Non-Nuclear Density Gauge Comparative Study

Draft Final Report
August 2005

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16. Abstract
Current non-nuclear methods of measuring asphalt pavement density use electrical properties of asphalt. Two known instruments, the PaveTracker^{TM} and the PQI Model 300, estimate pavement density by inferring the relative proportion of air-filled voids in the asphalt from a measure of dielectric permittivity. Under this project, currently available and new methods of determining in-place asphalt density were investigated. The investigation included a laboratory study of the PaveTracker^{TM}'s ability to accurately measure density under a variety of conditions, including coarse or fine aggregate in mix, presence of internal and/or surface moisture, sample area, and sample depth. Both the PaveTracker^{TM} and the PQI Model 300 were evaluated in the field by measuring density of measurement locations at each of 24 project sites and comparing to corresponding values measured by a nuclear gauge and laboratory tests. Recommendations for practice, including expected payoff results in using them, are given.

17. Key Words Asphalt pavement density, Nuclear density gauge, Non-nuclear density gauge, PaveTracker, PQI	**18. Distribution Statement** No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

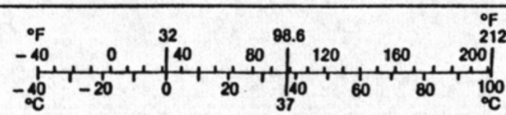
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

DRAFT

FINAL REPORT ON

NON-NUCLEAR DENSITY GAUGE

COMPARATIVE STUDY

for the

OHIO DEPARTMENT OF TRANSPORTATION

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1. Introduction

Real time determinations that asphalt pavement density is within acceptable limits are used to assure quality in asphalt paving projects. Currently, most paving contractors determine in-place density of asphalt pavements using a nuclear density gauge, sometimes verified by the collection of core samples. Nuclear results can vary greatly relative to core samples. In addition, the nuclear method entails cumbersome health, safety, and training requirements, including certification of operators, personnel exposure monitoring, nuclear source licensing, and special procedures for storage and transport of shielded field instrumentation. Because of their relative unreliability, health risks to the operator, and the costs of complying with the special requirements of using nuclear density gauges, there is a need for more cost-effective determination of in-place asphalt pavement density.

We undertook this study to characterize the performance of new non-nuclear instruments for real-time determination of in-place pavement density, so that their utility can be better predicted, and the cost-effectiveness of their use can be evaluated.

Successful implementation of a non-nuclear asphalt density test method would reduce costs, as the expenses associated with nuclear gauge maintenance and training and licensing of operators will be reduced. In addition, the capital cost of non-nuclear gauges is lower than that of the nuclear gauges. The lower cost associated with the non-nuclear gauge methods will allow the paving contractor to make testing of asphalt densities a more routine part of the paving operation. Increased testing of asphalt densities will result in a higher quality pavement, allow the pavement contractors to rapidly verify that the pavement meets the specified density, reduce over-compaction of the pavement, and better optimize the paving process.

2. Literature Review

Once available instruments had been identified, we conducted a literature search for studies that had evaluated the performance of these instruments and reviewed all publications found. Findings are presented below in chronological order of publication date.

Researchers at the University of Illinois at Urbana-Champagne examined the performance of both the earlier Transtech PQI model 100 and the later PQI model 300 non-nuclear density gauges in comparison to laboratory core analysis and nuclear results and published the results in two separate reports in 1999 and 2000. In both these studies, the investigators evaluated the gauges on several pavements having different asphalt mix designs and materials, different surface moisture conditions, and various sized air gaps between instrument and pavement.

Harrell and Buttlar (1999) found the PQI model 100 to be sensitive to surface moisture, temperature, and air gaps. These investigators concluded that the PQI Model 100 results “did not correlate as closely” with core sample results as did nuclear gauge results.

Hausman and Buttlar (2000) later reported that the PQI Model 300, which is claimed to compensate for moisture and temperature, showed less sensitivity to these variables than the earlier model, but they also concluded that it, too, does not correlate well with AASHTO T-166 measurements. These investigators also examined the influence of mineral filler to reduce the impact of surface voids, and found that its use did not significantly improve the variability of the Model 300 density measurement. Neither UIUC report presented statistical analyses to support the conclusions regarding correlation, and both lacked rigorous evaluations of either sampling error or confidence limits.

Henault (2001) evaluated the field performance of the PQI Model 300 by comparing its results to nuclear gauge results and laboratory analysis of cores from 10 projects using AASHTO T-166 procedures. He evaluated the correlation between PQI and core results and found the average R^2 value of 0.28 to indicate too poor a correlation to support the use of the PQI for quality assurance. In Henault's study, the PQI was calibrated for each test site using the average of five cores, each with five surrounding PQI measurements to determine an offset. The offset was then applied to ten subsequent PQI and nuclear gauge readings taken from the site.

Since this study sought statistical correlation between PQI and core results within individual projects, little correlation was found. From a study design perspective, this result is not surprising. Since the paving contractor aims to produce a consistent pavement from a consistent mix, the variability one would expect in evaluating a random sample from a single project should be dominated by random errors associated with each measurement technique. Only variation in the actual density, which the contractor's efforts are aimed at suppressing, would be expected to result in a correlation between measurement methods. Little correlation, if any, should be expected between methods within a project because true variation in the density of the samples is restricted by design. A more appropriate approach, and the one taken in the present study, would be to seek correlation among results combined from several different projects having various mix designs or other intended variation in density among projects. Averaging R^2 values from several projects does not compensate for the deficient study design.

Romero (2002) published perhaps the most comprehensive evaluation of non-nuclear density gauges we could find. This evaluation resulted from a pooled-fund study sponsored by the state highway agencies of Maryland, Pennsylvania, New York, Minnesota, Connecticut, and Oregon, as well as the Federal Highway Administration's Turner-Fairbank Highway Research Center. The pooled-fund study compared, both in the laboratory and in the field, accepted density values of hot-mix asphalt to density values obtained from both the PQI and the PaveTracker™, another non-nuclear density gauge. A laboratory study conducted in 1999 indicated that the PQI Model 300 output was linearly related to changes in density of slabs when measured under constant temperature and humidity conditions for a single asphalt mixture. The study indicated that a mixture-specific calibration procedure should be applied to measure density in the field. The study also indicated that it is necessary to correct for changes in moisture and temperature.

Based on the results from the laboratory study, a field study was conducted during the 2000 construction season. The field study found that the sensitivity of the PQI Model 300 was inadequate for measuring density changes in the field, and recommended changes in both the sensitivity of the device and the algorithms used to correct for moisture and temperature.

