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# Effectiveness study of Non-Nuclear Gauge for Hot Mix Asphalt (HMA) Pavement Construction

Ziqing Zhuang
*University of Nebraska-Lincoln*, zzhuang@unomaha.edu

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# Effectiveness study of Non-Nuclear Gauge for Hot Mix Asphalt (HMA) Pavement Construction

By

Ziqing Zhuang

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# Effectiveness study of Non-Nuclear Gauge for Hot Mix Asphalt (HMA) Pavement Construction

Ziqing Zhuang, M.S

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Advisor: Yong Cho

Density is an important measure for hot-mix asphalt (HMA) pavement quality control. Traditionally, the nuclear gauge method is widely used in pavement density testing. However, some disadvantages of nuclear gauges (such as the handling, storage, and transportation of radioactive materials) have created the need of non-nuclear technology. This thesis evaluated the Pavement Quality Indicator (PQI) model 301, which was promised to be more efficient than the nuclear method. The PQI utilizes many electrical impedance principles by using the current going through the pavement to determine its density and moisture content. Test data were collected in the field during pavements, and cores were taken to the laboratory for further testing. 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. Results showed that the PQI could be a better alternative to a nuclear gauge when the following benefits are considered: 1) economic savings, 2) faster data measurement, 3) no intense federal regulations, safety concerns, licensing and intense training, and 4) improved calibration techniques.

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# CHAPTER 1 INTRODUCTION

## 1.1 Introduction:

According to the Office of Highway Policy Information, the percentage of all the roads and highways which have a serviceability rate of less than 3.4 in the United States is about 53% (Office of Highway Policy Information 2007). This indicates that these roads are in poor condition. A good quality control mechanism is required to identify the problems of roads, thus density control of Hot Mix Asphalt (HMA) pavements was introduced in 1986 to evaluate the quality of HMA pavements (Andrewski 2003). The density control method includes measurement using a nuclear gauge to compare the cores density acquired from the same area (Andrewski 2003). The core density method gave a precise indication of the density; however, it is destructive and time consuming. Furthermore, the nuclear method is burdened with numerous intense federal regulations associated with the handling, storage, training, and transportation of radioactive materials (Allen 2003). For such reasons, different non-nuclear technologies have been developed to rapidly measure HMA densities. The non-nuclear gauges apply the principle of electromagnetic signals to test pavement density (Romero 2002). The non-nuclear method does not require intensive licensing, training, maintenance, storage issues, and transportation efforts, which are all common to nuclear gauges. The Pavement Quality Indicator (PQI), one of the non-nuclear density gauges, was developed by Transtech Systems, Inc. to measure the HMA density. PQI uses a constant voltage, radio frequency, and electrical impedance approach to take quick in-situ measurements, and adjust for moisture variations and mix types (Von Quintus, 2009). However, in order to standardize these technologies, their accuracy must be equal or even better to the nuclear gauge and core measurement method. They must also be economically beneficial both in short and long terms.

### 1.2 Research Problems

Current quality control (QC) and quality assurance (QA) of HMA pavements require the use of excessive manpower and time. Core density measurement is done in accordance with the American Association of State Highway and Transportation Officials (AASHTO) procedure AASHTO T166 (AASHTO T 166). The destructive coring process creates holes in the new pavement, though the holes are later patched. This creates an imperfection in the pavement that could cause long-term issues such as cracks and potholes. Furthermore, measuring cores generally takes time. Core results are not typically available until the next day to allow for corrections for the paving process and compaction. The required use of laboratory equipment is also a cost factor to be considered. A minimum of one full-time lab technician is usually required to run all the tests. Moreover, only a small number of cores are used to gauge the values for several miles of pavement because of the time-consuming coring and testing process. This small sample size leads to the core result not fully representing the density of the pavement. Finally, the coring process does not always provide accurate results as some loose particles can be lost and affect the density.

Nuclear gauge technology offers a faster method to measure in-place HMA density, and has been used successfully to replace and/or complement most coring in many states. Depending on the specifications, some states, including Nebraska, use just the coring method, or a combination of the coring system with a nuclear gauge. However, the use of the nuclear gauge has several 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 also received prior radiation safety and maintain current applicable safety procedures and safety 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 maintain the gauges. Strict licensing and re-licensing, record-keeping usage, and storage of the gauges are all complications of using the nuclear gauges’ technology. Finally, transporting radioactive materials is subject to rules and regulations.

Consequently, there is a high demand for a device that is accurate, easy to use, quick, non-destructive, and nonradioactive. It seems that non-nuclear gauges can overcome all the problems caused by the nuclear gauge and core sample method. In order to accept the non-nuclear gauges, their accuracy and effectiveness should be proven equivalent to or better than nuclear gauges. In the mean time, the effectiveness of PQI should be improved by other possible techniques to make itself better than nuclear gauges. However, no previous research has been conducted in this field.

### 1.3 Objective

<u>The main objective of this research is to find innovative ways by calibration and other methods to improve the current process which can increase accuracy of non-nuclear gauge.</u> The sub-objectives of this research are:

(1) To conduct intensive field tests for core sample, non-nuclear and nuclear gauge methods to determine their effectiveness for quality assurance of HMA pavement.

(2) To conduct economic alternatives for replacing the current nuclear gauge to minimize cost burden.

The accuracy and precision of the gauges were assessed by comparisons with traditional methods of density measurement, including field cores and the nuclear gauge. A thorough consideration of calibration procedures was conducted, and suggestions were made for incorporation into existing specifications to better the data accuracy.

### 1.4 Research Methodology

To achieve the research objective, the project examined the determination of field density of HMA mixtures. Some previous researchers stated that PQI was acceptable in the pavement quality control. According to Andrewski, test results showed PQI is more accurate than the nuclear gauge and quicker than the core method (Andrewski 2003). Sebesta (2003) stated that the density differentials measured from PQI is much more reliable than the nuclear gauge and PaveTracker without considering the bias comparison (Sebesta 2003). Remero (2002) concluded that PQI is acceptable in the pavement quality control as a replacement for the nuclear gauge (Remero 2002). Considering the effectiveness of the non-nuclear gauge, the project team chose PQI instead of other non-nuclear gauges based on previous researchers' conclusions. This project first examined the selected non-nuclear gauge for this study, Pavement Quality Indicator (PQI), as a possible new way to gather real-time quality control data. After the measurement technique was established, a strategy for the evaluation of the PQI was developed. The traditional core sampling method was selected as the 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 determining various calibration methods along with different techniques of measurement. Finally, a cost-benefit analysis was conducted to demonstrate the cost savings of using a non-nuclear gauge over a nuclear gauge.

