Non Nuclear Method for HMA density measurements

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Density is an important part of hot-mix asphalt (HMA) pavement quality control. The long-term performance of an HMA pavement can be affected by insufficient density of the pavement. This study evaluated the Pavement Quality Indicator (PQI) model 301, which utilizes electrical impedance principles by using the current going through the pavement to determine its density and moisture content. Test data was collected in the field during pavements, and cores samples that were tested in the laboratory for further measurements. Thirteen field site visits were used to evaluate the PQI in terms of accuracy and precision. A thorough investigation of calibration methods was also performed both in the lab, and in the field to improve the accuracy of the PQI's results. Data analyses showed that the PQI's accuracy is lower than the nuclear gauge's. However, 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) minimized safety concerns, 4) no licensing and intense training courses mandated by State and Federal authorities.

Key Words: Hot mix-asphalt (HMA), nuclear gauge, non-nuclear gauge, core sample, Pavement Quality Indicator

1 Introduction

Quality Assurance (QA) of Hot Mix Asphalts (HMA) pavements was introduced in 1986 (Andrewski, 2003) to insure that some selected variables were accounted for and conformed to standards. Density measurement was a control method which consisted of comparing nuclear gauge readings with cores taken from the same area. If within acceptable limit, (usually more than 96% of average of cores density), the nuclear gauges average densities would then be adopted as the relative density of the pavement. Previously, a way to obtain accurate density readings of in-place pavement was to physically take core samples at the test location which is both destructive and time consuming. However, with the adoption of nuclear gauges as an accepted test method, came burdensome federal regulations associated with the handling, storage, and transportation of radioactive materials. Problems with destructive core sampling and the hassles of maintaining a nuclear gauge have lead many different non-nuclear technologies to be developed as an alternative to measure HMA densities in a very short period of time. 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) 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 compared to the nuclear gauge and core measurement methods. They must also be economically beneficial both in the short term and long term. The purpose of this project is to study the effectiveness of a non-nuclear device, the PQI model 301 by comparing its density readings to a Troxler 3440 nuclear gauge and the traditionally used core measurement method.

1.1 Background

Density is measured as part of the quality control process by paving contractors and for the quality assurance by local or state agencies. Core density measurement is done in accordance with the American Association of State Highway and Transportation Officials (AASHTO) procedure AASHTO T 166 (AASHTO, 2010). However, the destructive coring process creates voids 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. Nuclear gauge technology offers a faster method of in-place HMA density measurement, and has been used successfully to replace and/or complement most coring in many states. Nuclear gauges operate with the use of radioactive materials that are hazardous to the health and well being of the operators should they be exposed to the source material in an unsafe manner. Therefore, proper precautions and care need to be taken during operation. All users must have also received prior radiation safety and become aware with the 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 well maintain the gauges. Strict licensing and re-licensing, record-keeping, and proper storage and transportation procedures of the gauges all add to the complications of utilizing nuclear gauges. Consequently, there is a high demand for a device that is accurate, easy to use, fast, non-destructive, and nonradioactive. The PQI seems like an ideal alternative to overcome many or all of the problems posed by the coring method and nuclear gauges.

The main 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 and life cycle cost. This project first examined the PQI, as a possible new way to gather real-time quality control data. The traditional core sampling method was selected as the controlling standard, while 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's accuracy by developing 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.

1.2 Literature Review

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 (Rogge and Jackson, 1999). Sully-Miller Contracting Company also compared a nuclear gauge to the first model of the PQI to study the variance (Miller and Sully, 2000). Standard deviations of the PQI were much lower and different 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. The investigation concluded that the PQI was accurate enough for HMA density measurements.

Conversely, Henault evaluated the effectiveness of the PQI model 300 for quality assurance testing study (Henault, 2001). The calibration method of five average core offset was used on the 10 different sites tested. The nuclear gauge results correlated much more to the core samples, and the PQI was not recommended for quality assurance tests. 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 average core 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 a nuclear gauge. A total of twenty site visits were made and revealed that the PQI gauge had improved, but was still inferior to the nuclear gauge for density measurements (Hurley et al., 2004).