A second field study was conducted during the 2001 construction season, following several improvements to the PQI and the introduction of the PaveTracker™. The study found an improvement over the prior performance and concluded that, in order to use non-nuclear gauges to obtain absolute pavement density, calibration using the same materials is needed. Neither the modified PQI model 300 nor the PaveTracker™ were recommended for quality acceptance (QA) measurements or to determine pay factors, but they were determined accurate for quality control (QC) applications.

Allen et al. (2003) compared two separate PQI Model 300 gauges and a nuclear gauge to laboratory results on cores. The basis of the comparison was measurements made during a single paving project involving an overlay. The investigators conducted two-sample t tests to compare each gauge with the core results and found that the difference between the cores and only one of the PQI gauges was not significant at 95% confidence. They also concluded, on the basis of a distribution overlap analysis, that among the gauges, the distribution of results from the same PQI gauge was most similar to the distribution of core results. The PQI and core distributions shared an 88% overlap. A pay factor analysis indicated that both PQI gauges, if used for quality acceptance, would have resulted in 100% overall pay, whereas the nuclear gauge would have resulted in a five percent reduction in pay for lane densities. The authors recommended non-nuclear gauges for quality control.

Like the study of Henault (2001), Hurley et al. (2004) sought statistical correlation between non-nuclear gauge results and core results within individual projects, using core and non-nuclear gauge data from multiple paving projects in five states. As one might predict from knowledge of the study design, little correlation was found. Confidence limits on R^2 were not assessed.

The same investigators also reported on a “numerical experiment,” in which they derived a linear calibration for the PQI Model 300 by trying out slope and intercept coefficients calculated by least squares fit to five randomly selected pairs of gauge and core results until coefficients were found that minimized the average difference between all paired gauge and core results. They then re-evaluated the correlation coefficient between “calibrated” gauge results and the core results. Their finding, that “calibrating” the results did not change the correlation coefficient, results wholly from the mathematical definition of correlation, and was therefore to be expected. Correlation is not a measure of accuracy; it is a measure of how well the variability in one population moves proportionally to, and in the same direction as, the variability in another population. The effect of linearly transforming the sample of one population by applying a first order calibration equation does not change the distribution of points about the “best fit” line defined by the least squares regression model; it only changes the position of the line. Therefore, applying a linear calibration cannot alter the value of the correlation coefficient. This study’s fundamentally poor design and the futility of its “numerical experiment” provide little credibility for its recommendation that neither the PQI nor the PaveTracker™ be used for quality assurance testing.

3. Method of Study

Following the literature review, we undertook both a laboratory study and a field study. The field study included an evaluation of both the PaveTracker™ and the PQI Model 300. The goal of the laboratory study was to evaluate the performance of PaveTracker™ under controlled conditions in the laboratory. In the laboratory study, the depth and lateral influence of the measurements were studied, which can not be done easily in the field. The measurement conditions investigated in the laboratory study are as follows:

- Temperature. The temperature is known to affect the electrical conductivity of asphalt cement. The change in temperature can affect the ability of PaveTracker™ to determine the density of asphalt concrete. Even though it is claimed by the manufacturer that the reading is not affected by the temperature [6], it is necessary to verify this claim.

- Moisture. The reading of PaveTracker™ is a sum of contributions of mix components -- their volumes and dielectric constants. The dielectric constant of moisture is 80 at 20°C (68°F), which is significantly larger than those of other components. Therefore, it is critical to determine if the presence of moisture would affect the performance of PaveTracker™. This can be verified with both surface moisture and internal moisture that can be introduced by a rolling compaction process in the field.

- Aggregate Size. The manufacturer claims that PaveTracker™ works well with fine-graded mixes but not as well with coarse-graded or gap-graded mixes. The aggregate gradation significantly affects the ability of PaveTracker™ to measure the density of hot-mix asphalt (HMA). Therefore, coarse and fine graded mixes were used to evaluate the sensitivity of PaveTracker™ to aggregate gradation.

- Sample Area. The PaveTracker™ manual recommends that the gauge calibration can be conducted upon a 6 inch (15 cm) core or Superpave gyratory compacted sample [6]. By referring to Figure 1, the materials being measured are larger than the area of the contact plate of PaveTracker™. The effect on readings of the specimen area compared to contact area of PaveTracker™ has to be evaluated

- Mat Thickness. According to the PaveTracker™ operation manual, the measuring depth is 1.75 inches (4.45 cm). This has to be verified. Furthermore, if the mat thickness is less than this value, the base material will have an impact on the reading of PaveTracker™ in which the materials being measured include HMA and base materials. Under this situation, the reading of the gauge will be a compound density value from both HMA pavement and base material.

The two purposes of the field study were to: (a) determine if either of the non-nuclear gauges produce results that are at least as good in comparison to laboratory core analysis as nuclear field density results, and (b) evaluate the potential impact to contractors in terms of pay factors.

We chose to measure the quality of agreement between gauge and core results by two types of statistical analysis – regression and hypothesis testing. Regression analysis yields the correlation coefficient, a measure of how well changes in the field gauge readings track changes in the laboratory results. That is, to what degree results from the two methods move proportionally and in the same direction from specimen to specimen. Hypothesis testing determines whether or not we can conclude, given the variability in the data, that the mean of differences between two measurement methods differs from some hypothesized value, usually zero.

In this study, we aggregated the results from multiple projects, involving three nominal maximum aggregate sizes (NMAS) to provide a range of pavement densities sufficient to elucidate correlation between the measurement methods, since we would expect variability in single-project results to be dominated by random error.

4. Equipment

The study began with the identification of all commercially available alternatives to nuclear density gauges. We identified two instruments that are electrically-based and appear to be the only alternatives currently available. The Pavement Quality Indicator™ (current model: PQI 300) is manufactured by TransTech Systems, Inc. (Schenectady, NY), and the PaveTracker™ Model 1B is manufactured by Donald G. Geisel & Associates, Inc. (Clifton Park, NY).

4.1. Principle of Operation

Asphalt pavement is composed of aggregate, binder, air voids, and possibly water. These materials have highly contrasting dielectric permittivity (e.g., air, 1; water, 80; aggregate, 4-20). Due to these contrasts, the relative proportion of air voids in a moisture-free pavement can be inferred from the dielectric of the mix. Both non-nuclear density gauges evaluated in this study infer pavement density from a measure of the dielectric permittivity of the pavement matrix. However, the two devices appear to differ in their method of dielectric determination.

According to the manufacturer’s literature, the Pavement Quality Indicator (PQI) uses a constant voltage, low frequency, electrical impedance approach, based on a toroidal electrical sensing field. A flat sensing plate establishes this field in the material to be measured. The electrical impedance of the material matrix is a function of the composite dielectric constant of the paving material and air trapped in its voids.

4.2. Practical Complications

Since the dielectric permittivities of air and water are respectively less than and greater than those of the other pavement materials, the influence of a little water can have the same effect on the measurement as a dramatic decrease in air-filled void space.

