Evaluation of the Nonnuclear Density Gauge for Quality Control of Hot-Mix Asphalt

Prepared by:

John W. Henault, P.E.

April 2010

Research Project: SPR-2267

Final Report

Report No. CT-2267-F-10-2

Connecticut Department of Transportation
Bureau of Engineering and Construction

Division of Research
James M. Sime, P.E.
Manager of Research

Office of Research and Materials
Ravi V. Chandran, P.E.
Division Chief, Research and Materials

DISCLAIMER

The contents of this report reflect the views of the author who is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Connecticut Department of Transportation or the Federal Highway Administration. The report does not constitute a standard, specification or regulation.

Technical Report Documentation Page

1.Report No. CT-2267-F-10-2	**2. Government Accession No.**	**3. Recipients Catalog No.**
4. Title and Subtitle Evaluation of the Nonnuclear Density Gauge for Quality Control of Hot-Mix Asphalt		**5. Report Date** April 2010 **6. Performing Organization Code** SPR-2267
7. Author(s) John W. Henault		**8. Performing Organization Report No.** CT-2267-F-10-2
9. Performing Organization Name and Address Connecticut Department of Transportation Division of Research 280 West Street Rocky Hill, CT 06067-3502		**10. Work Unit No. (TRIS)** **11. Contract or Grant No.** CT Study No. SPR-2267 **13. Type of Report and Period Covered** Final Report -2010
12. Sponsoring Agency Name and Address Connecticut Department of Transportation 2800 Berlin Turnpike Newington, CT 06131-7546		**14. Sponsoring Agency Code** SPR-2267
15. Supplementary Notes Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration.		

16. Abstract

This report presents the results of a study to evaluate a nonnuclear density gauge for quality control of hot-mix asphalt. The nonnuclear gauge evaluated was a Pavement Quality Indicator (PQI) Model 300 that was updated by TransTech in May 2009. It was concluded that the PQI tracked pavement density reasonably well, with some limitations. For instances where the H20 Number displayed on the PQI was below 5, a relatively strong correspondence was found between PQI density and core density. For instances where the H20 Number was between 5 and 10, a relatively strong correspondence was found between PQI density and nuclear gauge density. Finally, for instances where the H20 Number was greater than 15, a poor correspondence was found between PQI density and core density. Based upon these conclusions above, the updated PQI Model 300 was deemed to be adequate for contractor QC for instances where the H20 Number indicated on the gauge is less than 10. To ensure the most accurate density measurements, it was recommended that manufacturer calibration procedures be followed. The author suggested that the sensitively of the PQI density readings be increased, since the slope of the trend lines tended to be flat relative to core densities. For agency acceptance, it was recommended that cores be taken in the field and tested in a laboratory.

17. Key Words	**18. Distribution Statement** No restrictions. Hard copy of this document is available through the National Technical Information Service, Springfield, VA 22161. The report is available on-line from the National Transportation Library at http://ntl.bts.gov		
19. Security Classif. (Of this report) Unclassified	**20. Security Classif.(Of this page)** Unclassified	**21. No. of Pages** 53	**20. Price**

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

ACKNOWLEDGEMENTS

The author gratefully acknowledges the support of the Connecticut Department of Transportation (ConnDOT) and the U.S. Federal Highway Administration. The author thanks study participants employed at ConnDOT, including: Jeffery Scully who performed field operations, Susan Hulme who provided administrative assistance, and James Sime who provided project oversight, all of the Division of Research; Michael Cruess, Teresa Donahue, Douglas Harz, and Moses Marino, who operated the nuclear density gauge for comparative measurements and helped coordinate work; and Victor Grogan and David Parillo who provided laboratory testing services. Finally, the author thanks Bruno Valente for his assistance in taking PQI density measurements.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

In June 2001, a report titled "Field Evaluation of a Nonnuclear Density Pavement Quality Indicator" *(1)* was published by the Connecticut Department of Transportation (ConnDOT). The report presented results of a study to evaluate the nonnuclear Pavement Quality Indicator (PQI) for measuring hot-mix asphalt (HMA) pavement density. A poor correlation between PQI field measured densities and laboratory measured densities of cores was found. It was indicated that poor correlation likely owed to the existence of moisture introduced onto the HMA mat during rolling operations, as water was sprayed onto the drums of the rollers to keep asphalt from sticking to them *(2)*.

PQI output included a relative indication of moisture with a value called the "H20 Number." Previous research by Romero at the Bituminous Mixtures Laboratory Turner-Fairbank Highway Research Center *(3)* had indicated that H20 readings must remain less than 5 in order to "obtain meaningful density measurements." The vast majority of H20 Number readings recorded during the ConnDOT study were greater than 5. Poor correlation between field-measured PQI densities and core densities found during the ConnDOT study support Romero's statement. Sufficiently low moisture levels (H20 Number < 5 in instrument display) for meaningful PQI Model 300 operation were generally unobtainable during ConnDOT paving projects.

In light of the above results, Henault *(1)* strongly recommended that the PQI Model 300 not be used for agency acceptance and independent assurance (IA) testing. He also recommended it not be used for contractor quality control (QC) testing, although not as strongly as for the agency acceptance and IA.

In 2002, Romero and Kuhnow of the University of Utah urged users to view densities obtained with nonnuclear devices with caution *(4)*. They found that the nonnuclear density gauge could not track changes in core density as well as the nuclear gauge.

Later in 2002, TransTech claimed it made some improvements to their PQI Model 300 gauge in response to the initial results, reported above. Another device called the PaveTracker was also introduced following ConnDOT’s initial research. Romero did some follow-up research with these nonnuclear devices and indicated that they showed improvement *(5)*. Romero stated that nonnuclear devices were still not suitable for quality acceptance purposes, but were adequate for QC applications.

Since the abovementioned reports were published, TransTech Systems, Inc. developed the PQI Model 301, which

TransTech claims is better at adjusting readings for moisture. Because of these stated improvements and Romero’s statement that nonnuclear devices are adequate for QC, some state highway agencies (SHAs) are now permitting contractors to use nonnuclear density gauge for QC purposes. In 2009, ConnDOT announced that it would follow suit and begin allowing contractors to use nonnuclear density gauges for QC on ConnDOT projects. ConnDOT’s own PQI Model 300 was subsequently updated by TransTech and received in May 2009.

PROBLEM STATEMENT

Since ConnDOT now permits contractors to use nonnuclear density gauges for QC purposes, a better understanding of their performance is needed. Recent research at the University of Arkansas investigated the effect of moisture on the TransTech Model PQI 301 and the Troxler PaveTracker Plus Model 2701-B. They concluded “the presence of water on density readings was significant in some cases.” *(3)* A similar study recently conducted at the University of Virginia indicated that “the nonnuclear gauge density readings showed strong signs of being affected by moisture within the pavement, even when the moisture index was below 10.” *(4)*

OBJECTIVES

The objectives of this study were to evaluate the nonnuclear density gauge for QC of HMA, and to acquire a better understanding of the effects of moisture and pavement temperature on gauge readings. Strategies for using nonnuclear gauges within rolling patterns to minimize pavement moisture will be examined. Contingent upon whether continued use of the gauge is recommended, a training program for nonnuclear gauge operation for QC will be developed.

PROJECT SITES

Six sites were selected for study from ongoing paving projects in Connecticut. These are tabulated below in Table 1. The updated PQI Model 300 was used for all measurements.

TABLE 1 Six Projects Selected for Study from On-going Construction

Project	Route	HMA Plant	Coarse Aggregate	Fine Aggregate
28-197	Route 2	AEN Franklin	Crushed Gravel	Natural Sand Blend
171-344D	I-91	Tilcon Plainville	Crushed Basalt	Stone Sand/ Natural/RAP Blend
172-390A	Route 9	Tilcon Plainville	Crushed Basalt	Stone Sand/ Natural/RAP Blend
173-405C	Route 40	Tilcon North Branford	Crushed Basalt	Stone Sand/ Natural/RAP Blend
172-389E	Route 195	American Jewitt City	Crushed Gravel	Natural/Gravel Sand Blend
171-343C	I-84	Tilcon Newington	Crushed Basalt	Stone Sand/ Natural/RAP Blend

Project 28-197

Project 28-197 was a pavement resurfacing project on Route 2. The HMA was a SuperPave 12.5-mm Level 3 mix. The HMA plant was AEN out of Franklin, CT. Broken stone coarse and natural sand blend fine aggregates were used in the mix. The project included milling and paving six (6) FHWA Long-Term Pavement Performance (LTPP) Special Pavement Study (SPS) 9A Test Sections (090901, 090902, 090903, 090960, 090961, 090962). Sections 090901, 090902, and 090903 were located in the eastbound direction, and Sections 090960, 090961, and 090962 were located in the westbound direction. HMA was placed at a nominal thickness of 2 inches in the eastbound direction and 3 inches in the westbound direction, although actual thicknesses measured from cores were thicker (see Table 3).

FIGURE 1 Paving Train at Project 28-197.

FIGURE 2 Broken stone coarse and natural sand blend fine aggregate used in SuperPave Level 3 mix at Project 28-197 (sample calibrated asphalt content = 5.14%).

The PQI was operated in the “Average Reading Mode” for all tests performed on this project. The averaging consisted of five readings. The first was centered directly above the center of the core location. The PQI was moved approximately two inches up and to the right at the two o’clock position for the second reading relative to the first reading. The third, fourth, and fifth readings were taken in a similar manner at the four, eight, and 10 o’clock positions relative to the first reading. Since a 12.5-mm stone was used on the top course, the PQI was set to the Top/Surface setting as per the addendum to the Model 300 Operator’s Handbook.

The nuclear gauge was a CPN Model MC-3 (#588). It was operated in the AC mode for 30 second counts. Two readings were taken and averaged for each measurement. The readings were taken with the gauge facing transverse to the direction of travel. After the first reading, the gauge was turned 180 degrees to face the other way.

Five (5) cores were drilled within the limits of each 500-ft test section, except for Section 090903. Cores were not drilled at Section 090903 because the contractor needed to pick up the traffic pattern before the cores could be drilled. It was decided to omit this section in the research in order to avoid causing delays to the contractor, as work associated with this research was not included in their bid. The cores were drilled 100-ft on-center longitudinally and two-ft on-center transversely across the width of pavement in order to obtain a better cross section of material. PQI and nuclear gauge density readings were taken at each core location. The cores were subsequently tested in the laboratory for bulk specific gravity in accordance with AASHTO T311, “Standard Method of Test for Bulk Specific Gravity and Density of Compacted Hot Mix Asphalt (HMA) Using Automatic Vacuum Sealing Method.” The results of these tests are presented in Tables 2 and 3. Table 4 tabulates the core densities, along with PQI and nuclear gauge densities measured at the same locations as the cores.

A scatter diagram of PQI density versus core density is plotted in Figure 3. Linear regression trend lines were plotted for each test site within the limits of Project 28-197. Coefficients of determination (r^2) values were determined for each site, and are shown in Figure 3. The average of these five r^2 values was 0.69, which suggests some correspondence between PQI density and core density. When all of the sites were combined into one group in Figure 4, the r^2 value decreased to 0.48. This lower value may owe to slight differences in maximum specific gravities that occurred from day-to-day. The slope of the regression line generally ranged from 0.31 to 0.38, although it was steeper at Site 090962 where a limited range of values was observed. Considering the limited range at Site 090962, it is surmised that the regression slope of the other sites is more representative (0.31 to 0.38). Therefore, it appears PQI densities generally did not range in value as much as core densities, and perhaps the slope of the gauge needs to be adjusted (steeper).

