

FINAL REPORT

FIELD CORRELATION OF PQI GAUGE WITH NUCLEAR DENSITY GAUGE: PHASE 1

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<p>Traditionally, the Oklahoma Department of Transportation (ODOT) uses a nuclear density gauge as a quality control (QC) and quality assurance (QA) tool for in-place density. The nuclear-based devices, however, tend to have problems associated with licensing, equipment handling, and storage. The Pavement Quality Indicator (PQI), manufactured by TransTech Systems, Inc., is a non-nuclear device that determines the density of an asphalt pavement layer based on the principle of electrical impedance and the dielectric constants of associated materials. To this end, field data was generated from six field projects for calibration of a PQI 301 gauge. The performance of the PQI gauge was compared with a nuclear density gauge in four field projects and was validated against laboratory densities (AASHTO T 166) measured from selected cores extracted from the pavements. It was observed that 5-point data instead of 13-point data can be used for PQI density with 95% certainty in all the cases. It is recommended from this study that PQI 301 be used before the pneumatic roller than after the finish roller. A PQI gauge calibrated with 5 cores exhibits similar performances as the PQI gauge calibrated with 10 cores. Further study is required for validation of this conclusion. It was noticeable that PQI 301 produced better coefficient of determination than the nuclear gauge if the PQI gauge is used before the pneumatic roller. Finally, mean squared error as well as R-squared value should be used for calibration purposes.</p>			
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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol	Symbol	When you know	Multiply by	To Find	Symbol
LENGTH					LENGTH				
in	inches	25.40	millimeters	mm	mm	millimeters	0.0394	inches	in
ft	feet	0.3048	meters	m	m	meters	3.281	feet	ft
yd	yards	0.9144	meters	m	m	meters	1.094	yards	yds
mi	miles	1.069	kilometers	km	km	kilometers	0.6214	miles	mi
AREA					AREA				
in ²	square inches	645.2	square millimeters	mm ²	mm ²	square millimeters	0.00155	square inches	in ²
ft ²	square feet	0.0929	square meters	m ²	m ²	square meters	10.764	square feet	ft ²
yd ²	square yards	0.8361	square meters	m ²	m ²	square meters	1.196	square yards	yd ²
ac	acres	0.4047	hectares	ha	ha	hectares	2.471	acres	ac
mi ²	square miles	2.590	square kilometers	km ²	km ²	square kilometers	0.3861	square miles	mi ²
VOLUME					VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.0338	fluid ounces	fl oz
gal	gallon	3.785	liters	L	L	liters	0.2642	gallon	gal
ft ³	cubic feet	0.0283	cubic meters	m ³	m ³	cubic meters	35.315	cubic feet	ft ³
yd ³	cubic yards	0.7645	cubic meters	m ³	m ³	cubic meters	1.308	cubic yards	yd ³
MASS					MASS				
oz	ounces	28.35	grams	g	g	grams	0.0353	ounces	oz
lb	pounds	0.4536	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.1023	short tons (2000 lb)	T
TEMPERATURE (exact)					TEMPERATURE (exact)				
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C	°C	degrees Fahrenheit	9/5(°C)+32	degrees Celsius	°F
FORCE and PRESURE or STRESS					FORCE and PRESURE or STRESS				
lbf	poundforce	4.448	Newtons	N	N	Newtons	0.2248	poundforce	lbf
lbf/in ²	poundforce per square inch	6.895	kilopascals	kPa	kPa	kilopascals	0.1450	poundforce per square inch	lbf/in ²





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Draft Final Report

Field Correlation of PQI Gauge with Nuclear Density Gauge: Phase I



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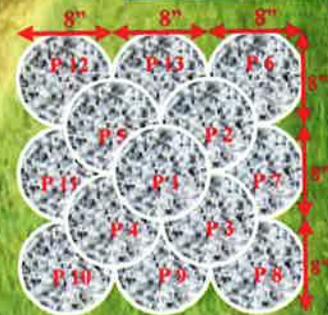
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1. Introduction

Traditionally, the Oklahoma Department of Transportation (ODOT) uses a nuclear density gauge as a quality control (QC) and quality assurance (QA) tool for in-place density. The nuclear-based devices, however, tend to have problems associated with licensing, equipment handling, and storage. The Pavement Quality Indicator (PQI), manufactured by TransTech Systems, Inc., is a non-nuclear device that determines the density of an asphalt pavement based on the principle of electrical impedance and the dielectric constants of materials (Hurley et al., 2004). The non-nuclear gauge, in this case PQI 301, offer several potential advantages: 1) nuclear licensing and training are not required; 2) there is no threat of exposing workers to radiation; 3) readings are faster than with a nuclear density gauge, almost instantaneous; and 4) they are lightweight (Hurley et al., 2004). However, the use of these devices in Oklahoma has been rather limited due to lack of data pertaining to their accuracy, repeatability, and ease of calibration in the field. To this end, field data was collected in this study from six field projects for calibration of a PQI 301 gauge. The performance of the PQI gauge was compared with a nuclear density gauge in four field projects and was validated against laboratory densities (AASHTO T 166) measured from selected cores extracted from the pavements.

2. Objectives

The specific objectives of this project are as follows:

- (1) Evaluate accuracy and repeatability of the PQI 301.
- (2) Justify current PQI 301 calibration procedure (OHD L-14) that uses 5 data points at each core location. Densities with 5 data points will be compared to densities with 13 data points.
- (3) Justify current PQI 301 calibration procedure that uses 10 cores for actual density, which is a time consuming, costly and destructive process.
- (4) Identify factors that influence the performance of the PQI 301.
- (5) Compare the performance of the PQI 301 gauge with the nuclear density gauge.