### 1.5 Chapter Organization

The first chapter contains an introduction of HMA density testing methods including the coring method, the nuclear gauge method, and the non-nuclear gauge method. Moreover, the problem statement, objectives and research methodology are presented. The second chapter is a literature review of the effectiveness of the nuclear gauge and the non-nuclear gauge. It also reviews the analysis for the coring method, the nuclear gauge method, and the non-nuclear gauge method. The third chapter is research methodology and contains the measurement process of the non- nuclear gauge, the nuclear gauge, and traditional coring method. The fourth chapter includes the analysis results for the different methods of density measurements. The fifth chapter presents economic analysis for the nuclear gauge and the non-nuclear gauge, which is the comparison of cost between operating the nuclear gauge and the non-nuclear gauge. Finally, the sixth chapter presents the conclusion and recommendations.

# CHAPTER 2 LITERATURE REVIEW

## 2.1 Effectiveness of Nuclear and Non-nuclear Gauges

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 each at forty-five different locations for six site visits. Both gauges were compared to cores that were also taken at each test area. Findings revealed that neither density values correlated well with core densities.

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

Henault evaluated the effectiveness of the PQI model 300 for quality assurance testing in his study. The calibration method of five core offset was used on the 10 different sites tested. The nuclear gauge results were much more correlated to the coring method than the PQI's, and so the PQI was not recommended for quality assurance tests (Henault, 2001).

Romero evaluated the performance of PQI, PaveTracker, and nuclear gauge through 5 different state highway agencies and 34 field projects. The PQI 300+, Pavetracker, and nuclear gauge were statistically different from core density in 68%, 82%, and 75%, respectively. The nuclear density gauge had better correlation with core than both non-nuclear gauges in most projects. To acquire relative pavement density, both PQI 300 and PaveTracker are suitable for quality control application (Romero, 2002).

Prowell and Dudley also did 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 a non-nuclear gauge's. The five core average offset calibration method was used to improve the PQI's density values. These findings validated the use of the PQI for quality control (Allen et al, 2003).

After improvements had been made to improve 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 which revealed that the non-nuclear gauge had improved, but was still inferior to the nuclear gauge for density measurements (Hurley et al, 2004). Schmitt, Rao, and Von Quitos did a study 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. Data revealed that nuclear gauge values were much better to the non-nuclear gauges'. Both PQI and PaveTracker have lower than nuclear gauge. They also reported that the difference in nuclear and non-nuclear measured densities increased when the pavement thickness increased. A mandatory calibration on each site test was then recommended before measurements. A ten core calibration was even made and showed improvements in the data (Schmitt, 2006).

Sebesta, Zeig and Schullion initiated a study to assess if any non-nuclear gauges could be used to replace nuclear gauges. The work in the first year focused on testing the repeatability and accuracy of the nuclear gauge, pavetracker, and PQI. Both lab and sites testing were performed to compare all the gauges' function. PQI "could be used to replace nuclear gauge for both density profiles and joint density evaluation" (Sebesta 2003). PQI also provides the most reliable estimate of density differentials if the gauge exhibited no bias comparing the nuclear gauge and the PaveTracker (Sebesta 2003).

Kvasnak, et. al (2007) also compared the PQI and Pave Tracker to the nuclear gauge to study factors that affect the non-nuclear gauges. It was found that roller pass, pavement moisture condition, and aggregate were among some of the factors that affected density measurements. Remero's report concluded PQI provides good results as nuclear devices, and it is perfectly accepted in the pavement quality control. Another important finding was the need to study a test strip or bed for calibration purposes (Kvasnak et al 2007).

Rao et al (2007) conducted a study involved field tests at 16 sites with 30 test points at each site using one nuclear gauge and three non-nuclear gauges. A consistent bias was examined between non-nuclear gauge data and nuclear gauge data. This bias, however, can be adjusted by using calibration factor which determined by using a slope function (Rao et al, 2007).

### 2.2 Economic Analysis for Nuclear and Non-nuclear Gauges

The Wisconsin Department of Transportation (WisDOT) started to use nuclear density readings as an alternative method to core samples, according to Schiro (2006). However, nuclear density readings require special handling and radioactive material license which may cost about $1,400 (Schmitt, 2006).

Kabassi et al (2011) conducted a study to investigate the life cycle cost comparison between nuclear gauges and non-nuclear gauges using manufacturers' recommendations. Without applying any rate of interest, the initial cost of PQI is $8,200 and the annual maintenance is estimated at $500. The nuclear gauge cost is $10,873 initially with a $2,155 maintenance fee annually. This result shows that the nuclear gauge is more expensive than the PQI both in initial and annual costs. (Kabassi et al, 2010)

### 2.3 Current Research

This thesis presents a new method to test the effectiveness of non-nuclear gauges. With the application of statistical methods such as outlier, T-test and coefficient of correlation, the data is analyzed to test the accuracy and precision of PQI. The core sampling was selected as standard, while the nuclear and non-nuclear gauge compare against it. Furthermore, an economic analysis is developed to compare the life cycle cost of nuclear and non-nuclear gauges.

# CHAPTER 3 METHODOLOGY

## 3.1 Introduction

As mentioned before, the nuclear gauge and non-nuclear gauge are compared to core sampling to decide their effectiveness. 13 site visits are conducted to collect the data of each measurement method. To improve the accuracy of results, the gauges need to be calibrated. This chapter will describe the methods used in filed data collection and gauge calibration.

## 3.2 Core Method

An infrared camera was used to choose each location for density testing, as shown in Figure 3.1. Cores need to be taken 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 very easy to be drilled out. To facilitate the coring process, the research team used dry ice ($CO_2$) as a method to cool down the asphalt, as shown below in Figure 3.2. Dry ice cools down the surface and leaves no trace of water to interfere with the density measurements done on site for calibration purposes. A coring machine was used to drill out the core from each location, as shown below in Figure 3.3. Important care needs to be taken when drilling to not include any underlying layer in the sample. Drilling depth is usually dictated by the bituminous layers (AASHTO T166 2010). 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 similar. This measure of density has been adopted as standard for the research. Nuclear gauge density and PQI density are both compared to this density to measure their 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 ambient temperature.