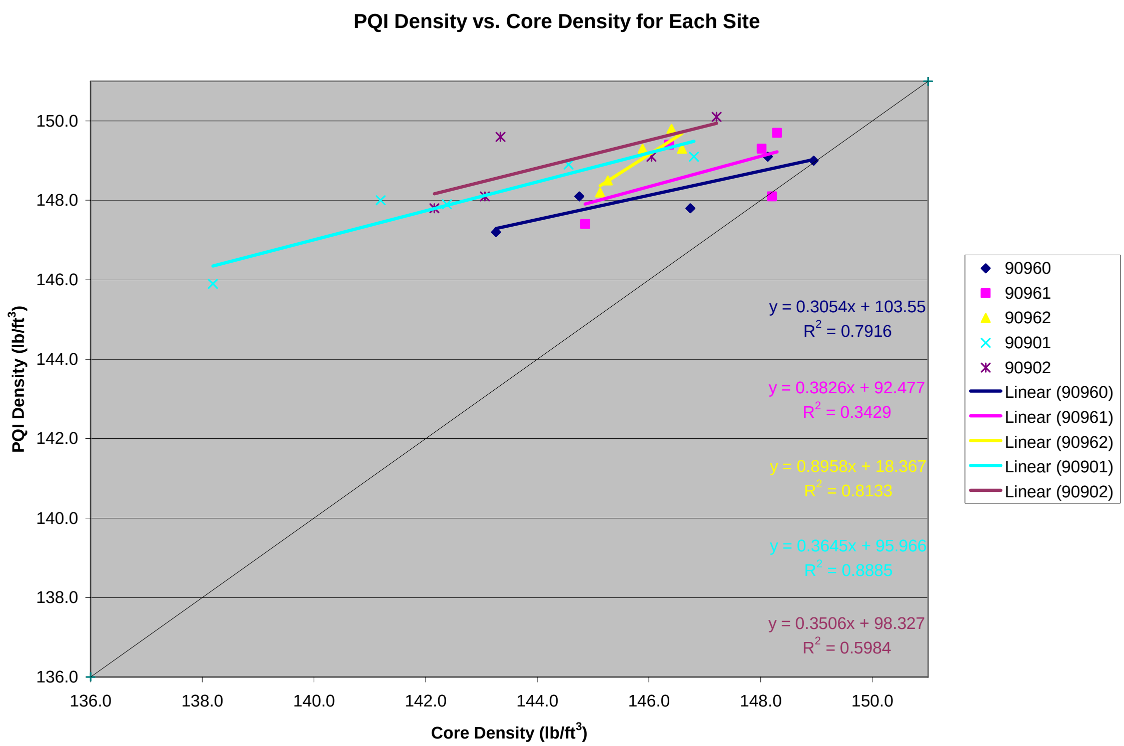

FIGURE 3 PQI density versus core density for the individual test sites grouped separately on Project 28-197.

TABLE 2 Project 28-197 General Hot Mix Asphalt Data

Rte. 2 Research, SHRP Sites 090960, 090961, 090962, 090901, 090902

Tested: 12/8/09

Plant:	A.E.N.	**Mix:**	12.5
Location:	Franklin	**Level:**	3
Date Placed:	11/4-11/11/2009	**Date Taken:**	11/4-11/11/2009
Project #:	28-197	**Rt. #**	2
Town:	Colchester	**Contractor:**	Empire

Double Bag Limit: ***75***

TABLE 3 Project 28-197 Core Test Results

Sample ID	Bag Weight (g)	Sample Weight before Sealing (g)	Sealed Sample Weight in Water (g)	Sample Weight after Water Submersion (g)	Density of Water (g/cm3) for temperature correction	Core Thickness (inch)	Maximum Specific Gravity	Bulk Specific Gravity (g/cm3)	% Air Voids	% Compaction
60-C1	50.0	3141.9	1770.7	3141.3	1	3.250	2.508	2.320	7.5	92.5
60-C2	29.1	3237.6	1851.1	3237.6	1	3.500	2.508	2.352	6.2	93.8
60-C3	29.1	3157.2	1824.7	3157.0	1	3.375	2.508	2.387	4.8	95.2
60-C4	29.0	2654.6	1526.6	2654.0	1	3.000	2.508	2.374	5.3	94.7
60-C5	29.2	3331.6	1870.2	3331.2	1	3.500	2.508	2.296	8.5	91.5
							% Average Compaction			93.5

TABLE 3 Project 28-197 Core Test Results (continued)

Sample ID	Bag Weight (g)	Sample Weight before Sealing (g)	Sealed Sample Weight in Water (g)	Sample Weight after Water Submersion (g)	Density of Water (g/cm3) for temperature correction	Core Thickness (inch)	Maximum Specific Gravity	Bulk Specific Gravity (g/cm3)	% Air Voids	% Compaction
61-C1	29.2	2998.2	1726.6	2998.5	1	3.125	2.521	2.375	5.8	94.2
61-C2	29.3	2966.6	1692.2	2966.5	1	3.250	2.521	2.346	7.0	93.0
61-C3	28.9	3658.6	2109.3	3658.9	1	3.750	2.521	2.377	5.7	94.3
61-C4	29.2	3274.7	1884.3	3274.6	1	3.500	2.521	2.372	5.9	94.1
61-C5	29.0	2969.2	1681.0	2969.5	1	3.250	2.521	2.321	7.9	92.1
							% Average Compaction			93.5

Sample ID	Bag Weight (g)	Sample Weight before Sealing (g)	Sealed Sample Weight in Water (g)	Sample Weight after Water Submersion (g)	Density of Water (g/cm3) for temperature correction	Core Thickness (inch)	Maximum Specific Gravity	Bulk Specific Gravity (g/cm3)	% Air Voids	% Compaction
62-C1	28.9	3058.9	1740.4	3058.3	1	3.125	2.525	2.338	7.4	92.6
62-C2	28.5	2179	1242.4	2178.5	1	2.500	2.525	2.349	7.0	93.0
62-C3	28.7	3359.4	1917.3	3358.9	1	3.125	2.525	2.346	7.1	92.9
62-C4	29.0	2985.4	1691.7	2984.8	1	3.125	2.525	2.326	7.9	92.1
62-C5	28.8	2668	1512.3	2667.5	1	3.125	2.525	2.328	7.8	92.2
							% Average Compaction			92.6

TABLE 3 Project 28-197 Core Test Results (continued)

Sample ID	Bag Weight (g)	Sample Weight before Sealing (g)	Sealed Sample Weight in Water (g)	Sample Weight after Water Submersion (g)	Density of Water (g/cm3) for temperature correction	Core Thickness (inch)	Maximum Specific Gravity	Bulk Specific Gravity (g/cm3)	% Air Voids	% Compaction
01-C1	28.8	2305.5	1317.8	2306.5	1	2.500	2.531	2.353	7.0	93.0
01-C2	28.6	1988.5	1108.4	1988.3	1	2.250	2.531	2.282	9.8	90.2
01-C3	29.0	2109.3	1190.1	2109.2	1	2.125	2.531	2.317	8.5	91.5
01-C4	28.8	2504.7	1388.4	2504.3	1	2.500	2.531	2.263	10.6	89.4
01-C5	50.0	2900.7	1575.0	2900.3	1	2.875	2.531	2.215	12.5	87.5
							% Average Compaction			90.3

Sample ID	Bag Weight (g)	Sample Weight before Sealing (g)	Sealed Sample Weight in Water (g)	Sample Weight after Water Submersion (g)	Density of Water (g/cm3) for temperature correction	Core Thickness (inch)	Maximum Specific Gravity	Bulk Specific Gravity (g/cm3)	% Air Voids	% Compaction
02-C1	28.7	2232.9	1250.0	2232.6	1	2.375	2.529	2.293	9.3	90.7
02-C2	28.5	2033.1	1139.7	2033.2	1	2.250	2.529	2.297	9.2	90.8
02-C3	28.5	2081.8	1190.7	2081.6	1	2.250	2.529	2.359	6.7	93.3
02-C4	28.8	2463.1	1401.3	2462.6	1	2.500	2.529	2.340	7.5	92.5
02-C5	28.9	2297.6	1280.2	2297.5	1	2.375	2.529	2.278	9.9	90.1
							% Average Compaction			91.5

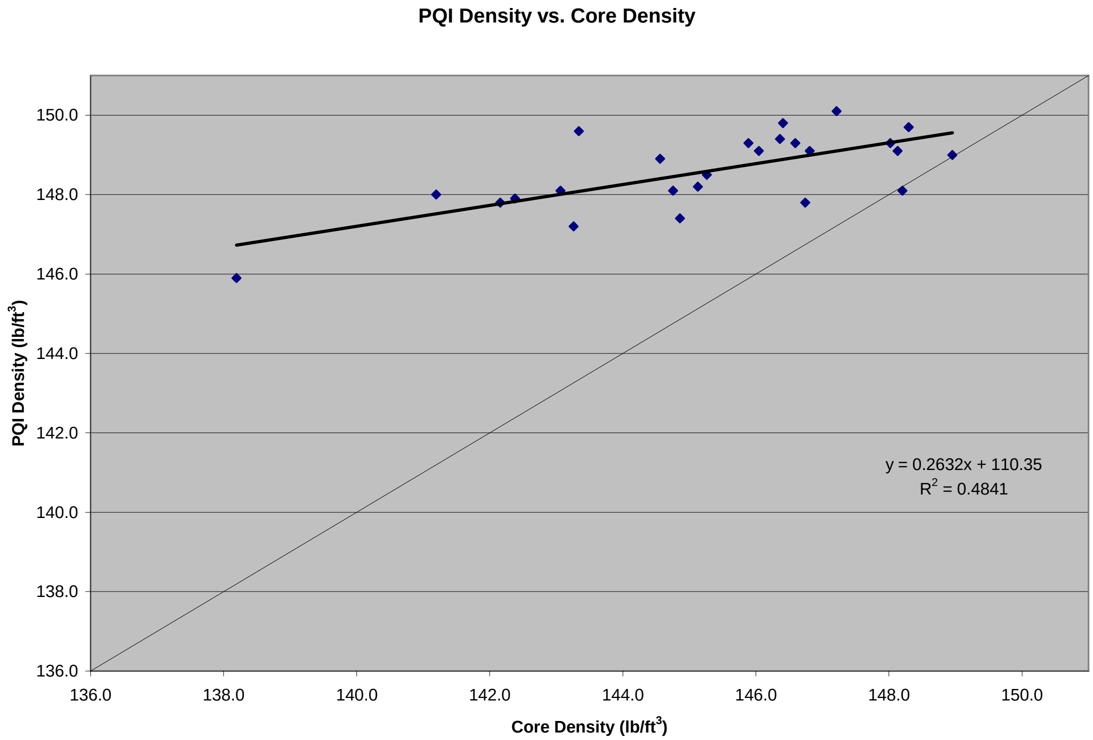

FIGURE 4 PQI density versus core density for the individual test sites grouped together on Project 28-197.

