. This demonstrates that if a core sample were to be taken at that location, the linear dependence between what the PQI reads and what the core sample tests at can be trusted with 17% more assurance.

Table 2.7. Level of confidence comparison in specific range

	89% to 93% of Core samples of MTD		Whole data	
	Core vs. PQI (98 data)	Core vs. Nuclear (98 data)	Core Vs PQI (139 data)	Core vs Nuclear (139 data)
Correlation	42%	56%	25%	41%

2.4.10 Number of Cores for PQI Calibration

This part of the project investigated a new method to determine the ideal number of cores for the PQI calibration and improve the accuracy of PQI data. Traditionally, the offset is used to decrease the difference between PQI data and core densities. In order to compare the differences between the traditional and new method; three, five, eight and ten cores calibration were investigated separately in this study.

First, the traditional method was adopted to calibrate the PQI densities. Three (or five, eight, or ten) cores are chosen randomly out of all data. The chosen set of cores is used to calibrate the PQI. The difference between the calibrated PQI densities and core densities is described as follows:

$$TD = | C1 - P2 |$$

Where,

C1-Core densities

P2-Calibrated PQI densities

Next, a linear regression was developed to obtain the difference. The calibrated PQI densities (P2) are assumed to be an independent variable with TD as the dependent variable. A linear regression equation $Y = a*X + b$ was set up. While there are considerable combinations to choose from, only the combination with the closest average R-square was adopted for further calibration. Matlab™ was used to obtain the closest average R square value for this part of the research. After substituting the calibrated PQI densities P2 for X, the adjusted difference Y2 was acquired. Adjusted PQI value (AP) and linear regression difference (LD) were calculated as follows:

$$AP = Y2 + P2$$

$$LD = | AP - C1 |$$

Where,

AP–Adjusted PQI value

LD–linear regression calibration difference

The results are attached in the appendix, and Figure 2.14 shows the TD and LD value.

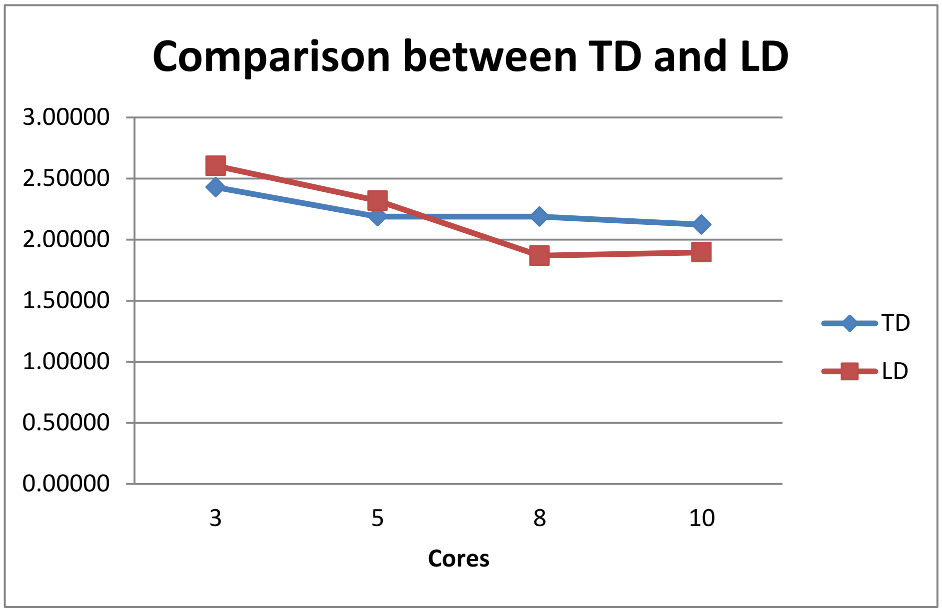


Figure 2.14. Comparison between traditional difference and calibration difference

As can be seen in Figure 2.14, both differences tend to trend lower with the increase of the number of cores. When 8 or 10 cores were chosen, the linear regression differences were less than the traditional differences. The linear regression difference is lowest when choosing 8 cores.

2.5 Conclusions

In conclusion, it was determined that the nuclear gauge has a slightly higher correlation value than the PQI when compared to the core samples. Its average difference between the nuclear gauge and the PQI was not significant (only a 0.82 lb/ft^3 difference) when the research team considered all the data pool. The PQI, however, shows more consistent results than the nuclear gauge, in consequence of a smaller standard deviation. Furthermore, when cores and PQI have higher densities than 90% of MTD, the PQI is statistically more accurate and has a much better coefficient of correlation than the nuclear gauge. To determine better ways to calibrate the PQI and eventually improve its accuracy, a trial model calibration was run.

Different combinations were tried to determine the best statistical way to improve the PQI's accuracy. It was concluded that the PQI performs at its best when 8 cores are used for calibration. Other analyses revealed that the cores with a density that falls within 89% and 93% of the MTD value should be used for calibration. Moreover, any PQI density that was greater than 90% of the MTD value was proven as reliable information. In the event that the density measured by the PQI is less than 90%, a core must be taken for density measurement.

Chapter 3 Soil

3.1 Methodology

To accomplish the objective of assessing soil compaction, a comparison study of usability and performance was conducted between a nuclear gauge (Troxler 3440) and three non-nuclear gauge alternatives, including the Electrical Density Gauge (EDG) and the Moisture Density (MDI) and the Light Weight Deflectometer (LWD). The EDG and the MDI were tested for in-place moisture and density. The LWD, a stiffness-strength based criterion for evaluating the QA/QC of a material, was also tested. The nuclear gauge was utilized to measure the in-situ dry density and moisture content. Finally, the previously mentioned measurements were all compared to a standard, the field dry unit weight measurement, which was determined by taking a sample representative of each measurement area either with a Shelby tube or other method for lab testing.

3.2 Literature Review

In 2000, McCook and Shanklin (2000) compared the accuracy of the nuclear gauge with various traditional methods including sand cone, density-drive cylinder and rubber balloon. Density test results from the nuclear gauge and sand cone were very similar. The few problems that were identified in this study included the following issue: that some errors could be observed with the sand cone due to the change in operating personnel and variation of density measurement readings. The drive-cylinder method was the most consistent of the traditional methods to measure density.

A similar study was done by Norrrany et al. (2000) to compare the sand cone method, the drive-cylinder method and a nuclear gauge on various compacted soil types. Both the sand cone and drive-cylinder methods resulted in a wider range of variability with the nuclear gauge, but with the sand cone being the least variable.

Studies have been done to introduce stiffness and modulus methods as replacement quality control methods of soil compaction. Livneh and Goldberg determined in their work in 2001 that the current unit weight quality control at the time was slow, hazardous, labor intensive, and of an uncertain accuracy.

In 2009, a study done in Thailand compared the sand cone with a nuclear gauge, the Dynamic Cone Penetrator (DCP), and the Soil Density gauge (SDG). It was concluded that non-nuclear technology had good potential with further development and research to be implemented for construction quality control of earthwork (Wacharanon et al. 2009).

In 2007, another comparison study was done among the nuclear gauge, the MDI and the EDG. Results showed good correlations of densities between both non-nuclear gauges and the nuclear gauge. Moisture content showed a big variability between gauges. It was also suggested that other in-place measurements should be done because the nuclear gauge data could not be entirely trusted and used as standards (Brown 2007).

The Minnesota Department of Transportation (Mn/DOT) did various studies where they compared the DCP, the LWD, a Percometer and Trident moisture content. It was concluded in 2006 that the LWD displayed a good level of accuracy close to the DCP and they also offered suggestions to improve the LWD (Davich et al. 2006). Since then, different techniques and methods were developed to estimate the LWD deflection target values for soil to assess the compaction state of a soil (Siekmeier 2011).

In 2007, the New Jersey Department of Transportation (NJDOT) compared the MDI with the nuclear gauge and concluded that very similar moisture contents measurements could be observed between both gauges (Jackson 2007). High differences existed, nevertheless, with dry density measurements. Improved calibration constants and methodology were recommended.

3.3 Testing Methods

3.3.1 Density-Drive Cylinder

The Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method (ASTM D2937-10) involves obtaining a relatively undisturbed soil sample by driving a cylinder open at both ends in the ground (Figure 3.1). Once flush, the material around the cylinder is then excavated. With the empty volume of the cylinder already known, the unit weight of the soil in the cylinder can then be calculated in the lab. While in the lab, a sample of the soil can be dried to provide a dry density of the material. This method was preferred over the sand cone test (ASTM D1556) which consists of determining the in-place density and unit weight of soils using a sand cone apparatus because of the inconsistency of density results. Similar to the sand cone method, the rubber balloon method (ASTM D2177) consists of excavating a sample of soil and measuring the volume of the hole dug out with a rubber-balloon apparatus. This method also provides variable results depending on the users and pressure applied to the apparatuses while filling the holes. A higher force applied on apparatuses will show a greater displacement. All these inconsistencies in readings and data have led the research team to adopt the density-drive cylinder as standard to measure in-place density.

Figure 3.1. Shelby Tube driven in the ground

3.3.2 Water Content of Soil by Oven Dry method

While previously mentioned methods only determine the in-place density, soil bulk density is determined by the weight of the soil per unit volume that is found by using an oven maintained at a temperature between 105°C and 115°C. This method (ASTM D2216) consists of drying a wet sample of soil in the oven for about 24 hours, and determining the weight of moisture. This method was used as the standard and baseline of comparison for moisture content measurement.

3.3.3 Nuclear Method

As with HMA, nuclear gauges emit gamma rays to measure density and moisture content. Measurements were done according to ASTM D6938-10, Standard Test Method for In-Place Density and Water Content of Soil and Soil Aggregate in Place by Nuclear Methods. Unlike the HMA measurement, the gauge probe was driven into the ground to take measurements at 4, 6, and 8 inches. Figure 3.2 shows a nuclear gauge taking soil density and moisture content measurements.