3. Prior Research

A study by the Oregon State University and the Oregon Department of Transportation reported that a PQI 100 gauge could be susceptible to moisture and temperature (Rogge and Jackson, 1999). A third generation model, PQI 300, is equipped with temperature and moisture probes to account for fluctuations in moisture and temperature and adjust the measured density accordingly. Henault (2001) reported a poor average R-squared value of 0.28 from ten on going paving projects in Connecticut using a PQI 300 gauge. Hausman and Buttlar (2002) conducted both laboratory and field tests using a PQI 300 gauge on three on-going pavement projects in Illinois and reported that a nuclear gauge exhibits better correlations than a PQI 300 gauge. It was concluded that the PQI 300 gauge has improved from earlier models, but the device is still influenced by moisture and temperature. Both the Connecticut and the Illinois studies did not recommend the PQI 300 for quality control or quality assurance purposes. Prowell and Dudley (2002) reported that the PQI 300 gauge produced fair to poor correlations with core densities from six field projects. A similar conclusion was reached by Romero and Kuhnnow (2003) from their 76 field projects using the same gauge (PQI 300). However, Sebesta et al. (2003) proposed that a PQI gauge is a suitable alternative to the nuclear gauge for density profiling and joint density testing. More recently, Hurley et al. (2004) evaluated the fourth generation Model PQI 301 and concluded that uncorrected measurements provides reasonable (an average R-squared value of 0.53) correlation with cores from 20 sites. Based on that study, the PQI 301 gauge was not recommended for quality assurance testing.

4. Method of Approach

The performance of a PQI 301 gauge was evaluated in this study using the data from six on-going projects in five Oklahoma residencies (Clinton, Duncan, Altus, Purcell and Oklahoma City). The performance of the PQI 301 gauge was compared with that of nuclear gauge in four sites. The ODOT Specification (OHD L 14) was followed for data collection. A minimum of ten cores were obtained from each site for laboratory density measurement (AASHTO T 166). At each core location 13 PQI measurements (called '*13-point data*' in this report) were obtained in four sites (see Figure 1 for the PQI gauge positions in a 2 ft-sq area) and 5 measurements (called '*5-point data*' hereafter) at the remaining two sites. At two of the





sites (Clinton and Duncan), the PQI measurements were obtained both before the pneumatic roller and after the finish roller. The sites contained three S3, two S4 and one S5 type Superpave surface and base mixes.

5. Results

Tables A.1-A.6 in APPENDIX A show all the PQI gauge density data collected from the aforementioned six sites. These tables also include pertinent averages and standard deviations. The nuclear gauge density data and AASHTO T 166 density data are also included in these tables for comparison.

6. Discussions

6.1 Calibration of PQI: Number of Data Points at Each Core Location

For each core location in Clinton, Duncan, Altus and Purcell, the *13-point PQI data* was compared with the *5-point PQI data*. A t test was performed for each core location at these four sites with the null hypothesis that the average of the *13-point PQI data* is equal to the average of the *5-point PQI data*. In all the 40 core locations at these four sites the null hypothesis that the average is equal was accepted with 95% confidence interval (for t values see Table 1). From average confidence intervals (a, b) in this table it is 95% certain that the difference between the average of the *13-point data* and the average of the *5-point data* is between -0.4 pcf and 0.5 pcf for Clinton, -0.4 pcf and 0.4 pcf for Duncan, -0.5 pcf and 0.5 pcf for Altus, and -0.5 pcf and 0.9 pcf for Purcell (see Table 1 for confidence intervals for each core location).

Coefficients of determination (R-squared value) between the average of the *13-point data* and core density, between the average of the *5-point data* and core density and between the 1-point data and core density were obtained. It can be noticed from Table 2 that coefficient of determination increases with the number of data points at each core location with the *13-point data* performing better than the *5-point data*, which is better than the 1-point data. However, R-squared values of the *5-point data* are between 0.49 and 0.86 (Table 2) at six sites. All these PQI measurements in this case were obtained before the pneumatic roller.

Coefficients of determination were also obtained for the *13-point data*, the *5-point data* and the 1-point data after the finish roller for two sites. It was found that the average of





the *5-point data* is better than the *13-point data* which is better than the *1-point data*. It could be due to the fact that *13-point data* was obtained from a 2 ft-sq area (not just over the core as seen from Figure 1). Therefore, *5-point PQI data* as used by the ODOT is recommended from this study.

6.2 Calibration of PQI: Before the Pneumatic Roller or After the Finish Roller

The individual tire arrangements of the pneumatic tire roller may cause deformations in the mat that are difficult or impossible to remove with further rolling. In this study it was found that the PQI 301 gauge performs better if the data is taken before the pneumatic roller than after the finish roller. Table 2 shows the coefficients of determination between the PQI density and the core density for all the six sites. In this study PQI density was measured before the pneumatic roller for all the six sites and after the finish roller for only two sites. A minimum R-squared value of 0.49 and a maximum of 0.86 were obtained for the *5-point data* (before the pneumatic) from these six sites. The R-squared values for the two projects with PQI density after the finish roller are 0.4 and 0.34 for the *5-point data* whereas the corresponding R-squared values before the pneumatic roller are 0.76 and 0.49, respectively for the same number of data points. Therefore, it can be concluded that PQI 301 produces much better correlation if the data is taken before the pneumatic roller. It is recommended that if PQI 301 is used for quality control or quality assurance it must be used for data before the pneumatic roller for a much higher coefficient of determination.