TABLE 4 Density Test Results at Project 28-197

Sample ID	Nuclear Density Reading 1 (lb/ft^3)	Nuclear Density Reading 2 (lb/ft^3)	Nuclear Density Average (lb/ft^3)	PQI Density (lb/ft^3)	PQI H20 Number	PQI Temp (F°)	Core Density (lb/ft^3)
60-C1	150.7	150.2	150.5	148.1	2.4	99.6	144.8
60-C2	145.7	146.6	146.2	147.8	1.9	114.1	146.7
60-C3	151.2	151.0	151.1	149.0	2.1	99.2	149.0
60-C4	149.6	149.6	149.6	149.1	2.0	111.7	148.1
60-C5	142.3	141.9	142.1	147.2	2.0	121.4	143.3
61-C1	150.7	149.4	150.1	148.1	3.5	104.8	148.2
61-C2	147.0	147.4	147.2	149.4	1.7	112.7	146.4
61-C3	147.9	149.5	148.7	149.7	2.0	105.7	148.3
61-C4	148.5	148.8	148.7	149.3	1.9	113.6	148.0
61-C5	144.0	144.1	144.1	147.4	2.0	111.4	144.9
62-C1	147.7	147.3	147.5	149.3	1.4	49.1	145.9
62-C2	146.3	147.4	146.9	149.3	1.4	56.9	146.6
62-C3	149.4	148.5	149.0	149.8	1.7	61.9	146.4
62-C4	146.1	145.8	146.0	148.2	1.8	51.1	145.1
62-C5	145.8	146.5	146.2	148.5	2.1	47.3	145.3
01-C1	149.3	147.9	148.6	149.1	2.1	116.0	146.8
01-C2	146.2	144.9	145.6	147.9	2.0	110.6	142.4
01-C3	147.7	147.5	147.6	148.9	2.1	107.0	144.6
01-C4	144.6	144.8	144.7	148.0	1.9	124.2	141.2
01-C5	138.8	139.5	139.2	145.9	2.1	124.1	138.2
02-C1	145.4	148.2	146.8	148.1	1.9	90.4	143.1
02-C2	146.5	146.7	146.6	149.6	2.5	84.4	143.3
02-C3	147.9	148.6	148.3	150.1	2.5	82.3	147.2
02-C4	146.7	146.9	146.8	149.1	1.9	91.4	146.0
02-C5	147.8	147.9	147.9	147.8	1.8	88.8	142.2

TABLE 5 PQI Density versus Core Density at Project 28-197 - Linear Regression

Sample ID	Average Lift Thickness (in.)	Date Paved	Equation	R-Squared Value	Ave PQI H2O No.	Ave PQI Temp (°F)
090960	3.325	11/4/09	0.30x + 103.6	0.79	2.1	109.2
090961	3.375	11/5/09	0.38x + 92.5	0.34	2.2	109.6
090962	3.000	11/7/09	0.90x + 18.4	0.81	1.7	53.3
090901	2.450	11/10/09	0.36x + 96.0	0.89	2.0	116.4
090902	2.350	11/11/09	0.35x + 98.3	0.60	2.1	87.5
Grouped Together	NA	NA	.26x + 110.4	0.48	2.0	95.2

FIGURE 5 Freshly Drilled Core

Low H2O Numbers were observed on the PQI gauge for all density measurements at core locations on Project 28-197. They ranged from 1.4 to 3.5, and the average of these 25 measurements was 2.0. These were all well below the threshold value of 5, which, if exceeded, Romero *(3)* indicated would diminish accuracy. Therefore, conditions were optimum for PQI operation. These are presented in Tables 4 and 5, along with PQI temperatures.

Next, nuclear gauge versus core densities were plotted for the individual sites in Figure 5. The average r^2 value for the five test sections was 0.58. Two of the five sites

(090961 and 090901) had r^2 values greater than 0.90, while one site (090902) had a very poor correlation (r^2 = 0.10). Removing Site 090902, the average r^2 value of the other four sites was 0.70. The average slope of the five sites was approximately equal to 1, which is ideal. In Figure 4, the data for all the sites were combined. The r^2 value in this instance was 0.59 and the slope of the trend line was 0.78. Overall, the correspondence between the nuclear gauge and core density was similar to that between the PQI gauge and core density; however, the trend line slope was closer to ideal for the nuclear gauge.

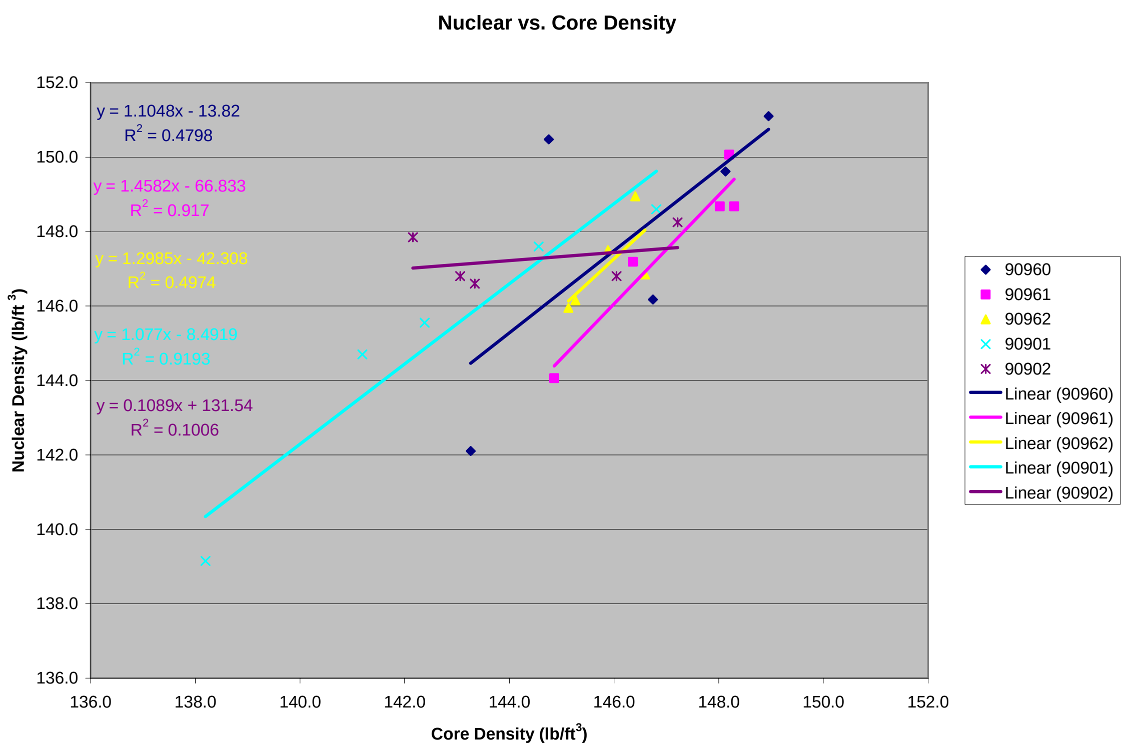

FIGURE 6 Nuclear gauge density versus core density at Project 28.197 for individual sites.

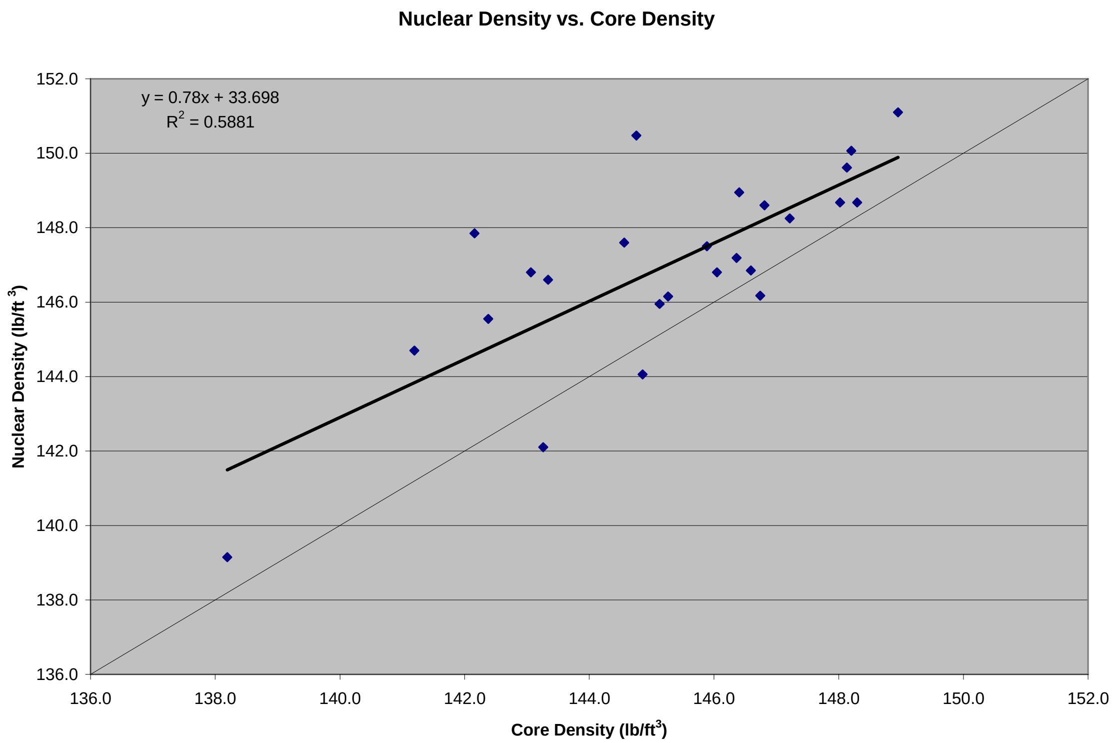

FIGURE 7 Nuclear gauge density versus core density at Project 28.197 for sites grouped together.

Finally, PQI versus nuclear density gauge measurements were compared individually by site in Figure 8 and grouped together in Figure 9. Note that comparisons between PQI densities and nuclear gauge densities included additional side-by-side tests, above and beyond the tests performed at the core locations. These additional tests are presented in Table 6.

The average r^2 value in Figure 8 was 0.59, but when Site 090902 was removed from the dataset, it improved to 0.74. The low correlation at Site 090902 likely owed to the nuclear gauge not performing well, as opposed to the

PQI, since the nuclear gauge also correlated poorly to core density at that site. An r^2 value of 0.76 at Site 090962 was relatively high considering that the dataset included 14 measurements. An r^2 value of 0.99 was calculated at Site 090901, although this dataset included only five measurements. The average regression line slope for these sites was 0.28. It increased slightly to 0.32 when Site 090902 was removed from the dataset because of its low correlation. When the five sites were combined in Figure 9, the r^2 value was 0.53 and the regression line slope was 0.30. So, a relatively good correspondence existed between PQI and nuclear density gauge measurements. The slope was less than desirable, but this can be easily compensated for by increasing the sensitivity of the PQI gauge.

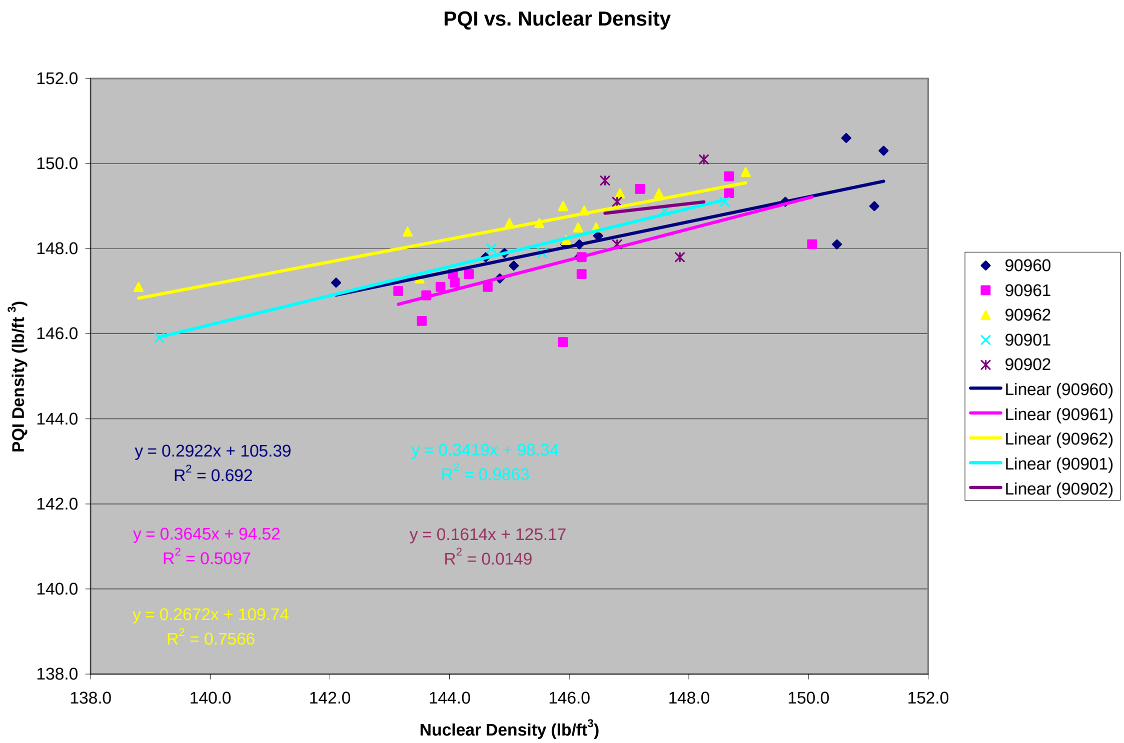

FIGURE 8 PQI density versus nuclear gauge density at Project 28-197 for individual sites.