Figure 3.2. Nuclear gauge taking soil measurements

3.3.4 The Electrical Density Gauge (EDG)

The EDG measures the electrical dielectric properties, along with moisture levels of the material's compacted soil to determine its density and moisture content. The EDG does so by measuring the radio-frequency current between four darts driven in the ground, as shown in Figure 3.3. In order to measure the in-place physical properties of the soil, a soil model or calibration process needs to have taken place in the lab. A sample representative of the soil to be tested needs to be excavated and tested in the lab with the EDG at different moisture and compaction levels. ASTM D7698-11 (Standard Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance Method) was applied for EDG testing. A minimum of three lab tests are recommended by EDG's manufacturer to have a good soil fit. The research team conducted nine lab tests to develop soil models.

Figure 3.3. Darts driven into ground for EDG test

3.3.5 The Moisture Density Indicator (MDI)

The MDI uses the Time Domain Reflectometry (TDR) methodology, which measures the travel time of an electromagnetic step pulse produced by the TDR pulse generator through spikes driven in the ground (Brown, 2007). A personal digital assistant (PDA) or a laptop is then used with the manufacturer-provided software to analyze the signal sent by the spikes (Figure 3.4). The apparent dielectric constant and electrical conductivity of the soil are derived from the MDI to estimate the soil's density and moisture content. Just like the EDG, soil models were also required to determine the dry density of the soil. The MDI required a typical moisture densities curve using the Standard Test Methods for Laboratory Compaction Characteristics of Soil Using the Standard Effort (ASTM D698-07) or Standard Test Methods for Laboratory Compaction Characteristics of Soil Using the Modified Effort (ASTM D1557-09). Once more than 4 points have developed, a soil compaction curve will then indicate the maximum density and moisture content for that material.

Figure 3.4. MDI connected to a laptop for density measurements

The MDI was acquired by the research team, but unfortunately failed to work during testing. Multiple extensive efforts were made by the MDI's manufacturer to assist the research to make the device function. During testing, systematic errors were consistent and did not allow the team to take sufficient measurements. For such reasons, the analysis report does not include the MDI data.

3.3.6 The Light Weight Deflectometer (LWD)

The LWD (Figure 3.5) consists of measuring a surface deflection as a result of applying an impulse load to it by using ASTM E2583-07, the Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD). The LWD consist of a light mass, an accelerometer and a data collection unit (Siekmeier et al. 2009). Because the LWD measures the deflection and modulus of elasticity of the soil, there was no direct relationship or method to compare its measurements with the other gauges being tested in this study. The research team therefore used a quality assurance procedure developed by the Mn/DOT (Siekmeier et al. 2009) along with their specifications for excavation and embankment (Minnesota 2010) to determine whether a soil area has been properly compacted. Based on a pass/fail criterion, comparisons can then be made with other gauges. More details about this methodology are discussed in the analysis section.

Figure 3.5. LWD is measuring stiffness of the soil

3.4 Test Procedures and Methodology

Two sites composed of brown dirt and peorian loess soils were tested for this research. The team first collected representative samples from each site to develop soil curves by the EDG, MDI and the Standard Proctor Method. The results were then used to calibrate the nuclear gauge, and determine in-place measurements for the EDG. Figure 3.6 and 3.7 are sites from Highway 370 near Gretna, NE and the Platteview Intersection site near Plattsmouth, NE, respectively.

Figure 3.6. Highway 370 site

Figure 3.7. Platteview Intersection Site

Once a spot was selected, all gauges were operated and their variables recorded at said location. The different densities and moisture contents of the EDG and nuclear gauge were then compared against the standard baselines of measurement methods mentioned above. Next, a pass/fail analysis of all the methods was developed according to the Standard Specifications for Construction in NDOR (Nebraska 2007). This analysis would give a better idea of what method correlates most closely with the LWD. For better accuracy, other important analyses were also run to compare the gauges.

3.5 Data Analysis

3.5.1 Outlier

Similarly to HMA data, outliers were also removed from the pool of data in order to better analyze soil measurements. Outliers were removed when the difference between the standard density and moisture was considerably greater or lower than the gauges' data—that is, a standard deviation plus or minus 3. Tables 3.1 and 3.2 respectively show the set of outliners removed from the density and moisture content measurements.

Table 3.1. Outliers removed for Density

Standard	Nuclear Gauge	EDG
110.4 pcf	75.63448 pcf	103.88 pcf

Table 3.2. Outliers removed for Moisture Content

Nuclear Gauge	Standard	EDG
74.30%	20.44%	18.30%
20.43%	29.87%	20.40%

3.5.2 Coefficients of Correlation (R) and Determination (R^2) analyses

To observe a linear relationship between the gauges and the standard measure, the whole pool of data were analyzed after removing the outliers (Figure 3.8 for density and Figure 3.9 for moisture). Table 3.3 summarizes the coefficients that were observed.

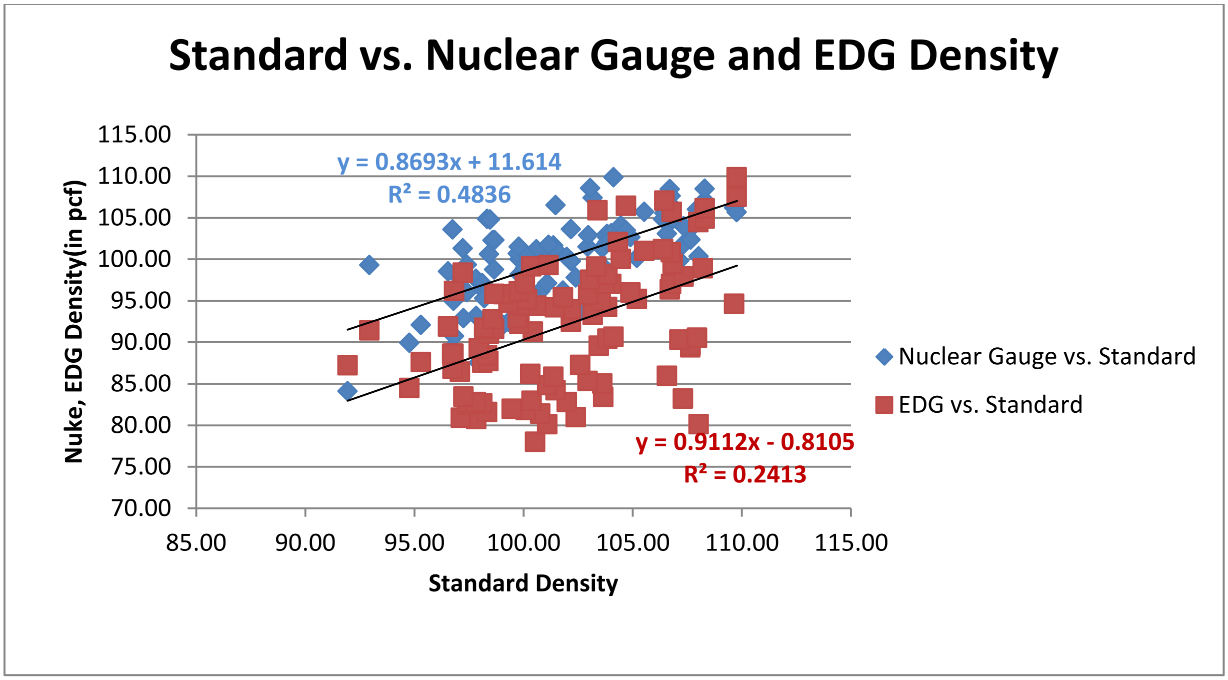


Figure 3.8. Standard vs. Nuclear Gauge and EDG Density

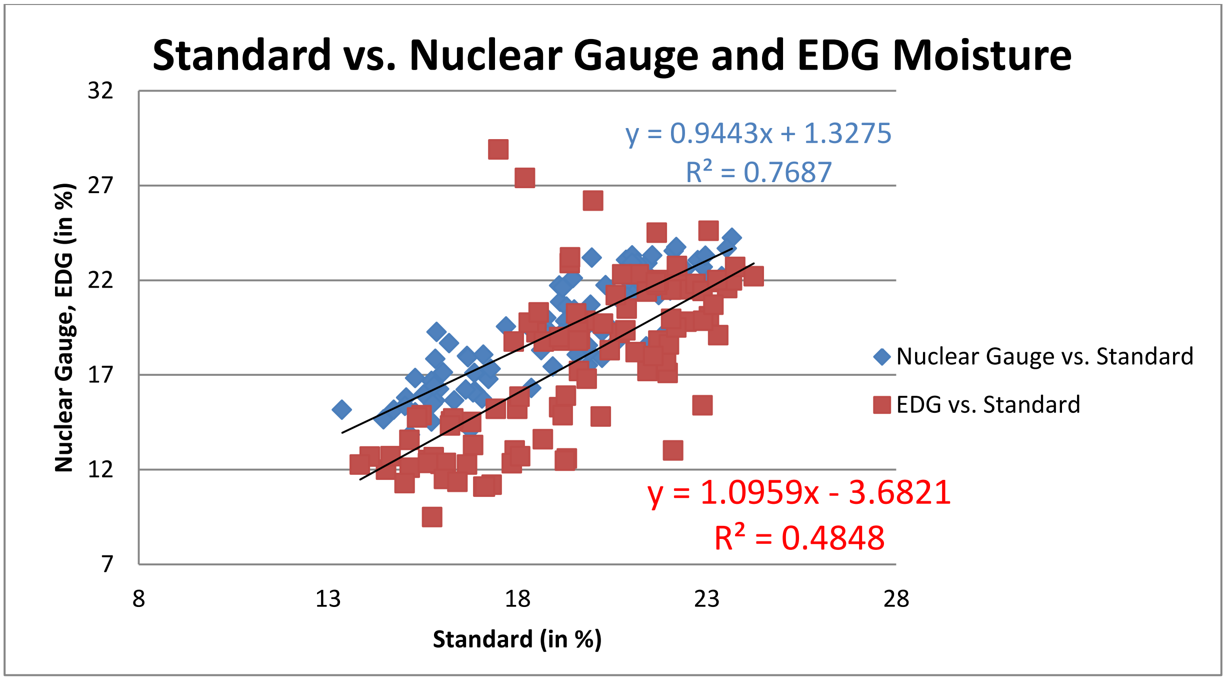


Figure 3.9. Standard vs. Nuclear Gauge and EDG Moistures

Table 3.3. Summary of R and R squared values

	Density		Moisture	
	Nuclear vs. Standard	EDG vs. Standard	Nuclear vs. Standard	EDG vs. Standard
Coefficient of Correlation (R)	0.695	0.491	0.876	0.695
Coefficient of Determination (R^2)	0.483	0.241	0.768	0.484

The nuclear gauge has a higher R^2 than the EDG's, and also correlates better with the standard measurement. This could be due to the fact that the nuclear gauge data have been corrected using the density and moisture corrections factors, as required by the Nebraska Department of Roads new Standard Test Method for Nuclear Density Testing for Soils (NDOR, 2011). When using the initial data, that is before adjusting the nuclear gauge density values, the coefficient of determination of the nuclear gauge and the standard is only 0.21 (Figure 3.10), a little lower than that of the EDG. There are no current recommended methods that allow for ways to improve and correct the EDG's data. The EDG and nuclear gauge have very similar results when unmodified and direct data are considered, but the nuclear gauge performs better when correction factors are applied.