It is expected that the finish roller will reduce the percent air voids and increase the density. Table 3 shows that the reductions in air void are only 0.7% and 0.1%, respectively for Clinton and Duncan sites. The PQI data was calibrated with respect to the densities of the cores that are obtained after the finish roller. Therefore, one can expect a possible source of error for uneven comparison. In this study good to high coefficients of determination (between 0.49 and 0.86) were obtained in all the six sites in the case of the PQI data before the pneumatic roller. So it is highly likely that the error related to uneven comparison due to finish roller is in the nature of biasness which does not affect the coefficient of determination. On the other hand, the PQI data after the finish roller causes significant reduction in the coefficient of determination due to the deformations in the mat.



6.3 Calibration of PQI: Five Cores or Ten Cores

Coring of a newly paved road is a destructive process. In this study the calibration of the PQI was evaluated for both five cores and ten cores. Due to limited time and resource, it was not possible to calibrate the PQI gauge first and then run test reading on a different day, rather a numerical evaluation was performed, as discussed below.

For each site, five core locations were selected randomly. The PQI was calibrated based on these five cores (called '*5-core calibration*' hereafter). The least squared regression model was then validated with the *rest of the 5 core* locations of that site. Mathematically, 252 combinations of 5 core locations were possible for each site. In this study six combinations (1-5, 2-6, 3-7, 4-8, 5-9, and 6-10) of five core locations from each site were selected and the PQI was calibrated for each combination and then was validated with corresponding *rest of the 5 cores* locations. Table 4 shows the results of this analysis.

The R-squared values from the 10 core locations (called '*10-core calibration*' in this report) were compared with the average R-squared values (6 combinations) of the *5-core calibration* for each of the four sites. It can be noticed that the average R-squared value of the *5-core calibration* increased for two sites and also reduced for two sites than the corresponding R-squared values from *10-core calibration*. Therefore, no conclusion can be drawn on whether the *5-core calibration* is better than the *10-core calibration* or not. However, it is noticeable that the two sites that have higher R-squared values with *10-core calibration* exhibited an increase in average R-squared values with *5-core calibration* and the two sites that have lower R-squared values with *10-core calibration* have produced a reduction in average R-squared values for *5-core calibration*.

The *10-core calibration* and *5-core calibration* were compared with respect to the mean squared error of the least squared regression model. It was found that the average mean squared error of the *5-core calibration* is lower than the mean squared error than that of the *10-core calibration* for all the four sites. Therefore, the *5-core calibration* performed better than the *10-core calibration* with respect to the mean squared error.

Each of the six *5-core calibration* regression model from each site was validated with the rest of the 5 cores as follows. The actual PQI density of the rest of the 5 cores (the 5 cores that were not used in the *5-core calibration* will be called '*rest of the 5 cores*' hereafter) was calibrated using the corresponding regression model (called '*calibrated PQI density*'





hereafter). The calibrated PQI density of the *rest of the 5 cores* was then compared with actual laboratory core density. It was observed that the average mean squared errors (for six combinations) based on the difference between the calibrated PQI density (*rest of the 5 cores*) and laboratory core density are between 0.51 and 2.97 for all the four sites. It was also observed that the average (of 6 combinations) mean squared errors between the calibrated PQI density (*rest of the 5 cores*) and laboratory core density have increased from the average mean squared errors between the calibrated PQI density (5 cores used for calibration) and actual laboratory density.

A better understanding of the performance of the *5-core calibration* is possible using confidence interval. It was observed that for the Purcell site, 28 actual laboratory core densities out of 30 (6 combinations X *rest of the 5 cores*) densities fall within the 95% confidence interval (2 times standard error) of the *5-core calibration* regression model. This is in complying with the *5-core calibration* average R-squared value of 0.91 and *10-core calibration* R-squared value of 0.86 for this site. In the case of the Altus site, the *5-core calibration* average R-squared value and the *10-core calibration* R-squared values are 0.46 and 0.65, respectively. This site exhibited lowest number of actual laboratory core densities within 95% confidence interval (24 out of 30 densities).

The paired t test was performed based on the null hypothesis that there is no difference between the corrected PQI density of the *rest of the 5 cores* and the actual laboratory core density. In the cases of Purcell and Duncan sites, the *5-core calibration* method performed very well. It is 95% certain that there is no difference between the corrected (*rest of the 5 cores*) and actual laboratory density in all of the six combinations for these two sites. The other way to say this is that the difference between the corrected and actual density in these cases will be within 95% confidence interval. It is important to note that in Duncan site, the R-squared values for both the *10-core calibration* and *5-core calibration* are the lowest among the four sites. But still this site performed very well for correction. This is also reflected in the mean squared error value. In summary, it can be reported from this study that *5-core calibration* method performs well but a further study is recommended. Also, it is highly recommended that mean squared error also be considered along with the R-squared value.



6.4 Comparison between PQI Density and Nuclear Density

The principal objective of this study is to evaluate a PQI 301 gauge against the nuclear gauge. Table 5 shows a comparison between the PQI 301 gauge and the nuclear gauge with respect to R-squared value, mean squared error, t test of the slope of the least squared line and 95% confidence interval.

Based on the R-squared value between the PQI density (before pneumatic roller) and core density and between nuclear density (before pneumatic roller in two sites and after finish roller for two sites) and core density, it was observed that PQI performs better than the nuclear gauge in three sites out of four sites. Most importantly PQI produced high values of coefficients of determination with a minimum of 0.49 and an extremely high average of 0.73 from six sites. Therefore, it is highly recommended that PQI be used before the pneumatic roller. In two sites, PQI densities were obtained after the finish roller. One of these two sites produced equal R-squared value of 0.34 and in the other nuclear gauge performed better than the PQI 301.