In addition, the dielectric permittivity of most materials is also known to vary in relation to temperature. This temperature variation can be expected to affect the accuracy of dielectric-based density measurements.

Other researchers who evaluated the original PQI Model 100 and the newer Model 300, which provides moisture and temperature compensation, found the PQI to be extremely sensitive to the presence of water on the sample surface.

To compensate for these variations, the manufacturer of the PaveTracker^{TM} (PT) recommends that for greater accuracy, the measurement should be offset to a nuclear gauge reading or core value, or tied directly to the laboratory design density by placing the PaveTracker^{TM} on top of a 150mm (6 inch) Gyratory compacted specimen.

Unfortunately, neither surface moisture condition nor pavement temperature were recorded in the present study, so their influence on agreement between gauges and cores can not be quantified given the available data.

5. Laboratory Study

5.1 Experimental Procedures

To Evaluate the effects of aggregate size on the density reading of PaveTracker^{TM}, two mix types (19 mm coarse-graded mix and 9.5 mm fine-graded mix) provided by MAR-ZAN, Inc, Zanesville, Ohio, were used to prepare Superpave Gyratory compacted samples and slabs. The coarse mix contained 30% recycled asphalt pavement (RAP) and the fine mix contained no RAP. Table 1 illustrates the aggregate gradation and the optimum binder contents for these two mixes. Also, the source and type of aggregates and asphalt binder are tabulated in Table 2. The gradation curves with 0.45 power are plotted in Figure 1. For each type of mixes, testing specimens of varying densities were prepared with a dimension of 6 inch (15 cm) diameter and 4.45 inch (11.3 cm) height.

Table 1. Mixture Design of HMA Used in Laboratory Testing

Sieve size (mm)	% Passing	
	Coarse Mix	**Fine Mix**
25.4	100	100
19.0	95	100
12.7	82	100
9.5	74	98
4.75	55	61
2.36	39	39
1.18	26	26
0.60	16	16
0.30	10	9
0.15	6	5
0.075	4.7	4.9
Optimum AC (%)	4.6	6.2
Max. Spe. Grav.	2.492	2.444

Table 2. Type and Source of Aggregate and Asphalt Binder

		Type	**Source**
Fine Mix	No. 8 coarse	Limestone	Columbus Limestone - Columbus, OH
	Sand 1	Limestone	Columbus Limestone - Columbus, OH
	Sand 2	Natural	AggRock – Columbus, OH
	AC	PG 64 - 22	S&S Terminal – Rayland, OH
Coarse Mix	No. 57 Coarse	Limestone	Columbus Limestone - Columbus, OH
	No. 8 Coarse	Limestone	Columbus Limestone - Columbus, OH
	Sand 1	Limestone	Columbus Limestone - Columbus, OH
	Sand 2	Natural	AggRock – Columbus, OH
	AC	PG 64 - 28	Project 474 - 85

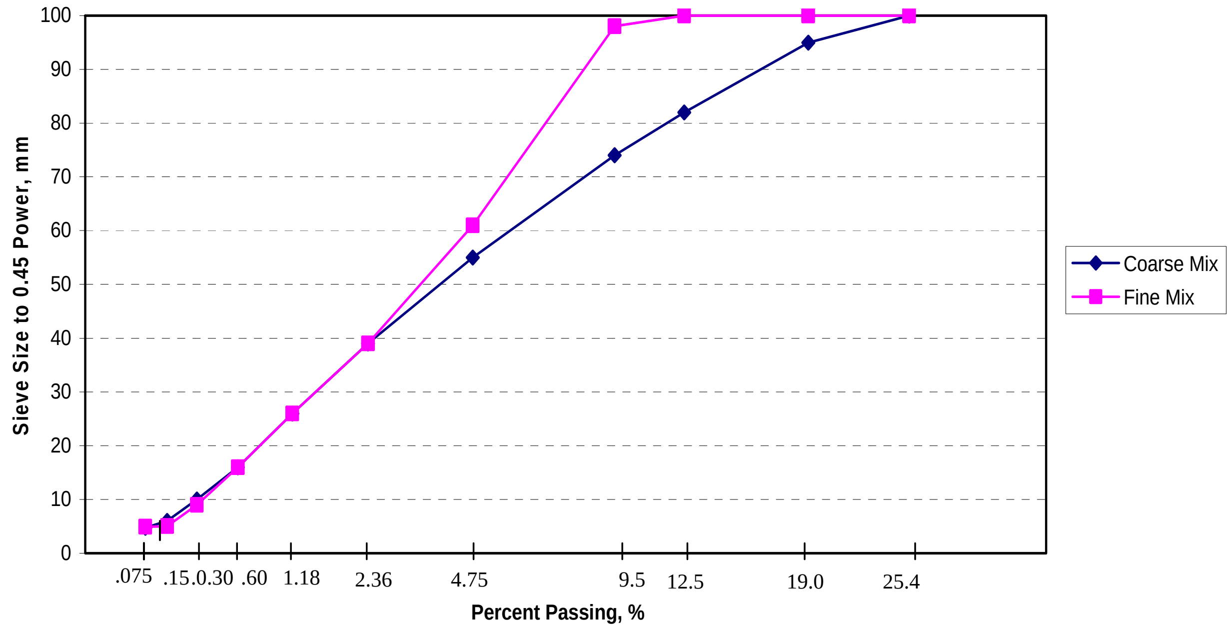

Figure 1. Aggregate Gradations for Coarse and Fine Mixes (25.4mm=1 inch)

To evaluate lateral and vertical depth of influence, slabs were compacted with varying densities and thicknesses. A compaction mold made of timber wood with a dimension of 22.5 inches (57 cm) square and 1.5 inch (3.8 cm) and 2.15 inch (5.46 cm) height were made as shown in Figure 2. So that the horizontal pushing force from wheel rolling compactor would act on the mixes as little as possible, the four legs of the mold are extended such that the compactor could be supported entirely before it reached the mixes. This modification greatly improved the compaction. Figure 3 shows the compaction in progress with a 1.5 ton roller.

Figure 2. Timber Wood Compaction Mold with Loose Mixes Inside

Figure 3. Compaction in Progress with 1.5 Ton Roller

To conduct testing, as the sample cooled, the temperature of each sample was measured with an infrared temperature gun and immediately the density of the sample was measured with the PaveTracker™. The temperatures were collected at five spots on the surface of each sample. The average of five readings was recorded as one measurement. The measurements of densities were collected at four locations of north, east, south, and west. The average of four readings was recorded as one PaveTracker™ density measurement. The sketch of measurement locations for temperature and density is illustrated in Figure 4. Figure 5 shows the PaveTracker™ placed on a Superpave gyratory compactor (SGC) specimen.