2 Methodology

2.1 Core Method

Cores need to be taken out 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 easily cut out. To facilitate the coring process, the research team used dry ice (CO2) as a method to cool down the asphalt. Dry ice cools the surface, and leaves no trace of water to help with the density measurements done on site for calibration purposes. Important care needs to be taken when drilling to prevent that additional pavement lifts are not included in the surface sample. Results could be affected if the cores are tested with excessive layers. After the cores have been drilled, their bulk specific gravity measurements are computed using the saturated surface dry method as specified in AASHTO 166 or similar (AASHTO, 2010). 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 accuracy.

2.2 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 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 (ASTM, 2010). 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.

2.3 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 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 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 is in a very close proximity (about 1 Foot).

2.4 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 reflect density values obtained by testing core samples of the same location. At the beginning, the research team calibrated 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 were next 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. 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. It should be noted 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 measures of the same property.

3 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 of the same location. Due to external variables inherent to the paving and coring process, data collected onsite 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.

3.1 Outliers

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 the findings are based is relatively small, and therefore very susceptible to data outliers. The most common cause of outlier is human error during operation of gauges; therefore it is reasonable to eliminate outliers before conducting statistical analysis. 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 1 left picture). However, 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). Outliners were taken out of the data pool to improve the results for this study.

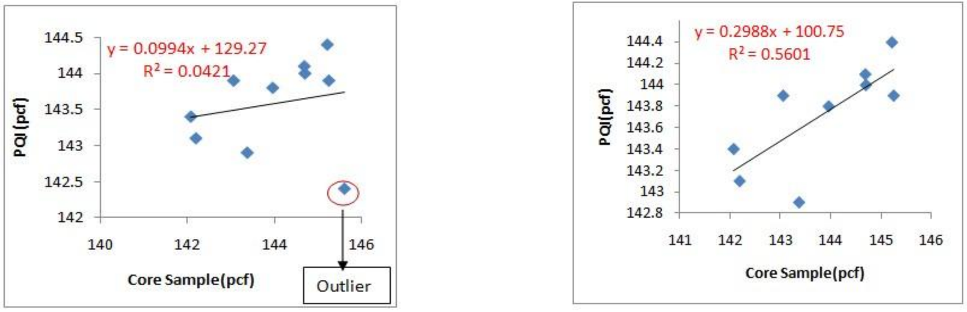

Figure 1: Before outliner on the left, and after outliners have been out on the right.

3.2 Poor Core Samples

Extreme care should be taken to avoid altering and damaging cores before and after coring. "Care should be taken to avoid distortion, bending, or cracking of specimens during and after the removal from the pavement or mold. Specimens shall be free from foreign materials such as seal coat, tack coat, foundation material, soil, paper, or foil" (AASHTO T166-05). 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. Figure 2 below illustrate what kinds of cores were accepted and rejected, based on AASHTO recommendations.

Figure 2: Example of rejected cores on the left, and an example of an accepted core on the right.

3.3 Average Difference (T-Test)

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 t-test) cannot assume that the gauge 'trend' changes in the core density. To highlight this point, Table 1 and Figure 3 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 3 shows that both gauges follow trends similar to that of the core sample densities. If these gauges were evaluated based on the average difference, the nuclear gauge would result in closer values to core samples than the PQI's.

3.4 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 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 1

Average difference and T-test results base 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		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 the cores. For the majority of the remaining sites, the nuclear gauge shows closer values to the cores according to the student t-test analysis.

3.5 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 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, this would indicate that there is significant correlation between gauge density and core density.

Table 2

Coefficient of Correlation and R-squared between both gauge density 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

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

3.6 Coefficient of Correlation R-Squared

Figure 3 indicates a weak correlation between both gauges' densities as compared to core density results; this is indicated by the low R^2 values. However, as shown in Table 2, four out of 13 sites show a 50%+ relationship between PQI density and core density. Additionally, 5 out of 13 sites indicated that there is a 50%+ relationship between nuclear gauge densities and core densities.