Mean squared error is an important statistical indicator. After the least squared line is obtained mean squared error shows the fitting. Table 5 shows that the performance of the PQI 301 and the nuclear gauge are similarly predicted by the mean squared error as the R-squared value. The significance of the use of the mean squared error lies elsewhere. If we consider the R-squared values of the PQI 301 from six sites before the pneumatic roller we find that OKC (NC-Intermediate) produced the highest R-squared value of 0.86 and Duncan exhibited the lowest R-squared value of 0.49. Conversely, analysis with the mean squared error showed that OKC (NC-Intermediate) produced the highest mean squared error of 0.96 and Duncan exhibited the lowest mean squared error of 0.29. The same is true for nuclear R-squared values and PQI 301 (after the finish roller) R-squared values. Therefore, R-squared as well as mean squared value should be considered during calibration.

Table 5 shows the individual and average 95% confidence intervals. Based on the average confidence intervals it is 95% certain that PQI densities (before the pneumatic roller) will be within ± 1.4 pcf of the calibrated PQI density. The intervals are ± 1.6 pcf and ± 1.9 pcf for calibrated nuclear gauge and calibrated PQI 301 (after the finish roller), respectively. It is noticeable that though the OKC (NC-Intermediate) and OKC (NC-Top) produced R-squared values of 0.86 and 0.76, respectively, their 95% confidence intervals are ± 2.1 pcf and ± 2.0 ,



pcf, respectively. The high R-squared values of these two sites are due to the higher differences in maximum and minimum percent air voids in the cores (6.1% and 4.5%, respectively).

The t test was performed in each case with the null hypothesis that the slope is zero. Accepting the null hypothesis would prove that the relationship is not true and R-squared value is just a coincident or a numerical value with no significance. It was observed that all the PQI regression models (before the pneumatic roller) rejected the null hypothesis at a 5% significance level. In the case of the nuclear regression models, the site with the lowest R-squared value (0.34) was proved to have zero slope. For PQI models (after the finish roller), both the sites exhibited zero slope even after having R-squared values of 0.4 and 0.34. However, emphasis should be given on mean squared values as both the R-squared values and t test are dependent on the slope while mean squared error is calculated over the regression line. In addition to these data Table 5 shows some mix design parameters of insignificant or no influence.

7. Comparison with Prior Research

Using PQI 300 Romero and Kuhnaw (2003) observed coefficient of determination less than 0.36 in 47 percent of the cases and greater than 0.72 in 22 percent of the cases. Comparatively, the nuclear gauge produced R-squared values less than 0.36 in 24 percent of the cases and greater than 0.72 in 46 percent of the cases. Hurley et al. (2004) used PQI 301 and produced R-squared values less than 0.36 in 25 percent of the cases and greater than 0.72 in 35 percent of the cases. In this study, PQI 301 exhibited R-squared values less than 0.36 in zero percent of the cases and greater than 0.72 in 67 percent of the cases (considering PQI density before the pneumatic roller in six sites). Comparatively, nuclear gauge produced R-squared value less than 0.36 in 25 percent of the cases and greater than 0.72 in 50 percent of the cases (considering densities before the pneumatic roller in two sites and after the finish roller in two sites).

8. Conclusions and Recommendations

The following conclusions and recommendations can be drawn from this project.





(1) 5-point data instead of 13-point data can be used for PQI density in the four sites with 95% certainty that their average is equal.

(2) PQI data produce much better correlation if the PQI is used before the pneumatic roller (average R-squared value of 0.73 for six sites) than after the finish roller (average R-squared value of 0.37).

(3) PQI can be calibrated with 5 cores with similar performance as the 10 cores. However, further study is required in this case.

(4) PQI 301 produces better coefficient of determination (average R-squared value of 0.73 for six sites) than the nuclear gauge (average R-squared value of 0.6 for two sites before pneumatic and two sites after finish roller) if PQI 301 is used before the pneumatic roller.

(5) Mean squared error as well as R-squared value should be used for calibration purposes. The lowest R-squared value in PQI measurement is 0.49 for Duncan site whereas, the mean squared error for the site is only 0.29. Conversely, the highest R-squared error is 0.86 for OKC (NC-Int.) which produces a mean squared error of 0.96. It was found that the very high R-squared value for this site is due to the larger difference in maximum and minimum air void percent (6.1%) than the Duncan site (1.6%).

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Table 1 Comparison between 5-Point data and 13-Point data with t Test

Clinton (Density in pcf)										
Core No.	1	2	3	4	5	6	7	8	9	10
5-point data avg.	136.6	136.1	135.7	134.7	135.8	136.1	136.5	135.7	135.9	137.2
13-point data avg.	136.3	135.9	135.8	134.7	135.7	136.1	136.4	135.9	136.0	137.1
t	1.14	1.01	-0.35	0.03	0.33	0.43	0.22	-0.54	-0.37	0.60
t(critical), +/-	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12
Conf. a	0.79	0.59	0.31	0.59	0.31	0.21	0.37	0.55	0.36	0.47
Conf. b	-0.24	-0.21	-0.43	-0.57	-0.22	-0.14	-0.30	-0.93	-0.51	-0.26
Duncan (Density in pcf)										
Core No.	1	2	3	4	5	6	7	8	9	10
5-point data avg.	138.1	137.5	135.9	137.4	135.9	136.9	136.3	137.7	136.5	137.5
13-point data avg.	138.2	137.6	135.8	137.4	136.1	137.0	136.5	137.3	136.5	137.4
t	-0.40	-0.52	0.24	0.39	-0.77	-0.32	-0.70	1.46	-0.48	1.12
t(critical), +/-	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12
Conf. a	0.26	0.21	0.68	0.43	0.35	0.47	0.31	0.94	0.16	0.42
Conf. b	-0.38	-0.34	-0.54	-0.29	-0.76	-0.63	-0.62	-0.17	-0.26	-0.13
Altus (Density in pcf)										
Core No.	1	2	3	4	5	6	7	8	9	10
5-point data avg.	131.5	132.1	132.2	131.9	133.2	133.1	133.6	133.9	134.2	132.9
13-point data avg.	131.6	132.1	132.2	132.0	133.1	133.2	133.4	133.8	134.0	133.2
t	-0.15	0.14	-0.20	-0.15	0.62	-0.24	0.69	1.16	0.81	-1.46
t(critical), +/-	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12
Conf. a	0.47	0.63	0.43	1.16	0.33	0.55	0.78	0.36	0.51	0.13
Conf. b	-0.55	-0.55	-0.52	-1.35	-0.18	-0.70	-0.40	-0.11	-0.23	-0.70
Purcell (Density in pcf)										
Core No.	1	2	3	4	5	6	7	8	9	10
5-point data avg.	141.3	142.3	138.9	140.2	141.2	140.8	141.4	141.0	141.0	140.7
13-point data avg.	141.1	142.0	138.5	139.9	140.8	140.9	141.4	141.0	140.8	140.2
t	0.51	0.55	1.35	0.62	0.97	-0.39	0.05	0.13	1.06	1.26
t(critical), +/-	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12
Conf. a	0.65	1.45	1.25	1.21	1.22	0.39	0.50	0.69	0.58	1.33
Conf. b	-0.40	-0.85	-0.28	-0.66	-0.45	-0.57	-0.48	-0.61	-0.19	-0.34