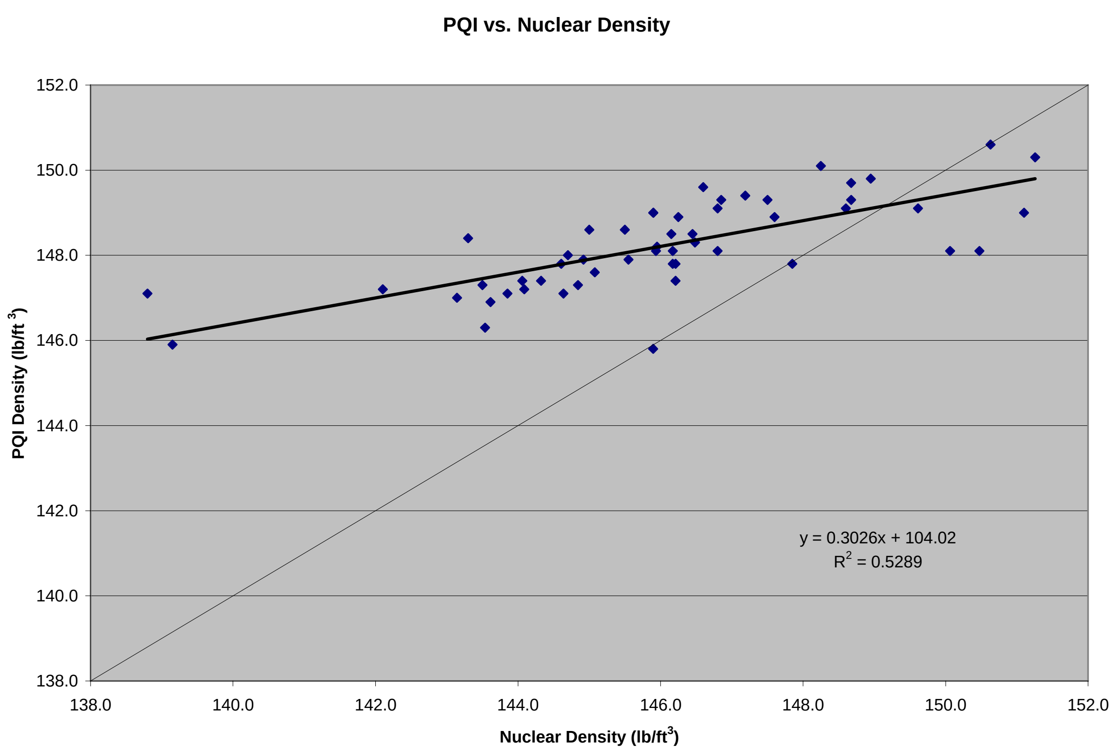

FIGURE 9 PQI density versus nuclear gauge density at Project 28-197 for sites grouped together.

TABLE 6 Additional PQI and Nuclear Gauge Side-by-Side Density Test Results at Project 28-197

Sample ID	Nuclear Density Reading 1 (lb/ft^3)	Nuclear Density Reading 2 (lb/ft^3)	Nuclear Density Average (lb/ft^3)	PQI Density (lb/ft^3)	PQI H20 Number	PQI Temp (F°)
60-R1	146.3	146.0	146.2	148.1	1.8	95.5
60-R2	146.5	146.5	146.5	148.3	2.0	95.2
60-R3	146.0	145.9	145.9	148.1	1.9	88.2
60-R4	144.9	144.9	144.9	147.9	1.9	95.9
60-R5	144.9	145.2	145.1	147.6	1.9	98.0
60-R6	144.8	144.4	144.6	147.8	2.0	92.5
60-R7	145.5	144.1	144.8	147.3	2.0	95.0
60-R8	151.3	149.9	150.6	150.6	1.7	94.4
60-R9	151.3	151.2	151.3	150.3	1.9	94.8
61-R1	147.4	145.0	146.2	147.4	2.4	157.7
61-R2	143.8	143.5	143.6	146.9	2.5	165.4
61-R3	144.4	144.9	144.6	147.1	2.3	143.2
61-R4	146.9	145.5	146.2	147.8	2.3	142.5
61-R5	143.5	142.8	143.1	147.0	2.3	130.4
61-R6	144.2	143.5	143.9	147.1	2.0	122.8
61-R7	144.4	144.2	144.3	147.4	2.0	126.4
61-R8	144.2	143.9	144.1	147.2	2.3	99.3
61-R9	142.2	144.9	143.5	146.3	2.8	96.1
61-R10	146.4	145.3	145.9	145.8	4.1	108.7
62-R1	144.0	143.0	143.5	147.3	1.5	48.8
62-R2	139.0	138.6	138.8	147.1	1.8	58.6
62-R3	147.1	145.8	146.5	148.5	1.6	54.1
62-R4	142.8	143.8	143.3	148.4	1.7	52.5
62-R5	145.2	144.8	145.0	148.6	1.6	60.2
62-R6	145.7	146.8	146.3	148.9	1.7	61.8
62-R7	146.1	145.7	145.9	149.0	1.7	54.9
62-R8	145.9	145.9	145.9	149.0	1.8	52.7
62-R9	145.5		145.5	148.6	2.3	46.8

Project 171-344D

Project 171-344D was for a pavement rehabilitation on I-91 in Cromwell. A 12.5-mm Level 3 SuperPave mix was used. Crushed basalt coarse aggregate was used with a stone sand/natural/RAP blend in the mix. The pavement cored and tested for density for this research was all paved between July 22 and July 30, 2009. Core drilling/PQI density measurements were performed the night of September 9-10, 2009.

Unlike for Project 28-197, PQI measurements were not taken under optimum conditions in this instance. All of the PQI H2O Numbers in this case were very high, as they ranged from 15.2 to 23.1. This is considerably higher than the threshold value of 5 identified by Romero where PQI accuracy diminishes. Measurements were taken on this project because cores needed to be drilled for dispute resolution purposes. Being opportunists, it was decided to take PQI measurements prior to coring. The H2O Numbers were high because over a month had passed between when the HMA was placed and when the cores were drilled. Therefore, the pavement was exposed to several rain storms in between placement and PQI density measurements. Apparently, the storm water did not evaporate or infiltrate from the pavement sufficiently after it rained, which resulted in high H2O Numbers.

For these measurements, the PQI was also operated in the “Average Reading Mode.” The averaging consisted of two readings with the gauge facing transverse to the direction of travel. After the first reading, the gauge was turned 180 degrees for the second reading. 12.5-mm stone was used on the top course, so the PQI was set to the Top/Surface setting. Comparative nuclear gauge readings were not made at this project site.

Tables 7 and 8 present laboratory test results on the cores. Table 9 presents PQI measurements and core densities. A scatter plot of PQI versus core density is presented in Figure 10. Note that no linear association is evident in the plot and that the r^2 value was very low (0.17). This poor association was expected because of the high H2O Numbers, but it helps validate that the PQI should not be used in such instances.

In order to see if a relationship existed, PQI densities versus PQI H2O Numbers were plotted in Figure 11. A strong linear association was evident and the r^2 value was 0.84. Note: H2O Numbers ranged between 15.2 and 23.1 in Figure 11. Because of this strong association, it was decided to make a similar plot for Project 28-197 (see

Figure 12) to see if the same relationship existed for a lower range of H2O Numbers. In looking at Figure 12, it can be seen that there is no such relationship between PQI densities and H2O Numbers for this range of values (H2O Numbers < 5).

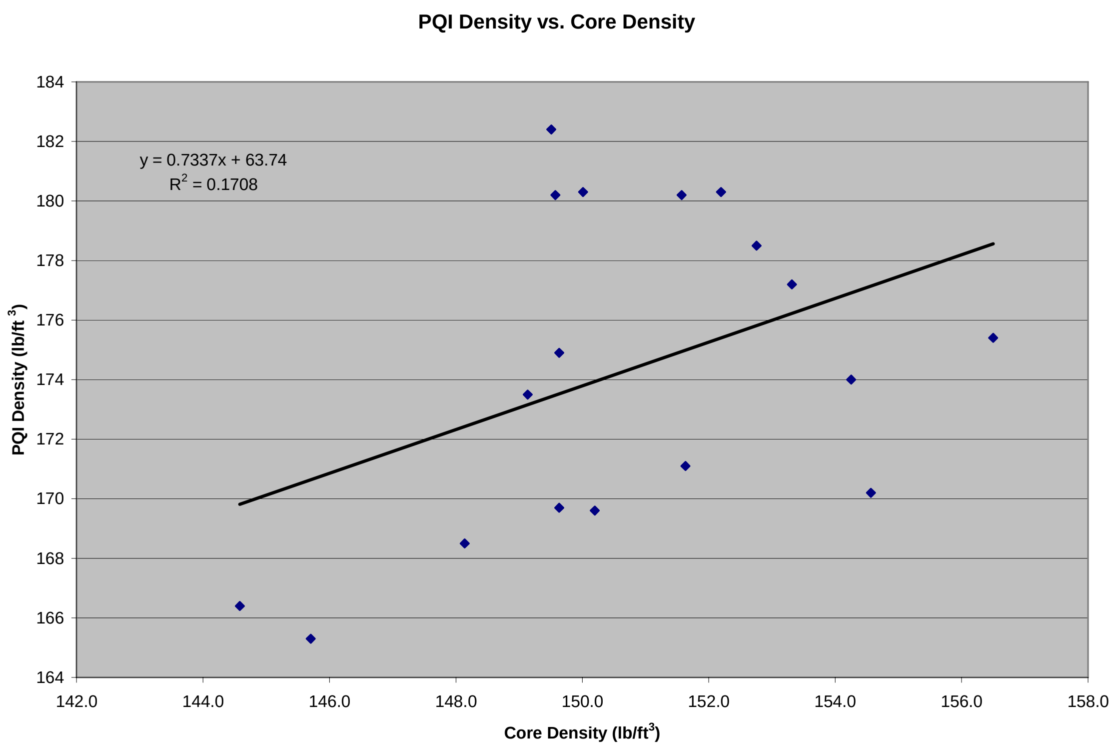

FIGURE 10 PQI density versus core density at Project 171-344D. Note the poor linear association between these variables in this instance for which H20 Numbers were all greater than 15.