**Figure 3.1: Use infrared camera to choose density testing location**

**Figure 3.2: Dry ice used to quickly cool down the HMA pavement for coring.**

**Figure 3.3: Use coring machine to drill cores**

### 3.3 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 number of 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 or similar. The first five cores taken were used to calibrate both the nuclear and non-nuclear gauges. 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 specification. Figure 3.4 below shows the Troxler 3440 nuclear gauge used for this study. The results are then later compared to the PQI's, and documented for analysis.

**Figure 3.4: Nuclear Gauge is shown measuring density**

### 3.4 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 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 is faster to use than a nuclear gauge. The PQI model 301 is shown in Figure 3.5. 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 at it in close proximity (about 1 foot).

**Figure 3.5: PQI model 301 taking measurements**

### 3.5 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 roller passes.

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. 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 better 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 the use of water to allow the cores to be measured 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. Figure 3.6 and 3.7 show the cores being measured both on site and later in the lab. Note here that the calibration method adopted by the research team conforms to what both manufacturers recommend, as well as what is recommended by both AASHTO and ASTM. Ideally, a calibration method will reconcile the differences between different measurements of the same property. However, because of the non predictability of the gauges and other biases, perfect agreements are not present and regressions are used in analyses to adjust one method to the others.

**Figure 3.6: On-site set up for core measurements**

**Figure 3.7: Field lab set up for core measurements**

### 3.6 Chapter Summary

In this chapter, the core, nuclear, and non-nuclear method were used to test pavement densities in same location. The project team used infrared camera to choose the testing spots, and put dry ice to cool down the pavement for the convenience of drilling cores. AASHTO T166 was applied to core density measurement. PQI and nuclear gauge were calibrated using the first five cores' density measurement.

# CHAPTER 4 DATA ANALYSIS

## 4.1 Introduction

After the data was obtained from both the nuclear and non-nuclear gauges in the field, we analyze the data to find out the accuracy and reliability of both gauges. Both gauges were compared separately against the study’s control density measurement (laboratory tested core samples of 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 on site does not follow an easily identifiable trend. Due to these external variables, each data point was accepted or rejected based on a few key criteria, such as outlier and quality of core.

## 4.2 Poor Core Samples

Extreme care should be taken to avoid altering and damaging cores before and after coring. Foreign material may be attached to the specimen, so layers of cores should be separated by sawing and other means without destroying the specimen (AASHTO T166). 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 4.1 and 4.2 below illustrate what kinds of cores were accepted and rejected.

**Figure 4.1: Example of a rejected core**

**Figure 4.2: Example of an accepted core**

### 4.3 Outlier

Though the use of the PQI allows the user to collect thousands of data points in a very short amount of time, it is cost and time prohibitive to collect hundreds or even thousands of core samples. Therefore, the data pool consisting of one hundred and fifty data points from which findings are based is relatively small, and therefore very susceptible to data outliers. Generally, an outlier is identified as all values above the mean plus or minus three standard deviations (Los Alamos, 2000).

$$O > [\sum (\text{core} - \text{gauge})] / n + 3 \text{ standard deviation}$$

$$\text{Or } O < [\sum (\text{core} - \text{gauge})] / n + 3 \text{ standard deviation} \qquad \text{(Equation 4.1)}$$

Where,

O = outlier

Standard deviation = standard deviation of the difference between core and gauge readings

Initially, the PQI density and core density correlation was found to be extremely low at 4.21% for site number five (Figure 4.3). However, as Figure 4.4 illustrates, when outliers are excluded from the dataset, the correlation between readings from the PQI and tested core samples increases dramatically to 56%. If observations are statistically determined to be outliers, it is suggested that an explanation should be provided for these outliers before their exclusion from further analysis. If an explanation cannot be found, then the observations should be treated as extreme but valid measurements (Bollen 1985). Outliers were taken out of the data pool to improve the results for this study.

