Final Report

Title:	Field Evaluation of the PQI Model 300
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Executive Summary

The Pavement Quality Indicator (PQI) model 300 was evaluated using 76 field projects in the states of Connecticut, Maryland, Minnesota, New York, Oregon, and Pennsylvania. In each project, side-be-side comparisons were made of pavement density obtained using the PQI, a nuclear density gage and cores. Each project follow different protocols depending on the quality control practices used on each state.

The correlation coefficient between the densities obtained from the PQI and cores was used to quantify the effectiveness of the gage. Based on the data from all the projects evaluated, the correlation between PQI density and cores was above 0.90 in 17 percent of the projects. The correlation was below 0.71 in 60 percent of the projects. By comparison, the density obtained using a nuclear gage had a correlation coefficient with cores greater than 0.90 in 29 percent of the projects and a correlation coefficient below 0.71 in 40 percent of the projects.

Based on the poor performance observed in the PQI, as determined from both the correlation coefficient and relative comparisons with nuclear density gages, it is concluded that the PQI-300 **is not** a reliable gage to determine pavement density. Until further gage adjustments are made, the only reliable method to determine pavement density is by taking cores and analyzing them in the laboratory.

Problem Statement

During construction of hot-mix asphalt pavements, density measurements are taken at various stages to monitor the effect of the rollers and ensure proper compaction. The most commonly used device for measuring density is the nuclear density gage. The nuclear density gage requires licensing, training, and specialized storage due to the radioactive source contained within the equipment. An alternative device that does not require a radioactive source, or is destructive, is desired. The Pavement Quality Indicator (PQI) has the potential to be such device. Research to determine the capabilities and accuracy of this non-nuclear gage currently on the market is needed.

Maryland State Highway Administration (MDSHA) initiated a pooled fund study with participation from Pennsylvania, New York, Connecticut, Minnesota, and Oregon Department of Transportation as well as the Federal Highway Administration (FHWA). The objective of the pooled fund study was to evaluate the PQI using laboratory and field data and provide a recommendation for its use.

Background

Around 1998, the original PQI device was introduced to measure uniformity in pavement joints. This device was based on the changes produced in an electromagnetic field as a result of changes in density. Immediately, the possibility of using this device to obtain relative density was suggested. A study was conducted at the FHWA's Turner-Fairbank Highway Research Center (TFHRC) to determine if the original PQI device, now called PQI-100, could be used to measure density. The results showed that the PQI-100 had serious problems when moisture was present in the asphalt mixture. A prototype version was tested at that time that was able to apply a correction factor based on the amount of moisture detected. This device showed promise in solving the problems associated with moisture. An updated version of the PQI device (Model 300) was introduced in late 1999 that incorporated advances from the 1998 prototype plus new algorithms based on data collected by the manufacturers of the PQI device (TransTech Systems Inc, Schenectady, NY).

The PQI model 300 was evaluated at FHWA's TFHRC in 1999 using different materials obtained from New York State Department of Transportation. The results were encouraging in showing that the PQI-300 could measure relative density of hot-mix asphalt. The conclusions of this laboratory study were:

1. The PQI-300 device can be used to determine relative changes in density[1] of asphalt concrete under constant temperature and humidity conditions for a single mixture type.
2. Changes in nominal maximum aggregate size produced only small changes in the density relation (slope) between the PQI and the slab density. Thus, it might be possible to use the same calibration factor for different aggregate size as long as the same asphalt binder is used.
3. The relationship between PQI readings and density is different for different aggregate sources. It is necessary to calibrate (i.e., determine both slope and offset) the device for individual mixtures.

[1] Terms such as density, relative density, and relative change in density are used throughout this report. The PQI device does not directly measure density. It measures changes in an electromagnetic signal that are proportional to changes in material density. It can, theoretically, be used to determine density by knowing the change in signal reading from a known density value and the proportionality constant for that material. The term 'relative density' is used to imply that the value is relative to an accepted density used as the baseline; not an absolute measurement in itself.

4. Small amounts of surface moisture in the asphalt concrete do not affect the ability of the PQI-300 device to provide a relative measure of density as long as the moisture level remains constant. Determination of any calibration constants must be done under constant moisture levels.
5. High contents of internal moisture continue to provide problems with the density determined using the PQI-300 device. However, the H2O value displayed is an indicator of potential moisture problems.

These results are shown graphically in figures 1 and 2. The complete results can be found in the report titled Laboratory Evaluation of the PQI Model 300 dated November 2000 (1).

From the laboratory study, it was clear that, in order to determine the density of hot-mix asphalt, two conditions must occur; i) the PQI-300 needs to be calibrated to each aggregate and binder type, and ii) environmental conditions such as temperature and moisture must remain constant throughout the measurements. The only way to know if these two conditions could be controlled during field operations was to test the device during the 2000 construction season.

A meeting was held on April 2000 at Maryland Department of Transportations to discuss the field evaluation of the PQI device. Members of the Technical Working Group representing the states of Connecticut, Maryland, Minnesota, New York, Oregon, and Pennsylvania, as well as FHWA, were in attendance and received training from TransTech System Inc. in the proper use of the PQI device. All participants received a training certificate similar to the one shown in figure 3. This training assisted in making certain that the participants had the knowledge to properly use the PQI during the field trials.

FIELD EVALUATION

The field evaluation of the PQI device was tailored to the specific practices used by each of the participant states. This implied that the selection of test projects, the selection of materials used for comparisons, the number of sites within each project, and the location of each site was determined by each State according to their own established procedures. It is understood that some experimental factors could be confounded if each State follows its own procedures and that, in some cases, not enough data would be available for a rigorous analysis. However, the field evaluation was meant to complement, not duplicate, the laboratory evaluation. Furthermore, by allowing each State to follow its on procedures, more projects could be incorporated and, more importantly, each State would be satisfied that the PQI-300 could be incorporated into their standard procedures to determine pavement density.

Density Measurements

Density was measured in the field using the PQI device according to the procedures recommended by the manufacturer. When a site was selected for measurement, five reading were taken using the PQI device. The first reading was taken right on top of the selected spot. The other 4 readings were taken around the same spot at approximately the 2, 5, 8, and 11 o'clock position (shown in figure 4). The readings were recorded independently (i.e., not averaged) along with the millivolt reading (actual signal recorded by the device) and a moisture factor (called H20 number). A nuclear gage was used at the same spot to measure density. Two or four density readings were taken using nuclear gage methods approved by each state DOT. Once all gage readings were taken, cores were obtained in as many locations as possible for comparison. The number of cores varied from project to project. The cores were transported to the laboratory where their bulk specific gravity was measured according to AASHTO T-166. Using the specific gravity, the density was obtained by multiplying this value by the density of water (62.4 pcf). This density, referred in this report as core density, is the standard value used for comparing the results from the different gages.

Each of the participant states recorded the data mentioned above and sent it electronically to be incorporated into a database for combined analysis. Over 75 projects were used for this evaluation. However, given the different practices used by each State Highway Agency when collecting density measurements, some projects contained more information than others.

Comparisons Between Core Density and Gage Density

In an ideal situation, the density recorded by any gage device will match the density obtained from the cores. This situation can be visually explained using two plots. Figure 5 shows that an increase or decrease in core density is match by a proportional change in gage density. Figure 6 shows that gage density, when compare against core density, plots along a 45-degree line. In other words, the gage density can 'track' core density. Unfortunately, in most field experiments the match between gage density and core density is not perfect. Thus, mathematical parameters must be developed for comparison purposes. Common statistical methods of comparison such as t-tests are not appropriate in this study due to the lack of replicate values for core density (core density is made up of one value while gage density is made up of 5). Instead, 4 parameters were chosen to quantify the relationship between core density and gage density. The parameters were the Average Difference, the Range, the Coefficient of Correlation, and the Slope of the regression between gage and core density. Out of these parameters two, correlation and slope, were used for comparisons. The meaning of each parameter and how they are used for comparisons is discussed in the following section.

Average Difference

The average difference is a method to calculate the average error between gage density and core density. Mathematically, the average difference is calculated using the following equation,

$$Ave.Diff = \frac{\sum((core - gage)^2)^{1/2}}{n}$$

It is required that the average difference between gage density and core density is small. Thus, this parameter is commonly cited as verification that a device is capable of measuring density. However, average difference does not take into account the effect of the offset value (calibration) and cannot answer the fundamental question: can the gage 'track' changes in core density? To illustrate this point, figure 7 shows a comparison between core density and two gages. Gage #1 perfectly matches an increase or decrease in core density with a proportional change in gage density; however, it has an offset of 5 pcf (i.e., always reads 5 pcf lower). The average difference for this gage is 5 pcf. On the same graph, Gage #2 always reads the same value (140 pcf), yet it has an average difference of 1.5 pcf. Clearly, Gage #1, with proper calibration, is better than Gage #2.

Range

The range of the readings can be used to determine sensitivity of the gage independently of the offset. It is calculated by subtracting the minimum density from the maximum density. This is particularly important when the gage provides relative density (as in the case of the PQI). However, a small range, in itself, does not imply a defective gage. It only indicates whether the 'gain' or signal amplification is adequate. The manufacturer, or the user, can adjust the gain with knowledge of two or more density values (i.e., calibration). In some cases, a low gain might be used to decrease the gage's sensitivity to factors such as water and temperature. This would indicate a problem with the algorithms used to compensate for these two variables. Figure 8 shows a comparison between two gages with different ranges. Gage #1 has a range of 4 pcf while Gage #2 has a range of 16 pcf. The graph shows that both gages 'track' the changes in core density and could be adjusted to provide the correct value. Thus, this parameter can not be used for comparisons.

Coefficient of Correlation

The coefficient of correlation is a mathematical term used to describe the relationship between two variables (e.g., core density and gage density). If gage density increases (or decreases) when core density increases (or decreases), then it can be said that the gage 'tracks' core density and has high correlation. In linear regression the coefficient of correlation is often expressed as r-squared and is used to indicate how close the data is to the predicted values. Mathematically, the coefficient of correlation is calculated by multiplying the normalized density according to the following equation.

$$r = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{Core - Ave.\_Cores}{S.D.\_Cores}\right)\left(\frac{Gage - Ave.\_gages}{S.D.\_Gages}\right)$$

The values of the coefficient of correlation range between +1 and –1. The closer this value is to +1, the better correspondence there is between gage density and core density with negative values indicating a reverse trend. The coefficient of correlation concentrates on how well the gage ‘tracks’ core density and it is insensitive to offset and range. Figure 9 shows a comparison between two gages. Gage #1 is able to ‘track’ the changes in core density and has a correlation of +1 even though it has an offset of 3 pcf and has half the range in density values. Gage #2 does not ‘track’ core density and has a correlation of 0.42 even though it has the same mean, a small average error and similar range as the cores.