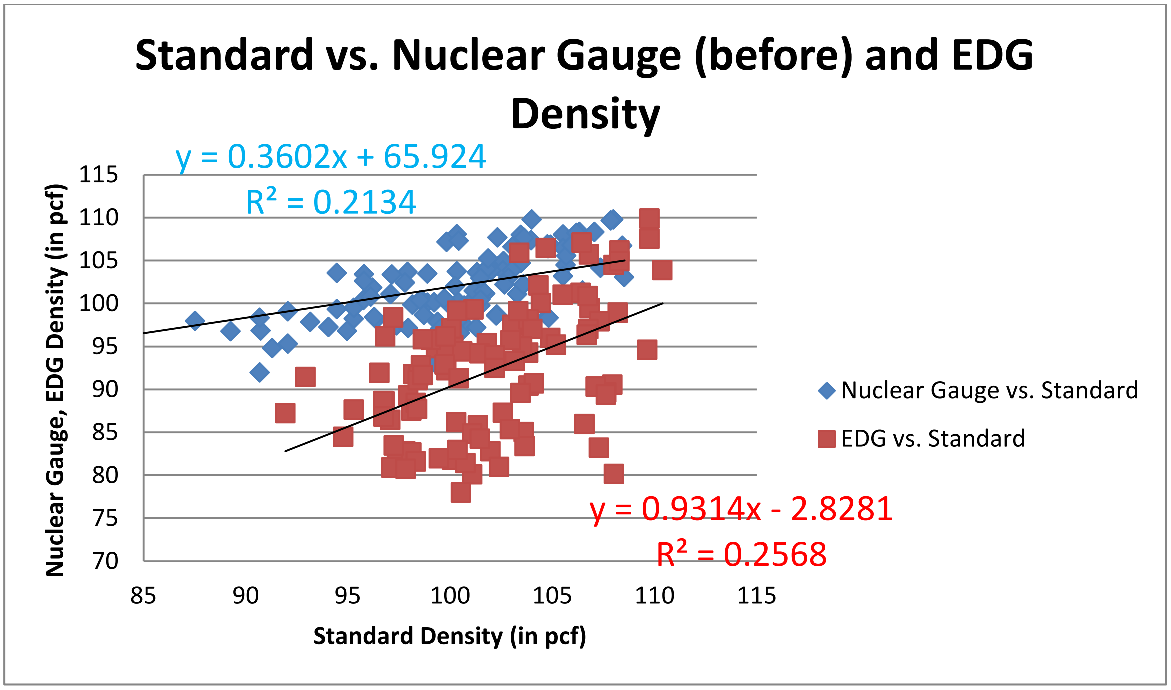


Figure 3.10. Standard vs. Nuclear Gauge (before correction factors) and EDG Density

For moisture content, both gauges have a high coefficient of correlations, but the nuclear gauge has more data close to the standard.

3.5.3 Average Difference and Error of Standard Deviation

To determine how both gauges vary within the lab data standard deviations (STTV), error of standard deviation and average difference analyses were conducted (Figures 3.11 , 3.12, and 3.13).