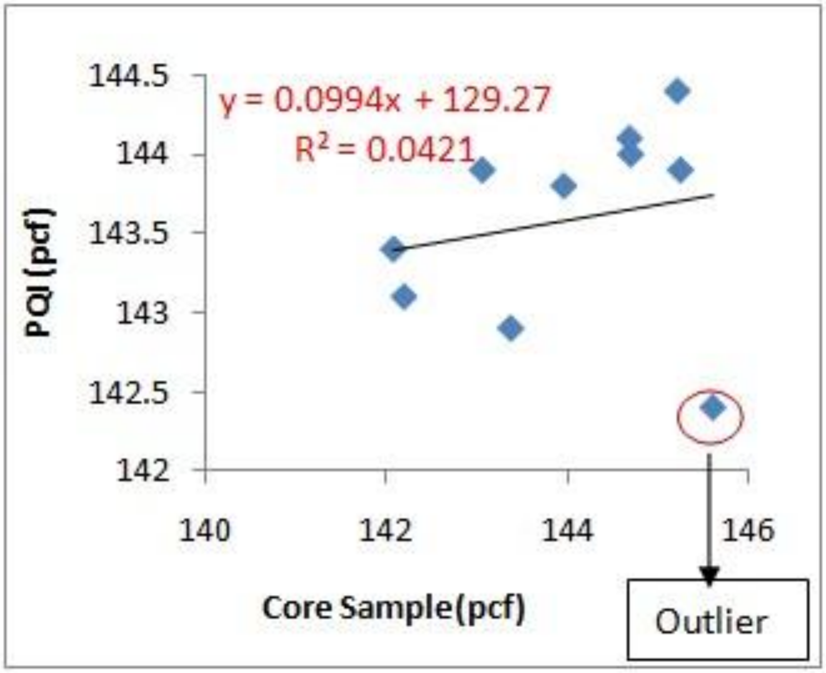

**Figure 4.3: Example of an accepted core**

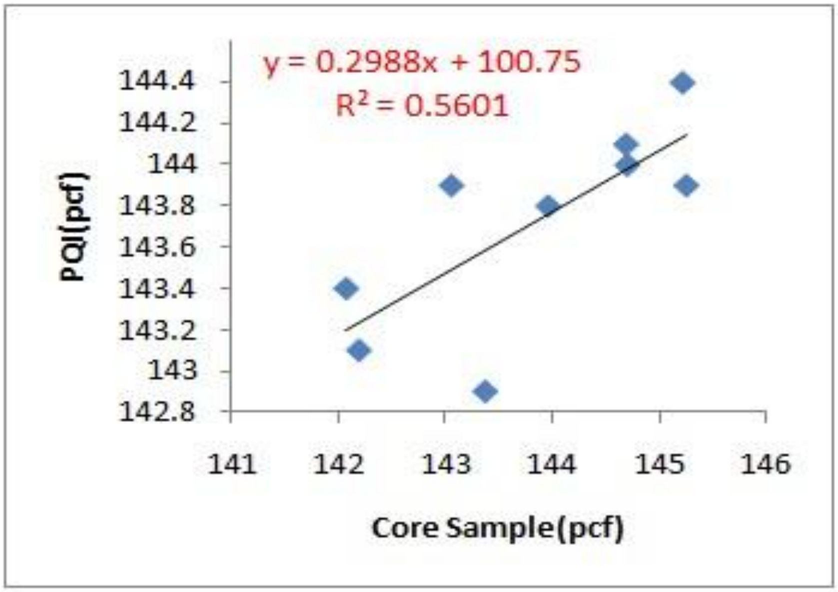

**Figure 4.4: After deletion of outliner**

### 4.4 Average Difference between Both the Gauges and Cores

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). The average difference is calculated as follows (Romero, 2002),

$$\text{Average Difference} = \left| \left[\sum (\text{core} - \text{gauge})\right] / n \right| \qquad \text{(Equation 4.2)}$$

Where,

Average Difference = average difference between core density and gauge density

Core = density of cores from laboratory testing

Gauge = density obtained from the gauge reading

N = number of cores

The average difference cannot assume that the gauge 'trend' changes in the core density. To highlight this point, Table 4.1 and Figure 4.5 describe data trends that were discovered through an analysis of data collected onsite. Figure 4.5 shows that both gauges follow trends similar to the core sample densities. As can be seen in Table 4.1, the average of PQI's readings is 1.89 $\text{lb/ft}^3$ lower than the cores, while the nuclear gauge's is 1.07 $\text{lb/ft}^3$. If both gauges were evaluated based on the difference, the nuclear gauge would result in closer values to core samples than the PQI.

Based on the results shown in Table 4.1, only four sites accept the hypothesis that the difference between core density and PQI density readings is zero. From these results, it can be concluded that there is a 69% statistical difference between PQI densities and the core densities. In fact, the average difference between the PQI and core samples is only 1.89 $\text{lb/ft}^3$ as shown in

Table 4.1. However, the hypothesis was rejected in only three sites when comparing nuclear gauge densities against core densities (see Table 4.1). As a result, it can be concluded that there is statistically no difference between nuclear densities and core densities with a degree of certainty of 76%.

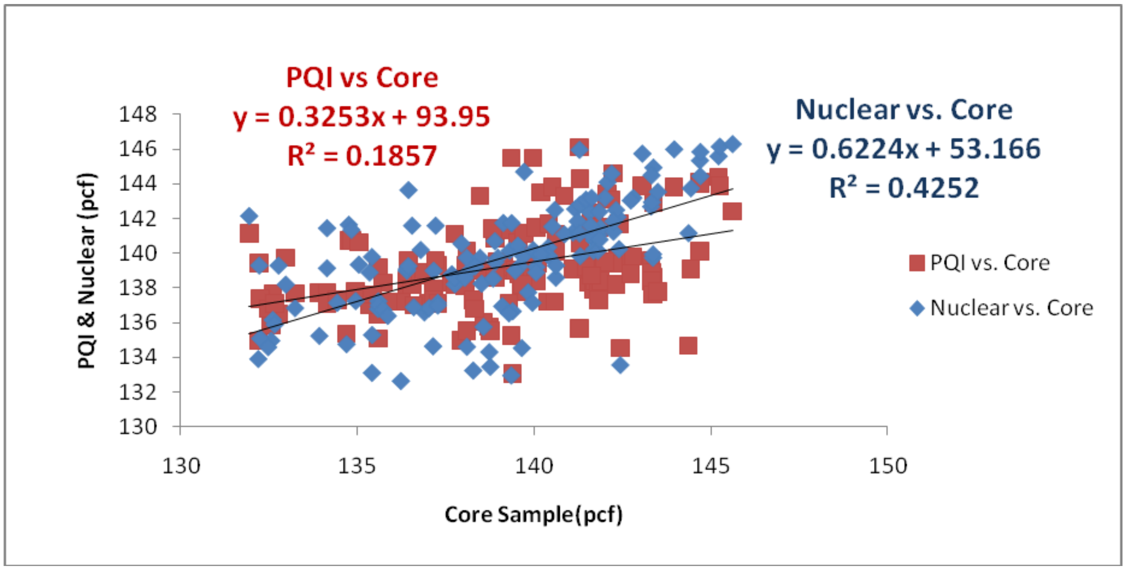

**Figure 4.5: "Trends" of each test method**

### 4.5 Student T-Test

To test for statistically significant differences between core samples and pavement gauges, students T-tests are a sound analysis. In this analysis, the hypothesis is that the difference between core density and gauges density readings measured in each spot has a mean value of 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 4.1: Average difference and T-test results between both gauges compared to core values**

| Site | Number of core | 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 | N/A | 1.89 | 1.07 | N/A | N/A |

For sites 3, 4, 11, and 13, the statistical difference between each gauge and the cores is more than the t-value (95% confidence interval).So the null hypothesis is accepted for these sites. For the majority of the remaining sites, the nuclear gauge shows closer values to the cores than PQI according to the student t-test analysis.

### 4.6 Coefficient of Correlation

The coefficient of correlation analysis is another method of evaluating the applicability of a new gauge to measure density (Remero, 2002). This analysis is used to decide if a statistically significant linear relationship exists between the gauges when comparing 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, this would indicate that there is significant correlation between gauge density and core density.