Slope

The slope of the regression line between core density and gage density can be used to compare results from gage measurements. Ideally, if gage density is plotted against core density, all points should fall along the line of equality (45 degree line) as in figure 6. This line has a slope of 1, indicating that for every increase in core density there is an equal increase in gage density. The slope is insensitive to the offset error but is very dependent of the ‘gain’ or constant of proportionality used. This parameter can indicate the general trend of the measurements (e.g., general increase in gage readings) thus it has limited capabilities when the range of data is small. However, it can complement the coefficient of correlation to evaluate the data.

Effect of Sample Size

It is well established that the density of asphalt pavements is not constant throughout the mat. Also, there are documented variations in the measurement methods used to determine this density (e.g., precision statements in AASHTO T166). Therefore, any density measurement must consider the effect of statistical variations or ‘noise’ in the data. Furthermore, the number of data points available for comparison will have an effect on any parameter used for evaluation (small sample size). Unfortunately, the amount of cores available for comparisons in some projects was below the desired minimum. Density from a nuclear gage was not reliable enough to be used for comparisons as originally planned. The effect of the small sample size should be considered when looking at results from individual projects. However, there were over 75 projects evaluated providing some confidence that the conclusions obtained from this study are reasonable.

Data Analysis

The data received from each state was incorporated into a database for analysis. The 5 PQI readings taken around a point were averaged into a single number that represented the PQI gage density at that location. The PQI density was corrected for offset error (i.e., a constant was added so that the average PQI density was the same as the core density for that project). As previously discussed, this reduced the average error but did not affect the correlation between gage and core density. The nuclear density gage readings were also averaged at each site; however, since nuclear gage provides absolute readings (i.e., not the change from a known value) no offset was added.

The objective of this study was to evaluate the PQI-300 device, not the nuclear density gage. However, to gain perspective of the ability of the PQI device to measure density, the data was compared to the density obtained using a nuclear density gage. Since both gages were used on the same location, any confounding errors in the PQI values should also be present in the nuclear gage values. In other words, a reference can be set such that the PQI must result in comparisons that are as good as existing nuclear density gages.

On March 2001, a meeting was held at Maryland Department of Transportation. At that meeting, the complete set of data used to generate this report was given to each of the participant State Highway Agencies, the FHWA, and Transtech System, Inc. The complete set of data is too big to be included in this report thus only a summary of the correlation and slope is shown. A summary of all projects evaluated is given in Appendix I. The complete set of data is available from each participant state or from the author upon request.

A draft of this report was made available to TransTech System, Inc. prior to distribution so that they could comment of the results and provide details on how they plan to improve the device. Their comments are included in Appendix II.

Evaluation of data

Two parameters were selected for evaluation based on the previous discussion, i) the correlation coefficient between core and gage density and ii) the slope between core and gage density. A correlation coefficient greater than 0.90 was considered an indication of good ‘tracking’ between gage and cores density. A correlation coefficient of less than 0.71 (r-squared of 0.5) was considered poor. Similarly, slopes closer to 1 are desired. An arbitrary range of 0.75 to 1.25 was selected as an indication of good correspondence between gage and core density. A slope value of less than 0.25 or greater than 1.75 was selected to indicate poor agreement between core and gage density.

Table 1 shows the number of projects evaluated in each state for which there were cores available for comparisons. The table also shows the number of projects in which the gage performed adequately (correlation greater than 0.90 and slope between 0.75 and 1.25) and the number of projects in which the gage did not perform at all (correlation less than 0.71 and slope lower than 0.25 or greater than 1.75). As explained, side-by-side comparisons of PQI and nuclear density gage are shown.

Summary

Based on table 1, and taking into account all 76 projects where cores were available for comparison, the PQI density correlates well (correlation greater than 0.90) with core density in only 17 percent of the projects. In contrast, in 60 percent of the projects the correlation between PQI and core density was poor (i.e., less than 0.71). The table shows that in some states the PQI did slightly better than other, but even in those states, good correlations occurred in less than 30% of the projects.

When evaluating the PQI based on the slope, the slope between PQI density and core density was between 0.75 and 1.25 in 11 percent of the projects. In 47 percent of the projects the slope was outside the desired values.

The nuclear density gage did not show perfect results either, however, in all categories it did better than the PQI device. The nuclear density gage correlated well with core density in 29 percent of the projects and had a poor correlation in 50 percent of the projects. The slope between the nuclear density gage and core density was acceptable in 42 percent of the projects and outside the desired values in 21 percent of the projects.

Figure 10 shows a graphical representation of the data shown in table 1 for the correlation coefficient. Figures 11 and 12 show two typical cases, one with high correlation between the PQI and the cores and one with a low correlation.

Discussion

Analysis of the data collected indicates that the PQI density correlated to core density less than 20 percent of the time. In Oregon, the PQI had the best performance where it correlated well to core density in 29 percent of the projects. Table 2 shows a comparison between PQI and nuclear gage. Based on the table, the PQI failed to perform at the same level as the nuclear density gage.

These results were unexpected given the encouraging data obtained in the laboratory. Many factors could have contributed to the poor field performance in the PQI device. Some of the factors might include moisture, temperature, and lack of range. Existing algorithms within the PQI-300 device are supposed to correct for these factors; however, the algorithms are based on limited data. Using the vast amount of data collected in this project, updated algorithms could be incorporated into the device. Only density averages were evaluated in this report. More research is needed to completely evaluate the data collected in this study, including the millivolts and H20 number.

Two issues that were suggested during the laboratory study and might explain the low correlations are the calibration procedure and the lack of a standard value. During field calibration only the offset is adjusted. Laboratory data showed that it is necessary to adjust both the offset (intercept) and the constant of proportionality (slope) for each mixture. A calibration standard is also needed to ensure that the PQI is not only reading the correct value but also that different devices give the same answer regardless of the location or operator. Perhaps future advancements in the gage can address these issues.

Summary of Results

Based on the data analyzed from 6 different state highway agencies and over 75 field projects the following results are obtained:

1- The density obtain from the PQI-300 had a high correlation with core density obtained using the method in AASHTO T-166 in 17 percent of the projects.
2- The density obtained from the PQI-300 did not correlate with core density (obtained using the method in AASHTO T-166) in 60 percent of the projects.
3- The slope of a linear regression between PQI-300 density and core density was in the range of 1 ± 0.25 in 11 percent of the projects.
4- The nuclear density gage did not provide perfect results either. However, it had better correlation with core density than the PQI-300.

Conclusion

The density of hot mix asphalt when placed on the road is one of the most critical parameters to control its quality. None of the two methods (nuclear density gage and PQI-300) evaluated provided a consistent alternative to taking cores. Until more research is performed on the algorithms used to obtain density by means of the Pavement Quality Indicator, the only acceptable method to obtain pavement density is taking cores and analyzing them in the laboratory.

Recommendations

Based on the results obtained from this study it is recommended that the PQI-300 **not** be used to obtain pavement density for quality acceptance until further improvements in the gage algorithms are made.

Further analysis of the data is recommended to provide answers for the low correlations between core density and PQI density.

Acknowledgements

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Disclaimer

The opinions, conclusions, and recommendations included in this report, are those of the author. They do not necessarily represent any State or Federal Highway Agency.

References

(1) Romero, P. Laboratory Evaluation of the PQI Model 300. Report to FHWA and the PQI Technical Group, November 2000.

Table 1 – Results from the PQI and Nuclear Density Gage

State	Number of Projects		PQI	Nuclear Gage
Connecticut[1]	☺	Corr. ≥ 0.90	2	5
	9	Slope within tolerances	0	4
	☹	Corr. < 0.71	4	3
		Slope outside tolerances	5	2
Maryland[2]	☺	Corr. ≥ 0.90	0	3
	11	Slope within tolerances	0	6
	☹	Corr. < 0.71	10	7
		Slope outside tolerances	9	2
Minnesota[3]	☺	Corr. ≥ 0.90	2	5
	15	Slope within tolerances	0	7
	☹	Corr. < 0.71	10	3
		Slope outside tolerances	9	1
New York[4]	☺	Corr. ≥ 0.90	3	2
	10	Slope within tolerances	0	3
	☹	Corr. < 0.71	6	5
		Slope outside tolerances	4	2
Oregon[5]	☺	Corr. ≥ 0.90	0 (0)	2 (2)
	7	Slope within tolerances	0 (0)	5 (5)
	☹	Corr. < 0.71	4 (5)	1 (2)
		Slope outside tolerances	3 (3)	0 (0)
Pennsylvania[6]	☺	Corr. ≥ 0.90	6	5
	24	Slope within tolerances	8	7
	☹	Corr. < 0.71	12	12
		Slope outside tolerances	6	9

See notes on the following page

Table 1 notes:

(1) Each project was separated into two groups, field data and calibration. Only the first group is used for comparisons.
(2) One of the projects (Hickory Bypass) expanded over different days. Since each day had different aggregates size and different blends, each day was treated as a separate project.
(3) One project (Carlton, 7/11/00) was not included in the analysis due to lack of core data available.
(4) One project (NY 219) expanded over several days. Each day was treated as a separate project.
(5) Numbers in parenthesis represent the results from sanded tests.
(6) One project (Tioga) expanded over several days. Each day was treated as a separate project.

Table 2 – Comparison between the PQI 300 and the Nuclear Density Gage

	PQI 300	**Nuclear Gage**
High Correlations, %	17	29
Slope within range, %	11	42
Low Correlations, %	60	40
Slope outside range, %	47	21

Table 2 notes:

High correlations refer to a correlation between gage density and core density greater than 0.90. Low correlations refer to a value less than 0.71.
Slope within range refers to slope vales between 0.75 and 1.25. Slope outside range refers to value lower than 0.25 or higher than 1.75.