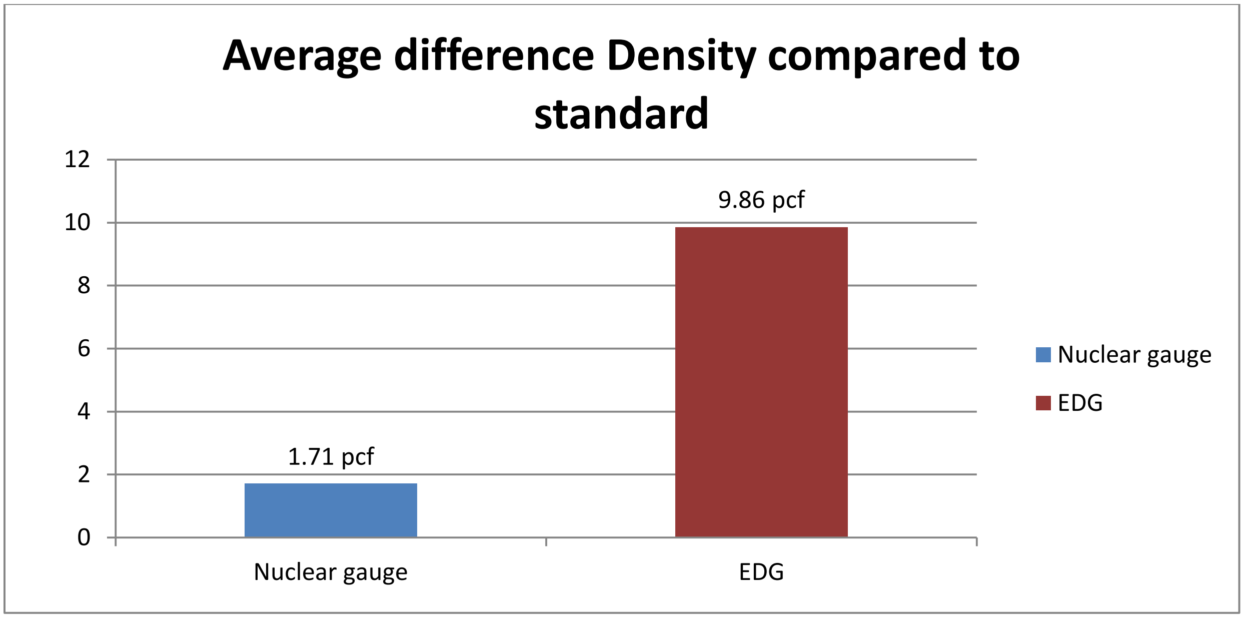


Figure 3.11. Average Density Difference of gauges compared to standard

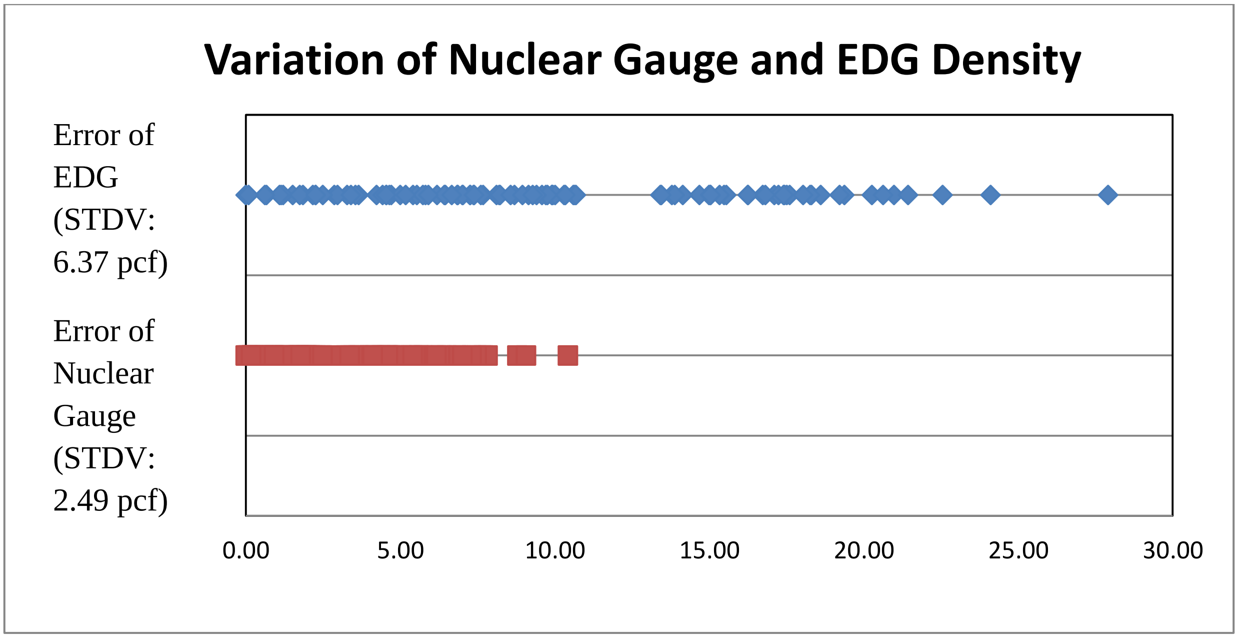


Figure 3.12. Variation of Nuclear Gauge and EDG Density

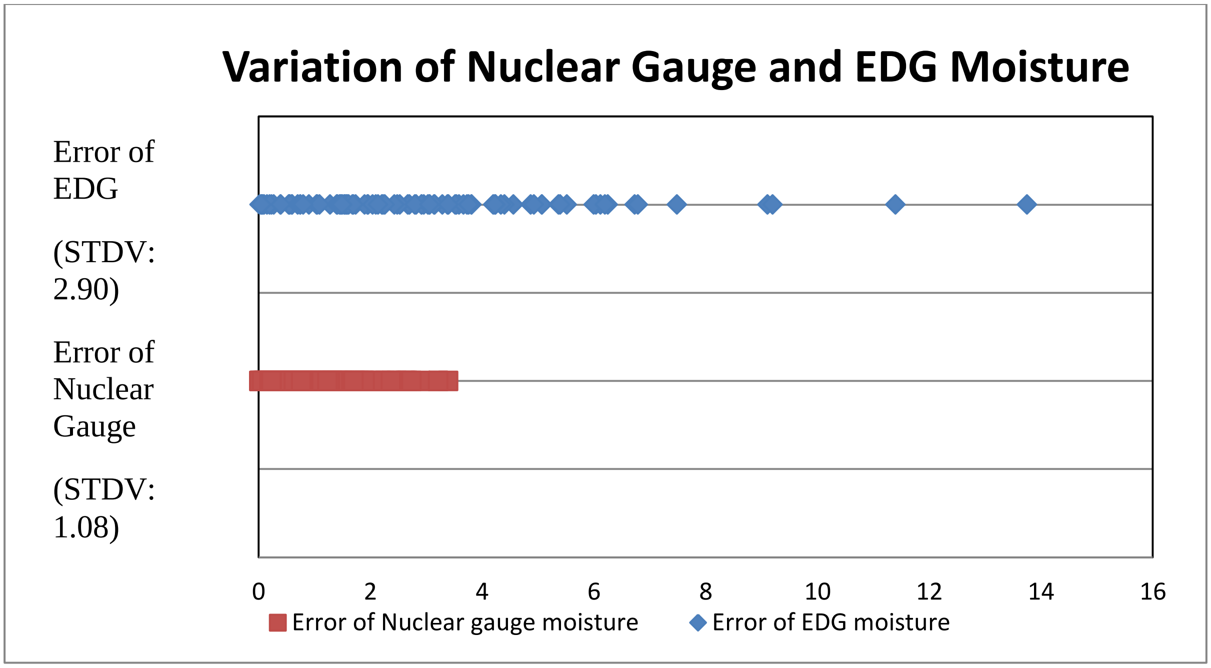


Figure 3.13. Variation of Nuclear gauge and EDG Moisture Content (%)

Table 3.4 summarizes the STDV and the average differences of both gauges. Average differences of 1.71 pcf for the nuke density data and 0.22% for moisture content compared to 9.86 pcf and 1.66%, respectively, for the EDG density and moisture content not only support the coefficient of determination analyses, but also show a high variation among the EDG data. This could be due to the fact that the soil model range used for the EDG might be too wide, which could in turn widen the range of the EDG's measured data. Site by site analyses can also reveal some other information about both the sites and soil tested.

Table 3.4. Summary of STDV and average differences for gauges

	Density		Moisture	
	Nuclear Gauge	EDG	Nuclear Gauge	EDG
Average Difference	1.71	9.86	0.22	1.66
STDV	2.49	6.37	1.08	2.90

3.5.4 Site by Site Analysis

Coefficient of correlations, determinations, average difference and standard deviation analyses were all run with information derived from each site. Figures 3.14 through 3.21 illustrate this data through graphing.