**Table 4.2: Coefficient of Correlation and R-squared between both gauge density and Core density**

| Site | Coefficient of Correlation( R ) | Coefficient of Determination( R2 ) |
|---|---|---|

| | 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 |

For the most of the sites, coefficients of correlations values of the nuclear gauge were higher than the PQI's. This shows that the nuclear gauge is in accordance with cores more than PQI. Note that there were few instances when the PQI's showed better correlation (sites 2, 7, 9).

### 4.7 Coefficient of Determination

As shown in figure 4.5, low $R^2$ values (PQI: 0.19 and Nuclear: 0.43) indicates a weak correlation between both gauges' individual densities as compared to core density. However, as shown in Table 4.2, four sites out of 13 sites show R-squared are more than 50% between PQI density and core density. Additionally, 5 out of 13 sites have an R-square value more than 50% between nuclear gauge densities and core densities. As the results showed in Table 4.2, the PQI's coefficient of correlation was lower than 0.50 in 7 out of 13 sites (54%) and the nuclear gauge in 6 out of 13 sites (46%). The PQI had a coefficient of correlation greater than 0.85 in 0 out of 13 sites (0%), and the nuclear gauge in 2 out of 13 sites (15%). Therefore, it can be concluded that there is a 25% correlation between PQI densities and core densities, and 41% correlation between nuclear densities and core densities.

Two different methods are conducted to find the correlations between two gauges densities and core samples. In the first scenario, all the spots in 13 sites were considered as a whole data pool, and R-Square was obtained as shown in Figure 4.5 in an earlier section. In the second scenario, the project team acquired the average density of each site. The regression line is shown in Figure 4.6 with R-square. Table 4.3 shows the analysis results of both gauges'correlation to core samples when considering site averages and individual locations.

**Table 4.3: Correlation between Gauge and Cores at each location or based on Site Averages**

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

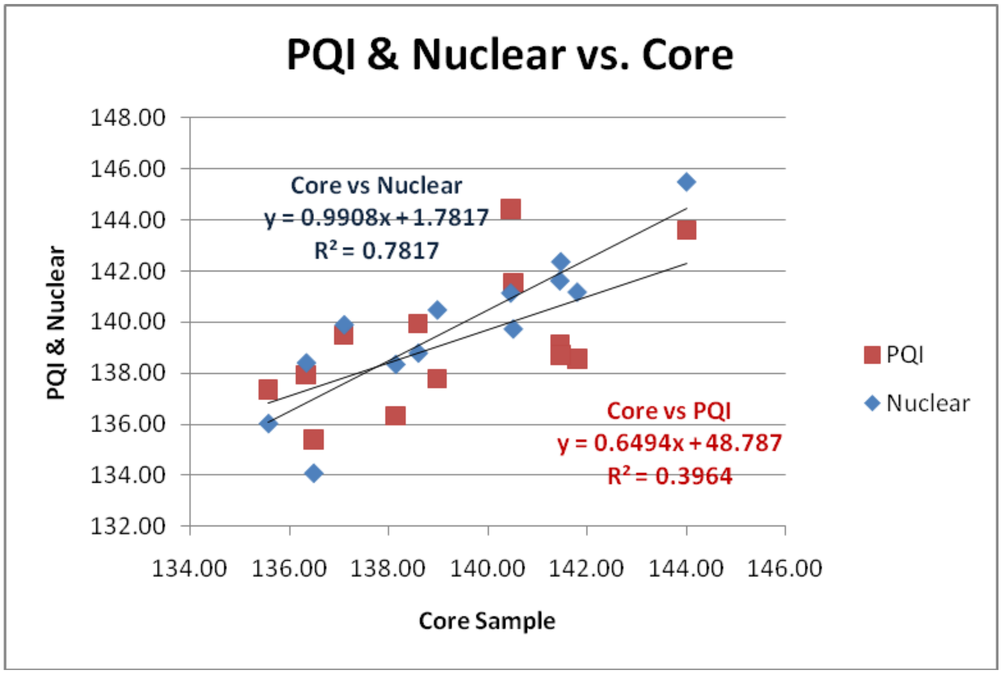

**Figure 4.6: Linear regression between each Gauge and Core Samples in each site average densities**

### 4.8 PQI and Nuclear Density Error of the Standard Deviation

Figure 4.7 below shows the absolute density differential variation for both gauges. When taken as a whole, the average difference, or standard deviation, between both gauges is very similar, varying by only 0.04 lb/ft$^3$. This finding alone lends itself to the case advocating for the replacement of nuclear gauges due to their cost and safety issues.

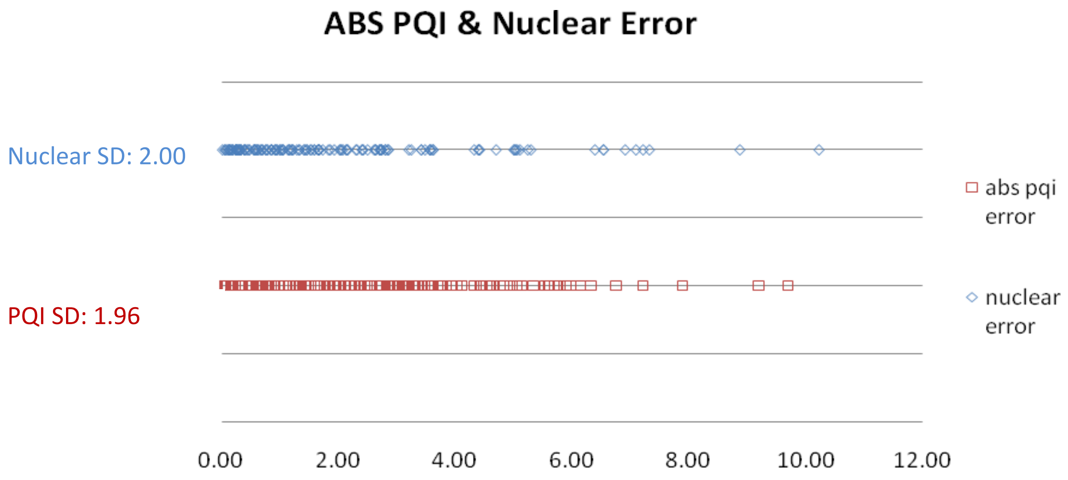

**Figure 4.7: Absolute value difference for each gauge and Core Sample**

### 4.9 Data Reliability

When comparing both the nuclear density gauge and PQI density gauge, it is important to look at not only how each gauge trends as compared to the project's benchmark points (core samples), but also an overall tolerance. The maroon portion of Figure 4.8 indicates the upper and lower boundary of the core samples' mean plus or minus one standard deviation. A clear grouping of PQI readings can be seen in Figure 4.8, whereas the nuclear gauge readings are spread more evenly throughout the one and two SD (standard deviation) boundaries.