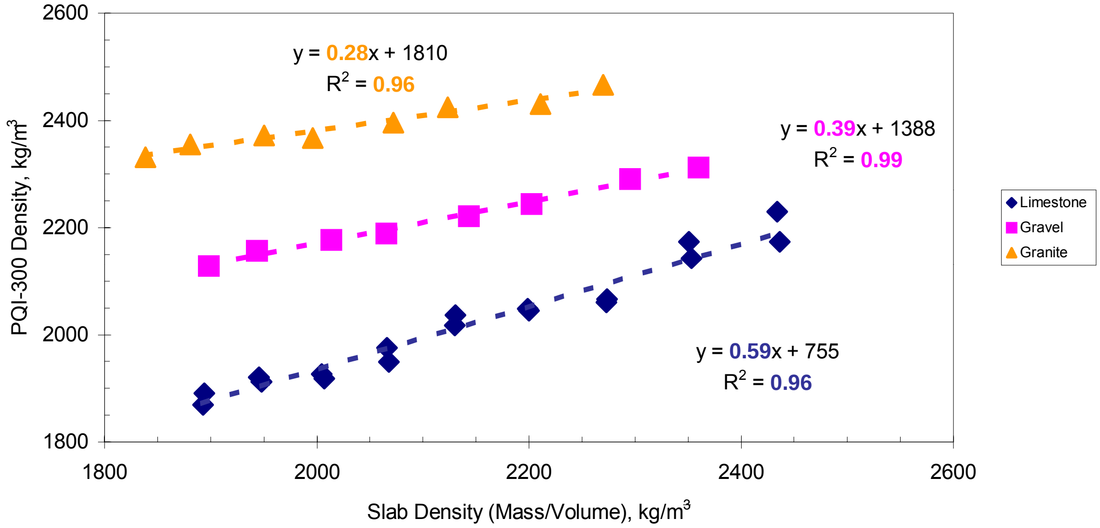


Figure 1 – Relationship between slab density and PQI-300 density for three different aggregate types all with 12.5 mm NMAS gradations.

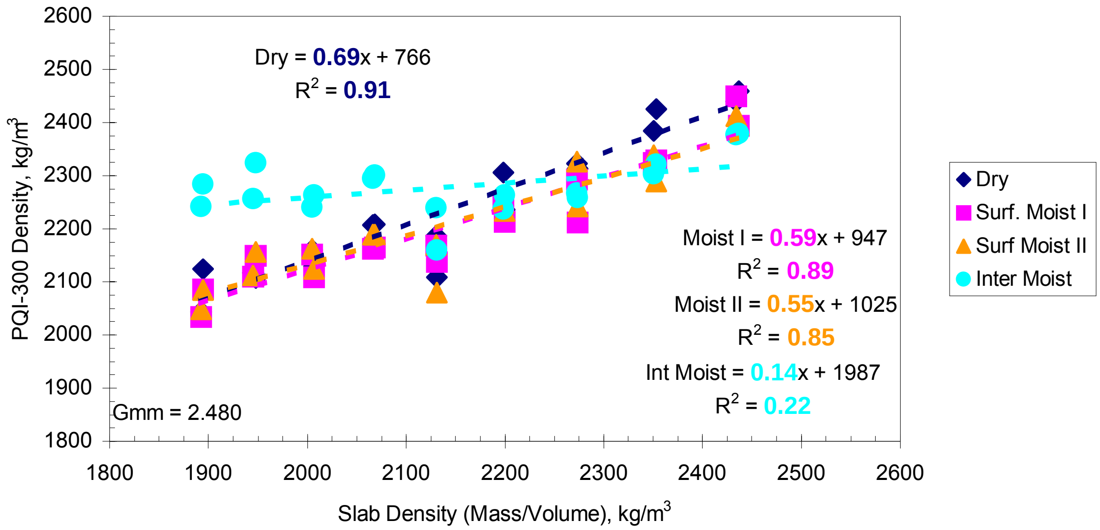


Figure 2-- Comparison of PQI-300 density readings after different levels of moisture for the limestone aggregate with the 12.5-mm NMAS gradation.

Figure 3 – Training certificate provided by TransTech System, Inc. to all participant of the March 2000 meeting.

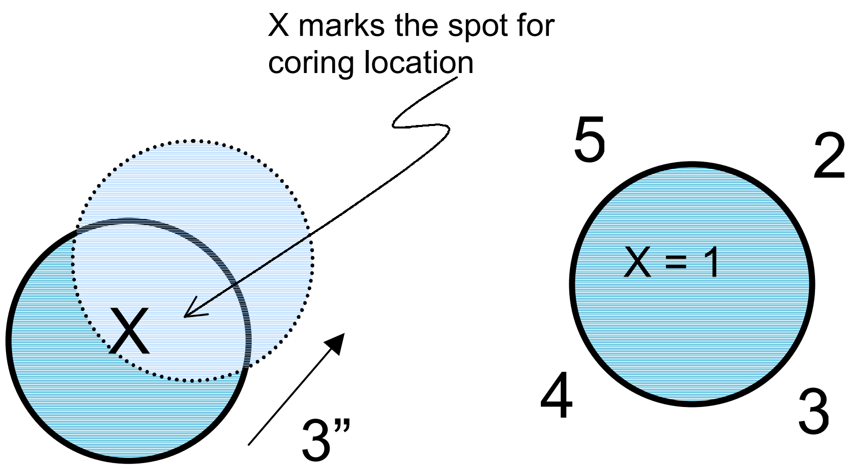


Figure 4 – Sketch indicating the location of the 5 measurements taken to arrive at a density value using the PQI-300.

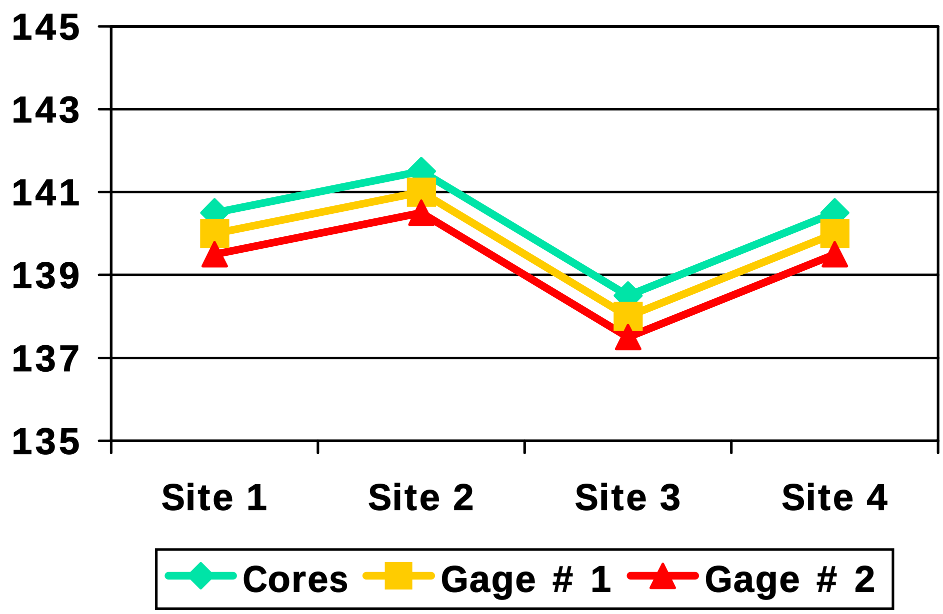


Figure 5 – Graph showing perfect 'tracking' between cores and gages.

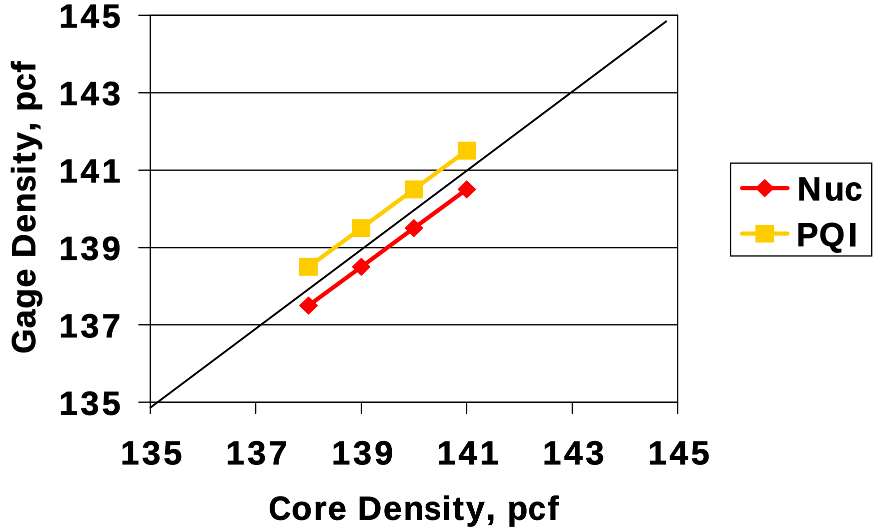


Figure 6 – Graph showing the situation where gage density, when plotted against core density, falls along the line of equality.

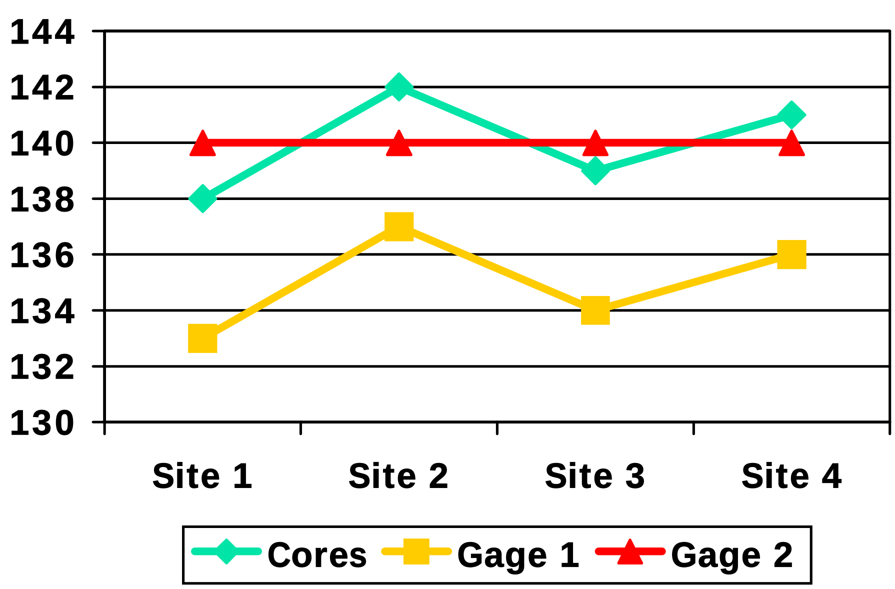


Figure 7 – Example showing two gages, Gage #1 perfectly 'tracks' core density while Gage #2 does not. Gage #2 has a lower average error.