TABLE 7 General Project 171-344D Hot Mix Asphalt Data

I-91, Project 171-344D

Tested: 9/10/09

Plant:	Tilcon	**Mix:**	12.5
Location:	Plainville	**Level:**	3
Date Placed:	7/22/-7/30/2009	**Date Taken:**	9/9/2009
Project #:	171-344D	**Rt. #**	91
Town:	Cromwell	**Contractor:**	Tilcon

Double Bag Limit: ***75***

TABLE 8 Project 171-344D Core Test Results

Sample ID	Bag Weight (g)	Sample Weight before Sealing (g)	Sealed Sample Weight in Water (g)	Sample Weight after Water Submersion (g)	Density of Water (g/cm3) for temperature correction	Core Thickness (inch)	Maximum Specific Gravity	Bulk Specific Gravity (g/cm3)	% Air Voids	% Compaction
J-1	27.5	2903.1	1670.8	2902.6	1	2.625	2.671	2.374	11.1	88.9
J-2	27.8	2646	1496.2	2646.9	1	2.250	2.671	2.317	13.2	86.8
J-3	27.9	2382.3	1353.0	2382.1	1	2.625	2.671	2.335	12.6	87.4
J-11	21.3	2183.7	1287.2	2183.0	1	2.000	2.666	2.457	7.8	92.2
J-12	21.2	2423.4	1405.0	2423.1	1	2.250	2.666	2.397	10.1	89.9
J-13	21.2	2297.7	1344.5	2297.6	1	2.000	2.666	2.429	8.9	91.1
J-14	21.3	2133.7	1239.6	2132.8	1	2.000	2.666	2.407	9.7	90.3
J-15	21.2	2726.1	1577.1	2725.3	1	2.500	2.666	2.390	10.4	89.6

TABLE 8 Project 171-344D Core Test Results (continued)

Sample ID	Bag Weight (g)	Sample Weight before Sealing (g)	Sealed Sample Weight in Water (g)	Sample Weight after Water Submersion (g)	Density of Water (g/cm3) for temperature correction	Core Thickness (inch)	Maximum Specific Gravity	Bulk Specific Gravity (g/cm3)	% Air Voids	% Compaction
J-21	21.6	2253.8	1305.1	2252.9	1	2.000	2.678	2.396	10.5	89.5
J-22	21.5	2211.8	1297.1	2210.9	1	2.000	2.678	2.439	8.9	91.1
J-23	21.5	2122.1	1229.4	2121.4	1	2.000	2.678	2.398	10.5	89.5
J-24	21.2	2433.8	1413.6	2433.1	1	2.125	2.678	2.404	10.2	89.8
J-25	21.3	2391.2	1385.8	2390.2	1	2.250	2.678	2.398	10.5	89.5
M-21	21.6	2350.5	1383.0	2350.2	1	1.750	2.678	2.448	8.6	91.4
M-22	21.5	2347.9	1392.4	2347.3	1	2.000	2.678	2.477	7.5	92.5
M-23	21.2	2291.1	1370.0	2290.4	1	1.750	2.678	2.508	6.3	93.7
M-24	21.5	2652.2	1571.2	2651.6	1	2.000	2.678	2.472	7.7	92.3
M-25	21.6	2337.8	1367.5	2336.8	1	1.750	2.678	2.430	9.3	90.7

TABLE 9 Project 171-344D PQI Measurements and Core Test Results

Sample ID	PQI Density (lb/ft^3)	PQI H20 Number	PQI Temp (F°)	Bulk Specific Gravity	Core Density = Bulk S.G. x 62.4 (lb/ft^3)
J-1	168.5	16.8	63.0	2.374	148.1
J-2	166.4	16.2	61.9	2.317	144.6
J-3	165.3	15.2	61.8	2.335	145.7
J-11	177.2	21.0	61.0	2.457	153.3
J-12	180.2	20.5	62.7	2.397	149.6
J-13	180.2	19.8	60.6	2.429	151.6
J-14	169.6	19.0	60.6	2.407	150.2
J-15	173.5	19.5	61.5	2.390	149.1
J-21	182.4	23.1	60.9	2.396	149.5
J-22	180.3	21.3	57.8	2.439	152.2
J-23	169.7	18.1	58.9	2.398	149.6
J-24	180.3	22.2	55.3	2.404	150.0
J-25	174.9	20.8	56.5	2.398	149.6
M-21	178.5	21.7	60.7	2.448	152.8
M-22	170.2	17.5	57.7	2.477	154.6
M-23	175.4	19.9	56.6	2.508	156.5
M-24	174.0	20.3	54.0	2.472	154.3
M-25	171.1	19.2	54.4	2.430	151.6

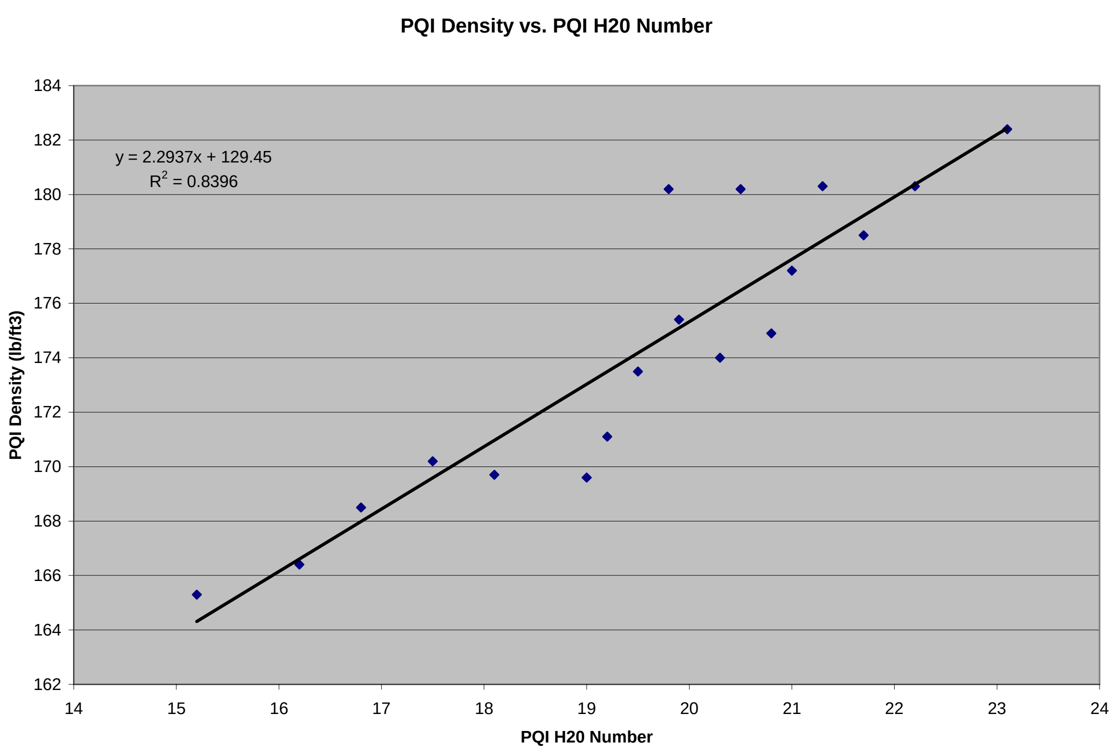

FIGURE 11 PQI densities versus H20 Numbers at Project 171-344D. Note that there is a strong linear association between these variables for this project with all H20 Numbers greater than 15.

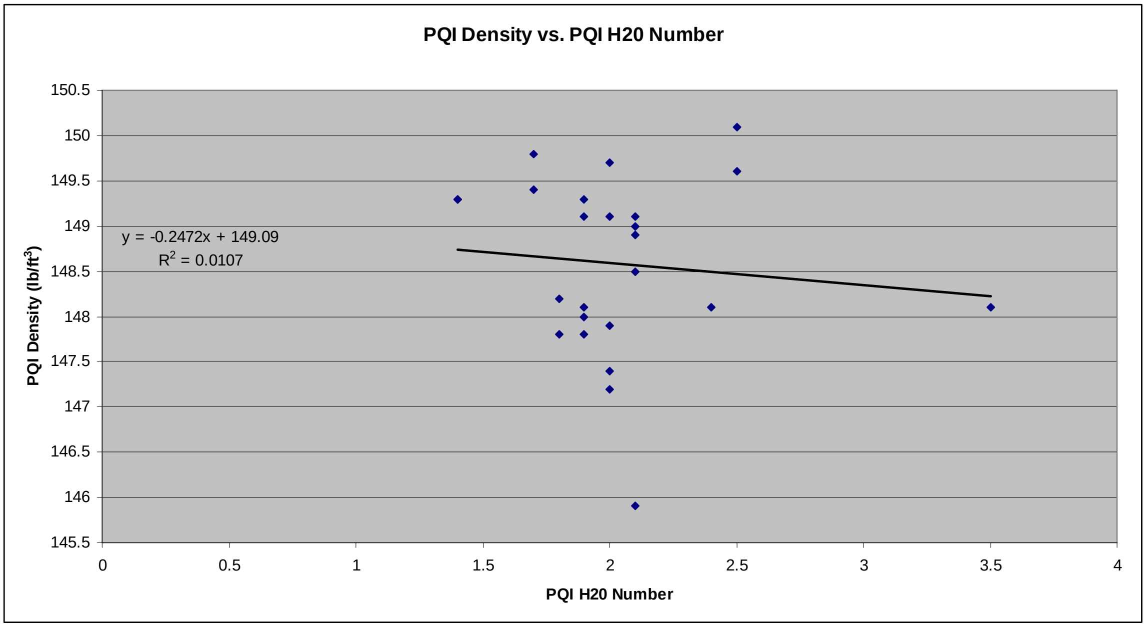

FIGURE 12 PQI density versus H20 Number at Project 28-197. Note that there is no linear association between these variables for this project with all H20 Numbers less than 5.

Project 172-390A

This was a pavement rehabilitation project on Route 9 in Chester. A 12.5-mm Level 3 mix was used for construction. It consisted of crushed basalt coarse aggregate with a stone sand/natural/RAP blend. PQI versus nuclear gauge comparisons were made on this project by taking readings with both gauges at the same locations during construction. Cores were not drilled.

On the night of September 2-3, 2009, 42 comparative measurements were made between the PQI and a CPN Model MC-3 (#588) nuclear gauge. The PQI was operated in the “Average Reading Mode” and was set to the Top/Surface setting, in the same manner as described for Project 28-197. The nuclear gauge was operated in the same manner as it was for Project 28-197 for a number of tests, although several measurements consisted of just one 30-second count reading.

Table 10 presents these comparative test results. A scatter plot of PQI versus nuclear gauge density is presented in Figure 13. A strong linear association was found, as the r^2 value was 0.76. The slope of the regression line was 0.28, so again it was flat. This is similar to the slope of the regression lines for Project 28-197. The fact that the regression line slopes were similar between projects strengthens the apparent relationship in that it demonstrates consistency.