As can be seen in Table 4.4, the PQI can be expected to fall within one standard deviation of the core sample's mean 79.86% of the time, whereas the nuclear gauge will only be as accurate 66.91% of the time. Within the accepted range of quality data, the PQI's readings within two standard deviations from the average core sample is 99.28%, while the nuclear gauge is just as accurate at 96.4%.

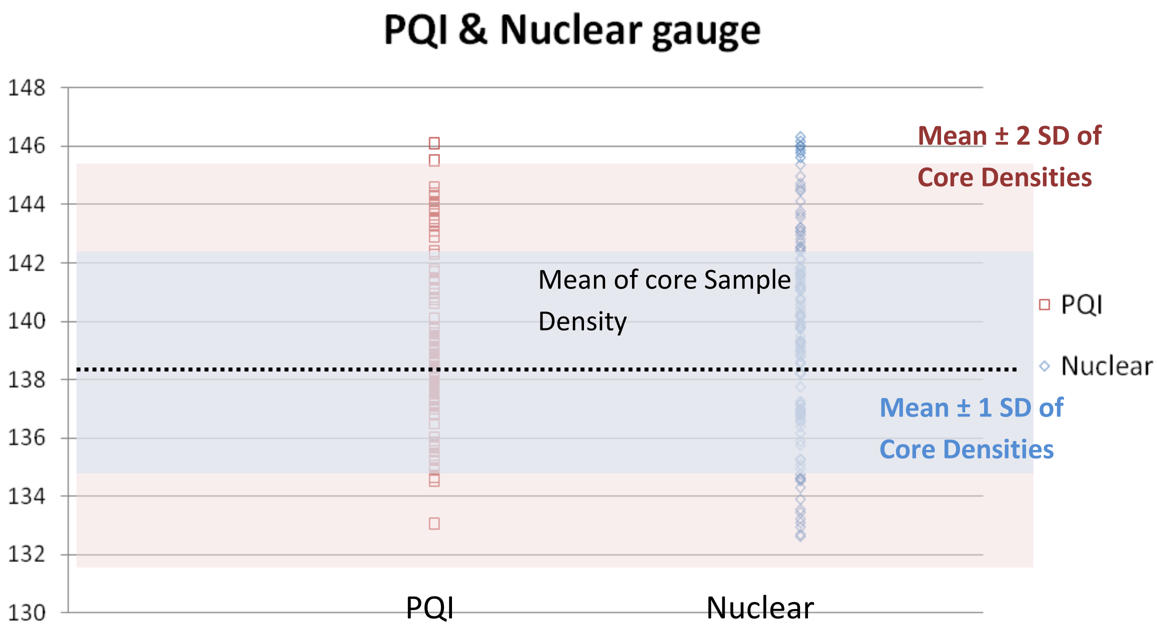

**Figure 4.8: PQI & Nuclear Gauge Data distribution**

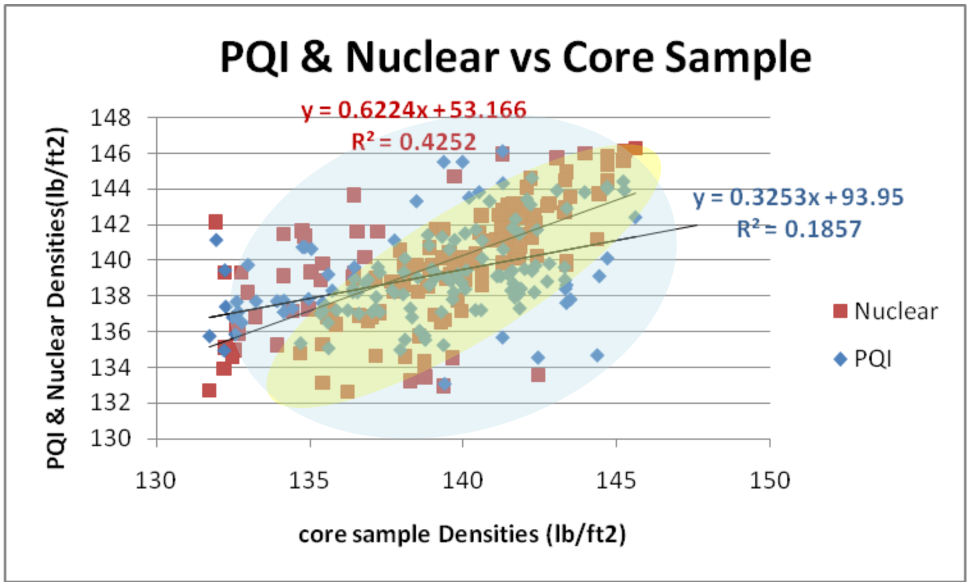

**Figure 4.8a: PQI & Nuclear Gauge Data distribution range comparison**

**Table 4.4: ± 1, 2 Standard deviation error ± Core**

| | ± 1 SD | ± 2 SD |
|---|---|---|
| PQI | 111 | 138 |

| | | |
|---|---|---|
| proportion | 79.86% | 99.28% |
| Nuclear | 93 | 134 |
| proportion | 66.91% | 96.40% |

Describing individual gauge readings as comparing to a mean of all collected benchmark data is integral to showcase very simply how both gauges perform overall, but it does not directly express to what extent each gauge reading can be trusted when comparing to its paired core sample. Table 4.5 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 MTD value (maximum theoretical density 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 Pavement Quality Indicator's previously collected readings, an average difference in density was found between the corresponding core sample and initial PQI readings. Thus, this reading range (89-93%) should be used in selecting calibration spots for PQI.

**Table 4.5: Comparison between Core Sample Density and MTD values**

| Ratio of Core sample density and the MTD (%) | Num of Sample | Percentages of the core | 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 |

In order to dissect this outcome further, Table 4.6 is referenced. This table shows specifically whether the PQI or the nuclear gauge should be trusted according to the collected data. Results indicate that when a core sample tests between 90% and 94% of the MTD for the mix, the PQI will give a very accurate comparison to traditional coring methods. In this range, 73% of all collected data for this project can be found. In other words, 73% of all collected data by the PQI can be considered accurate.