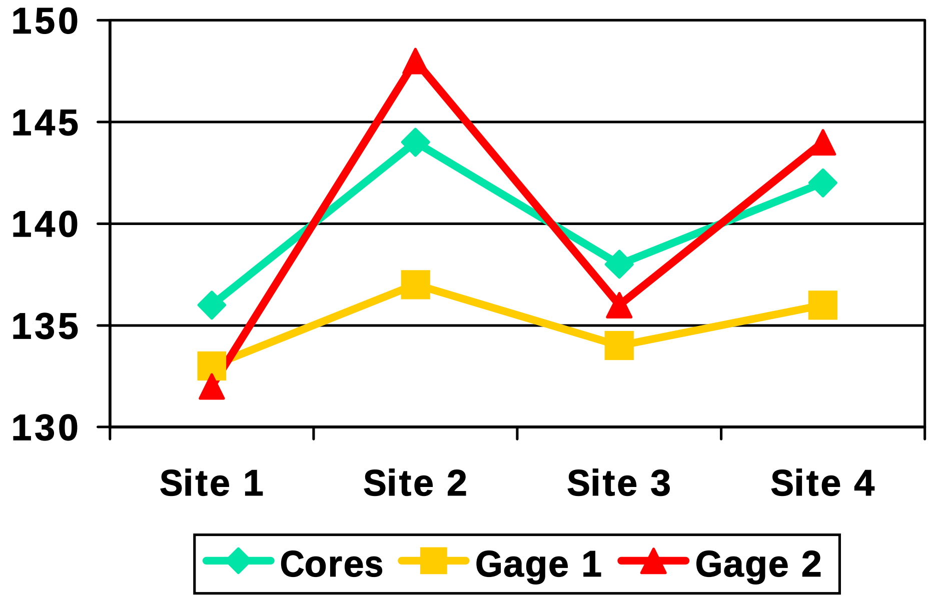


Figure 8 – Example showing two gages, both of which are able to 'track' core density even though they have different ranges.

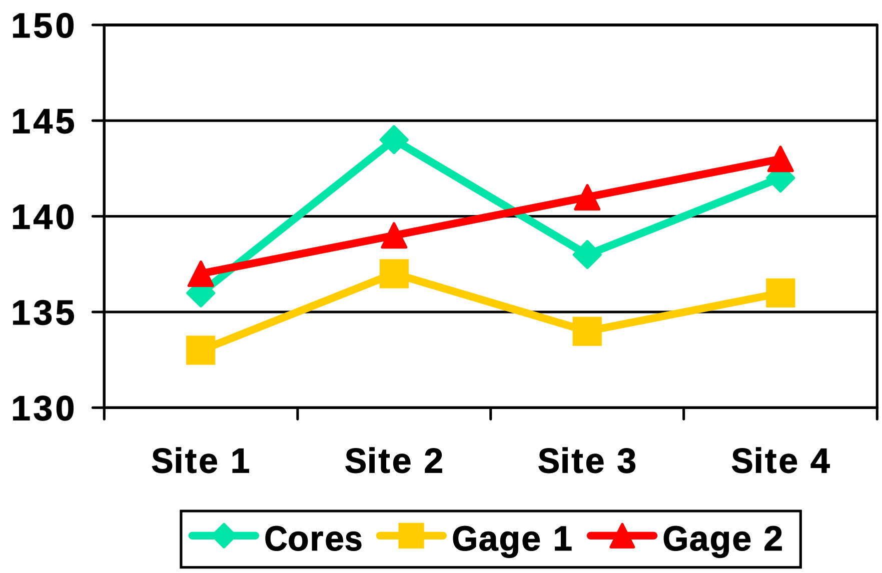


Figure 9 – Example showing two gages. Gage #1 is able to 'track' core density and has a correlation of +1. Gage #2 does not 'track' core density and even though, on the average, it gives the same density as cores. It has a low correlation of 0.42.

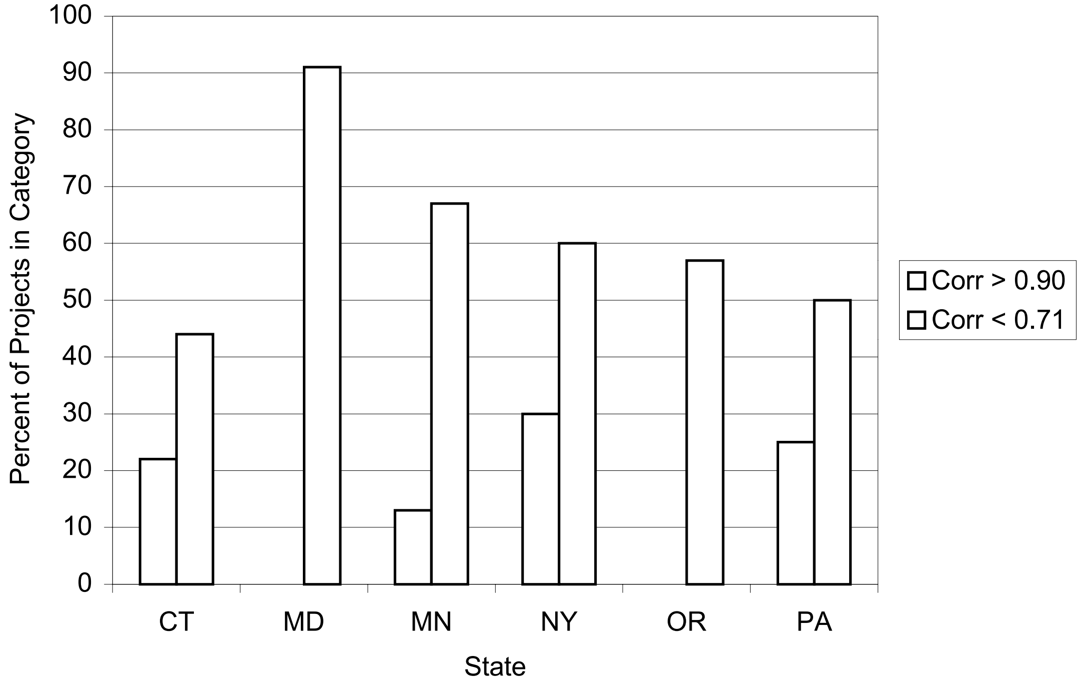


Figure 10 – Graphical representation of the correlation between PQI density and Core density.

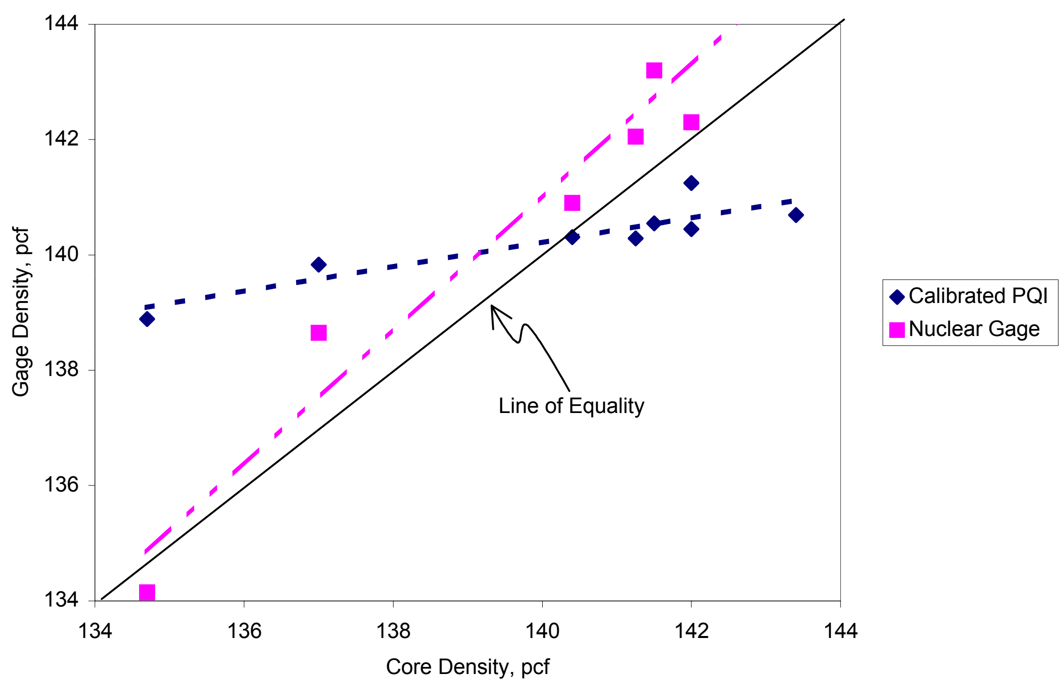


Figure 11 – Plot showing good correlation (0.91), but low slope, between the PQI density and core density for a project in Lyon, MN.

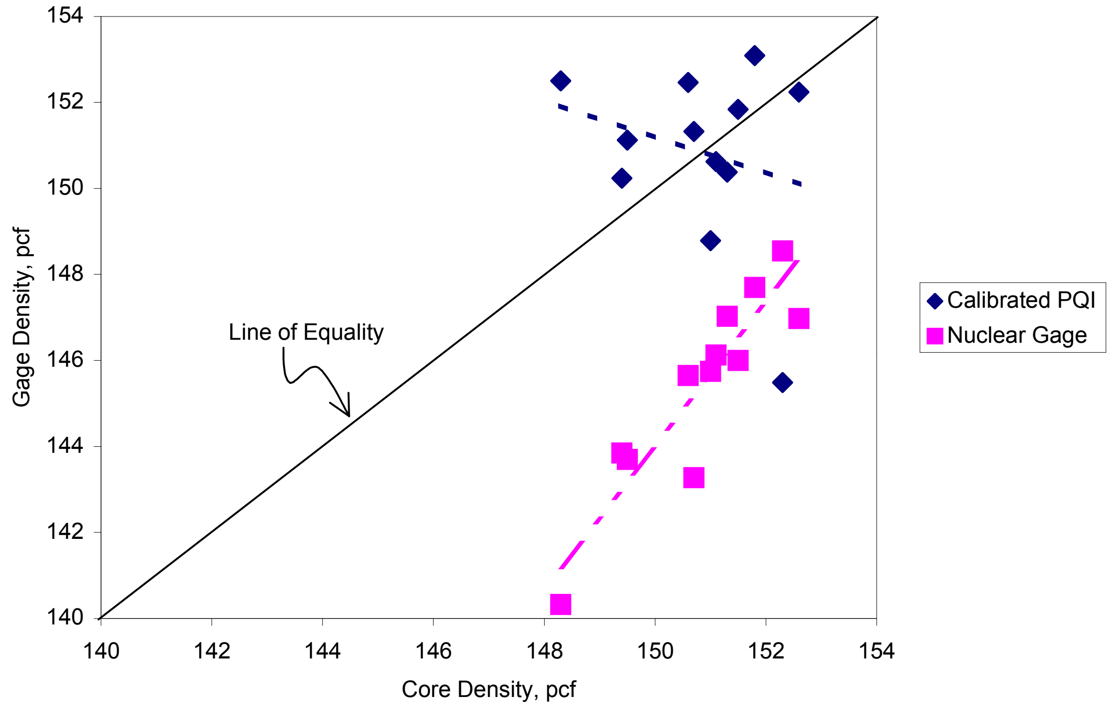


Figure 12 – Plot showing poor correlation (-0.09) between PQI density and core density for a project in Interstate 87 in New York.