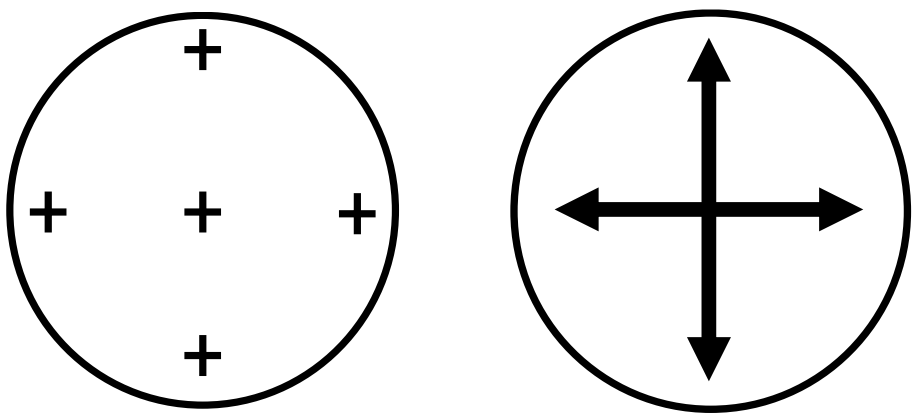

Figure 4. Temperature Measurement Spots (Left) and Gauge Locations (Right) for SGC Specimens

Figure 5. PaveTracker^{TM} on Superpave Gyratory Sample

To evaluate the effect of the presence of the moisture on the performance of the PaveTracker^{TM}, two types of the moisture were considered. One is surface moisture applied only on the top surface of dry samples in order to simulate the application of water during rolling compaction in the field. The other is the combination of internal and surface moisture with partially saturated samples. After the surface moisture experiment, the samples were soaked into water for 24 hours to obtain partial saturation to simulate the field case in which the water leaks into pavement at the beginning of roller compaction. After saturation period, the top surface of the specimen was wiped off with towel and then dried with cool air from hairdryer for 5 seconds to obtain a dry surface. The density measured at this condition was referred to as a gauge reading with internal moisture only. For each measurement, four readings were taken at the 12, 3, 6, and 9 o'clock positions and averaged to obtain density value. The bulk specific gravity of each SGC sample was determined following the procedure in AASHTO T–166, Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens. In addition, the bulk specific gravity after 24 hours of soaking in water was calculated as

$$G_{\text{sb, 24-hour soaking}} = \frac{Mass, SSD}{Mass, SSD - Mass, Underwater}$$

To examine the effect of sample size or lateral zone of influence, slab specimens were compacted first and then cut into progressively smaller sizes while measuring density at the center of the slab. Dry sawing was used to avoid the introduction of water into slab. Coring was used for the first mat. Three sizes were used: 22.5 in. x 22.5 in. (57 cm x 57 cm), 12 in. x 12 in. (30 cm x 30 cm), and 6 in. x 6 in. (15 cm x 15 cm) . For the first mat, no 12 in. x 12 in. (30 cm x 30 cm) slab was made.

Based on 1.75 in. (4.45 cm) measuring depth of PaveTracker™, two 1.5 in. (3.8 cm) thick (shallower than the probing depth) slabs were compacted and two 2.15 in. (5.46 cm) thick (thicker than the probing depth) slabs were compacted. Three density measurements were made by placing the slab on three types of materials: timber wood, HMA and Portland cement concrete. If the readings of PaveTracker™ are affected by base materials, they should vary.

The factors and their levels used in the laboratory study are summarized as shown in Table 3. Each SGC and slab ID was coded as follows. The first letter in mix ID means gradation (C =coarse, F=fine); the second letter stands for density, (H=high density, M=medium density, L=low density); the third letter represents the shape of specimen, (S=150 mm SGC specimen, M=slab); the last number represents replication. Densities and air voids of SGC specimens and slabs prepared for this study are given in Table 4.

Table 3. Factor Levels Used in the Study

Factor	Level
Density	High: 4 % air; Medium: 7 % air; Low: 10% air for SGC specimens High: 7 % air ; Medium: 10 % air for slabs
Temperature	Hot: 60 ~ 80°C; Intermediate: 40 ~ 60°C; Room: ~ 25°C
Surface Moisture Level	Level I: < 0.05 lbs/ft^2 (0.24 kg/m^2) Level II:0.05 ~0.10 lbs/ft^2 (0.24 ~ 0.49 kg/m^2) Level III: 0.10 ~ 0.20 lbs/ft^2 (0.49 ~0.98 kg/m^2) for coarse mix Level I: < 0.02 lbs/ft^2 (0.098 kg/m^2) Level II: 0.02 ~ 0.05 lbs/ft^2 (0.098 ~ 0.24 kg/m^2) Level III: 0.05 ~ 0.10 lbs/ft^2 (0.24 ~ 0.49 kg/m^2) for fine mix
Internal Moisture	Dry; Partially Saturated
Slab Thickness	1.5 in.(3.8 cm); 2.15 in. (5.46 cm)
Slab Size	22.5 in. x 22.5in. (57 cm x 57 cm); 12 in. x 12 in.(30 cm x 30 cm); 6 in. x 6 in. (15 cm x 15 cm)

Table 4. Laboratory Density and Air Void of Specimens (1 pcf=16.033 kg/m^3)

Gradation	MIX ID	Height (mm)	Unit Weight (pcf)	Air Void (%)	Wet Unit Weight (pcf) (After 24 hour soaking)
Coarse	**CHS1**	112.6	151.7	2.5	152.8
	CHS2	111.6	152.4	2.0	153.1
	CHS3	112.3	151.9	2.3	152.9
	CMS1	112.7	147.7	5.0	149.0
	CMS2	112.7	149.0	4.2	150.0
	CMS3	112.7	147.4	5.2	149.2
	CLS1	112.1	143.6	7.7	145.6
	CLS2	112.1	143.4	7.8	145.9
	CLS3	112.1	143.6	7.6	146.5
	CHM1	38.1	145.6	6.4	-
	CMM1	38.1	147.6	5.1	-
	CHM2	54.6	139.7	10.1	-
	CMM2	54.6	143.7	7.6	-
Fine	**FHS1**	112.4	149.5	3.9	149.8
	FHS2	112.2	149.3	4.0	149.8
	FHS3	112.5	149.5	3.8	149.8
	FMS1	112.8	144.6	7.0	145.1
	FMS2	112.8	144.8	6.9	145.1
	FMS3	112.8	145.2	6.6	145.5
	FLS1	112.2	135.5	12.8	137.9
	FLS2	112.2	134.5	13.5	137.1
	FLS3	112.2	133.8	14.0	136.9

Note: First letter in Mix ID means gradation, C---coarse, F---fine;
Second letter stands for density, H---high density, M---medium density, L---low density;
Third letter represents the shape of specimen, S---150 mm Superpave Gyratory sample, M---rolling wheel compacted mat sample

5.2. Results

5.2.1 Effect of Surface Temperature on the Gauge Readings

As illustrated in Figures 6 and 7, the PaveTracker^{TM} exhibited a general trend of an increased gauge reading with increased surface temperature for both fine and coarse mixes with only one exception (CHS1). On average, a 50C° (90F°) drop in temperature would cause an average decrease in gauge readings of 1.0 pcf (16 kg/m^3) with a standard deviation of 0.7 pcf (11 kg.m^3) for coarse mixes and an average decrease in gauge readings of 1.5 pcf (24 kg/m^3) with a standard deviation of 0.5 pcf (8 kg/m^3) for fine mixes. Thus the fine mix shows less variability in temperature-PaveTracker^{TM} density relationship than the coarse mix.