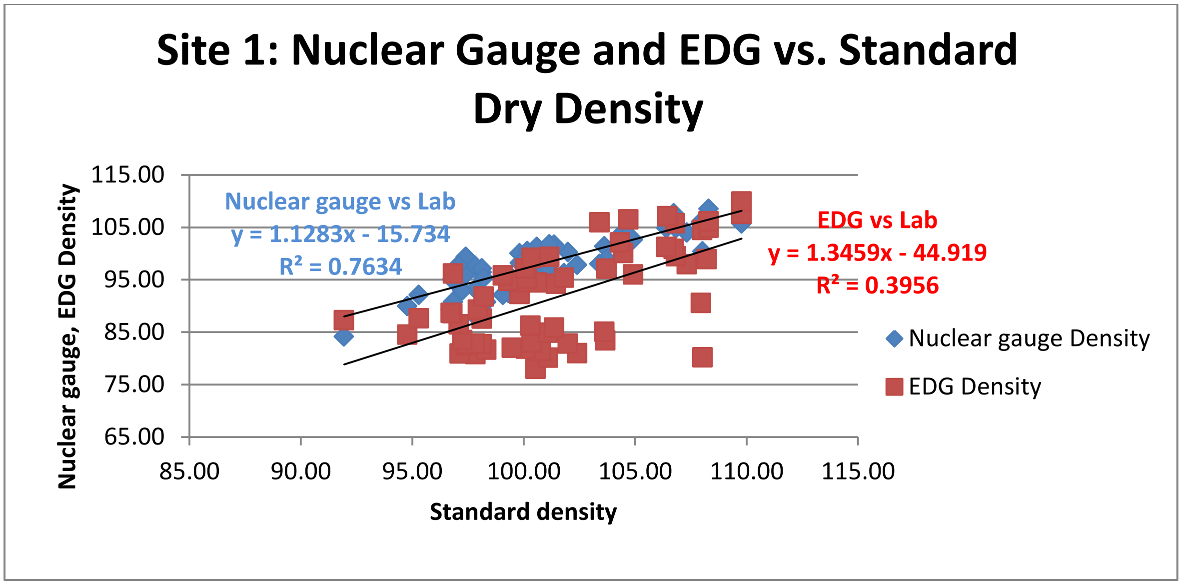


Figure 3.14. Nuclear Gauge and EDG vs. Standard Density for Site 1

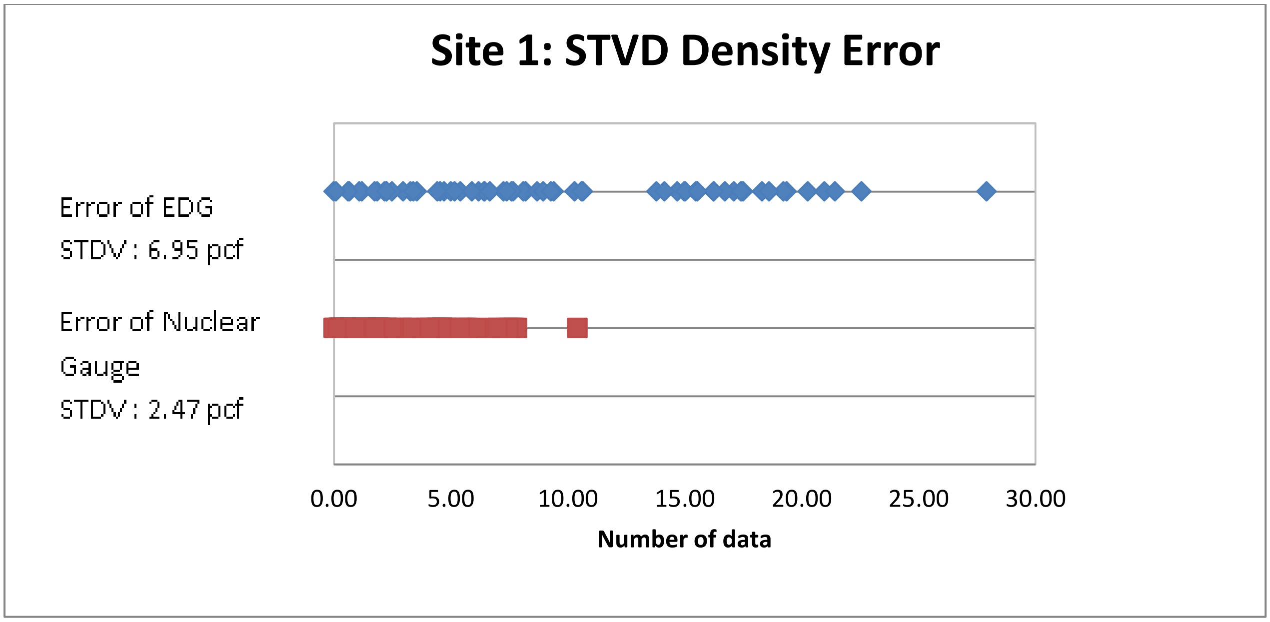


Figure 3.15. STVD Density Errors for Site 1

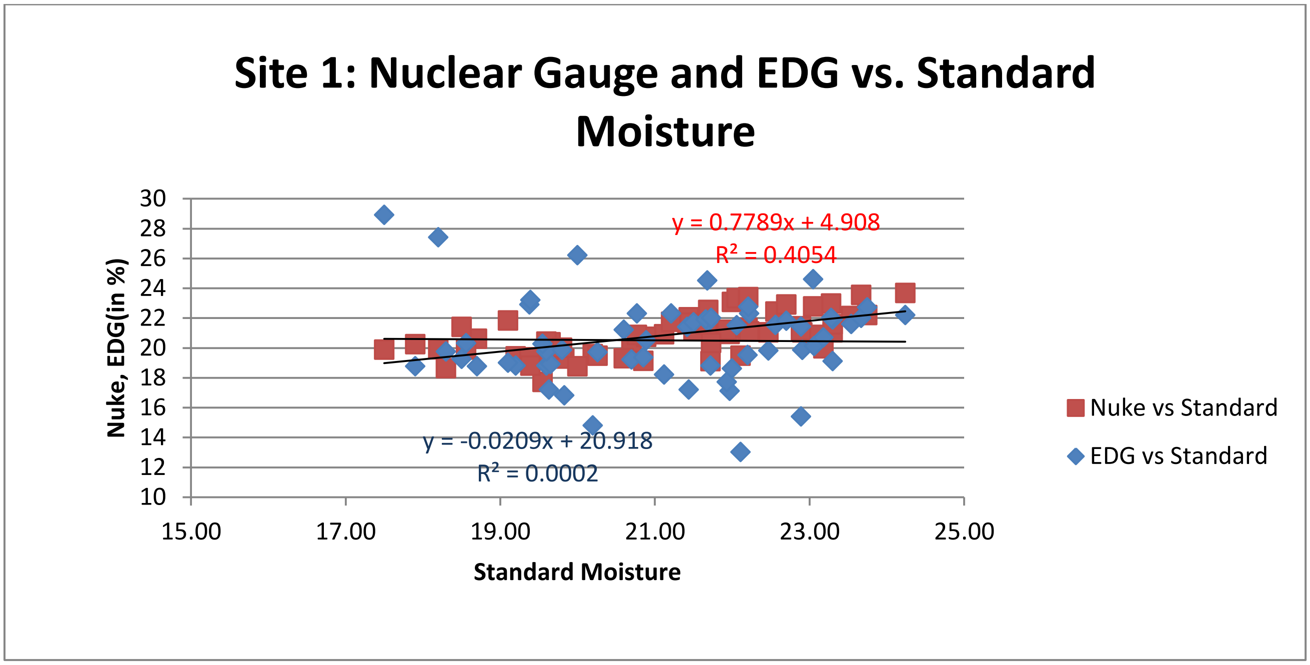


Figure 3.16. Nuclear Gauge and EDG vs. Standard Moisture Contents for Site 1

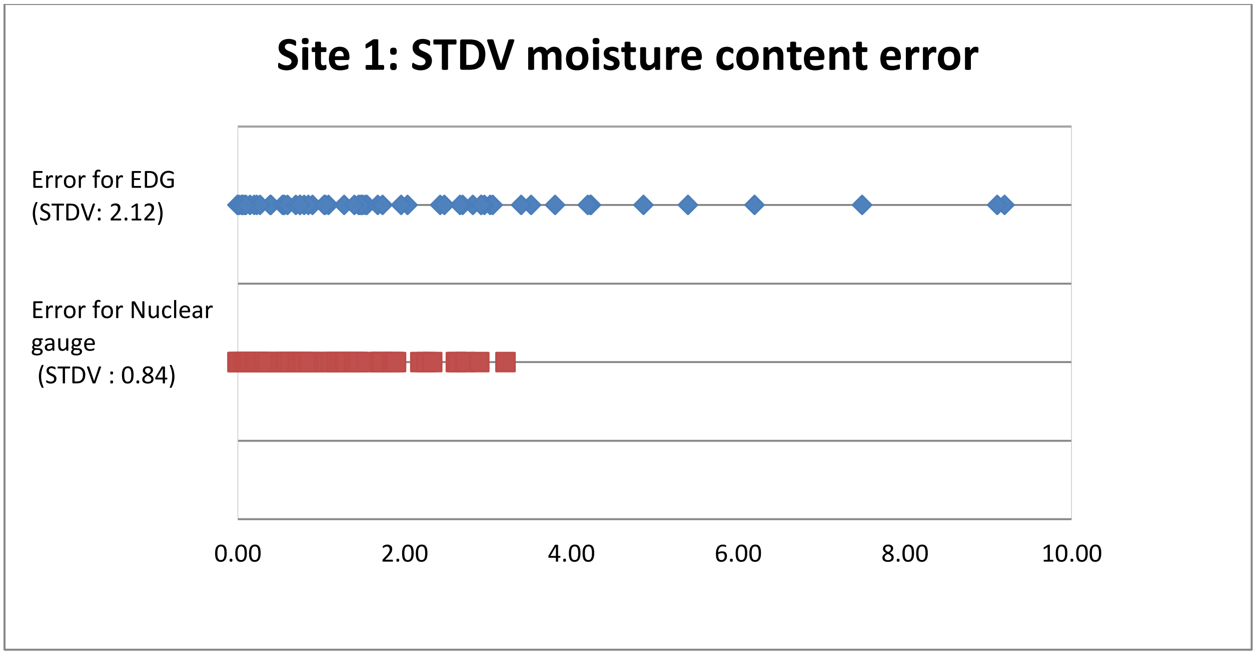


Figure 3.17. STDV Moisture Content (%) Errors for Site 1

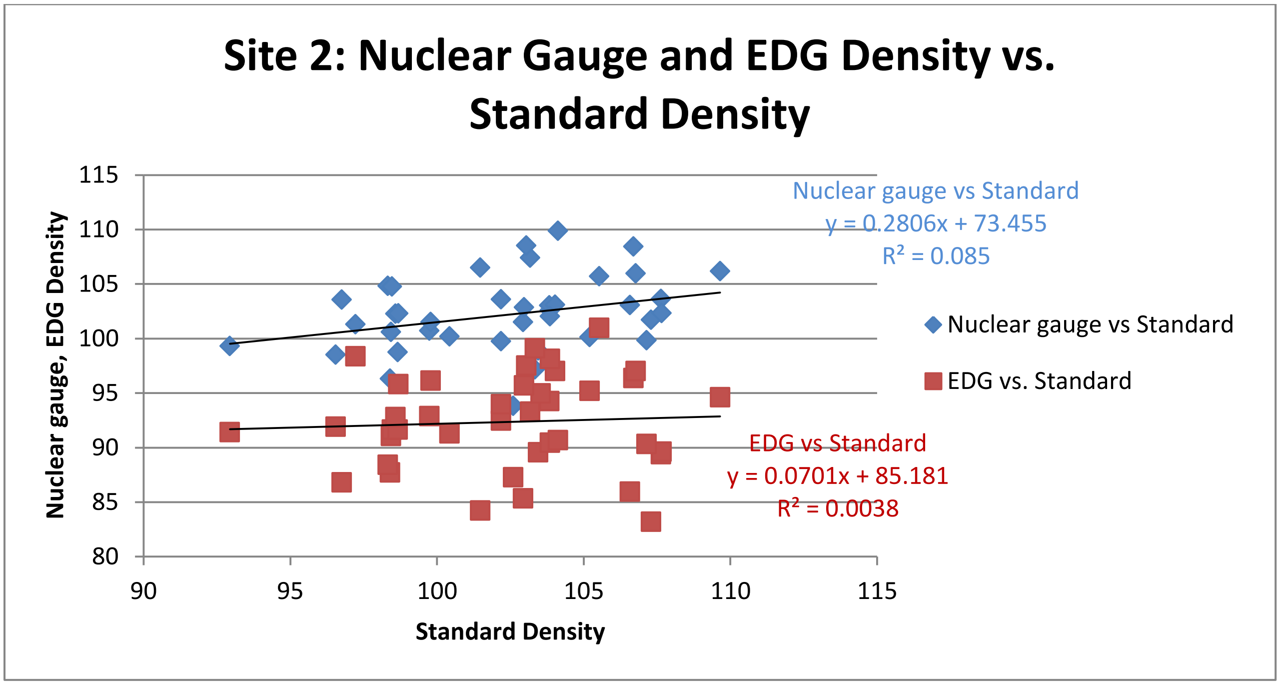


Figure 3.18. Nuclear Gauge and EDG vs. Standard Density for Site 2

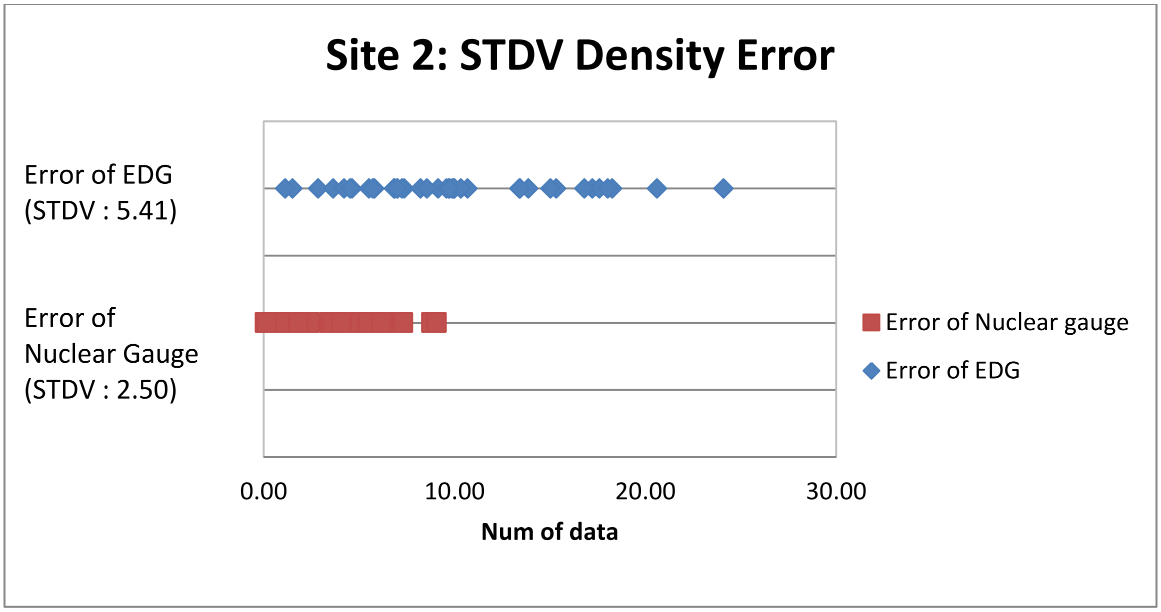


Figure 3.19. STVD Density Errors for Site 2

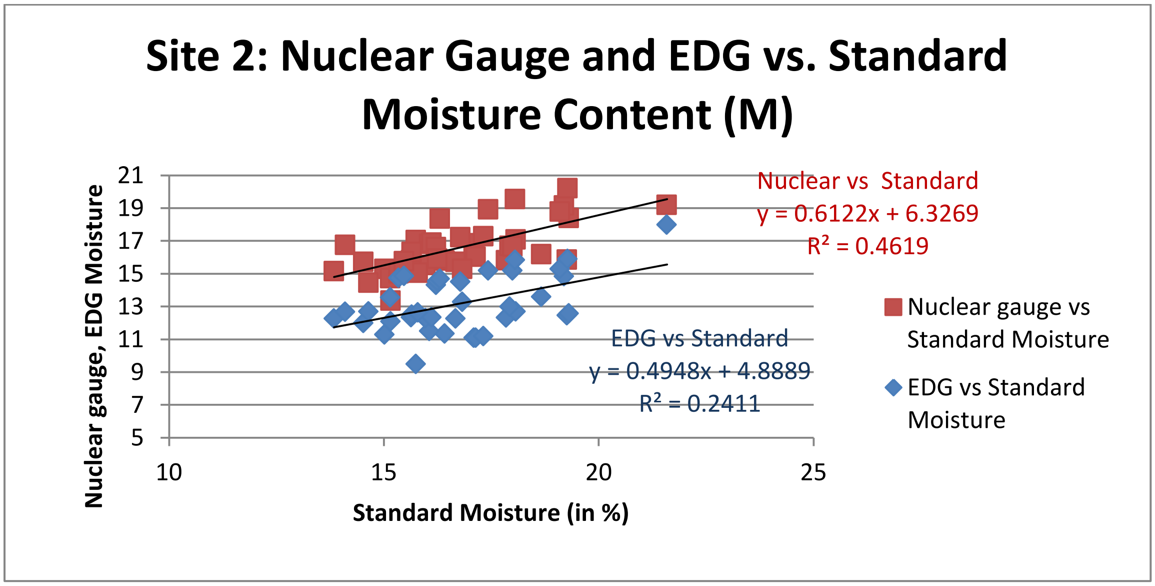


Figure 3.20. Nuclear Gauge and EDG vs. Standard Moisture Contents for Site 2

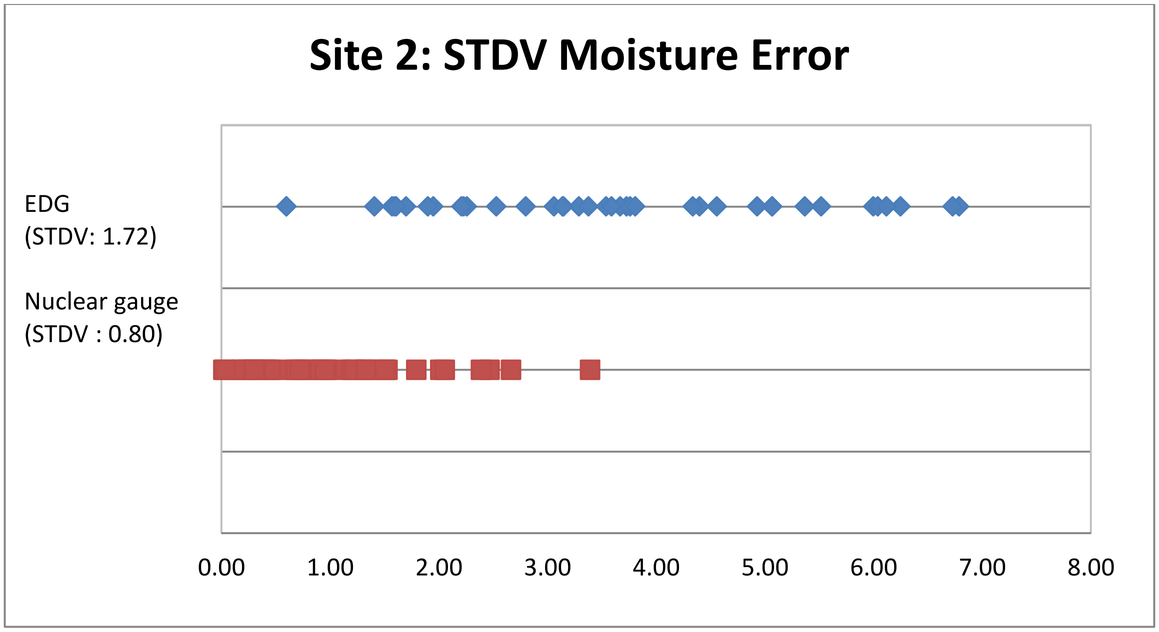


Figure 3.21. STDV Moisture Content(%) Errors for Site 2

Figures 3.14 through 3.21 show consistent observations regardless of the site:

- The coefficient of determination of the nuclear gauge density is always higher than the EDG;
- Site 2 had a very low correlation for both the nuclear gauge and the EDG in density measurement.

In summary, site 1 showed better results than site 2. This may be due to the fact that more data measurements were taken on site 1 (63 vs. 40 for site 2). Site 2 testing area may have also had different soil types, which could have altered the results. In order to utilize the data gathered by the LWD, a test status using NDOR's current quality assurance was used.

3.5.5 Test Status Analysis

To meet the compaction requirements, a test is deemed passed or failed when the measured density is within 95% of the maximum density determined by the soil curve, and also within the moisture content requirements (NDOR 2007). The research team only took random measurements at various spots on both sites to compare all gauges. Some measurements were taken at areas that were not previously compacted; therefore, some measurement spots would fail the quality assurance test. As a consequence, the LWD, which measures soil deflection and elastic modulus, could not be then directly compared with the nuclear gauge and the EDG. The Mn/DOT has developed an excavation and embankment specification (Minnesota 2006) that allowed the research team to know when the LWD passed or failed the testing. A pass or fail test status comparison was made to view the relationship of each gauge with the standard. A successful relationship would be one in which a gauge would pass when the standard passes, and would fail when the standard method fails. The whole data used to develop this analysis is included in the appendix section. Table 3.5 below summarizes the test status comparison.

Table 3.5. Test status Analysis of all gauges

Test Status Relationship with Standard Method	Site 1	Site 2	Average
Nuclear Gauge	80.62%	65%	72.81%
LWD	41.24%	67.50%	54.37%
EDG	41%	37.50%	39.80%

The nuclear gauge and LWD were the most correlated with the standard method when using a pass or fail quality assurance method of analysis. The quality assurance method used for the LWD is not yet a standard, and is currently being improved by the Mn/DOT. A better way to estimate the target value of the LWD might improve its correlation with the standard method. Furthermore, when the nuclear gauge data did not apply the correction factor, its test status relationship was only 63%, which is closer to the LWD. It means that the nuclear gauge raw data had similar results with the LWD.