Appendix I

Summary of projects used for evaluation of the PQI-300 density gage.

The following tables contain a summary of the projects used for evaluating the PQI-300 gage. A complete set of data is available in a CD from the participant states or from the author upon request.

State	Project Location	Date of Testing	Cores Number	Cores Average	Cores Range	PQI Correlation	PQI Slope	PQI Range	Nuclear Gage Correlation	Nuclear Gage Slope	Nuclear Gage Range
CT	Stonington	5/16/00	5	152.1	4.1	0.80	0.42	2.9	0.99	2.02	8.9
	Stonington Cal		5	151.8	1.9	-0.81	-0.21	5.9	0.32	0.84	5.9
	Barkhamstead	6/1/00	5	150.4	5.4	0.74	0.49	4.5	0.97	1.11	8.7
	Barkhamstead Cal		5	151.0	1.7	-0.41	-0.34	1.4	0.10	0.10	2.0
	Sherman	5/31/00	5	150.1	5.6	-0.20	-0.13	3.2	0.93	0.96	7.2
	Sherman Cal		5	151.8	1.6	0.67	0.41	1.0	0.80	1.36	2.6
	Waterbury	6/8/00	5	154.2	6.1	0.43	0.13	6.2	0.87	0.80	5.3
	Waterbury Cal		5	156.0	2.2	-0.26	-0.16	1.5	-0.52	-0.58	2.7
	Old Saybrooke	6/19/00	5	149.0	3.0	-0.71	-0.23	3.3	0.27	0.44	9.4
	Old Saybrooke Cal		5	149.2	0.6	-0.82	-1.90	1.4	-0.53	-2.46	2.4
	Southbury	7/12/00	5	148.6	1.8	-0.75	-0.59	1.5	-0.32	-0.72	5.7
	Southbury Cal		5	145.0	3.6	0.61	0.51	2.8	-0.12	-0.30	8.7
	Plainville	9/13/00	5	152.7	8.2	-0.87	-0.48	4.7	1.00	1.09	9.1
	Plainville Cal		5	149.8	6.5	0.45	0.29	3.4	0.95	1.00	6.0
	Rocky Hill	9/19/00	5	142.5	10.9	0.91	0.31	5.0	0.96	1.50	16.9
	Rocky Hill Cal		5	146.6	7.4	-0.11	-0.02	1.7	0.60	0.37	4.6
	Bristol	7/18/00	5	152.8	2.4	0.95	0.44	1.7	0.49	0.48	6.5
	Bristol Cal		5	153.1	1.6	-0.17	-0.06	0.6	0.61	0.44	1.3
Maryland	BWI Demonstration	4/19/00	6	149.8	3.4	0.03	0.02	2.1	0.57	0.51	3.2
	RT 113	5/9/00	5	153.6	3.4	0.62	0.26	1.5	0.64	0.76	4.1
	RT 16	5/10/00	5	147.7	2.0	-0.89	-0.29	2.5	0.89	0.99	7.2
	RT 50	5/12/00	4	148.6	6.3	0.51	0.44	5.3	0.11	0.11	6.5
	RT 113	5/15/00	6	149.6	2.4	-0.07	-0.10	4.5	0.91	1.03	6.7
	Hickory ByPass	8/25/00	5	159.6	2.3	0.81	0.11	0.3	0.74	0.83	2.7
		9/11/00	5	165.2	1.7	-0.38	-0.45	1.9	0.98	1.12	2.1
		9/12/00	3	162.4	1.8	-0.14	-0.02	0.2	0.49	0.77	2.8
		9/14/00	5	165.1	1.7	-0.18	-0.12	1.0	0.33	0.56	2.8
		9/21/00	5	161.5	1.7	0.45	0.08	0.9	0.94	0.48	2.2
		9/27/00	10	159.6	8.2	0.27	0.14	3.2	0.26	0.12	3.9

State	Project Location	Date of Testing	Cores Number	Cores Average	Cores Range	PQI Correlation	PQI Slope	PQI Range	Nuclear Gage Correlation	Nuclear Gage Slope	Nuclear Gage Range
Minnesota	Dakota	6/6/00	8	148.2	3.0	0.64	0.61	3.5	0.68	0.79	3.7
	Beltrami	6/8/00	10	155.8	8.8	0.83	0.28	2.6	0.73	0.99	10.1
		6/9/00	8	158.9	4.7	0.70	0.47	2.7	0.86	2.05	10.3
	Carlton	7/11/00	0					3.7			9.8
	Freeborn	7/31/00	8	141.3	5.7	0.75	0.51	4.0	0.85	1.27	9.2
	Hennepin	8/25/00	10	146.0	4.3	0.32	0.12	1.9	0.86	1.07	6.3
	Ramsey	7/9/00	11	144.1	8.3	0.54	0.49	7.9	0.75	0.94	9.9
	Lyon	7/28/00	8	140.3	8.7	0.90	0.21	2.4	0.97	1.16	10.7
		7/26/00	8	139.5	4.4	-0.26	-0.64	12.4	0.91	1.34	6.0
		7/27/00	6	140.3	7.7	0.49	0.05	1.0	0.63	0.49	7.2
	Lyon II	7/26/00	8	143.3	1.1	0.05	0.02	0.6	0.26	0.34	1.9
		7/27/00	7	143.4	4.5	0.33	0.18	2.2	0.93	1.31	6.4
	Ottertail	8/23/00	7	144.6	4.4	0.90	0.34	1.8	0.93	1.61	8.5
	Washington	9/25/00	8	146.1	4.3	-0.19	-0.07	1.4	0.95	1.03	4.3
		9/27/00	7	144.9	5.7	0.77	0.15	1.1	0.81	0.72	5.1
		9/29/00	8	145.2	2.8	0.41	0.18	1.4	0.71	1.16	3.8
New York	NY 15	6/1/00	4	142.2	4.8	-0.16	-0.87	22.9	0.95	1.58	7.9
	NY 415	6/20/00	8	138.8	5.9	0.31	1.31	19.6	0.47	0.62	7.1
	NY 219	7/5/00	8	148.3	4.1	0.94	0.43	2.6	0.99	1.22	5.1
		7/6/00	8	147.6	5.3	0.98	0.44	2.5	0.88	1.46	9.5
		7/12/00	8	145.2	2.4	0.69	0.41	1.6	0.50	1.06	4.3
		7/13/00	8	145.3	4.1	0.90	0.43	2.0	-0.52	-0.57	6.5
	NY 17	7/19/00	4	141.9	2.8	0.76	0.30	2.8	0.89	1.85	9.4
	I490	7/24/00	12	146.1	5.9	0.01	0.18	4.3	0.66	0.95	8.0
	I87	8/28/00	12	150.8	4.3	-0.09	-0.42	7.6	0.85	1.65	8.2
	Palisade	9/13/00	4	159.3	2.3	0.66	2.20	8.5	-0.10	-0.11	3.0

State	Project Location	Date of Testing	Cores Number	Cores Average	Cores Range	PQI Correlation	PQI Slope	PQI Range	Nuclear Gage Correlation	Nuclear Gage Slope	Nuclear Gage Range
Oregon	OR 47 Unsanded	5/18/00	10	2327.7	94.0	0.29	0.13	39.6	0.87	0.93	98.0
	Sanded					0.42	0.14	25.6	0.54	0.54	113.5
	OR 47 Unsanded	6/1/00	10	2268.2	88.0	0.73	0.39	43.8	0.81	1.02	113.0
	Sanded					0.77	0.32	31.4	0.95	0.95	151.0
	OR 99W Unsanded	6/8/00	10	2266.0	145.0	0.54	0.20	43.8	0.82	0.72	121.5
	Sanded					0.56	0.19	35.6	0.82	0.82	102.0
	OR 204 Unsanded	9/14/00	10	2409.5	40.0	0.52	0.33	26.0	0.53	1.01	80.5
	Sanded					0.67	0.31	16.2	0.68	0.68	65.0
	I84 Unsanded	9/7/00	10	2392.9	118.0	0.62	0.17	35.2	0.92	1.07	146.0
	Sanded					0.42	0.09	33.6	0.89	0.89	146.0
	OR 42 Unsanded	7/26/00	10	2362.1	125.0	0.88	0.39	46.2	0.95	1.24	147.0
	Sanded					0.78	0.39	54.4	0.95	0.95	154.5
	OR 62 Unsanded	7/17/00	10	2322.0	79.5	0.83	0.58	54.4	0.82	1.62	149.0
	Sanded					0.70	0.40	45.8	0.86	0.86	128.0