Table 2 Comparison between the R-Squared Values of 13-Point data, 5-Point data and 1-Point Data

R-Squared Value (Before the Pneumatic Roller)			
Site	13-Point Data	5-Point Data	1-Point Data
Clinton		0.76	0.59
Duncan		0.49	0.37
Altus	0.7	0.65	0.65
Purcell	0.92	0.86	0.83
OKC (NC-Intermediate)		0.74	0.63
OKC (NC-Top)		0.86	0.75
R-Squared Value (After the Finish Roller)			
Site	13-Point Data	5-Point Data	1-Point Data
Clinton	0.38	0.40	0.33
Duncan	0.28	0.34	0.17

Table 3 Comparison of Percent Air Voids before the Pneumatic Roller and After the Finish Roller

Core No.	Clinton (Percent Air Voids)			Duncan (Percent Air Voids)		
	Nuclear	PQI (Before the Pneumatic R.)	PQI (After the Finish R.)	Nuclear	PQI (Before the Pneumatic R.)	PQI (After the Finish R.)
1	6.0	11.4	10.8	6.0	10.0	9.4
2	7.1	12.2	11.1	7.0	10.3	9.8
3	6.4	12.0	11.4	6.7	10.3	10.9
4	9.1	12.8	12.0	6.1	10.1	9.9
5	7.0	11.9	11.3	6.9	10.5	10.9
6	7.7	12.1	11.1	7.0	10.9	10.2
7	6.0	11.6	10.9	7.6	10.4	10.6
8	7.6	12.0	11.4	6.5	9.8	9.7
9	6.9	11.8	11.2	7.5	10.9	10.5
10	7.3	11.6	10.4	6.8	10.3	9.8
Avg.	7.1	11.9	11.2	6.8	10.3	10.2
St. Dv.	0.9	0.4	0.4	0.5	0.4	0.5

Table 4 Comparison between the 5-Core Calibration (PQI) and 10-Core Calibration (PQI)

Site	10-Core Calibration			5-Core Calibration			Corrected for Rest of the 5 Cores			
	R-Sq.	MSE	95% Conf. Int.	Avg. R-Sq.	Avg. MSE	Avg. 95% C. Int	Avg. MSE	Avg. 95% C. Int	Within 95% C. Int	Paired t Test for 6 Combinations (No Difference between Calibrated PQI and Core Density)
Clinton	0.76	0.44	1.48	0.86	0.20	1.11	1.17	1.62	26/30	4 out of 6
Duncan	0.49	0.29	1.20	0.39	0.26	1.30	0.51	0.98	25/30	6 out of 6
Altus	0.65	0.90	2.13	0.46	0.45	1.51	2.97	2.38	24/30	5 out of 6
Purcell	0.86	0.19	0.98	0.91	0.06	0.58	0.86	1.13	28/30	6 out of 6



Table 5 Comparison between the Performance of the PQI 301 and the Nuclear Gauge

PQI (Before Pneumatic Roller)							
	R-Sq.	Significant (5%)	95% Conf. Int. (+/- pcf)	MSE			
Clinton	0.76	Yes	1.5	0.44			
Duncan	0.49	Yes	1.2	0.29			
Altus	0.65	Yes	2.1	0.90			
Purcell	0.86	Yes	1.0	0.19			
OKC (NC-Int.)	0.86	Yes	2.1	0.96			
OKC (NC-Top)	0.74	Yes	2.0	0.84			
Nuclear (Before Pneumatic (BP) and After Finish (AF) Roller)							
	R-Sq.	Significant (5%)	95% Conf. Int. (+/- pcf)	MSE			
Clinton	0.58 (AF)	Yes	2.0	0.76			
Duncan	0.34 (AF)	No	1.4	0.37			
Altus	0.73 (BP)	Yes	1.9	0.69			
Purcell	0.8 (BP)	Yes	1.2	0.27			
PQI (After Finish Roller)							
	R-Sq.	Significant (5%)	95% Conf. Int. (+/- pcf)	MSE			
Clinton	0.4	No	2.3	1.09			
Duncan	0.34	No	1.4	0.37			
Important Mix Properties							
	Mix Type	% AC	Binder Type	Measure. Temp. (°F)	Thickness, inch	Max.-Min. Air Void (%)	Mineral Filler (%)
Clinton	s4	4.7	PG64-22	160	1.5	3.2	4.1
Duncan	s5	5.8	PG64-22	185	1.75	1.6	6.1
Altus	s3	4.4	PG76-28	140	3	3.4	5.4
Purcell	s4	4.6	PG70-28	175	2	2.5	2.9
NC-Int	s3	4.3	PG 64-22	130	3	6.1	3.7
NC-Top	s3	4.3	PG 64-22	130	3	4.5	3.7