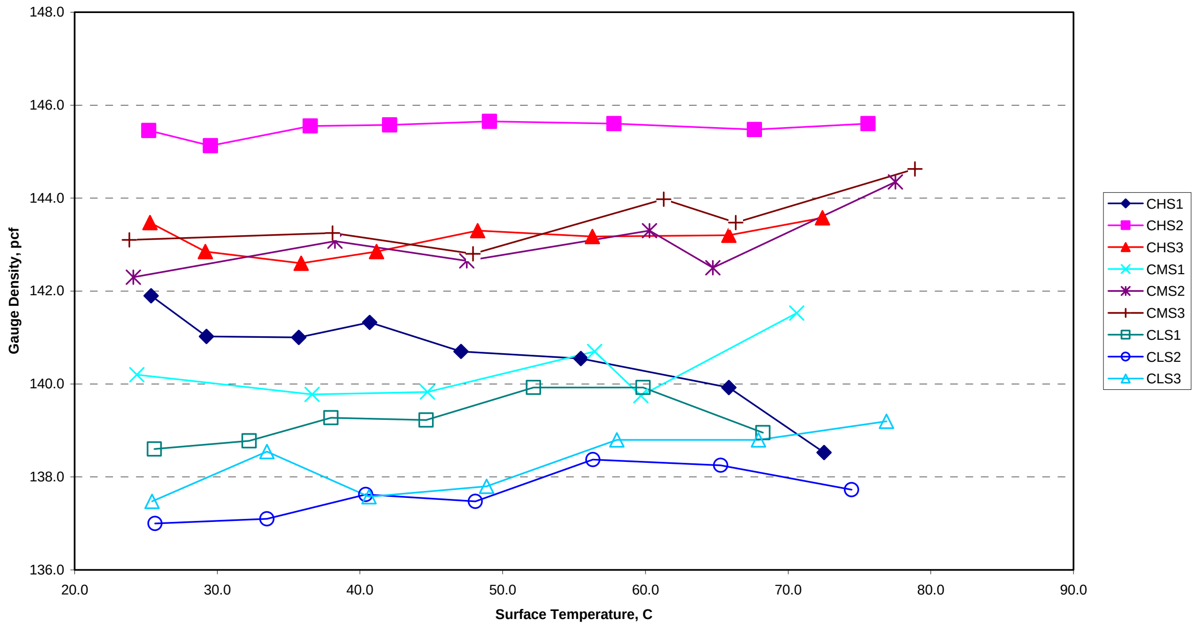

Figure 6. Effect of Temperature on Gauge Readings (Coarse Mix)

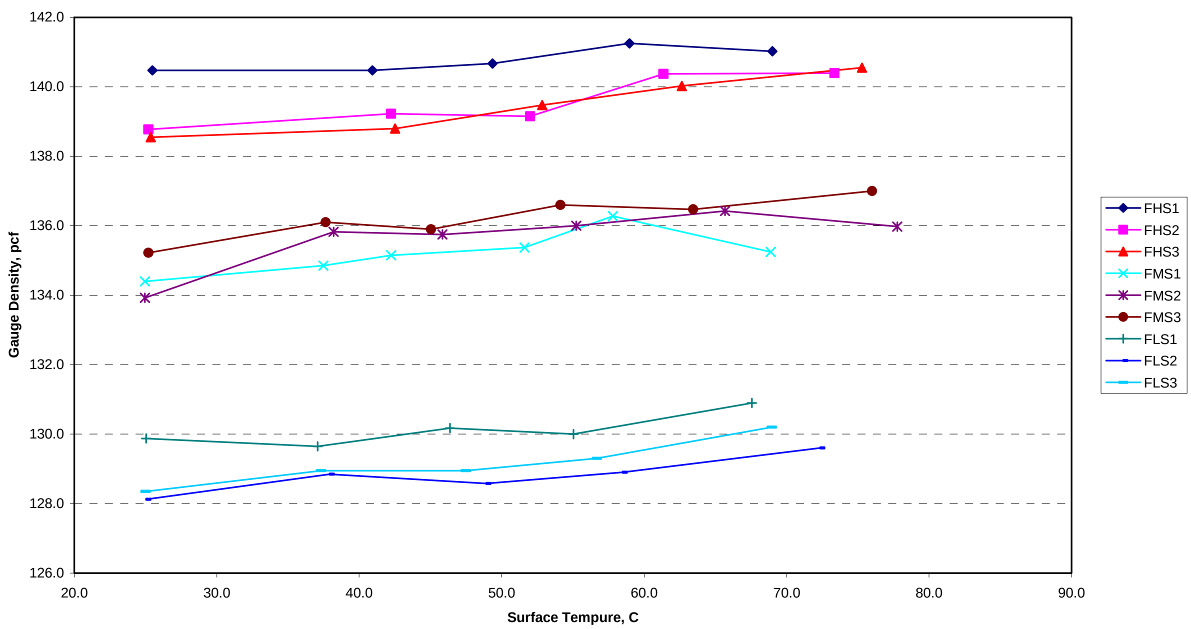

Figure 7. Effect of Temperature on Gauge Readings (Fine Mix)

Figures 8 and 9 represent the effect of the change in surface temperature on the relation between gauge readings and densities determined by AASHTO T-166 (defined as core densities) at different temperature ranges for coarse and fine mixes, respectively. To investigate the effects of temperature more closely, data were subdivided into three temperature groups; hot temperature refers to the temperature higher than 50°C (122°F); intermediate temperature ranges from 40°C (104°F) to 60°C (140°F); room temperature is about 25°C (77°F). For all temperature ranges, the relationships between gauge reading measured by the PaveTracker™ and core density determined by AASHTO T-166 are relatively good, having a better coefficient of determination (R^2) for the fine mix than for the coarse mix. However, slope of the best-fit line is significantly less than unity, indicating that the change in core density is not completely captured in the gauge reading. Furthermore, different mix compositions result in different slopes. In the present study, the slope for the coarse mix ranges from 0.68 to 0.78, and for the fine mix the slope ranges from 0.67 to 0.69. Both mixes use aggregates from the same source. If the aggregate source changes, there might be larger changes in the slope of the gauge density-core density curve.