TABLE 10 Nuclear Gauge Density and PQI Density Measurements for Project 172-390A

Sample ID	Nuclear Density Reading 1 (lb/ft^3)	Nuclear Density Reading 2 (lb/ft^3)	Nuclear Density Average (lb/ft^3)	PQI H20 Number	PQI Temp (F°)	PQI Density (lb/ft^3)
0002-0002	159.5		159.5	7.9	149.3	158.2
0002-0003	152.8		152.8	6.6	153.2	155.8
0002-0005	155.1		155.1	5.6	141.3	155.6
0002-0006	154.8		154.8	6.4	125.6	155.9
0002-0007	157.1		157.1	6.4	126.6	157.6
0002-0008	153.4		153.4	6.5	132.0	156.8
0008-0001	149.6	152.6	151.1	5.3	73.5	156.4
0008-0002	154.1	155.2	154.7	4.3	90.4	156.5
0008-0004	155.4	157.1	156.3	3.8	101.8	156.3
0008-0005	146.8	151.3	149.1	3.3	76.3	154.3
0008-0006	156.7	156.3	156.5	3.8	89.6	155.7
0008-0007	163.7	164.0	163.9	6.1	99.5	159.6
0008-0008	147.6	151.0	149.3	5.1	71.1	154.4
0008-0009	152.7	152.0	152.4	5.9	98.6	155.1
0008-0011	126.1		126.1	8.4	83.3	149.3
0200-0001	161.8	161.8	161.8	6.2	121.1	157.5
0200-0002	161.6	162.4	162.0	6.4	123.0	158.6
0200-0003	161.0	161.9	161.5	6.4	121.5	158.7
0200-0004	159.7	161.8	160.8	6.4	119.8	158.4
0200-0005	159.3	161.3	160.3	6.1	119.4	157.6
0200-0006	160.3	161.8	161.1	6.3	118.3	158.3
0200-0007	161.4	162.7	162.1	6.4	117.2	158.6
0200-0001	157.6	154.7	156.2	5.3	94.5	157.7
0200-0002	152.5	154.5	153.5	5.0	106.5	156.2
0200-0003	154.4	151.8	153.1	4.8	110.3	155.1
0200-0004	145.8	147.3	146.6	4.2	106.4	153.2
0200-0005	153.8	155.2	154.5	7.9	103.3	158.7
0020-0006	153.0		153.0	7.1	124.0	155.8
0020-0007	152.9		152.9	7.3	106.5	157.7
0020-0008	150.8		150.8	7.4	129.7	156.7
0020-0009	146.9		146.9	5.7	79.9	154.3
0020-0010	150.4		150.4	4.3	102.4	154.0
0020-0011	149.2		149.2	4.5	97.3	153.8
0020-0012	149.2		149.2	5.0	87.8	154.3
0020-0013	159.6		159.6	4.0	98.3	158.1
0020-0014	157.4		157.4	4.0	92.9	158.3
0020-0015	153.3		153.3	4.8	89.0	156.2
0020-0016	151.6		151.6	7.6	102.9	158.1
0020-0018	152.3		152.3	7.3	97.2	158.5
0020-0019	150.3		150.3	5.3	104.7	155.5
0020-0020	149.1		149.1	4.3	98.3	154.6
0020-0021	148.4		148.4	5.2	78.8	152.7

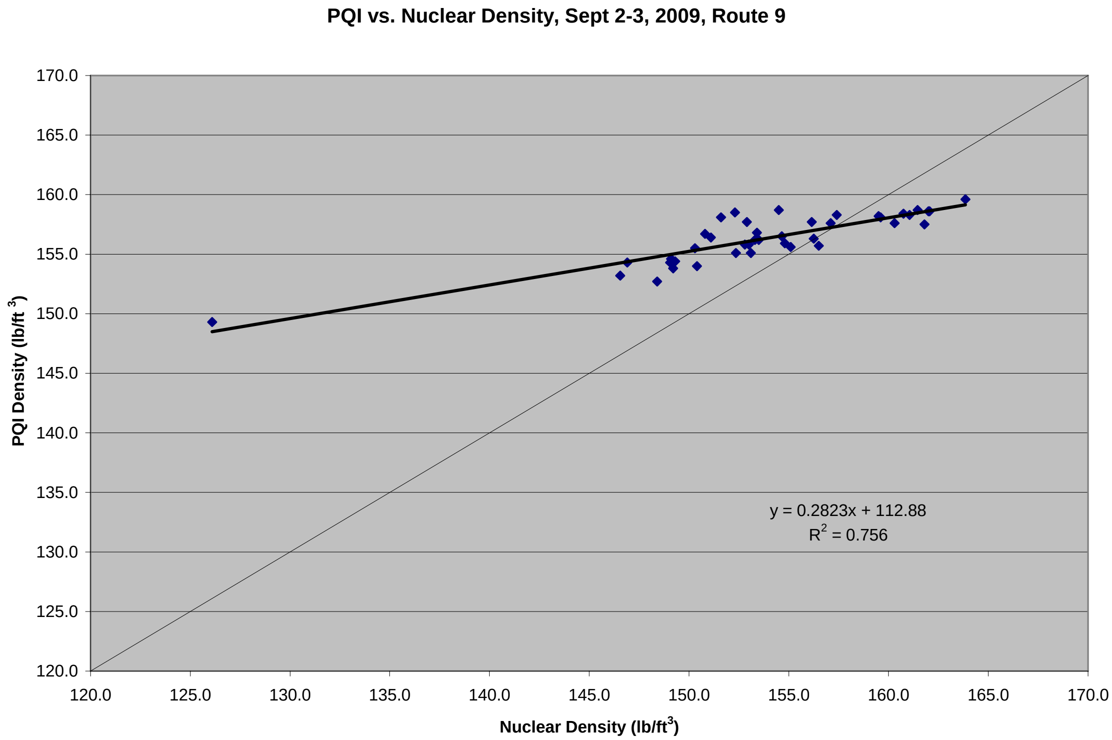

FIGURE 13 Project 172-390A, Scatter Plot of PQI versus Nuclear Gauge Density

On September 16, 2009, the PQI was compared to another nuclear gauge, owned and operated by the contractor. This was a Seamans Model C-200 nuclear gauge. The nuclear density gauge was operated in the same manner as the nuclear gauge operated at the other projects described above.

In total, ten companion density measurements were made and are presented in Table 11. A scatter plot is presented in Figure 13. The linear association between the PQI and nuclear gauge was strong, as the r^2 value was 0.87. The slope of the regression line was again flat (0.38) relative to the ideal (1.00).

TABLE 11 Nuclear Gauge (Contractor) Density and PQI Density Measurements

Sample ID	Nuclear Density Reading 1 (lb/ft^3)	Nuclear Density Reading 2 (lb/ft^3)	Nuclear Density Average (lb/ft^3)	PQI H20 Number	PQI Temp (F°)	PQI Density (lb/ft^3)
0100-0001	159.7	161.6	160.7	6.5	66.7	159.3
0100-0002	148.3	149.3	148.8	5.2	77.8	154.5
0100-0003	161.5	159.7	160.6	5.7	68.6	158.2
0100-0004	156.7	156.0	156.4	5.3	74.4	157.2
0100-0005	157.7	156.2	157.0	5.2	64.0	158.7
0100-0006	143.9	143.8	143.9	4.6	81.2	152.3
0100-0007	156.9	156.0	156.5	8.1	75.6	157.5
0100-0008	161.2	160.2	160.7	5.3	64.7	159.3
0100-0009	158.7	159.4	159.1	4.3	77.6	158.8
0100-0010	160.3	158.7	159.5	4.2	66.6	156.6

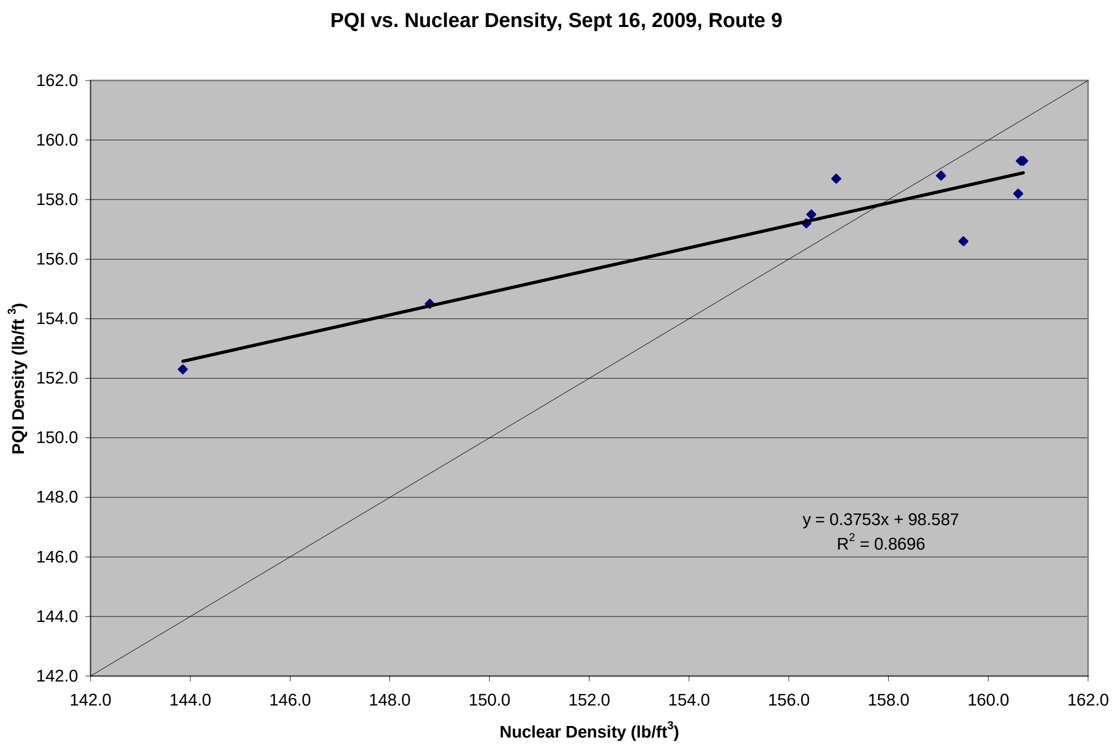

FIGURE 14 Scatter plot of PQI versus nuclear density for tests performed the night of September 16-17, 2009.

Project 173-405C

This was a pavement rehabilitation project on State Route 40 in North Haven. On the night of September 8, 2009, companion density measurements were made between the

PQI and a CPN Model MC-3 (#559) nuclear gauge, owned and operated by ConnDOT. The results of these tests are presented in Table 12 and Figure 15. Again, the gauges corresponded well to one another ($r^2 = 0.78$). The slope of the regression line in this instance was not quite as flat as the others, but still was only 0.50. Note: this was not the same CPN Model MC-3 gauge that was used for the other projects.

TABLE 12 Nuclear Gauge Density and PQI Density Measurements on Project 173-405C

Sample ID	Nuclear Density Reading 1 (lb/ft^3)	Nuclear Density Reading 2 (lb/ft^3)	Nuclear Density Average (lb/ft^3)	PQI H20 Number	PQI Temp (F°)	PQI Density (lb/ft^3)
0100-0004	153.5	154.4	154.0	8.9	134.8	154.2
0100-0005	154.6		154.6	8.9	141.7	154.4
0100-0006	152.5		152.5	9.1	168.0	153.2
0100-0007	151.7		151.7	9.3	168.3	153.6
0100-0008	147.9		147.9	8.3	150.4	150.8
0100-0009	151.0		151.0	9.6	149.6	153.6
0100-0010	151.4		151.4	9.7	146.4	154.6
0100-0011	151.6		151.6	9.4	158.9	153.3
0100-0012	155.5		155.5	8.4	115.4	154.5
0100-0013	156.9		156.9	10.6	123.4	156.6
0100-0014	153.3		153.3	10.4	140.0	155.0
0100-0015	155.9		155.9	9.7	115.4	155.7
0100-0016	154.3		154.3	9.7	120.1	154.9
0100-0017	154.3		154.3	9.3	123.6	154.4
0100-0018	154.3		154.3	9.5	124.3	154.4