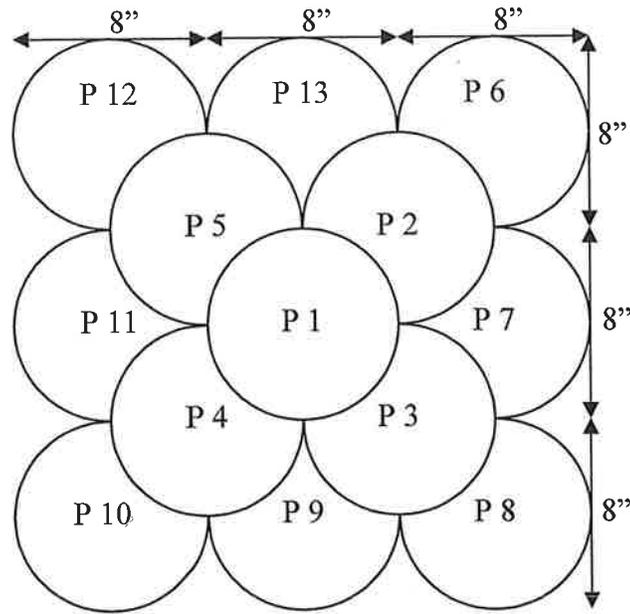


Figure 1 Positions of the PQI Readings

APPENDIX A

Table A.1 PQI, Nuclear and AASHTO T 166 Density Data for Clinton Site

PQI Readings Before Pneumatic Roller (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	135.8	134	134.4	133.3	134.5	134.7	135	134.7	134.4	134.7
2	136.2	134.5	135	133.3	134.8	134.1	135.5	135.2	135.2	135.4
3	135.5	134.1	134.9	133.6	134.9	134	135.4	135.2	135	135.5
4	135.4	135.1	134.7	133.5	135.1	134.8	135.5	134.7	135.4	135.7
5	135.5	134.7	135.1	133.9	135	135.2	135.4	134.1	135.5	
Average	135.7	134.5	134.8	133.5	134.9	134.6	135.4	134.8	135.1	135.3
Std. Dev.	0.33	0.45	0.28	0.25	0.23	0.50	0.21	0.45	0.44	0.43
Nuclear Readings After Finish Roller (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	144.4	141.2	140	136.7	143	140.3	144.3	138.1	143.2	142.5
2	143.6	142.1	135.6	134.2	141.6	143	145.8	140	146.2	143.2
3	143.3	138.7	141.4	134.4	141.1	143.3	144.3	135.8	140.7	142
4	142.1	141.8	138.1	133.8	142.5	142.5	146	140.3	141.6	141.8
Average	143.4	141.0	138.8	134.8	142.1	142.3	145.1	138.6	142.9	142.4
Std. Dev.	0.95	1.55	2.51	1.31	0.86	1.36	0.93	2.08	2.42	0.62
PQI Readings After Finish Roller (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	136.9	136.3	135.3	134.6	135.5	136.2	136.3	135.6	135.5	136.9
2	136.7	136.4	135.6	134.9	135.6	135.9	136.3	135.7	135.8	137.3
3	136.9	135.9	135.9	135.3	135.7	136.2	136.4	136.6	135.6	137.7
4	136.5	136.2	135.9	134.2	136	136.1	136.8	135.6	136.5	137.1
5	136.1	135.5	135.8	134.7	136.1	136.2	136.6	134.9	136.3	136.9
6	136.6	135.4	136.3	135.5	135.7	136.3	135.7	136.7	135.7	137.5
7	136.8	135.7	136	135.6	135.3	136	136.3	137.1	136.2	137.3
8	136.8	135.9	135.7	134.6	135.8	136.2	136.1	136.5	135.4	136.8
9	136	135.7	135.7	134.9	135.8	136	136.4	136	136.3	137.1
10	135.9	135.9	136.1	133.6	135.6	136	136.7	135.7	136.3	136.8
11	135.6	135.5	135.8	134.3	135.7	135.7	136.8	134.9	136.3	136.5
12	135.5	135.5	135.9	134.9	136.1	136.1	136.6	135.3	136.3	136.9
13	136.2	136.4	134.9	134.4	135.7	136.2	136.8	135.7	136	137.2
Average	136.3	135.9	135.8	134.7	135.7	136.1	136.4	135.9	136.0	137.1
Std. Dev.	0.49	0.36	0.35	0.55	0.23	0.16	0.32	0.68	0.37	0.32
AASHTO T 166 (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	144.0	142.3	143.3	139.1	142.4	141.4	143.9	141.6	142.6	142.0