On the other hand, the nuclear gauge does not provide as convenient of a range of MTD values. According to project data, the nuclear gauge should be accepted when readings are 88 - 90% and 93% -94% of MTD values.

**Table 4. 6: Comparison between PQI or Nuclear gauges Density and MTD values**

| Ratio of PQI and Nuclear gauge density and the MTD % | No. of Sample | Difference =\|PQI-Core\| | No. of sample | 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 |

### 4.10 Verify Data Reliability

Based on the results shown in Table 4.7, 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 maximum theoretical density of the mix being used. Improvements are most significant when comparing the correlation coefficient between this range and the whole data. Correlation can be simply considered as the strength of dependency between the two variables being investigated. This indicates that improvement of correlation may be significant without consideration of collected data out of the recommended MTD range.

**Table 4.7: Comparison of correlation**

| | 89% to 93% of Core sample of MTD | | Whole data | |
|---|---|---|---|---|
| | Core vs. PQI ( 98 measurements) | Core vs. Nuclear (98 measurements) | Core vs. PQI ( 139 measurements) | Core vs. Nuclear (139 measurements) |
| Correlation | 42% | 56% | 25% | 41% |

### 4.11 Determine Number of Cores for PQI Calibration

This part investigated a new method to find out the ideal number of cores for the PQI calibration to improve 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 are investigated in this study separately.

There are two steps in this process. In the first step, the traditional method was adopted to calibrate the PQI densities. Three (or five, eight, ten) cores are chosen randomly out of all data. These three cores are used to calibrate PQI densities. The difference between the calibrated PQI densities and core densities is described as follows:

$$TD = | C1 - P2 | \quad \text{(Equation 4.3)}$$

Where,

C1—Core densities

P2 – Calibrated PQI densities

In the second step, linear regression was chosen to obtain the difference. Assume calibrated PQI densities (P2) as an independent variable and TD as the dependent variable. A linear regression equation Y= a*X + b was set up with R-square. While there are considerable combinations to choose from, only the combination with closest average R-square was adopted for further calibration. Matlab™ was used to obtain the closest average R square value in this study. 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:

$$AP = Y2 + P2 \quad \text{(Equation 4.4)}$$

$$LD = | AP - C1 | \quad \text{(Equation 4.5)}$$

Where,

AP – Adjusted PQI value

LD – linear regression calibration difference

The results are attached in the appendix; Figure 4.9 shows the TD and LD value.

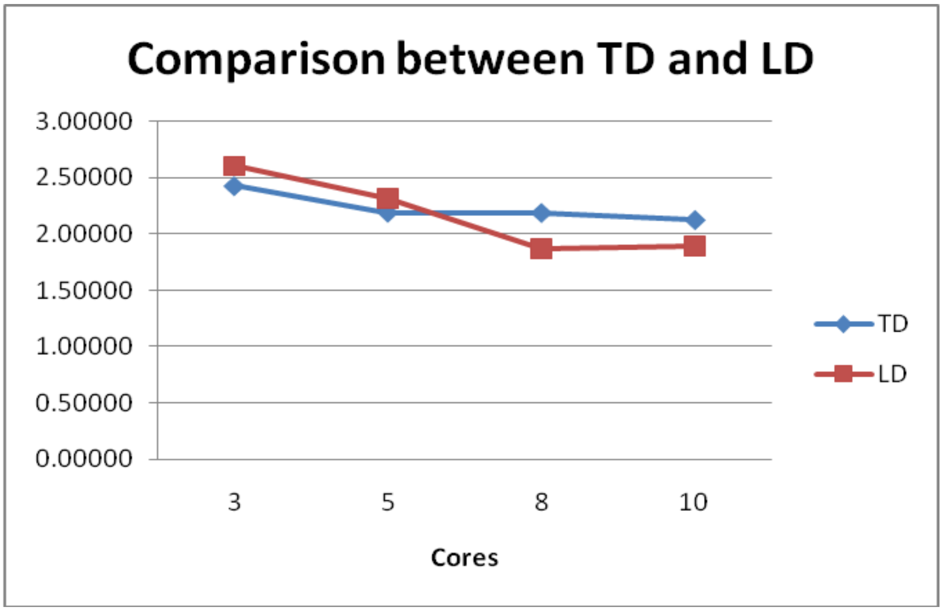

**Figure 4.9: Comparison between traditional difference and calibration difference**

As can be seen in Figure 6.9, 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.

### 4.12 Chapter Summary

In this chapter, PQI and nuclear gauges were compared based on the analysis. First, outlier and bad cores were taken out to decrease the human error factor. By using the average difference and T test, PQI and nuclear gauges were compared with cores respectively. The R-square value was investigated to find out the relationship between PQI and the core method, and nuclear gauges and the cores method. Furthermore, the consistency of both gauges was discussed by using the standard deviation and the range of the MTD value. In addition, in order to determine the number of the cores which were used in the calibration to improve the accuracy of the PQI gauge, a new calibration method was proposed.

# CHAPTER 5 ECONOMIC ANALYSIS

## 5.1 Life Cycle Costs Calculation

To compare the nuclear and non-nuclear gauge economically, a life cycle analysis is conducted between two gauges determined by their initial and annual costs. The initial prices are from retailers' quotes. Annual costs such as maintenance and non direct measurable costs were evaluated using manufacturers' recommendations (Kabassi et al, 2011). Annual maintenance and re-calibration fee is not required in this case.

Table 5.1 and Table 5.2 below summarize costs associated with the use of the PQI and the nuclear gauge.

**Table 5.1 Cost associated with owning the PQI**

| | |
|---|---|
| Cost of PQI model 301 | $8,200 |
| Annual maintenance and re-calibration | $500 |

**Table 5.2 Costs associated with owning the nuclear gauge**

| Item | Cost |
|---|---|
| Cost of nuclear gauge | $6,950 |
| Radiation safety & Certification Class | $750 |
| Safety training | $179 |
| HAZMAT certification | $99 |
| RSO training | $395 |
| Shipping | $120 |
| Radioactive Materials License | $1,600 |
| Reciprocity | $750 |
| TLD Badge monitoring | $140/year |
| Life of source capsule integrity | $15/year |
| Maintenance & Re-calibration | $500/year |
| Re-licensing | $1,500/year |

The analysis is done using the lesser of the gauges' life expectancies (15 years). The Figure 5.1 shows the cumulative costs comparison between PQI and the nuclear gauge (Kabassi et al. 2011). By applying a 10% annual percentage rate (APR), the net present value can be obtained as Table 5.3.