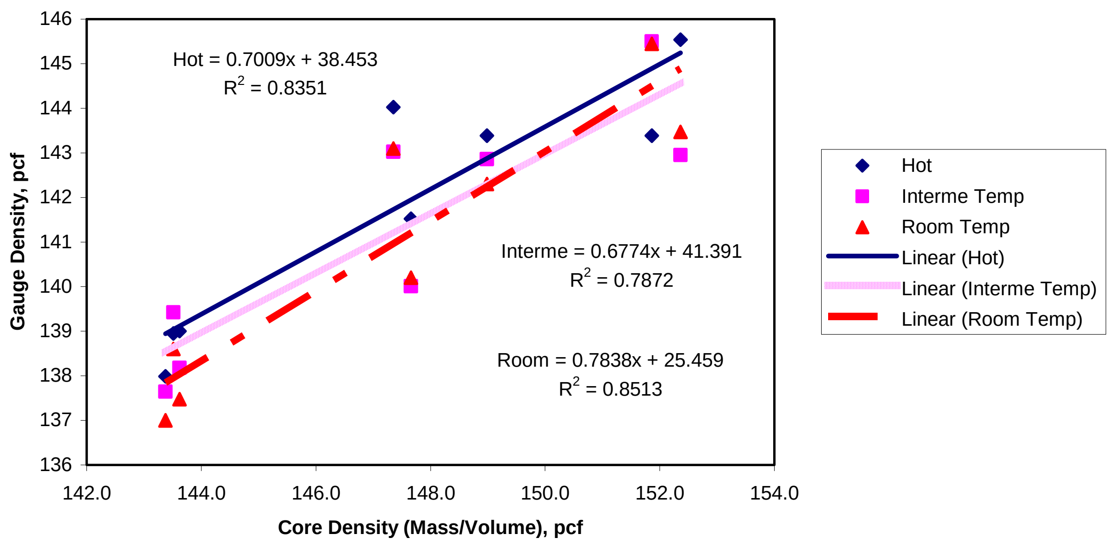

Figure 8. Effect of the Change in Surface Temperature on the Relation Between Gauge Density and Core Density for Coarse Mixtures (Without CHS1)

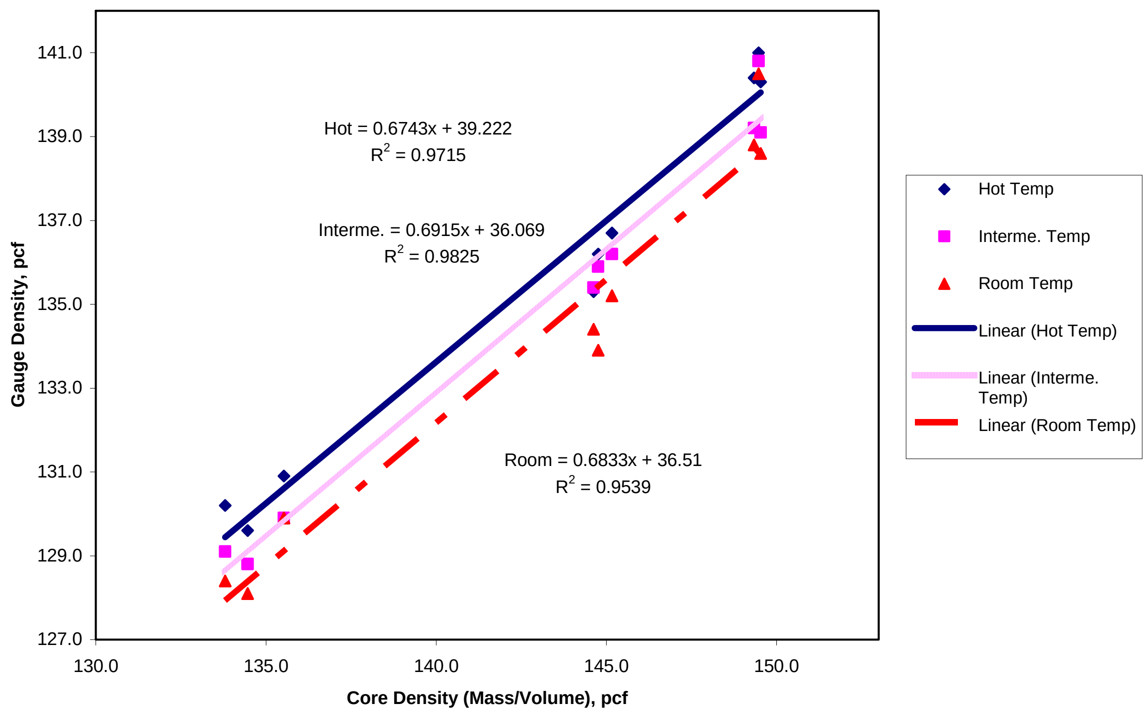

Figure 9. Effect of the Change in Surface Temperature on the Relation Between Gauge Density and Core Density for Fine Mixtures

5.2.2 Effect of the Presence of Surface Moisture on Gauge Readings

To simulate the field conditions where water is applied throughout the process of roller compaction, various quantities of moisture were sprayed onto the surface of the dry specimen without internal moisture. Right after each application of surface moisture, four readings were collected at the same locations and averaged as a gauge reading. The gauge readings collected are plotted against moisture contents as shown in Figures 10 and 11. These figures show that an increase in surface moisture content would lead to a decrease in gauge reading. With the application of 0.10 lbs/ft^2 (0.49 kg/m^2) surface moisture, the average drop in gauge readings was 6.9 pcf (110 kg/m^3) and the standard deviation was 4.1 pcf (66 kg/m^3) for coarse mixes. For fine mixes, an average drop of 8.9 lbs/ft^2 (430 Pa) and a standard deviation of 1.5 pcf (24 kg/m^3) were observed. By considering all data, it can be found that gauge readings hardly change after the surface moisture reaches about 0.10 lbs/ft^2 (0.49 kg/m^2). This is because moisture began to pond on the surface of the specimen when moisture reached this level and the excess moisture overflowed when the gauge was placed on the surface. This overflowing caused no further decrease in gauge readings and even a bit of an increase.