Note: Density reported in kg/m^3

State	Project Location	Date of Testing	Cores			PQI			Nuclear Gage		
			Number	Average	Range	Correlation	Slope	Range	Correlation	Slope	Range
Pennsylvania	Cumberland	5/2/00	3	148.9	3.0	0.74	0.04	3.9	0.98	1.37	7.7
	Tioga	6/23/00	3	145.1	2.3	1.00	0.66	6.2	0.84	1.10	19.0
		6/24/00	3	146.1	1.8	-0.33	-0.50	6.1	-0.99	-0.43	11.4
		6/26/00	3	144.8	2.8	-0.52	-1.09	17.8	0.04	0.05	17.5
		6/29/00	3	148.0	5.0	0.92	0.75	6.5	0.90	2.00	18.7
		6/30/00	3	150.0	2.4	0.88	0.39	1.1	0.99	0.73	1.7
		7/13/00	3	145.4	2.7	-0.88	-0.46	2.7	-0.49	-0.73	14.3
		7/16/00	3	148.1	1.7	0.91	0.79	3.8	0.84	4.78	13.8
		6/24/00	3	149.5	3.1	0.67	0.49	6.3	-0.85	-0.95	21.5
		9/17/00	6	146.4	3.6	0.96	1.01	4.1			
		6/21/00	3	149.9	5.8	0.72	0.90	14.4	1.00	0.14	17.7
		6/22/00	3	147.0	1.5	0.03	0.23	14.6	0.65	3.95	9.6
		7/10/00	7	145.7	5.9	0.96	0.96	6.4	0.87	0.92	6.4
		7/27/00	10	144.9	5.5	0.63	0.31	8.0	0.50	0.62	9.8
		7/28/00	15	144.8	5.0	0.34	0.66	7.8	0.53	0.79	5.2
		7/31/00	15	143.7	4.9	0.34	0.17	2.4	0.65	0.76	7.4
		8/3/00	12	144.6	4.2	0.80	0.59	15.6	0.90	1.64	8.2
		8/4/00	15	146.8	7.2	0.65	0.56	5.5	0.84	0.64	3.5
		7/31/00	15	143.7	4.9	0.80	0.62	4.4	0.65	0.76	7.4
		9/27/00	12	144.5	6.9	0.69	0.91	8.9	0.53	0.41	5.1
		9/29/00	8	142.7	4.0	0.96	0.69	2.7	0.72	0.89	6.0
	Blosberg	11/12/00	16	145.3	7.4	0.77	0.84	8.1	0.81	1.37	10.7
	Franklin	4/26/00	3	145.8	4.1	0.50	1.15	6.5	0.68	1.01	7.3
	Cumberland	4/28/00	3	147.0	1.6	0.60	0.47	4.5	-0.04	-0.03	10.7

Appendix II

TransTech Systems, Inc. response to the data.

A draft copy of this report was provided to TransTech prior to distribution. Following is their interpretation of the results. This section was provided by TransTech System, Inc. and reflects their view only. The author had no input on this section and did not edit or change its content.

Manufacturer's Comments
Field Evaluation of the PQI Model 300
June 2001

Introduction

This document was prepared in June, 2001 by TransTech Systems, Inc. in response to the findings expressed in the "Field Evaluation of the PQI Model 300", the final report of the "Pooled Fund Study." The purpose of the Pooled Fund Study was to evaluate TransTech's Pavement Quality Indicator (PQI), a Hot Mix Asphalt (HMA) density gage.

The design objective of an HMA density gage is to measure the density of HMA paving material over a range of approximately 82% MTD (density after being applied by the paver) to 96% MTD (final rolled density). As such, it would seem that the best evaluation method would be to compare gage readings to a standard (e.g. core measurements) over the full operating range. The Pooled Fund Study took a different approach, which was to use gage readings and core measurements over a small density range and to use a statistical function to predict the performance of the gage over the full operating range.

The main points of this document are:

- No reasonable conclusions can be drawn from the calculated gage/core correlations, given the small number of samples and narrow range of measured densities.
- The proper operation of the gauge needs to be better conveyed to operators if subsequent testing is to be performed.
- The slope of the PQI may vary with aggregate type so further investigations should be performed to confirm this finding and to possibly refine the PQI slope setting.
- The PQI moisture compensation algorithms should be refined if the gage is going to continue to be used in extremely moist conditions.
- A more meaningful gage evaluation could be achieved by constructing a test mat where each section of the mat would be subjected to a different number of roller passes. Such a mat would provide a much wider range of densities and could be cored in a number of locations.

Each of these points will be discussed in more detail in the following sections.

Observations and Conclusions

1. Correlation is not an appropriate analysis tool for the acquired data

An asphalt density gage is typically used as a quality assurance tool which measures density at the conclusion of the rolling process, and as a quality control tool which measures density during the rolling process in order to establish rolling patterns. While the best measure of a gage for either application would be average "error" (actually, the average difference from core reading), it is appropriately pointed out in the body of the report that this measure is not sufficient for the acquired data due to the narrow range of density values. Therefore, the correlation between gage and core measurements is used as a measure of gage performance with the expectation that a high correlation coefficient will predict small density measurement errors at densities outside of the range of values actually tested. Unfortunately, limitations in the acquired data preclude the extraction of meaningful data from the use of the correlation function. The following will discuss the factors that limit the effectiveness of the correlation function for this application.

As stated in the body of the report, the performance of the nuclear gage is not good enough to allow it to be used as a reference for PQI readings so PQI readings are compared to core samples. While we fully agree with this conclusion, using core samples presents two logistical problems:

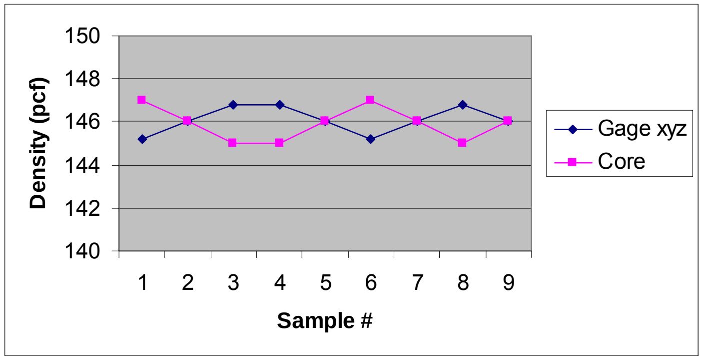
- coring is typically only performed on the finished mat so the range of core values is very limited
- coring is a time-consuming process so a limited number of samples can be obtained

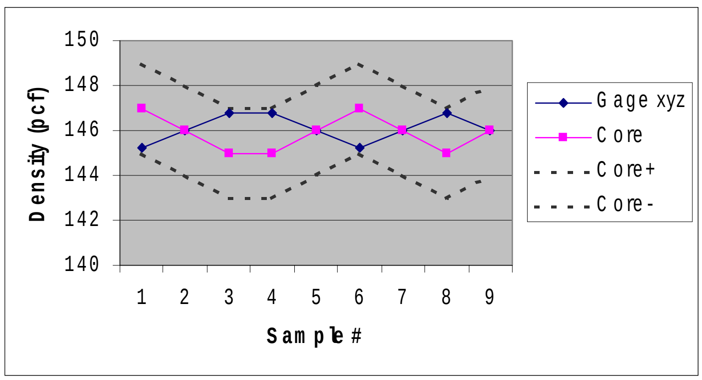
Limited Density Range

The objective of the rolling process is to achieve optimal compaction level and uniform density over the entire mat. The cores used in this study were all extracted from finished mats so the range of core density values was very small. For example, as part of this study Minnesota performed a total of 15 tests. The average core range for these tests was 5.2 pcf, with many of the tests having a core range less than 4.0 pcf. (In the three tests where the core range was greater than 8 pcf the average PQI/core correlation was 0.73; in the remaining tests the average PQI/core correlation was 0.37).

The problem with the limited range of available core values is compounded by the uncertainty in the core density determination using the AASHTO-T166 method. As stated in the body of this report, +- 2 pcf differences can be expected using this method. This uncertainty can be seen in the Minnesota data, where 62 companion cores were taken and measured. The companion core measurements differed from the primary core measurements by an average of 0.9 pcf with a maximum difference of 8.4 pcf. Similar results were observed in Oregon where 60 companion cores were taken, resulting in an average difference of 0.8 pcf with a maximum difference of 4.4 pcf. Obviously, few meaningful conclusions can be drawn from a data set where the uncertainty in the readings approaches the total range of the readings.

As an illustration of this problem, consider the following figures which show the performance of a hypothetical gage. The gage data is offset from the core data by 2 pcf, the accepted accuracy of the core measurement data, and the trends are shifted by 180 degrees. A simple analysis would show that the gage performed extremely poorly with a correlation of –1.0. However, when the uncertainty in the core determination is considered, it can be seen that all gage readings fall within the core measurement uncertainty range, and that the gage may in fact have had perfect performance and a 1.0 correlation. The uncertainty of the value of the correlation coefficient determination due to the sample size is discussed more rigorously below.

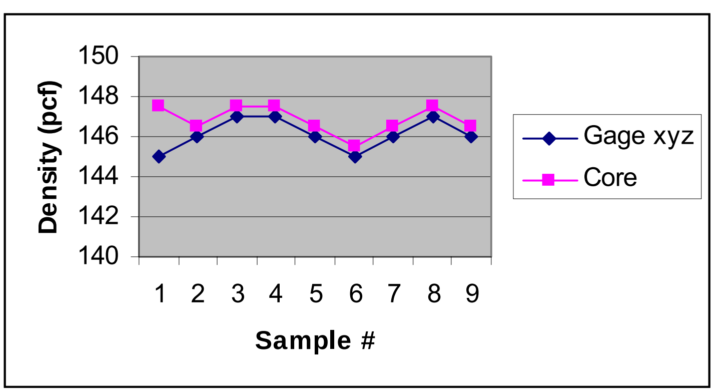




Limited Number of Data Points

The sensitivity of the correlation function increases as the number of data points decreases. While a minimum of 30 data points should be used to achieve a reasonable sensitivity when analyzing data in the range of this study, the majority of the tests used less than 10 cores. As an example, Pennsylvania conducted 22 tests – 14 of these tests used 8 cores or less and 11 of the tests used 3 cores.

The following figure demonstrates the unacceptable sensitivity of the correlation function when analyzing a deficient number of data points:



The preceding figures show the hypothetical results of a nine-sample test. The core and gage values are identical (gage is shown offset by 0.5 pcf for illustration purposes) but the core measurement of the first sample is 2.0 pcf (still within the uncertainty range of the core measurement method) higher than the gage reading. The gage/core correlation coefficient for this data set is 0.60, which would be categorized as poor in this study. The small number of total samples resulted in the correlation function being greatly influenced by a single data point.

Two additional examples demonstrating the behavior of the correlation function using a small number of samples are attached are attached as Exhibits 1 & 2.