3.6 Conclusions

A direct density comparison between the nuclear gauge and the EDG revealed that the nuclear gauge had a better correlation to the standard method. The EDG had similar results with the nuclear gauge before the nuclear gauge correlation factors were used to improve the gauge. Many researches are ongoing to find a way to improve the measured EDG's data, which could then perform similarly or better than the nuclear gauge. Different mold shapes and compaction methods are currently being tested by the manufacturer to improve the EDG's soil model. The nuclear gauge has been used much longer, so methods of improvement have been developed for better results.

The LWD, which measures the soil deflection, also displayed similar results with the nuclear gauge when using raw data. However, the nuclear gauge had better correlation with the standard method when the data was corrected. Different methods to estimate the LWD's target values can also researched and tested.

Chapter 4: Economic Analysis

4.1 Life Cycle Costs

Various techniques can be used to predict and analyze how much equipments would cost over time. A lifecycle cost analysis considers all the costs associated with owning, operating, and maintaining equipment for the duration of their useful life. For the lifecycle analysis done in this case, costs such as maintenance and any other non-directly measurable costs were estimated using previous data, quotes, and manufacturers' recommendations. Initial costs were those received from retailers when acquiring the gauges.

Tables 4.1 and 4.2 summarize the costs associated with possessing the nuclear and non-nuclear gauges.

Table 4.1. Costs associated with owning and operating a nuclear gauge

Cost of nuclear gauge	$6,950
Radiation safety & Certification Class	$750
Safety training	$179
HAZMAT certification	$99
RSO training	$395
TLD Badge monitoring	$140/yr
Life of source capsule integrity	15 yr
Maintenance & Recalibration	$500/year
Leak test	$15
Shipping	$120
Radioactive Materials License	$1,600
License Renewal	$1500/ year
Reciprocity	$750

Table 4.2. Costs of owning and operating the non-nuclear gauges

	Initial Costs	Annual Maintenance
EDG	$9,000	$0
LWD	$8,675	$0
PQI	$8,200	$500

4.2. Analysis

A basic analysis done by adding costs incurred over the gauges' life expectancies show that a nuclear gauge always costs more than any combination of the PQI and non-nuclear soil gauge as shown in Table 4.3 and Figure 4.1. The analysis is done using the lesser of the gauges' life expectancies, which is equivalent to 15 years.

In order to view the current benefit of using non-nuclear gauges, a net present worth cost of all gauges can be computed as explained below:

- Net Present Worth of Costs (NPW) = Initial Costs + Yearly Costs (P/A, 15 yrs, 10%)
- NPW of Nuclear Gauge = \$10,873 + \$2,155 (P/A, 15yrs, 10%)
- NPW of PQI + Average Soil Gauge = \$17,038 + \$500 (P/A, 15yrs, 10%)
- NPW of Nuclear Gauge = \$27,264
- NPW of PQI + Average Soil Gauge = \$20,840

Despite the high initial cost of the non-nuclear gauges, they still hold an economic advantage over the nuclear gauge when maintenance and operating costs are included. Figure 4.1 can help to calculate the break-even point for both investments.