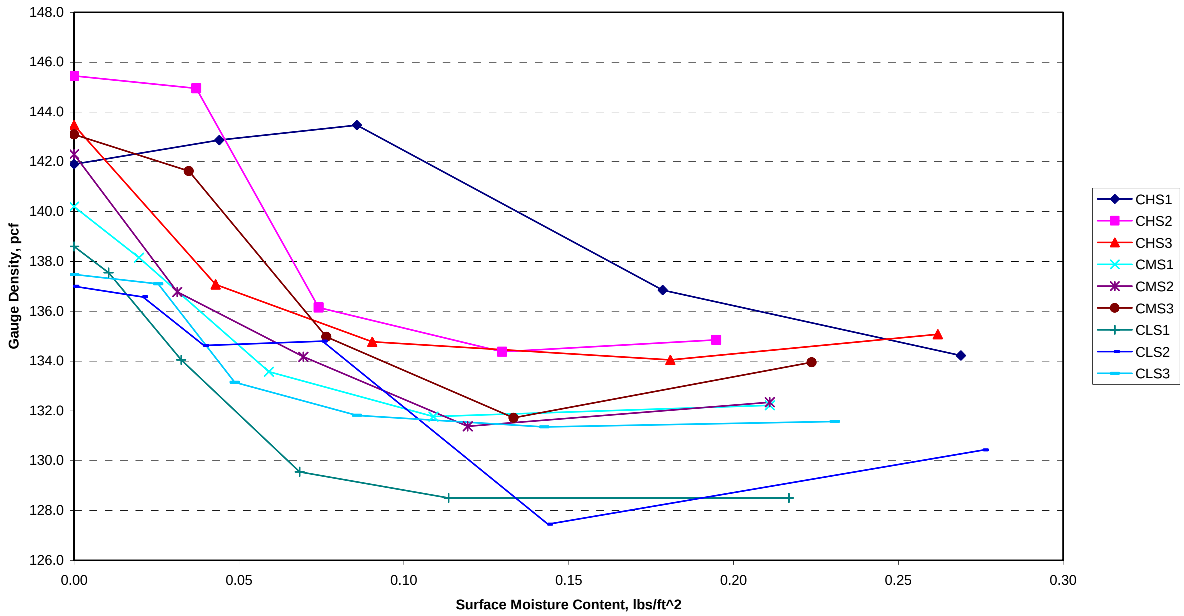

Figure 10. Effect of Surface Moisture on Gauge Readings (Coarse Mix Without Internal Moisture)

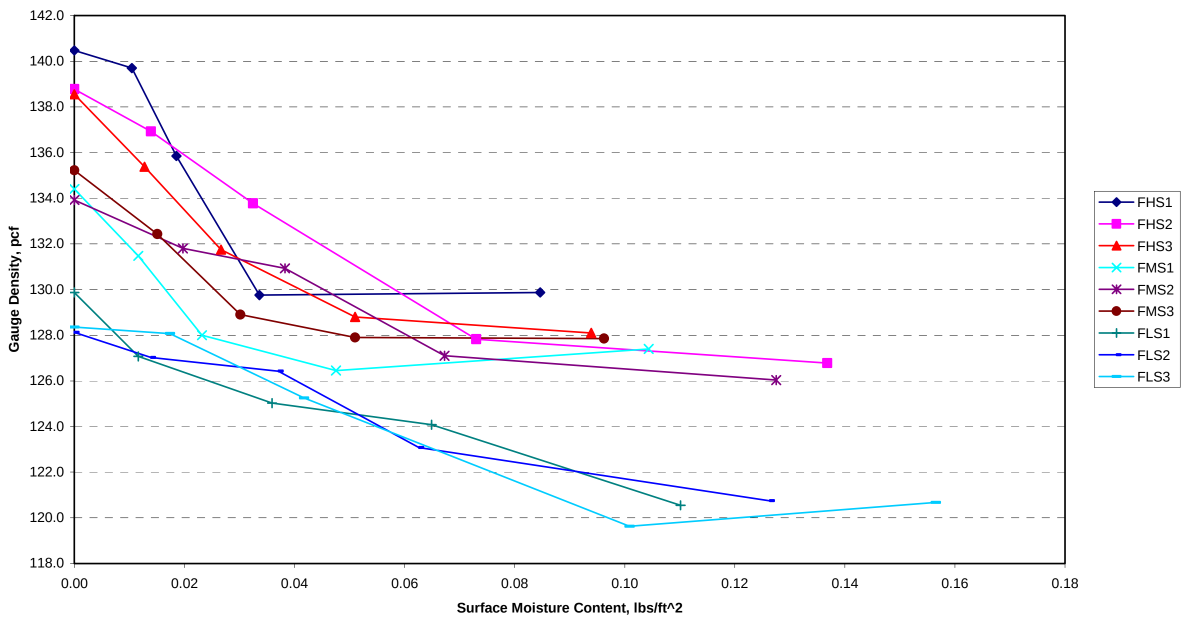

Figure 11. Effect of Surface Moisture on Gauge Readings (Fine Mix Without Internal Moisture)

The applications of surface moisture are divided into three levels. For coarse mixes, they are: (1) surface moisture level I for less than 0.05 lbs/ft^2 (0.24 kg/m^2); (2) surface moisture level II for between 0.05 lbs/ft^2 (0.24 kg/m^2) and 0.10 lbs/ft^2 (0.49 kg/m^2); (3) surface moisture level III for between 0.10 lbs/ft^2 (0.49 kg/m^2) and 0.20 lbs/ft^2 (0.98 kg/m^2). For fine mixes, due to good finishing of specimen surface, the applied amount of surface moisture was reduced slightly. The levels are: (1) surface moisture level I for less than 0.02 lbs/ft^2 (0.098 kg/m^2); (2) surface moisture level II for between 0.02 lbs/ft^2 (0.098 kg/m^2) and 0.05 lbs/ft^2 (0.24 kg/m^2); (3) surface moisture level III for between 0.05 lbs/ft^2 (0.24 kg/m^2) and 0.10 lbs/ft^2 (0. 49 kg/m^2). For both mixes, as the surface moisture level increases, the gauge density decreases for the same value of core density. Figures 12 and 13 show this effect of surface moisture when there is no internal moisture. For each level of surface moisture, there is a similar relationship seen in the dry condition.