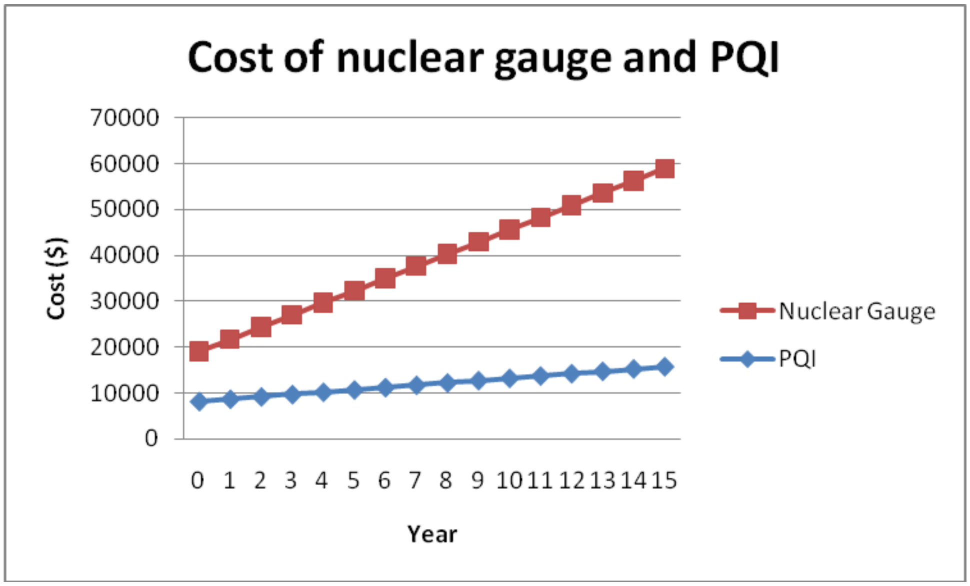

**Figure 5.1: Nuclear gauge and PQI cumulative operating costs**

**Table 5.3 Net present value of both gauges**

| | PQI | Nuclear Gauge |
|---|---|---|
| **Net present value** | **$12,003.04** | **$27,234.1** |

Figure 5.1 shows that both the initial and annual costs of PQI are lower than that of the nuclear gauge. Table 5.3 illustrates that the net present value of the nuclear gauge is more than the PQI. This indicates that PQI is more economic.

### 5.2 Chapter Summary

This chapter calculated the life costs of PQI and nuclear gauges. The life costs of the gauges consisted of their initial costs and maintenance. The net present values of both gauges were investigated; it can be concluded that nuclear gauge is more expensive than PQI.

# CHAPTER 6 CONCLUSIONS AND RECOMMENDATION

## 6.1 Conclusions

The main objective of this thesis was to find innovative ways to calibrate and improve the accuracy of non-nuclear gauges.. Five cores densities were used to calibrate the gauges for 13 sites. Outliers and bad core samples were taken out of the data pool to increase the accuracy of the results. The average difference, student T-test and coefficient of correlation were used to evaluate the precision of both gauges. Furthermore, data reliability was verified based on comparison between gauges density and MTD values, and the following conclusions were drawn:

1. Compared to PQI, nuclear gauges shows closer values to the core values according to the T-test results.
2. Generally, nuclear gauges values were more similar to the cores values as the coefficient of correlation of PQI is less than the nuclear gauge.
3. PQI is more consistent than the nuclear gauge according the analysis result of the standard deviation.
4. PQI and nuclear gauges may have an acceptable difference to core samples within a specific range of MTD values.
5. 8 cores were recommended as the ideal number for linear regression calibration for the PQI.

In addition, to improve the correlation between the gauges and core samples, the data within 89% and 93% of the MTD value was used.

Another objective of this research was to conduct a field evaluation of the effectiveness of each density test method. To achieve this, PQI, nuclear gauge and the core sampling method were selected to conduct this research. Each method was used to gain the density data for each pavement spot. 13 sites' density data were collected and evaluated to determine their effectiveness for quality assurance of HMA pavement. The core sample density measurement was conducted according to the American Association of State Highway and Transportation Officials (AASHTO) procedure AASHTO T 166. The PQI and nuclear gauge method were used in accordance with the manufacturer's manual.

The last objective of this thesis was to develop an economic study to determine the costs of each gauge. A life cycle analysis was conducted to find out the costs of both gauges. Included in the analysis were the maintenance costs and the equipments' APR. This cost comparison has shown that PQI is far more economic than the nuclear gauge.

### 6.2 Recommendations

The following recommendations are made to more effectively use the PQI:

1. Eight cores were recommended as the ideal number to calibrate.
2. Use the cores which have 89%-93% of MTD value for calibration.
3. Use PQI values over 90% of MTD value as the reliable data.
4. Use core sample to test the spots which show less than 90% of MTD value from PQI measurement.

### 6.3 Contribution

Several contributions were made from this research:

This research proposed a new method to evaluate the effectiveness of PQI that may affect the quality assurance process of road, highway, and pavements. This thesis demonstrates a methodology to improve calibration; it may be used in the future HMA pavement quality control.

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# APPENDIX

## APPENDIX A: JOBSITE DATA

### Site 1

Date: 8/28/2009

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 |

### Site 2

Date:

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 |

## Site 3

Date:

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 |

## Site 4

Date:

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 |

## Site 5

Date:

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 |

## Site 6

Date:

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 |

## Site 7

Date:

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 |

## Site 8

Date:

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 |

Site 9

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Date:

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 |

Site 10

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Date:

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 |

Site 11

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Date:

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 |

## Site 12

Date:

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 |

Site 13

Date:

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 B: Calibration results of different numbers of cores

| | | 3 cores | | | 5 cores | | | 8 cores | | | 10 cores | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NO | Date | 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 |

Where,

TD= Traditional difference

LD= Linear regression difference