Table A.2 PQI, Nuclear and AASHTO T 166 Density Data for Duncan Site

PQI Readings Before Pneumatic Roller (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	136.9	136.9	136.7	137.1	136.1	136.2	136.6	137.6	135.3	136.4
2	137.6	137.1	136.6	137.3	137.1	135.8	136.8	137.8	136	137.1
3	137.5	136.6	136.6	137.2	136.2	135.2	137	137.4	135.4	136.9
4	137.2	136.8	137.1	136.7	136.1	136.1	136.2	137.2	136.4	136.8
5		136.8	137.1	137.3	137	136	136.4	137.4	136.2	137
Average	137.3	136.8	136.8	137.1	136.5	135.9	136.6	137.5	135.9	136.8
Std. Dev.	0.32	0.18	0.26	0.25	0.50	0.40	0.32	0.23	0.49	0.27
Nuclear Readings After Finish Roller (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	145.1	145.5	143.5	146.9	143.6	145.1	143.7	145.1	143.6	144.5
2	143.9	145.2	140.1	146.1	144	143.3	143.5	144.9	142.5	144.9
3	145.2	146.6	143.1	144.6	143.4	144.8	142.7	146	142.8	145.4
4	146.6	146.6	143.9	145.9	142.5	146.1	142.3	144.7	142.8	145
Average	145.2	146.0	142.7	145.9	143.4	144.8	143.1	145.2	142.9	145.0
Std. Dev.	1.10	0.73	1.73	0.95	0.63	1.16	0.66	0.57	0.47	0.37
PQI Readings After Finish Roller (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	138.1	137.6	135.6	137.2	135.9	137.5	136.7	138	136.3	137.6
2	138.4	137.8	136.1	137.8	136.5	137.4	136.4	137.7	136.4	137.7
3	138.2	137.6	136.2	137.7	136.1	137.2	136.4	137.7	136.6	137.4
4	138.2	137.3	136	137	135.6	136.2	136.6	137.5	136.6	137.2
5	137.8	137.4	135.6		135.5	136.4	135.4	137.7	136.4	137.6
6	138.4	137.9	136.9	137.2	136.4	137.5	136.4	136.7	136.2	137.2
7	138.2	137.6	136.9	137.4	137.2	137.4	136	137.8	136.4	137.1
8	138.6	137.9	135.7	137.9	136.8	137.2	136.5	137.6	136.7	137.4
9	137.7	137.2	135.8	137.4	136.5	137.3	136.7	136.5	136.6	137.5
10	138.4	137.5	134.7	137.2	135.9	136.4	136.7	136.6	137	137.3
11	138.6	137.4	135.2	137	135.5	136.7	136.8	136.5	136.4	137.4
12	138.3	138.1	135.4	137.3	135.7	137	136.7	137.2	136.6	137.5
13	137.7	137.6	135.7	137.2	136	137.1	136.6	137.9	136.4	136.7
Average	138.2	137.6	135.8	137.4	136.1	137.0	136.5	137.3	136.5	137.4
Std. Dev.	0.31	0.26	0.61	0.30	0.53	0.45	0.38	0.57	0.21	0.26
AASHTO T 166 (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	143.3	141.8	142.3	143.3	142.0	141.9	140.9	142.5	141.1	142.2





Table A.3 PQI, Nuclear and AASHTO T 166 Density Data for Altus Site

PQI Readings Before Pneumatic Roller (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	131.9	132.5	132.7	132.5	133	133.8	133.6	134.2	134.5	133.4
2	132.3	132.5	132.4	130.7	133.4	132.1	133.5	133.6	134.1	132.8
3	130.9	132.3	132.2	130.5	133.5	133.4	133.6	133.9	133.7	132.5
4	131.5	132	131.8	133.1	133.2	133	133.7	133.9	134.2	133.2
5	131.1	131.4	131.9	132.9	133	133.3	133.4	134	134.4	132.7
6	132	131	133	131.3	133.1	132.8	133	133.5	133.9	133.1
7	131.9	132.3	132.7	131.4	133.3	133.2	131.7	133.5	134.2	133.8
8	131.9	131.5	132.8	132.1	133.2	132.9	133.1	133.8	133.5	133.4
9	131.1	132.8	132.2	132.9	133.2	133.5	134.2	133.6	133.5	133.3
10	131.3	131.9	131.7	133.3	133.3	134.1	133.6	133.9	133.8	133.4
11	131.6	132	131.6	133	132.8	133.5	133.9	133.9	134	133
12	131.6	132.2	132.1	130.2	133.2	132.5	133	133.7	134.3	133.5
13	131.4	132.9	132.1	132.5	132.7	133.4	133.5	133.8	134.4	133.6
Average	131.6	132.1	132.2	132.0	133.1	133.2	133.4	133.8	134.0	133.2
Std. Dev.	0.41	0.55	0.45	1.08	0.23	0.53	0.61	0.21	0.34	0.38
Nuclear Readings After Finish Roller (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	133.4	138.2	138.3	138.2	137.6	140	140.3	142.6	142.2	138.6
2	135.2	137.8	137.6	136.9	141.8	141	140.9	142.3	141.5	137.8
3	135.9	137.4	139.3	133.8	141.1	138.4	142.1	143	142.7	139.1
4	129.9	138.4	137.9	137.9	139.9	142.1	140.8	142.5	142.8	142.4
Average	133.6	138.0	138.3	136.7	140.1	140.4	141.0	142.6	142.3	139.5
Std. Dev.	2.68	0.44	0.74	2.01	1.84	1.57	0.76	0.29	0.59	2.02
AASHTO T 166 (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	139.5	142.9	140.6	142.5	143.5	144.0	143.9	144.6	144.0	144.4