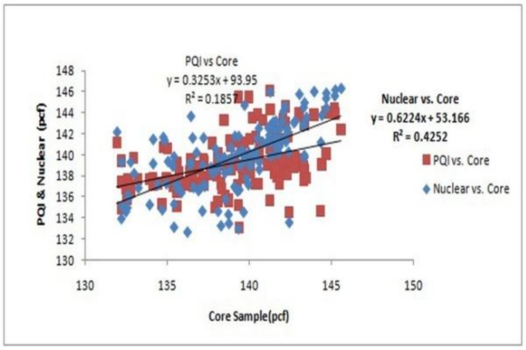

Figure 3: PQI & Nuclear Gauge relationship vs. Core Samples

3.7 Analysis

Based on the results shown in Table 1, only four sites have a t-test value greater than the t-value between PQI densities and core densities. It can be concluded that there is a 69% statistical difference between PQI densities and the core densities. As showed in Table 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 zero 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.

Based on the above results from thirteen sites and 150 total data, the density difference for the PQI is 1.89 lb/ft^3 while the nuclear gauge's difference is 1.07 lb/ft^3 compared the cores. While the nuclear gauge appears to be more correlated with cores, the PQI is not so far off. There is only a 0.81 lb/ft^3 density difference between the PQI and the nuclear gauge. On some projects, the nuclear gauge displayed measurements that were not correlated with the cores. Again, this could be due to human errors or biases ignored while cores were taken. It shows that the nuclear gauge itself is not perfect, and neither is the coring process which can be susceptible to errors. In summary, the nuclear gauge performed better than the PQI when being compared to the cores, but the gap between both gauges is minimal.

4 Economic Analysis

A life cycle cost analysis would show all the costs associated with the use of the both gauges. An economic comparison is conducted between the nuclear and non nuclear gauge. Costs to determine density measurements only using the core method are not taken into consideration. The prices used below all come from retailers' quotes. Anything else such as maintenance and non direct measurable costs were estimated using manufacturers' recommendations. The only costs associated with the PQI are the initial cost of $8,200 and the annual maintenance and re-calibration that can be estimated at $500.0. The nuclear gauge's costs however are more complex and summarized below in Table 3.

Table 3

Costs associated with owning the nuclear gauge

Item	Cost
Cost of Nuclear Gauge	$6,980
Radiation Safety & Certification Class	$750
Safety Training	$179
HAZMAT Certification	$99
RSO Training	$395
TLD badge Monitoring	$140/year
Maintenance & Re-calibration	$500/year
Leak Test	$15/year
Shipping	$120
Radioactive Materials Licensing	$1,600
Re-licensing	$1,500/year
Reciprocity	$750

The analysis is done using the lesser of the gauges' life expectancies (15 years). Without applying any rate of interest, one can visualize below in Table 4 the yearly costs that come with owning and operating both devices.

Table 4

Cost summary of operating both gauges

Year	Nuclear Gauge Costs	PQI Costs
0	$10,873	$8,200
1-15	$2,155	$500

A look at the accrued costs over 15 years can be viewed in Figure 4.

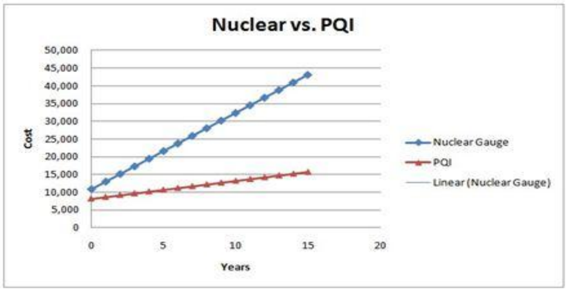

Figure 4: Nuclear gauge V. PQI cumulative operating costs

The previous figure shows that the nuclear gauge incur both higher and annual costs, and therefore make the PQI much more economical.

5 Conclusion

Intense regulations and destruction of pavement all call for a new method to measure density of HMA pavements. Like other non-nuclear gauges, the PQI offers rapid density measurement, and is much more economical than the nuclear gauge. Its effectiveness, however, in terms of accuracy in regards to the cores measurement could not be achieved. However, the PQI gauge could be a better alternative to a nuclear gauge when the economic benefits of using the PQI were considered. Also, data would be measured faster as it takes the nuclear gauge about a minute to read a point when the PQI can read it is as little as two seconds. The safety and security regulations that come with owning a nuclear gauge would not exist with the PQI that also does not require licensing and intensive trainings. The average difference between the nuclear gauge and the PQI's densities measured during the project was small and can be acceptable when one considers the other aforementioned benefits of the PQI.

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