For a more rigorous investigation of the effect of a small number of samples, we will consider the confidence level that the actual or true value of the correlation coefficient lies within a range of values about the calculated value. If we calculate the correlation coefficient (r_{calc}) between the data set from gage readings and core measurements, we know that there is some uncertainty in this calculation due to mathematics and statistics alone, ignoring any inaccuracies in the measurements themselves. Statistically, we can compute the range in which the actual correlation coefficient (r_{act}) lies. The computation of the range depends on the measured value, the number of data point and the confidence level that we wish to assign to the probability that the actual value of the correlation coefficient lies between a lower limit (r_{ll}) and an upper limit (r_{ul}). The range increases as the number of samples (data points) decreases and as our required confidence level (probability) increases. The accepted value of the confidence level in statistical operations is 95%; that is, we are requiring that the true value of the correlation coefficient will fall within the range 95% of the time. So, given a sample data set, we will calculate the range that we are 95% sure the actual correlation coefficient falls within. The confidence limits can be calculated as follows:

$r_{ll} = (e^{2C1}-1) / (e^{2C1}+1)$ $\quad$ $r_{ul} = (e^{2C2}-1) / (e^{2C2}+1)$ $\quad$ where

$C1 = \ln ((1+ r_{calc})/(1- r_{calc})) / 2 – 1.96/\text{sqrt}(n-3)$
$C2 = \ln ((1+ r_{calc})/(1- r_{calc})) / 2 + 1.96/\text{sqrt}(n-3)$
n = number of samples in the data sets

For an example we will assume that one of the tests used 10 cores and that the calculated correlation was 0.6 and calculate the limits.

$C1 = \ln ((1.6)/(.4)) / 2 – 1.96 /\text{sqrt}(8-3) \quad = -0.181$
$C2 = \ln ((1.6)/(.4)) / 2 + 1.96 /\text{sqrt}(8-3) \quad = 1.570$

$r_{ll} = (e^{2* -.181}-1) / (e^{2 * -.181}+1) \quad = -0.18$
$r_{ul} = (e^{2* 1.570}-1) / (e^{2 * 1.570} +1) \quad = 0.92$

Therefore, given the data set in this example, we are only able to state that we are 95% sure that the actual correlation coefficient between the gage and the cores lies between –0.18 and +0.92. In other words, regardless that calculated value of the correlation coefficient was 0.6, the true value of the correlation coefficient could quite possibly be anywhere from –0.18 to +0.92. This analysis assumes that there is no uncertainty in the core measurements. If the core measurement uncertainty were factored in, the range of uncertainty of correlation coefficients would be even greater. This wide range of possible correlations means that the data set actually can tell us very little about the actual correlation between the gage and the cores.

2. PQI operating procedure needs better definition

There were a number of instances where there appeared to be errors in the data taking procedure. A more concise list of operating instructions would help to alleviate these problems in the future. Some examples are:

- At least one state took PQI readings on the day following the paving. The PQI does not correct for embedded moisture and should not be used in this manner because any rainfall occurring prior to the measurements could affect the readings.
- As can be expected in a large data-taking operation, a number of transcription errors were found. While gross errors (e.g. misplacing a decimal point so a value is in error by a factor of 10) are easy to detect and correct, smaller errors which might have gone uncorrected could greatly influence the very sensitive correlation analysis.
- In cases where all five PQI readings were reported, there are a number of instances where one of the five readings differed from the other four by more than 10%. This situation is almost certainly the result of the gage not being properly seated on the mat.
- While we believe that it was beneficial for all states to have received operations training at a March 2000 meeting, we do not believe it was "certain that the device was properly used in the field". One potential problem is that in some instances the representative at the training was not the person operating the gage in the study.

Errors of this nature are to be expected in a large data-taking operation but the manufacturer believes that steps could be taken to significantly reduce these errors if future studies are performed.

3. Slope varies with different mixes

The laboratory phase of the study indicated that the slope of the PQI varies with aggregate type, and possibly other parameters of the mix.

4. Range of moisture compensation should be expanded

The laboratory phase of the study indicated that the PQI's surface moisture compensation logic does not perform well over a wide operating range of moisture levels. While the existing range is sufficient for the majority of applications, improving the compensation for higher moisture levels could improve field performance.

Actions

TransTech will perform the following actions in response to the results of this study:

1. The following modifications will be made to the PQI software:
    - Averaging mode will be simplified so this mode can be used for all testing. This mode will reduce operating errors by warning the operator when one of the readings is suspicious.
    - Internal data logging will be simplified. Use of this feature, along with direct downloading of the data to a PC, will reduce the data-taking effort and should eliminate transcription errors.
    - The slope of the PQI may vary with aggregate type so further investigations should be performed to confirm this finding and to possibly refine the PQI slope setting.
    - Moisture compensation will be refined. Readings with moisture levels in excess of a predetermined threshold will be rejected by the PQI.
2. Revised operating instructions will be provided in an effort to encourage more uniform operation of the PQI.
3. TransTech will conduct a research project which will attempt to characterize the behavior of the PQI on a wide range of HMA samples with various aggregate types, sizes, etc. The results of this project will supplement results from the laboratory study and may be used to further refine the PQI calibration.

Recommendations

1. Participating states should assist TransTech with its HMA characterization project by providing gyratory samples.
2. TransTech should update PQIs with new software that will help reduce errors during the data-taking process.
3. The PQI-300 should be reevaluated using a more suitable test/analysis method. A more meaningful gage evaluation could be achieved by constructing a test mat where each section of the mat would be subjected to a different number of roller passes. Such a mat would provide a much wider range of densities and could be cored in a number of locations, alleviating two of the problems with the original testing. A fabrication procedure for such a mat is attached as Exhibit 3.

Exhibit A - Correlation Example #1

The use of the correlation function in the evaluation of the performance of asphalt density gauges using a relatively small set of data points over a very narrow measurement range can produce unexpected results.

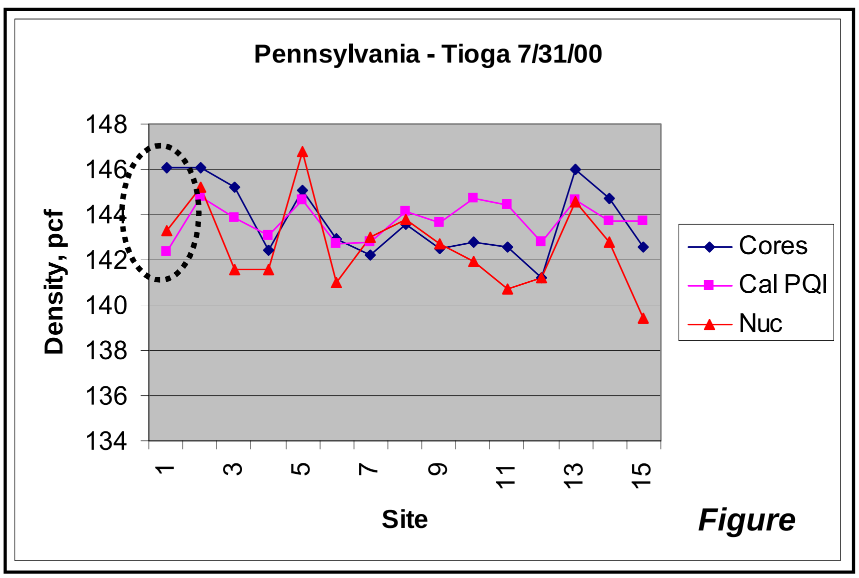
For example, consider the following showing density readings from the PQI, Nuc, and cores at 15 sites taken in Pennsylvania on July 31, 2000. A visual examination of this data seems to indicate that both the PQI and Nuc readings track the core readings relatively well. However, the correlation of PQI/Core and Nuc/Core for the 15 points are as follows:

Correlation for all 15 Sites	
PQI/Core	0.34
Nuc/Core	0.65

Closer visual examination of the plot would suggest that the measurements from the first site (circled in Figure 1) might be contributing to the poor correlations. Recalculating the correlation of the last fourteen sites yields the following results.

Correlation for last 14 Sites	
PQI/Core	0.65
Nuc/Core	0.67

Amazingly, the elimination of a single site increases the PQI correlation from 0.34 to 0.65. While the eliminated Nuc reading was similar to the eliminated PQI reading, the Nuc correlation only increased from 0.65 to 0.67.



Further visual examination of the data suggests that the PQI correlation would be improved if the PQI reading from the 15th site had been lower (see circled area in Figure

2). To test this observation, 2.0 pcf was subtracted from the 15th PQI data point and the data was re-plotted (see Figure 3). The altered data plotted in Figure 3 suggests a much-improved PQI performance relative to core measurements. However, when the correlation for the last 14 sites is now calculated, the PQI/Core correlation is actually *lower* (0.62 vs. 0.65) for the altered data set.

Correlation for last 14 Sites (Site 15 Data Altered)	
PQI/Core	0.62
Nuc/Core	0.67

