ISSN 1997-1400 Int. J. Pavement Res. Technol. 2(5):181-187
Copyright @ Chinese Society of Pavement Engineering

Calibration of Non-Nuclear PQI Gauges and Field Comparison of PQI and Nuclear Gauge Densities

Nazimuddin M. Wasiuddin[1+], Musharraf M. Zaman[2], and Sesh Commuri[3]

Abstract: Traditionally, a nuclear density gauge is used as a quality control (QC) and quality assurance (QA) tool for in-place density of asphalt pavements. 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. PQI densities exhibited better correlation with AASHTO T 166 densities when the PQI was used before the pneumatic roller. A PQI gauge calibrated with 5 cores exhibited similar performances as the PQI gauge calibrated with 10 cores. It was noticeable that PQI 301 produced better coefficient of determination than the nuclear gauge when the PQI gauge was used before the pneumatic roller. Finally, both mean squared error as well as R-squared values should be used for calibration purposes.

***Key words**: Calibration; Density; Nuclear gauge; Pavement; PQI gauge.*

Introduction

Traditionally, a nuclear density gauge is used as a quality control (QC) and quality assurance (QA) tool for in-place density of asphalt pavements. 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 [1]. 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 [1]. 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 Troxler nuclear density gauge in four field projects and was validated against laboratory densities (AASHTO T 166) measured from selected cores extracted from the pavements.

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.

Prior Researches

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 [2]. 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 [3] 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 [4] 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.

---

[1] PhD, Assistant Professor of Civil Engineering College of Engineering and Science, Louisiana Tech University, Ruston, LA, 71272-0046, USA.

[2] PhD, P.E. David Ross Boyd Professor and Aaron Alexander Professor of Civil Engineering Associate Dean for Research, College of Engineering, University of Oklahoma, Norman, OK, 73019, USA.

[3] PhD, Associate Professor, School of Electrical and Computer Engineering College of Engineering, University of Oklahoma, Norman, OK, 73019, USA.

[+] Corresponding Author: E-mail wasi@latech.edu

Note: Submitted April 25, 2009; Revised July 25, 2009; Accepted July 28, 2009.

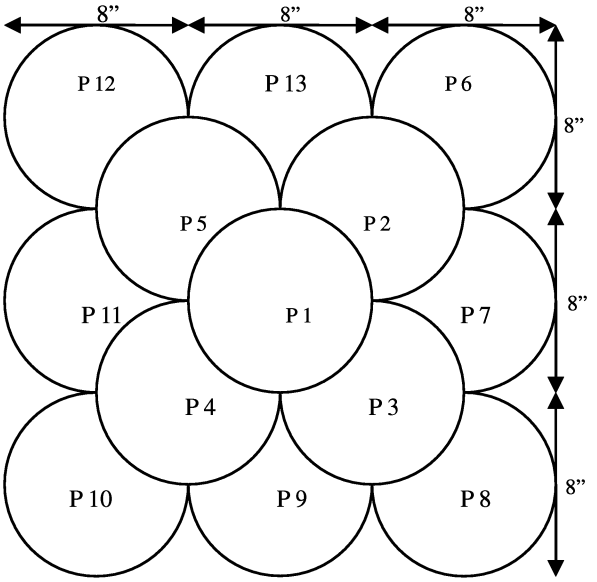

Fig. 1. Positions of the PQI Readings (1*in* = 2.54*cm*).

Both the Connecticut and the Illinois studies did not recommend the PQI 300 for QC or QA purposes. Prowell and Dudley [5] 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 Kuhnow [6] from their 76 field projects using the same gauge (PQI 300). However, Sebesta et al. [7] proposed that a PQI gauge is a suitable alternative to the nuclear gauge for density profiling and joint density testing. Hurley et al. [1] 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 QA testing. Rao et al. [8] recommended that independent calibration be established for each day of paving. The need for a correction factor associated with moisture content in the mat is not evident from this study. Very recently, Smith and Diefenderfer [9] from Virginia Transportation Research Council concluded that the PQI is more suitable than the nuclear density gauge for measuring pavement density on dense-graded hot mix asphalt (HMA), provided that the readings are corrected using the qualitative moisture index. Williams and Hall [10] reported that non-nuclear devices offer a viable alternative for the measurement of in-place HMA density. However, procedures for use should include a requirement to place the gauge parallel to the direction of paving, ensure that no sand or debris is present on the surface, and remove as much surface water as possible.

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 Oklahoma Department of Transportation (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 Fig. 1 for the PQI gauge positions in a $2ft^2$ ($0.0929m^2$)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 (19-*mm* nominal maximum size), two S4 (12.5-*mm* nominal maximum size and one S5 (9.5-*mm* nominal maximum size) type Superpave surface and base mixes.

Results and Discussions

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.* At 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-ponit 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 and 0.5*pcf* ($8.01kg/m^3$) for Clinton, -0.4 and 0.4*pcf* ($6.41kg/m^3$)for Duncan, -0.5 and 0.5*pcf* ($8.01kg/m^3$) for Altus, and -0.5 and 0.9*pcf* ($14.42kg/m^3$)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 $2ft^2$ ($0.0929m^2$) area (not just over the core as seen from Fig. 1). Therefore, *5-point PQI data* as used by the ODOT is recommended from this study.