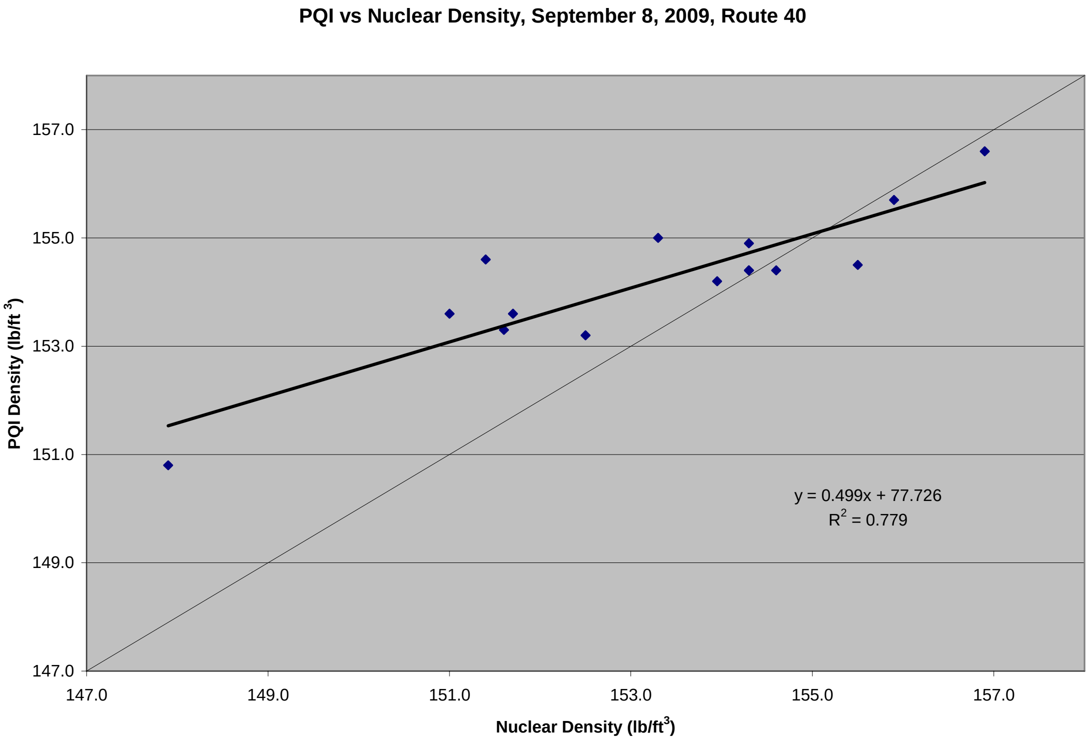

FIGURE 15 PQI density versus nuclear gauge density scatter plot for Project 173-405C.

Project 172-389E

Project 172-389E was for pavement rehabilitation on State Route 195 in Mansfield. The pavement tested was a 12.5-mm SuperPave mix used for the top/surface layer. The top/surface layer was placed 1.5 to 2 inches thick. It consisted of crushed gravel coarse aggregate and natural/gravel sand blend fine aggregate.

PQI and nuclear gauge test results are presented in Table 13, and a scatter plot of PQI versus nuclear gauge density is presented in Figure 16. The linear association between the PQI and nuclear gauge was not as strong here as it was for other projects, but some relationship did exist.

The r^2 value was 0.37 and the slope was 0.20. This same scatter plot is split on production dates in Figure 17. It is notable that the day of production (Sept 29) with the greatest number of data points (22) and greatest range had the highest r^2 value (0.51).

TABLE 13 Nuclear Gauge Density versus PQI Density Measurements on Project 172-389E

Location	Nuclear Density Reading 1 (lb/ft^3)	Nuclear Density Reading 1 (lb/ft3	Nuclear Density Average (lb/ft^3)	PQI Density (lb/ft^3)	PQI H2O Number	PQI Temp (°F)	Date
1	145.9	145.6	145.8	147.4	3.3	122.9	9/28/2009
2	147.0	146.8	146.9	148.6	2.9	118.5	9/28/2009
3	145.4	144.8	145.1	147.2	4.3	117.4	9/28/2009
4	148.1	147.2	147.7	147.3	3.6	123.2	9/28/2009
5	146.0	146.4	146.2	147.9	3.0	126.0	9/28/2009
6	151.2	149.7	150.5	148.5	3.8	115.3	9/28/2009
7	146.8	146.3	146.6	147.5	3.0	121.3	9/28/2009
8	144.2	143.6	143.9	147.4	2.6	127.1	9/28/2009
9	147.2	146.8	147.0	146.4	2.8	120.9	9/28/2009
10	148.7	147.8	148.3	148.5	2.6	125.2	9/28/2009
11	148.3	148.8	148.6	148.9	2.5	127.5	9/29/2009
12	146.3	146.4	146.4	148.1	2.8	129.3	9/29/2009
13	146.6	146.6	146.6	147.9	2.4	139.3	9/29/2009
14	147.3	148.3	147.8	148.5	2.7	122.3	9/29/2009
15	146.9	145.9	146.4	146.4	2.8	124.5	9/29/2009
16	148.3	147.9	148.1	148.5	2.9	138.4	9/29/2009
17	147.6	150.4	149.0	148.5	2.7	129.5	9/29/2009
18	146.4	147.6	147.0	148.3	2.7	126.9	9/29/2009
19	144.7	146.6	145.7	148.6	2.5	139.1	9/29/2009
20	144.0	144.3	144.2	147.5	2.1	129.9	9/29/2009
21	147.9	147.3	147.6	148.1	2.3	123.4	9/29/2009
22	143.4	142.8	143.1	147.2	2.6	133.5	9/29/2009
23	149.3	147.9	148.6	148.5	2.8	106.1	9/29/2009
24	148.2	148.0	148.1	149.2	2.1	107.2	9/29/2009
25	146.4	144.7	145.6	147.9	2.8	104.9	9/29/2009
26	149.5	149.7	149.6	148.9	2.4	107.6	9/29/2009
27	149.7	149.7	149.7	149	3.3	98.4	9/29/2009
28	146.2	146.4	146.3	148.6	2.4	103.8	9/29/2009
29	145.2	144.2	144.7	147.3	2.5	103.2	9/29/2009
30	146.4	148.2	147.3	148.2	3.1	95.4	9/29/2009
31	146.9	146.4	146.7	148.1	2.9	98.5	9/29/2009
32	141.3	142.7	142.0	147.4	2.2	98.6	9/29/2009
33	145.0	147.0	146.0	148.6	2.3	85.6	9/30/2009

TABLE 13 Gauge Density versus PQI Density Measurements on Project 172-389E (cont'd)

Location	Nuclear Density Reading 1 (lb/ft^3)	Nuclear Density Reading 1 (lb/ft3	Nuclear Density Average (lb/ft^3)	PQI Density (lb/ft^3)	PQI H2O Number	PQI Temp (°F)	Date
34	148.7	147.2	148.0	148.9	1.8	93.9	9/30/2009
35	147.4	146.8	147.1	148.5	2.1	107.2	9/30/2009
36	150.3	149.0	149.7	148.5	2.5	105.7	9/30/2009
37	146.0	147.1	146.6	147.9	2.4	110.6	9/30/2009
38	145.8	146.0	145.9	148.2	2.2	128.3	9/30/2009
39	149.2	148.4	148.8	149.3	2.4	120.3	9/30/2009
40	149.5	151.0	150.3	148.9	2.2	131.1	9/30/2009
41	150.2	151.1	150.7	149.1	2.5	121.3	9/30/2009
42	147.3	150.1	148.7	148.4	2.4	123.5	9/30/2009
43	144.3	145.2	144.8	147.7	1.7	76.6	10/1/2009
44	147.3	145.7	146.5	147.6	2.2	78.1	10/1/2009
45	140.6	143.0	141.8	147.6	2.6	94.0	10/1/2009
46	147.7	146.6	147.2	148.6	2.5	99.4	10/1/2009
47	142.7	143.6	143.2	148	1.8	96.4	10/1/2009
48	142.8	150.9	146.9	146.1	2.1	105.0	10/1/2009
49	144.7	143.9	144.3	147.9	1.8	97.7	10/1/2009
50	148.1	147.4	147.8	148.2	2.1	107.2	10/1/2009
51	144.0	144.5	144.3	147.7	2.8	116.6	10/1/2009
52	145.0	143.8	144.4	148	2.5	108.2	10/1/2009
53	147.6	145.1	146.4	147.7	2.1	106.7	10/1/2009
54	142.6	142.8	142.7	146.9	2.4	104.8	10/1/2009
55	146.3	145.6	146.0	147.9	2.7	110.0	10/1/2009
56	142.6	142.7	142.7	147.2	2.1	98.9	10/1/2009
57	146.3	145.6	146.0	147.9	2.6	104.1	10/1/2009
58	144.8	144.0	144.4	147.9	1.8	98.4	10/1/2009

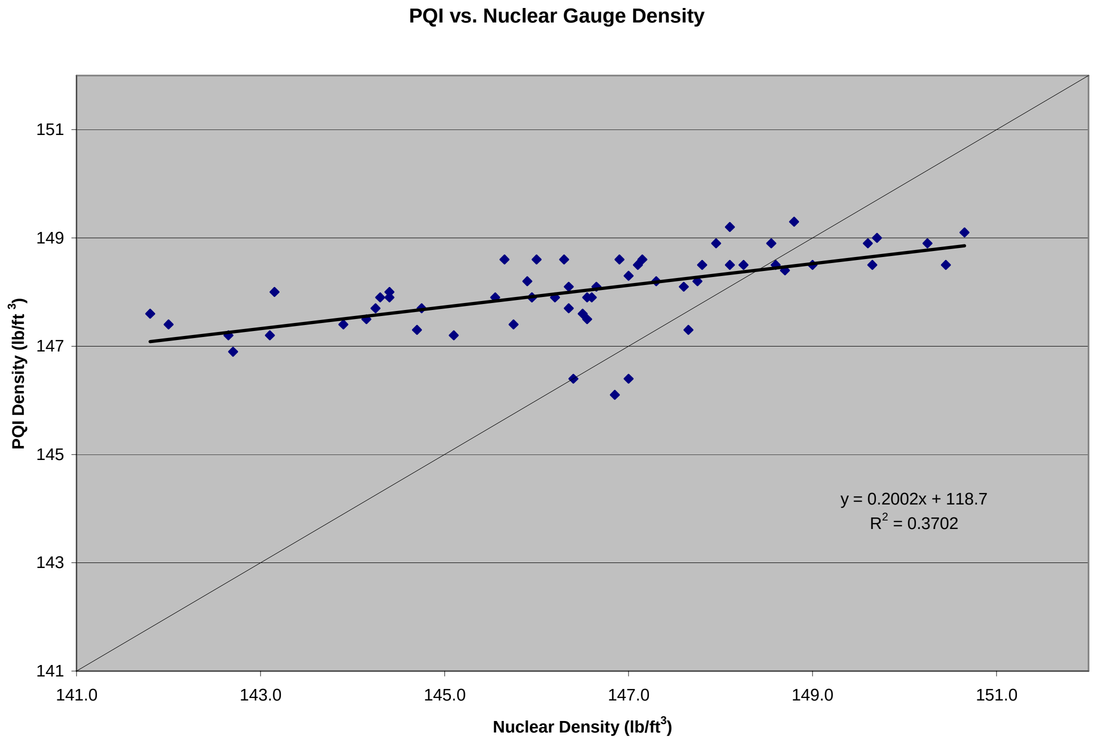

FIGURE 16 PQI density versus nuclear gauge density scatter plot for Project 172-389E.