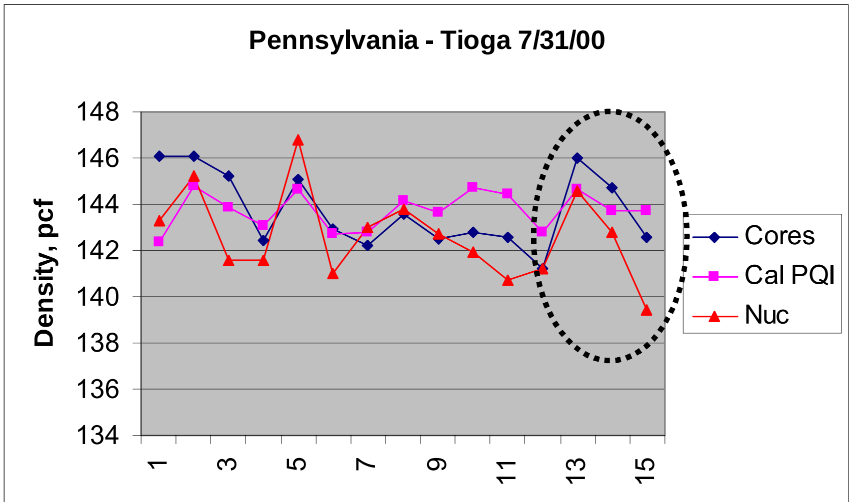


Figure 2

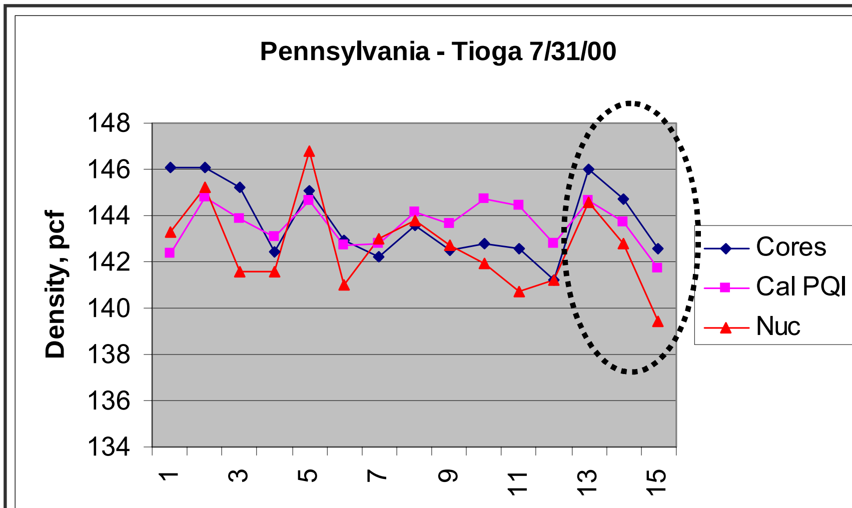
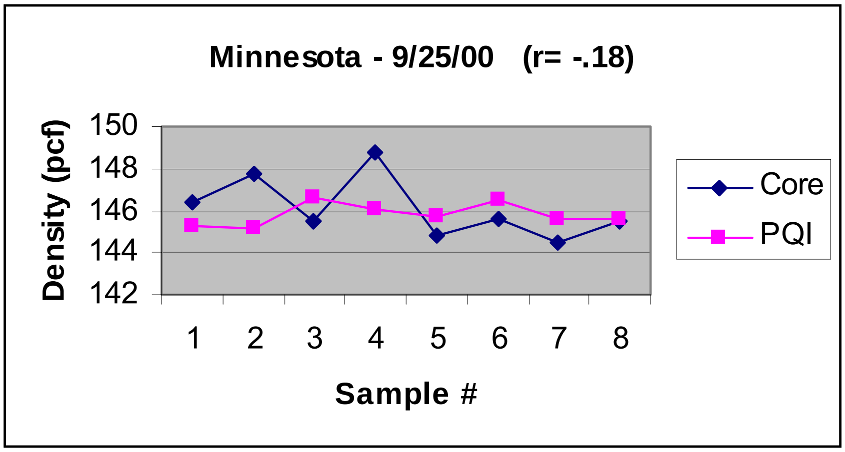


Figure 3

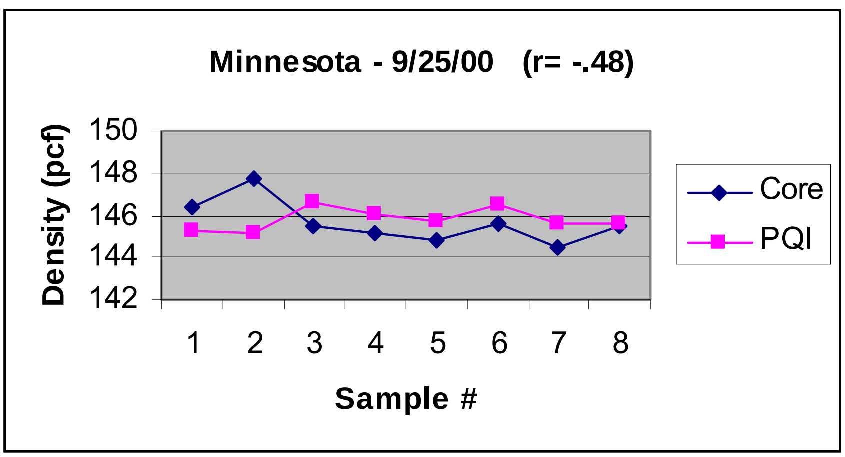
These two small manipulations of actual test data demonstrate that the correlation function can be extremely sensitive to a single data point and that using the correlation function as a quality index can produce results that are counter-intuitive.

Exhibit B - Correlation Example #2

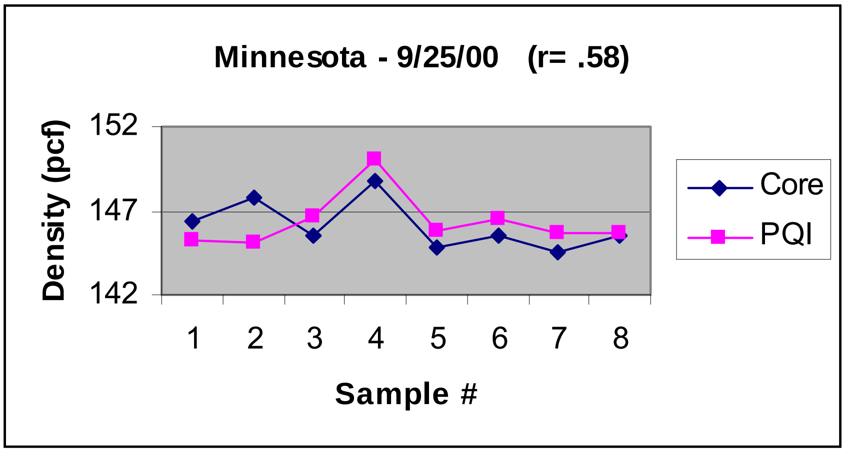
Consider the following PQI and core data from a 9/25/2000 test in Minnesota. Analysis of the 8 data points shows a poor (-0.18) correlation between the PQI readings and the core measurements.



Visual examination of the data suggests that there is a large difference in readings on the fourth sample. The relatively high (97% of MTD) core measurement might cause one to suspect this measurement and ask "what would the correlation be if the core measurement had been lower?". The following figure re-plots the data with the value of core measurement #4 changed from 148.75 to 145.1. Surprisingly, while the data from the PQI and core measurements appears to track more closely than before, the correlation of the revised data set is actually much worse (r = -0.48)



A second hypothetical situation would be to keep the core measurements unchanged, but to see what would have happened if the PQI had read higher for sample #4. The following figure re-plots the data with the PQI reading for sample #4 changed from 146.04 to 150.0. This 4 pcf modification in a single reading changes the correlation from –0.18 to 0.58, demonstrating the high sensitivity of the correlation function.



A final demonstration of the problems with using correlation for this application is shown in the following figure. An acceptable (> 0.70) correlation is achieved by using all of the original data but introducing a 110 pcf (increase reading from actual 146.04 to hypothetical 256.0) error in the fourth PQI reading. While the difference in reading #4 is now more than 100 pcf, and the average difference in readings for the entire dataset is now > 14 pcf, the hypothetical gage achieves an acceptable gage/core correlation coefficient. Surely, this hypothetical gage has poorer performance than the actual gage, but its gage/core correlation coefficient is acceptable, while the coefficient of the actual gage is unacceptable.

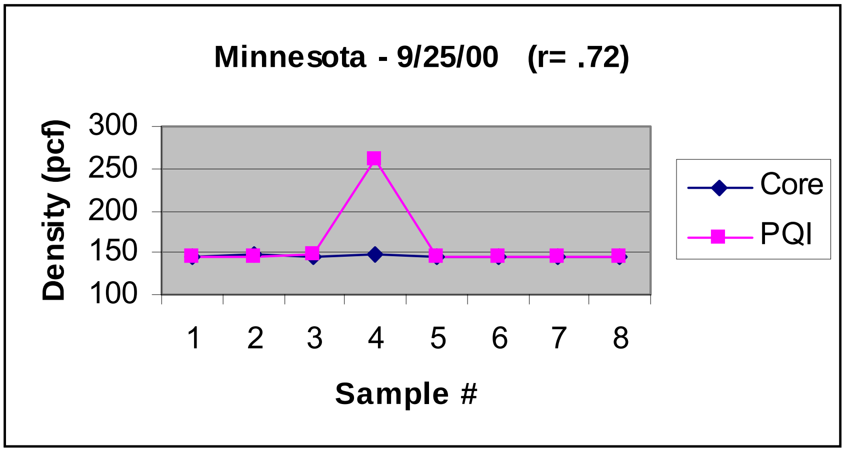


Exhibit C - MultiDensity Mat Fabrication Procedure
DRAFT

- Three test strips will be constructed, each using a different HMA mix.
- For each strip, a mat 10’ wide by 100’ long should be applied with a minimum uncompacted thickness of 2.5”.
- Assuming 150 lb/ft^3 MTD and 82% compaction by paver:

  Tonnage per strip = 10’ x 100’ x (2.5/12)’ * (150 * .82)
  = 12.8 tons
- The first 15-25 feet of the mat will not be used but the rolling pattern on the remainder of the mat is critical. A spotter will ensure that the following rolling instructions are carefully observed:
  1. Start at beginning of mat on the left hand side of the mat
  2. Roll forward until center of front drum reaches the 85’ mark
  3. Reverse to beginning of mat
  4. Roll forward until center of front drum reaches the 60’ mark
  5. Reverse to beginning of mat
  6. Roll forward until center of front drum reaches the 35’ mark
  7. Reverse to beginning of mat and proceed off the mat
  8. Repeat step 1-8 on the right hand side of the mat. Leave an unrolled strip approximately 6” wide between the left-hand and right-hand roller passes.
- The previous procedure will produce the following rolling pattern on the mat:

Feet	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Front Drum (forward)				■	■	■	■	■	■	■	■	■	■	■	■	■	■			
Rear Drum (forward)		■	■	■	■	■	■	■	■	■	■	■	■	■	■					
Front Drum (backward)		■	■	■	■	■	■	■	■	■	■	■	■	■	■					
Rear Drum (backward)				■	■	■	■	■	■	■	■	■	■	■	■	■	■			
Front Drum (forward)				■	■	■	■	■	■	■	■	■								
Rear Drum (forward)		■	■	■	■	■	■	■	■	■										
Front Drum (backward)		■	■	■	■	■	■	■	■	■										
Rear Drum (backward)				■	■	■	■	■	■	■	■	■								
Front Drum (forward)				■	■	■	■													
Rear Drum (forward)		■	■	■	■															
Front Drum (backward)		■	■	■	■															
Rear Drum (backward)				■	■	■	■													
Zone		8		7		6			5		4			3		2			1	
Total Drum Passes		?		12		10			8		6			4		2			0	