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

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

Note: 1*pcf* = 16.0191kg/m^3

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 QC or QA 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

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.

	Clinton (Percent Air Voids)			Duncan (Percent Air Voids)		
Core No.	Nuclear	PQI (before the Pneumatic Roller)	PQI (after the Finish Roller)	Nuclear	PQI (before the Pneumatic Roller)	PQI (after the Finish Roller)
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).

	10-Core Calibration			*5-Core Calibration*			Corrected for *Rest of the 5 Cores*			
Site	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

in the mat.

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 cores* 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 (MSE) 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

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	0.80 (BP)	Yes	1.2	0.27
	PQI (after Finish Roller)			
	R-Sq.	Significant (5%)	95% Conf. Int. (±*pcf*)	MSE
Clinton	0.40	No	2.3	1.09
Duncan	0.34	No	1.4	0.37

	Important Mix Properties						
	Mix Type	% AC	Binder Type	Meas. Temp. °F(°C)	Thickness (*in*)	Max.-Min. Air Void (%)	Mineral Filler (%)
Clinton	s4	4.7	PG64-22	160(71.1)	1.5	3.2	4.1
Duncan	s5	5.8	PG64-22	185(85.0)	1.75	1.6	6.1
Altus	s3	4.4	PG76-28	140(60.0)	3	3.4	5.4
Purcell	s4	4.6	PG70-28	175(79.4)	2	2.5	2.9
NC-Int	s3	4.3	PG 64-22	130(54.4)	3	6.1	3.7
NC-Top	s3	4.3	PG 64-22	130(54.4)	3	4.5	3.7

Note: 1*pcf* = 16.0191kg/m^3 and 1*in* = 2.54*cm*.

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 × *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 the 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.

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* (±22.427*kg/m*^{3})of the calibrated PQI density. The intervals are ±1.6 and ±1.9*pcf* (±25.631 and ±30.436*kg/m*^{3})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 and ±2.0*pcf* (±33.640 and ±32.038*kg/m*^{3}), 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 slopes. 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.

Comparison with Prior Research

Using PQI 300 Romero and Kuhnow [6] 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. [1] 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).

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%).

Acknowledgements

The authors would like to express their sincere appreciation to the Oklahoma Department of Transportation (ODOT) for providing funding for this project. Special thanks and appreciation are due to Mr. Danny Gierhart and Mr. Eric Roberts from ODOT Materials Division, for their assistance throughout this project, particularly during the selection of sites. Thanks are also extended to the Resident Engineers of the Clinton, Duncan, Altus, Purcell and Oklahoma City Residencies.

References

1. Hurley, G.C., Prowell, B.D., and Cooley Jr., L.A., (2004). Evaluation of Non-Nuclear Density Measurement Devices for Determination of In-Place Pavement Density, *Transportation Research Record*, No. 1900, pp. 56-64.
2. Rogge, D.F. and Jackson, M.A., (1999). Compaction and Measurement of Field Density for Oregon Open-Graded (F-mix) Asphalt Pavement, *Final Report, FHWA-OR-RD-99-26*, Federal Highway Administration (FHWA) and Oregon

Department of Transportation, USA.

3. Henault, J.W., (2001). Field Evaluation of a Non-Nuclear Density Pavement Quality Indicator, *Report No. 2227-F-01-3*, Connecticut Department of Transportation, Connecticut, USA.
4. Hausman, J.J. and Buttlar, W.G., (2002). Laboratory and Field Analysis of the TransTech Model 300 Pavement Quality Indicator^{TM} (PQI) for Determining Asphalt Pavement Density, *Proceedings of the 81st Annual Meeting of the Transportation Research Board*, Washington, DC, USA, CD-ROM.
5. Prowell, B.D. and Dudley, M.C., (2002). Evaluation of Measurement Techniques for Asphalt Pavement Density and Permeability, *Transportation Research Record*, No. 1789, pp. 36-45.
6. Romero, P. and Kuhnow, F., (2003). Evaluation of New Non-Nuclear Pavement Density Gauges with Data from Field Projects, *Transportation Research Record*, No. 1813, pp. 47-54.
7. Sebesta, S., Zeig, M., and Scullion, T., (2003). Evaluation of Non-Nuclear Density Gauges for HMAC: Year 1 Report, *Report No. FHWA/TX-04/04577-1*, Texas Transportation Institute, Texas, USA.
8. Rao, C., Quintus, H.V., and Schmitt, R.L., (2007). Calibration of Nonnuclear Density Gauge Data for Accurate In-Place Density Prediction, *Transportation Research Record*, No. 2040, pp. 123-136.
9. Smith, B.C. and Diefenderfer, B.K., (2008). Comparison of Nuclear and Nonnuclear Pavement Density Testing Devices, *Transportation Research Record*, No. 2081, pp. 121-129.
10. Williams, S.G. and Hall, K.D., (2008). Critical Factors Affecting Field Determination of Hot Mix Asphalt Density Using Nonnuclear Devices, *Transportation Research Record*, No. 2081, pp. 150-157.