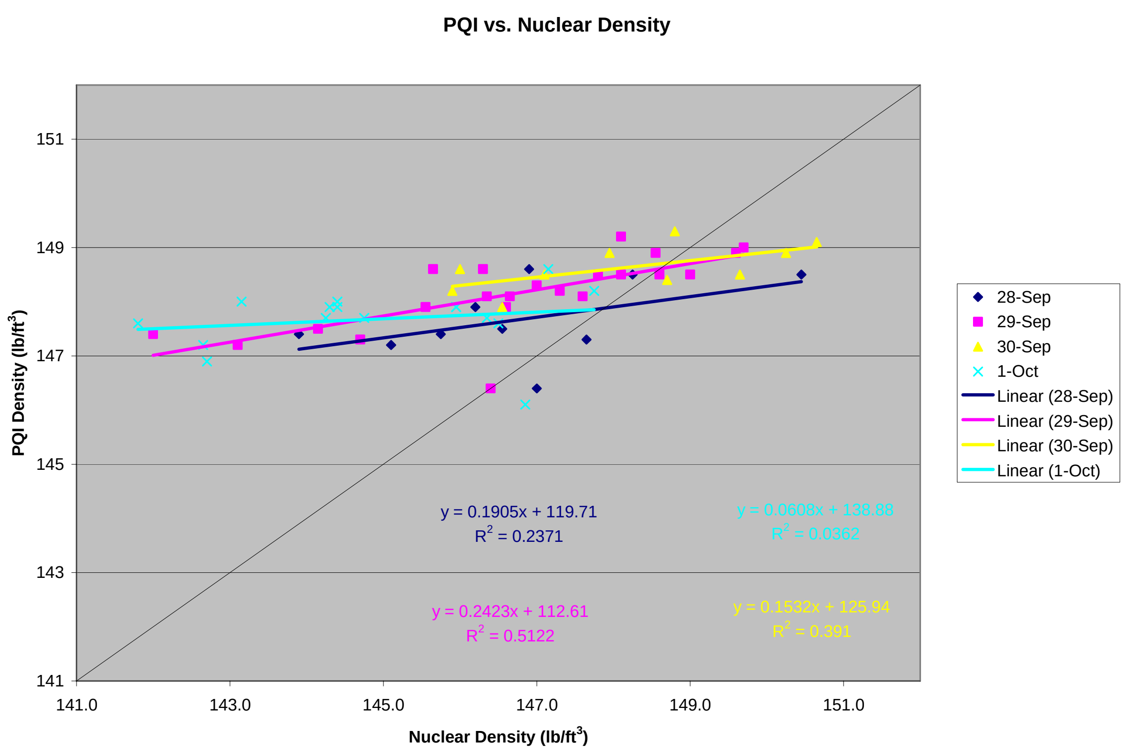

FIGURE 17 PQI density versus nuclear gauge density scatter plot for Project 172-389E for individual days of production.

Tracking Density behind the Screed

In order to see if the PQI could be used to track large density changes during compaction, several measurements were taken behind the screed as the mat was compacted. The first measurement was taken immediately after placement, prior to any rolling. In this instance, the initial density was measured at 143.4 lb/ft^3. The second measurement was taken immediately following the first pass with the vibratory breakdown roller. Most of the compaction was achieved at that point, as the PQI measured 149.0 lb/ft^3. The third reading was taken immediately after the first pass with the intermediate vibratory roller. The density was measured to be 150.3 lb/ft^3 at that point, which was approximately the maximum density achieved. This instance presented was typical of others, as the procedure of monitoring compaction was repeated several times on various projects.

Another reason for doing this was to track the H2O Number during compaction, since it was previously theorized that high H2O Numbers owed to water introduced onto the mat via the rollers. It was found that while H2O Numbers would spike temporarily after roller compaction, the general trend was for H2O Number to drop as the mat cooled.

Invariably, it was found that by the time normal QC testing was performed, H2O Number would drop below 10

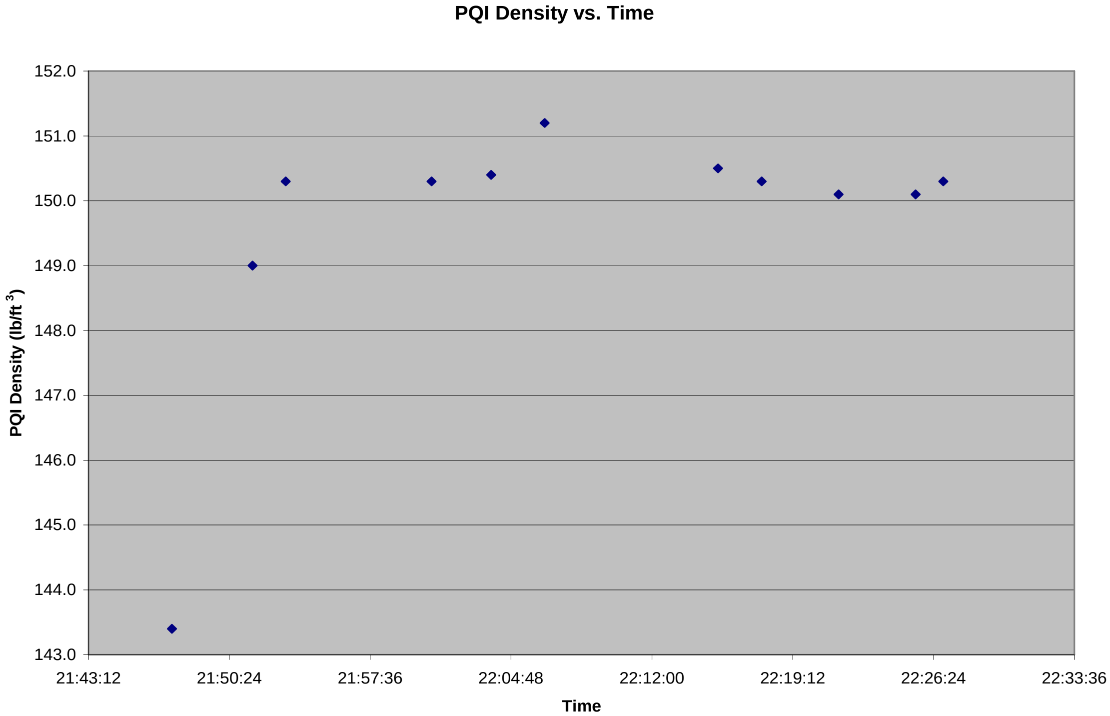

FIGURE 18 PQI Density versus Time (typical)

TABLE 14 PQI Density Measurements taken during Compaction

Measurement	Time	H20 Number	Temp.	Density	Comment
1	21:47:28	11.5	245.3	143.4	Immediately behind screed, prior to any rolling
2	21:51:35	11.9	197.2	149.0	Immediately after 1st pass of vibratory breakdown roller
3	21:53:17	11.7	214.8	150.3	Immediately after 1st pass of vibratory intermediate roller
4	22:00:44	10.9	194.0	150.3	Immediately after 2nd pass of vibratory intermediate roller
5	22:03:47	10.6	183.6	150.4	Immediately after 3rd pass of vibratory intermediate roller
6	22:06:31	10.2	168.3	151.2	Immediately after 4th pass of vibratory intermediate roller
7	22:15:23	9.6	152.2	150.5	no rolling since last reading
8	22:17:37	9.5	150.8	150.3	no rolling since last reading
9	22:21:33	9.1	139.8	150.1	no rolling since last reading
10	22:25:29	8.9	133.5	150.1	After 1st pass of finish static roller
11	22:26:54	9	132.1	150.3	After 2nd pass of finish static roller

CONCLUSIONS

Based upon the results of this study, it is concluded that the updated PQI Model 300 tracked pavement density reasonably well, with some limitations that will be described below.

For Project 28-197, the H20 Number remained below 5 for all of the PQI density measurements. This was thought to be optimum conditions for testing because previous research had shown that density measurement accuracy tends to diminish when the H20 Number exceeds 5 *(3)*. PQI densities corresponded well to both core densities and nuclear gauge densities in this instance. The average coefficient of determination (r^2) relating PQI density to core density for the five Project 28-197 sites was 0.69. Similarly, the average r^2 value comparing PQI density to nuclear gauge density for the five sites was 0.59. The slope of the regression lines in comparing PQI density to both core density and nuclear gauge density tended to be flat.

For Project 171-344D, all H20 Numbers were greater than 15. In this instance, PQI densities did not correspond very well to core densities. This bears out what should be expected insofar as the PQI's performance. It worked well for lower H20 Numbers observed on Project

28-197, but not so well for higher numbers observed on Project 171-344D.

The PQI was shown to track density well, relative to nuclear gauge density, at higher H20 Numbers at Projects 172-390A and 173-405C. At Project 172-390A, H20 Numbers ranged from 3.3 to 8.4 and the r^2 values were 0.76 and 0.87 between the PQI and two different nuclear gauges, respectively. Then at Project 173-405C, H20 Numbers ranged from 8.3 to 10.6 and the r^2 value was 0.78 between the PQI and a nuclear gauge. Again, the slope of the regression line tended to be flat in plotting PQI density versus nuclear gauge density. Therefore, consistency in how PQI and nuclear gauge densities corresponded to one another was evident.

At Project 172-389E, PQI and nuclear gauge densities did not correspond quite as well, but a linear relationship was still evident.

The theory that the existence of high H20 Numbers owe largely to water from the rollers was dispelled. It was repeatedly shown that H20 Number readings steadily decreased during compaction. While it is true that water is introduced onto the mat during compaction, it appeared that the rate of evaporation exceeded the rate at which water was introduced by the rollers. This was evident in tracking H20 Numbers during compaction operations.

The magnitude of the H20 Number did vary from project to project. For Project 28-197, the value was always less than 5 when density measurements were performed, whereas the value was between 5 and 10 for other projects. By the time compaction operations were complete and pavement was ready for density testing, H20 Number readings were generally less than 10.

RECOMMENDATIONS

Based upon the above conclusions, the updated PQI Model 300 appears to be adequate for contractor QC for instances where the H20 Number indicated on the gauge is less than 10. ConnDOT should permit contractors to use the PQI for QC. To ensure the most accurate density measurements, manufacturer calibration procedures should be followed.

The PQI is best used during construction immediately after compaction. Once a pavement has cooled and is subsequently exposed to storm water, sufficiently low H20 Numbers (less than 10) are more difficult to obtain. It appears that without the heat that exists on the mat during compaction, the pavement layer has little capacity to remove moisture. Water on the surface will evaporate via the sun and wind, but beneath the surface the asphalt tends to act like a sponge, not allowing sufficient water to infiltrate deeper into the pavement structure and not allowing it to evaporate because it is not exposed. Special attention should be given when operating the PQI on pavements that have been open to traffic and exposed to storm water, as sufficiently low H20 Numbers will be more difficult to achieve.

Since the slope of the regression line comparing PQI density to core density was flat, caution is urged in interpreting results. Pavement density may actually be lower than the value shown on the PQI gauge. At this time, the PQI provides more of a relative number for evaluating density. Therefore, contractors should bear this in mind, or they may face penalties once core density test results are presented.

PQI and nuclear gauges are not recommended for agency acceptance testing. Cores should be taken in the field and tested in a laboratory for this purpose.

REFERENCES

1. Henault, John W., *Field Evaluation of a Non-nuclear Density Pavement Quality Indicator*, Final Report, Report No. 2227-F-01-3, Connecticut Department of Transportation, 2001.
2. Henault, John W., *Evaluation of the Nonnuclear Density Gauge for Quality Control of Hot-Mix Asphalt*, Proposal Number P-09-6, Connecticut Department of Transportation, July 2009.
3. Romero, Pedro, *Evaluation of the Next Generation PQI Model 300*, Final Draft Report, Contract number DTFH61-00-P-00549, Bituminous Mixtures Laboratory Turner-Fairbank Highway Research Center, 2000.
4. Romero, P. and F. Kuhnow, Evaluation of New Nonnuclear Pavement Density Gauges with Data from Field Projects, In *Transportation Research Record: Journal of the Transportation Research Board, No. 1813,* Transportation Research Board of the National Academies, Washington D.C., 2002, pp 47-54.
5. Romero, P., *Evaluation of Non-Nuclear Density Gauges to Measure Density of Hot-Mix Asphalt Pavements*, Pooled Fund Study, Final Report, The University of Utah, Department of Civil and Environmental Engineering, July 2002.

6. Williams, S.G. and K.D. Hall, Critical Factors Affecting Field Determination of Hot-Mix Asphalt Density Using Nonnuclear Devices, In *Transportation Research Record: Journal of the Transportation Research Board, No. 2081*, Transportation Research Board of the National Academies, Washington D.C., 2008, pp. 150-157.