Table 4.3. Cumulative Cost Combination of PQI and a soil gauge

Year	PQI + EDG	PQI + LWD	Nuclear Gauge
0	$17,200	$16,875	$10,873
1	$17,700	$17,375	$13,028
2	$18,200	$17,875	$15,183
3	$18,700	$18,375	$17,338
4	$19,200	$18,875	$19,493
5	$19,700	$19,375	$21,648
6	$20,200	$19,875	$23,803
7	$20,700	$20,375	$25,958
8	$21,200	$20,875	$28,113
9	$21,700	$21,375	$30,268
10	$22,200	$21,875	$32,423
11	$22,700	$22,375	$34,578
12	$23,200	$22,875	$36,733
13	$23,700	$23,375	$38,888
14	$24,200	$23,875	$41,043
15	$24,700	$24,375	$43,198

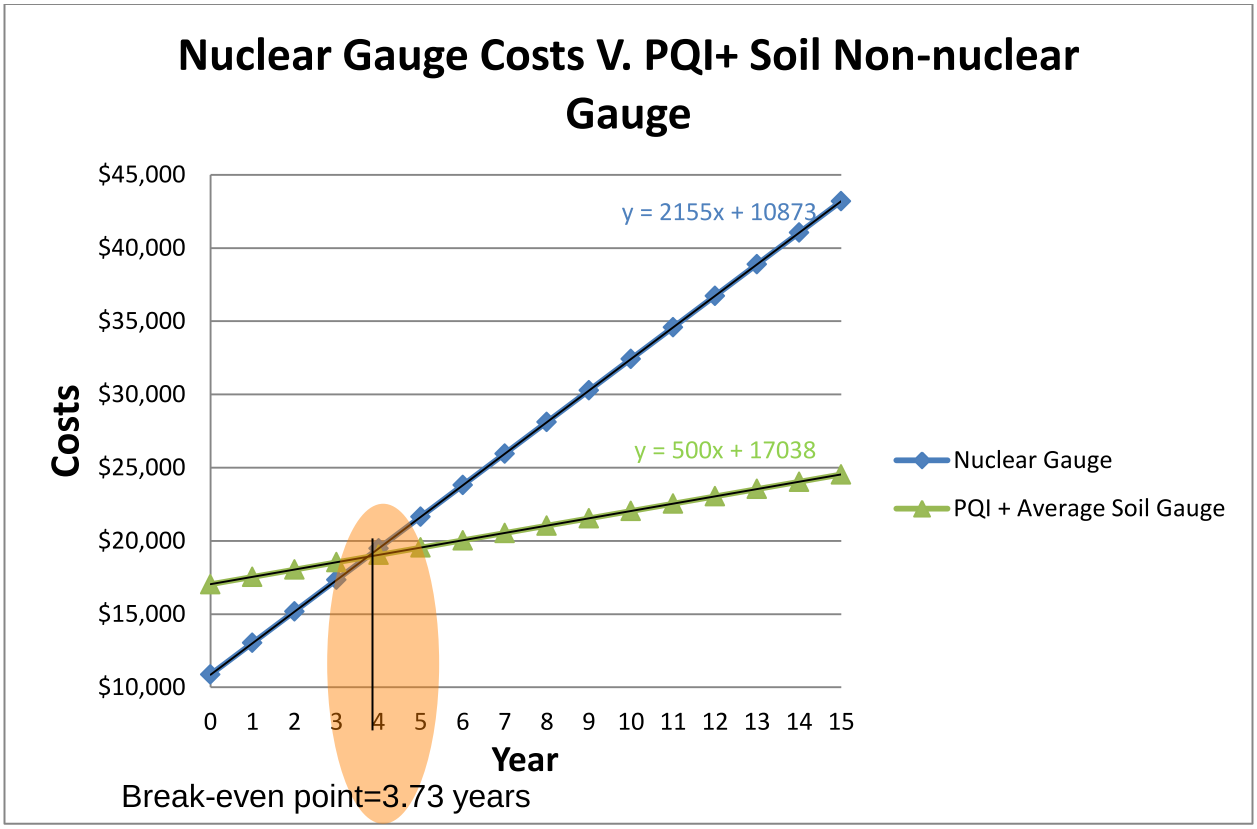


Figure 4.1. Fifteen year break-even lifecycle cost comparison graph

Although the initial costs of investing in the non-nuclear technology are higher than the initial cost of the nuclear gauge, the yearly maintenance, along with savings from maintaining and operating radioactive equipment, make the investment for non-nuclear gauges very profitable in the long term. With a break-even point of 3.73 years, the investment in non-nuclear technology makes sense. The EDG and the LWD cost about the same over their lifecycles. Costs can therefore be a negligible factor in selecting one of the two gauges for soil QC and QA.

Chapter 5 Conclusions and Recommendations

Intense regulation and destruction of materials all call for a new method for HMA and soil QA and QC. For HMA, the PQI offers a rapid measure of measurement, and is much more economical than the nuclear gauge. Test results showed that the PQI can have similar and better results than other alternatives. When the PQI reading is over 90% of the MTD value, the density measured is completely reliable and better than the nuclear gauge. Coring of the pavement should be done when the PQI gives values less than 90% of the MTD value. In that instance, the research team recommends using cores that have measured densities within 89 to 93% of the MTD value to calibrate the PQI.

Density and stiffness were introduced as ways to evaluate the compaction of soil. Testing was done with non-nuclear technologies that were not as accurate as the nuclear gauge. Nuclear technology has been around for so long, and various researches have been done to improve initial means of measurement. These improvements have resulted in proven ways to improve the nuclear gauge's accuracy, which has been adopted as a standard by some states and agencies. The EDG data was very comparable to the nuclear gauge before correction factors were applied. Numerous researches are ongoing to improve ways to develop soil models, which will in turn improve the EDG's correlation with the standard. The LWD also showed better correlation with the nuclear gauge when the initial data was used. Other methodologies to find target values and properly assess soil compaction will lead to better results.

Generally, the tested non-nuclear gauges (PQI, EDG, and LWD) take much less time to record measurements. Their initial costs are higher than the nuclear gauge, but have a greater return on investments; namely, some manufacturers, like Transtech, offer a trade-in credit for the PQI, for example.

Chapter 6 NDOR Implementation Plan

From the findings of this research, the NDOR will consider future implementation of the non-nuclear device for HMA acceptance for in-place density. The specification will utilize similar parameters found in the research testing, such as the final acceptance standard, being the actual roadway core for any tests under the 90% of Gmm. This is commonly the current practice adopted for low density results when using the current acceptance devices, i.e. nuclear gauges or cores. This will allow the contracting industry to utilize non-nuclear equipment with no permitting, fewer regulatory standards and less equipment safety training and/or documentation requirements, at an overall lower total ownership and operating cost.

The NDOR is going to expand on the initial findings of the non-nuclear soil density testing through 'in-house' research with the Soils and Geotechnical Sections. This expanded testing is an effort to test, quantify and accept soil compaction based on soil stiffness and modulus values in conjunction with the Nebraska Soils Index system by utilizing the LWD equipment. This will be used along with field moisture tests to create a new acceptance system for in-place engineered grading and fill. The goal of this research is to identify an improved testing and acceptance system utilizing non-nuclear devices and have much lower costs by less permitting and regulatory requirements, less accounting and documentation systems, as well as lower storage and maintenance costs on the equipment and personnel.

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Appendix A: Site 1

Rice value: 151.00 (pcf)

Num	Core(pcf)	PQI(pcf)	Nuclear(pcf)	Diff in Density	Diff in Density
				ABS (Core – PQI)	ABS (Core – Nuclear)
1	139.36	145.5	141.75	6.14	2.39
2	141.29	144.3	142.8	3.01	1.51
3	139.97	145.5	140.2	5.53	0.23
4	141.28	146.1	141.15	4.82	0.13
5	140.85	143.3	141.1	2.45	0.25
6	140.51	143.8	141.55	3.29	1.04
7	138.47	143.3	139.75	4.83	1.28
8	142.23	144.6	141.85	2.37	0.38
9	140.18	143.5	139.95	3.32	0.23
Average	140.46	144.43	141.12	3.97	0.66
Average difference (pcf)				3.97	0.81

Appendix B: Site 2

Rice value: 154.40(pcf)

Num	Core(pcf)	PQI(pcf)	Nuclear(pcf)	Diff in density	Diff in density
				ABS (Core – PQI)	ABS (Core – Nuclear)
1	141.3	140.6	139.85	0.7	1.45
2	143.36	138.6	139.75	4.76	3.61
3	141.7	138.4	140.75	3.30	0.95
4	140.39	137.2	140.35	3.19	0.04
5	142.35	139.7	142.1	2.65	0.25
6	141.68	137.9	140.15	3.78	1.53
7	141.56	138.3	142.4	3.26	0.84
8	143.3	139.6	142.7	3.70	0.60
9	141.81	138.1	141.05	3.71	0.76
10	140.58	137.2	142.5	3.38	1.92
Average of difference (pcf)				3.24	1.20

Appendix C: Site 3

Rice value: 154.75(pcf)

Num	Core(pcf)	PQI(pcf)	Nuclear(pcf)	Diff in density	Diff in density
				ABS (Core – PQI)	ABS (Core – Nuclear)
1	144.70	144	145.85	0.70	-1.15
2	144.69	144.1	145.35	0.59	-0.66
3	143.05	143.9	145.75	-0.85	-2.70
4	143.96	143.8	146	0.16	-2.04
5	145.61	142.4	146.3	3.21	-0.69
6	145.21	144.4	145.6	0.81	-0.39
7	145.25	143.9	146.15	1.35	-0.90
8	142.07	143.4	144.1	-1.33	-2.03
9	142.19	143.1	144.6	-0.91	-2.41
10	143.37	144	144.95	0.47	-1.58
Average of difference (pcf)				-0.42	-1.46

Appendix D: Site 4

Rice value: 150.76(pcf)

Num	Core(pcf)	PQI(pcf)	Nuclear(pcf)	Diff in density	Diff in density
				ABS (Core – PQI)	ABS (Core – Nuclear)
1	135.86	137.2	136.4	-1.34	-0.54
2	135.35	137	138.9	-1.65	-3.55
3	142.73	138.8	143.05	3.93	-0.32
4	136.59	137	136.9	-0.41	-0.31
5	141.46	139.2	143.1	2.26	-1.64
6	141.62	138.7	143.2	2.92	-1.58
7	143.49	137.8	143.55	5.69	-0.06
8	138.32	136.8	139.25	1.52	-0.93
9	135.41	137.6	139.8	-2.19	-4.39
Average of difference (pcf)				1.19	-1.48

Appendix E: Site 5

Rice value: 151.88(pcf)

Num	Core(pcf)	PQI(pcf)	Nuclear(pcf)	Diff in density	Diff in density
				ABS (Core – PQI)	ABS (Core – Nuclear)
1	138.84	141.4	138.55	-2.56	0.29
2	137.75	141.1	138.6	-3.35	-0.85
3	141.85	141.5	140.8	0.35	1.05
4	141.60	141.8	141.05	-0.20	0.55
5	141.70	142.3	140.25	-0.60	1.45
6	141.80	141.5	140.15	0.30	1.65
7	140.62	141.1	139.3	-0.48	1.32
8	140.41	141.7	139.85	-1.29	0.56
9	140.05	141.5	138.9	-1.45	1.15
Average of difference (pcf)				-1.03	0.80

Appendix F: Site 6

Rice value: 151.6(pcf)