Table A.4 PQI, Nuclear and AASHTO T 166 Density Data for Purcell Site

PQI Readings Before Pneumatic Roller (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	141.8	142.7	139		141	140.9	141.6	141.1	140.8	140.5
2	141.1	142.1	138.8	140.1	141.4	140.9	141.8	141.3	141.1	140.6
3	140.7	142	139.4	139.9	141.1	140.8	141.3	141.9	140.7	140
4	141.6	142.2	138.2	140.6	141	141	140.7	140.4	141	141.3
5	141.1	142.3	139.3	140.1	141.3	140.5	141.7	140.5	141.4	141
6	141	144.2	138.4	140.1	140.6	140.6	141.7	140.8	140.7	139
7	141.4	142.4	137.6	138.2	139.2	140	140.9	141.2	141.1	138.5
8	140.2	141	138.1	138.8	141.1	141.5	140.8	140.3	140.1	140.2
9	141.3	141.3	139.1	139.2	141.7	141.3	141.4	142	141.2	140.2
10		139.1	137	139.2	140.2	141.2	141	140.8	140.7	139.3
11	141.8	142.4	137.5	141.7	139.1	141.3	142.1	141.1	140.4	140.6
12	140.8	142.6	138.9	140.9	141.6	140.2	141.8	141.4	140.9	140.9
13	140.8	141.2	138.6	140		141.6	141.5	140.2	140.4	140.3
Average	141.1	142.0	138.5	139.9	140.8	140.9	141.4	141.0	140.8	140.2
Std. Dev.	0.48	1.18	0.74	0.95	0.86	0.49	0.44	0.57	0.36	0.81
Nuclear Readings After Finish Roller (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	143.9	145.6	141.7	142.8	145.2	145	145.9	146.4	145.5	144.1
2	143.8	145.5	139.1	144.5	145.7	146.7	145.4	146.6	145.8	143.9
3	145.2	147.4	140.8	143.7	145.8	143.9	146.9	146.7	144.3	145.3
4	145.4	146.4	138.5	144.5	143.7	144.9	146.7	145.4	144.8	144.3
5	144	146.1	139.4	141.2						
Average	144.5	146.2	139.9	143.3	145.1	145.1	146.2	146.3	145.1	144.4
Std. Dev.	0.77	0.76	1.31	1.39	0.97	1.16	0.70	0.60	0.68	0.62
AASHTO T 166 (pcf)										
Position	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	Core 10
1	144.1	144.4	140.6	142.0	143.6	143.2	144.2	143.8	143.7	141.9

Table A.5 PQI, Nuclear and AASHTO T 166 Density Data for OKC (NC-Intermediate) Site

PQI Readings Before Pneumatic Roller (pcf)								AASHTO T 166	
Position	1	2	3	4	5	Average	Std. Dev.	Position	1
Core 1	142.0	141.2	138.2	141.7	142.0	141.0	1.6	Core 1	139.0
Core 2	145.1	144.3	145.6	143.7	144.9	144.7	0.7	Core 2	142.9
Core 3	145.4	146.0	145.9	147.0	146.2	146.1	0.6	Core 3	147.7
Core 4	145.0	147.0	146.9	144.4	144.3	145.5	1.3	Core 4	144.3
Core 5	148.4	146.9	147.2	148.2	148.2	147.8	0.7	Core 5	146.3
Core 6	143.5	145.1	143.9	138.7	139.4	142.1	2.9	Core 6	140.4
Core 7	148.5	147.2	147.5	147.9	149.3	148.1	0.8	Core 7	146.7
Core 8	147.3	148.4	147.0	143.4	148.1	146.8	2.0	Core 8	145.8
Core 9	147.7	146.5	146.5	146.2	146.5	146.7	0.6	Core 9	146.0
Core 10	149.2	146.9	146.6	149.6	149.0	148.3	1.4	Core 10	148.5
Core 11	147.0	147.9	147.5	147.3	147.4	147.4	0.3	Core 11	146.7
Core 12	146.6	146.7	145.8	146.9	147.1	146.6	0.5	Core 12	144.9
Core 13	148.2	147.8	147.9	148.4	148.0	148.1	0.2	Core 13	147.5
Core 14	146.6	146.0	146.3	145.6	147.7	146.4	0.8	Core 14	143.4
Core 15	145.5	144.0	144.3	146.0	147.0	145.4	1.2	Core 15	143.0
Core 16	142.6	142.8	144.7	142.7	143.9	143.3	0.9	Core 16	142.2

Table A.6 PQI, Nuclear and AASHTO T 166 Density Data for OKC (NC-Top) Site

PQI Readings Before Pneumatic Roller (pcf)								AASHTO T 166	
Position	1	2	3	4	5	Average	Std. Dev.	Position	1
Core 2	143.1	141.6	142.3	143.5	143.2	142.7	0.8	Core 1	148.2
Core 3	142.5	142.5	142.9	143.3	142.8	142.8	0.3	Core 2	147.1
Core 4	141.8	140.5	140.3	141.8	140.3	140.9	0.8	Core 3	143.2
Core 5	141.7	142.5	142	142.6	143.3	142.4	0.6	Core 4	144.8
Core 6	143.3	142.7	142.8	143	143.3	143.0	0.3	Core 5	148
Core 7	142.9	142.8	142.6	142.4	142.7	142.7	0.2	Core 6	147.9
Core 8	142.2	142.6	142	142.2	142.2	142.2	0.2	Core 7	147.1
Core 9	142.3	141	141.4	142	142.2	141.8	0.6	Core 8	146.4
Core 10	141.2	141.7	141.2	142.5	141.9	141.7	0.5	Core 9	144.5
Core 11	141.3	141.9	141.7	141.6	141.9	141.7	0.2	Core 10	145.8
Core 12	142	140.6	142.4	140.8	141.1	141.4	0.8	Core 11	146
Core 13	141.6	141.3	141.8	141.5	141.6	141.6	0.2	Core 12	146.6
Core 14	141.6	141.7	142	141.5	141.1	141.6	0.3	Core 13	146.1
Core 15	142.6	141.8	141.8	141.2	142.7	142.0	0.6	Core 14	145.5
Core 16	141.4	142.8	142.1	141.3	141.9	141.9	0.6	Core 15	147.2
Core 17	142.2	142.4	142.2	142.5	142.9	142.4	0.3	Core 16	148.1
Core 19	140.8	141.4	141.7	141.6	140.8	141.3	0.4	Core 17	144.1
Core 20	139.9	140.6	139.6	139.9	139.3	139.9	0.5	Core 18	141.2