Num	Core(pcf)	PQI(pcf)	Nuclear(pcf)	Diff in density	Diff in density
				ABS (Core – PQI)	ABS (Core – Nuclear)
1	139.46	139	139	0.46	0.46
2	141.59	139.4	141.6	2.19	-0.01
3	144.43	139.1	143.75	5.33	0.68
4	139.69	138.2	139.85	1.49	-0.16
5	141.09	139.1	141.2	1.99	-0.11
6	144.7	140.1	144.45	4.60	0.25
7	142	139.5	143.2	2.50	-1.20
8	138.9	138.6	139.5	0.30	-0.60
9	141.23	139.1	141.85	2.13	-0.62
Average of difference (pcf)				2.33	-0.15

Appendix G: Site 7

Rice value: 153.4(pcf)

Num	Core(pcf)	PQI(pcf)	Nuclear(pcf)	Diff in density	Diff in density
				ABS (Core – PQI)	ABS (Core – Nuclear)
1	135.58	136.5	136.8	-0.92	-1.22
2	133.92	137.7	135.25	-3.78	-1.33
3	139.65	137.8	134.55	1.85	5.10
4	138.97	139.5	139.75	-0.53	-0.78
5	136.4	138.2	139	-1.80	-2.60
6	136.79	138.7	140.2	-1.91	-3.41
7	132.77	136.5	139.3	-3.73	-6.53
8	136.4	138.4	139.1	-2.00	-2.70
9	136.55	138.2	141.6	-1.65	-5.05
Average of difference (pcf)				-1.61	-2.06

Appendix H: Site 8

Rice value: 152.82(pcf)

Num	Core(pcf)	PQI(pcf)	Nuclear(pcf)	Diff in density	Diff in density
				ABS (Core – PQI)	ABS (Core – Nuclear)
1	137.2105	139.6	141.6	-2.39	-4.39
2	142.8013	139.8	143.2	3.00	-0.40
3	142.2401	139.4	141.25	2.84	0.99
4	143.3141	138.9	144.5	4.41	-1.19
5	136.4442	139.6	143.65	-3.16	-7.21
6	141.8341	137.3	142.4	4.53	-0.57
7	142.3126	138.2	142.5	4.11	-0.19
8	141.8765	138.4	141.45	3.48	0.43
9	143.3574	137.6	139.95	5.76	3.41
10	143.3295	138.4	142.95	4.93	0.38
Average of difference (pcf)				2.75	-0.87

Appendix I: Site 9

Rice value: 153.4(pcf)

Num	Core(pcf)	PQI(pcf)	Nuclear(pcf)	Diff in density	Diff in density
				ABS (Core – PQI)	ABS (Core – Nuclear)
1	139.5378	140.6	140.45	-1.06	-0.91
2	136.8946	138.9	136.6	-2.01	0.29
3	137.2703	139.3	137.15	-2.03	0.12
4	138.0902	140.1	139.75	-2.01	-1.66
5	137.6734	138.3	138.8	-0.63	-1.13
6	140.6103	140.1	138.6	0.51	2.01
7	142.3972	141.7	140.25	0.70	2.15
8	135.5922	139.2	137.25	-3.61	-1.66
9	139.3049	141.3	140.15	-2.00	-0.85
Average of difference (pcf)				-1.35	-0.18

Appendix J: Site 10

Rice value: 151.63(pcf)

Num	Core(pcf)	PQI(pcf)	Nuclear(pcf)	Diff in density	Diff in density
				ABS (Core – PQI)	ABS (Core – Nuclear)
1	136.229	137.19	132.65	-0.96	3.58
2	135.724	138.29	136.75	-2.57	-1.03
3	135.416	137.59	135.3	-2.17	0.12
4	138.0347	138.09	138.6	-0.06	-0.57
5	138.274	137.29	133.25	0.98	5.02
6	137.14	137.29	134.65	-0.15	2.49
7	134.4266	137.29	137.15	-2.86	-2.72
8	137.0279	137.09	136.85	-0.06	0.18
9	137.2721	137.09	137	0.18	0.27
10	134.1401	137.09	139.15	-2.95	-5.01
11	133.2356	137.69	136.85	-4.45	-3.61
12	132.2507	137.39	135.1	-5.14	-2.85
13	132.662	137.09	135.9	-4.43	-3.24
14	132.477	136.79	134.6	-4.31	-2.12
15	139.283	137.09	136.55	2.19	2.73
Average of difference (pcf)				-1.78	-0.45

Appendix K: Site 11

Rice value: 152.94(pcf)

Num	Core(pcf)	PQI(pcf)	Nuclear(pcf)	Diff in density	Diff in density
				ABS (Core – PQI)	ABS (Core – Nuclear)
1	135.34	134.77	134.6929	0.57	0.65
2	135.84	134.97	132.5612	0.87	3.28
3	134.94	133.92	132.1983	1.02	2.74
4	136.04	135.77	138.5644	0.27	-2.52
5	135.54	133.47	138.7553	2.07	-3.22
6	135.24	132.97	139.3517	2.27	-4.11
7	134.54	133.57	142.4331	0.97	-7.89
8	135.74	132.72	131.7215	3.02	4.02
9	135.54	134.62	138.0946	0.92	-2.55
Average of difference (pcf)				1.33	-1.07

Appendix L: Site 12

Rice value: 153.19(pcf)

Num	Core(pcf)	PQI(pcf)	Nuclear(pcf)	Diff in density	Diff in density
				ABS (Core – PQI)	ABS (Core – Nuclear)
1	139.2268	137.757	139.8241	1.47	-0.60
2	139.3268	138.807	138.0621	0.52	1.26
3	137.9268	139.007	137.1564	-1.08	0.77
4	139.0268	138.257	138.5112	0.77	0.52
5	139.0268	136.957	139.0936	2.07	-0.07
6	139.4268	139.957	140.0971	-0.53	-0.67
7	140.8268	140.707	138.8858	0.12	1.94
8	138.8268	139.257	139.5808	-0.43	-0.75
9	140.6268	139.357	135.0415	1.27	5.59
10	139.7268	138.207	132.98	1.52	6.75
11	139.2268	141.757	139.1269	-2.53	0.10
12	140.7268	141.657	134.7572	-0.93	5.97
13	138.7268	137.157	139.9493	1.57	-1.22
14	139.1268	142.557	141.1577	-3.43	-2.03
15	141.1268	142.157	131.9402	-1.03	9.19
16	139.4268	139.307	132.222	0.12	7.20
17	140.7268	141.357	134.831	-0.63	5.90
18	137.7268	141.457	134.1427	-3.73	3.58
19	141.1268	144.707	139.7142	-3.58	1.41
20	137.8268	137.257	134.9493	0.57	2.88
Average of difference (pcf)				-0.40	2.39

Appendix M: Site 13

Rice value: 153.19(pcf)

Num	Core(pcf)	PQI(pcf)	Nuclear(pcf)	Diff in density	Diff in density
				ABS (Core – PQI)	ABS (Core – Nuclear)
1	137.76	138.17	138.22	-0.41	-0.46
2	140.06	138.37	139.22	1.69	0.84
3	144.36	134.67	141.17	9.70	3.20
4	138.73	135.77	134.32	2.96	4.41
5	137.94	134.97	140.57	2.97	-2.63
6	141.28	135.67	145.97	5.61	-4.69
7	139.39	133.07	136.67	6.32	2.72
8	135.60	135.07	137.02	0.53	-1.42
9	135.41	137.17	133.12	-1.76	2.29
10	132.61	137.67	136.17	-5.06	-3.56
11	136.44	138.97	139.27	-2.53	-2.83
Average of difference (pcf)				1.82	-0.19

Appendix N: Calibration results of different numbers of cores

NO	Date	3 cores			5 cores			8 cores			10 cores		
		R	TD	LD	R	TD	LD	R	TD	LD	R	TD	LD
1	8.28.09	-0.760	2.53269	1.35023	-0.973	1.86626	0.80506	0.902	1.86626	0.76633	-0.948	1.86626	0.73917
2	9.10.09	0.994	1.81987	0.90231	0.906	1.85501	0.85382	0.837	1.69901	0.98451	0.839	1.71616	0.76501
3	9.17.09	0.938	1.21021	1.79222	0.074	0.87958	0.90645	0.320	1.02632	1.09369	0.394	0.87798	0.98762
4	10.20.09	0.993	4.25486	2.37950	0.779	2.51261	6.68436	0.733	2.44728	1.69430	0.606	2.43110	1.66937
5	10.26.09	0.614	1.23372	1.12386	0.614	1.23372	1.12386	0.515	1.21085	1.15910	0.599	1.21907	1.16051
6	10.27.09	-0.680	2.61162	2.76696	-0.680	2.61162	2.76696	0.242	1.74819	2.17230	0.578	1.64344	3.07808
7	5.27.10	0.845	2.41408	6.53573	0.584	2.41948	2.95257	0.328	2.53447	2.77716	0.045	2.49281	2.51979
8	6.24.10	0.391	2.61909	2.17532	0.764	2.38895	1.74972	0.619	2.55776	1.77889	0.767	2.39969	1.60920
9	6.30.10	0.799	2.82318	3.01438	0.121	2.72540	2.80460	0.082	2.78722	2.79331	0.562	2.73893	2.86695
10	8.6.10	0.944	2.16671	2.07993	0.831	2.08830	1.63053	0.576	2.59676	1.60077	0.719	2.34962	2.24542
11	8.25.10	0.715	3.38246	3.58584	-0.050	3.55134	3.59592	-0.474	3.38246	3.67834	-0.152	3.38246	3.36337
12	9.16.10	0.701	1.46234	1.95816	0.390	1.31725	1.46138	0.035	1.55122	1.55760	0.090	1.31514	1.32753
13	9.17.10	-1.000	3.02991	4.17139	-0.744	3.00478	2.79913	-0.613	3.01491	2.22898	-0.577	3.15433	2.29440
	Avg	N/A	2.42775	2.60276	N/A	2.18879	2.31803	N/A	2.18636	1.86810	N/A	2.12208	1.89434

NOTE: Where, TD= Traditional difference, and LD= Linear regression difference