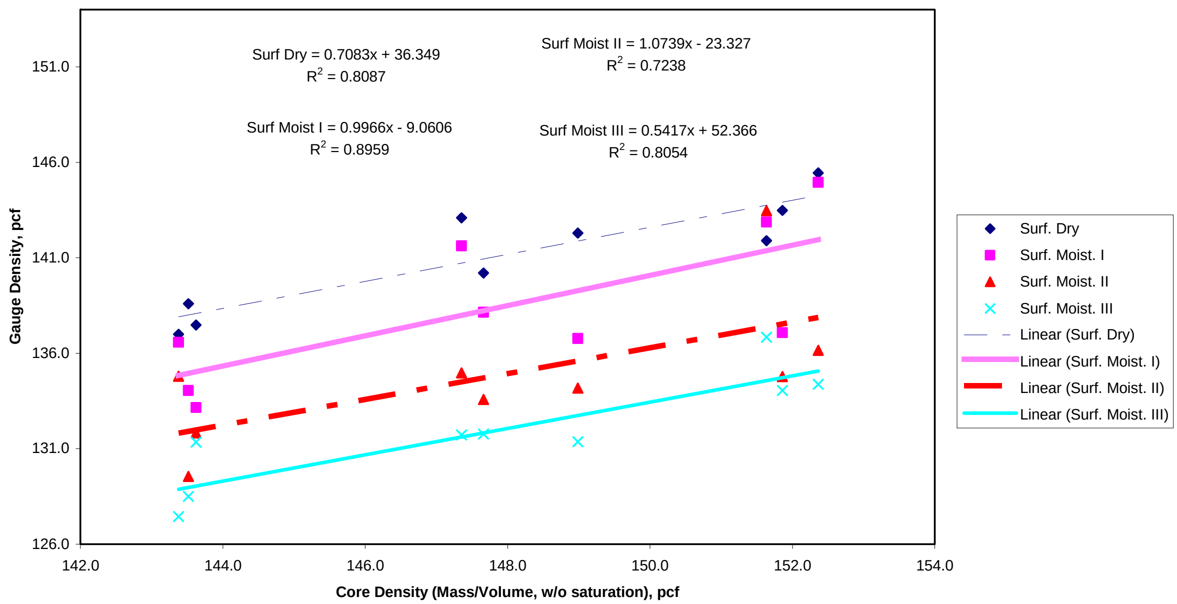

Figure 12. Effect of Surface Moisture on the Gauge Density as a Function of Core Density for Coarse Mixtures (No Internal Moisture)

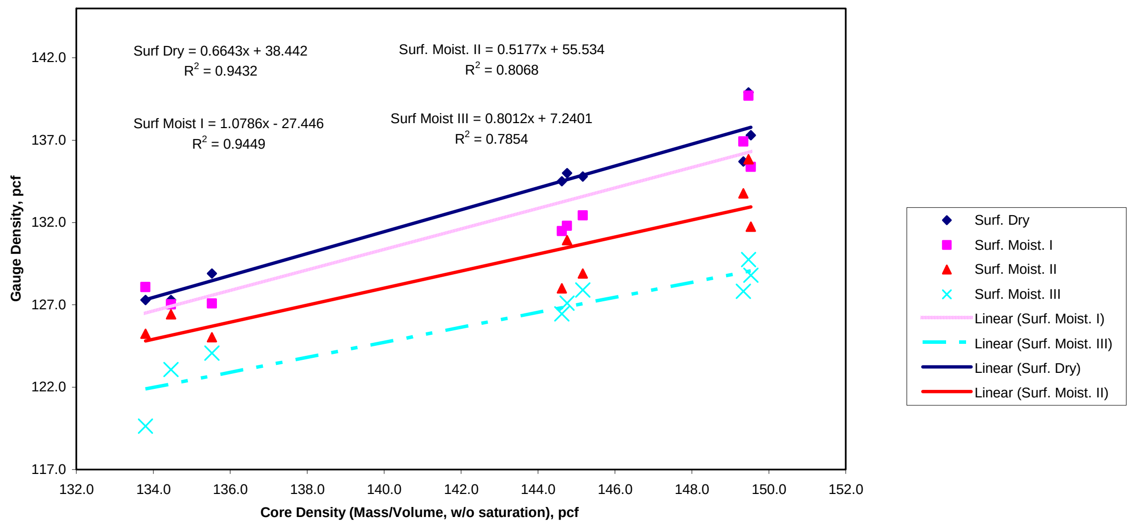

Figure 13. Effect of Surface Moisture on the Gauge Density as a Function of Core Density for Fine Mixtures (No Internal Moisture)

5.2.3. Effect of Combined Surface and Internal Moisture on Gauge Readings

During the application of roller compacting in the field, some of moisture applied would enter into mixtures at the beginning of the compaction when the mixture is loose enough for moisture infiltration. To determine how this situation would affect the performance of the gauge, the combination of surface moisture and internal moisture was introduced to specimens in the laboratory.

Before the application of surface moisture, samples were submerged in water for 24 hours to obtain partial saturation. With each sample, a first set of measurements was taken without surface moisture; any surface moisture from the soaking period was removed from sample surface with towel and cool air from a hairdryer. After that, surface moisture was applied to the sample surface as described in the previous section. Figures 14 and 15 show the combined effects of surface and internal moisture on gauge readings. The gauge readings decreased with increasing surface moisture as observed in the experiment without internal moisture.

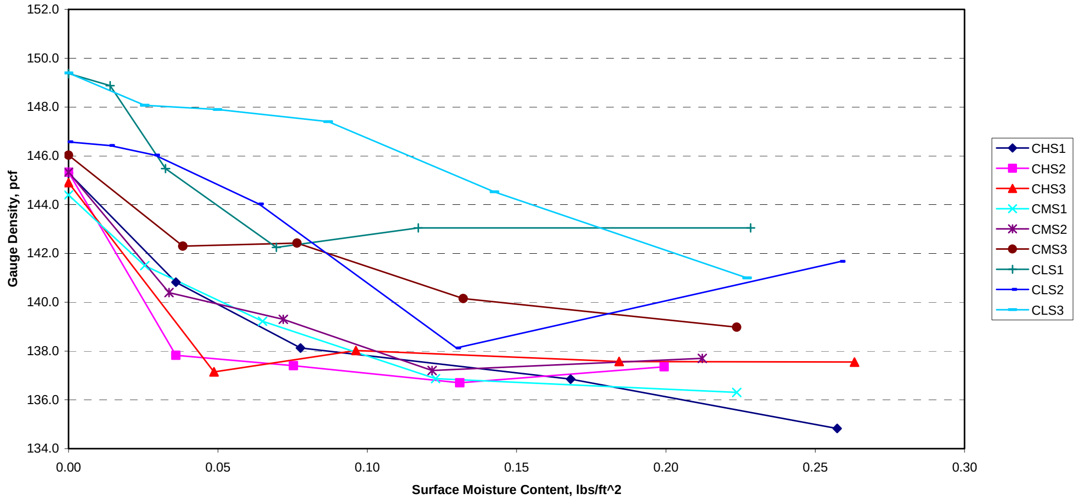

Figure 14. Effect of the Combination of Surface and Internal Moisture on the Gauge Density (Coarse Mix, Partial Saturation)

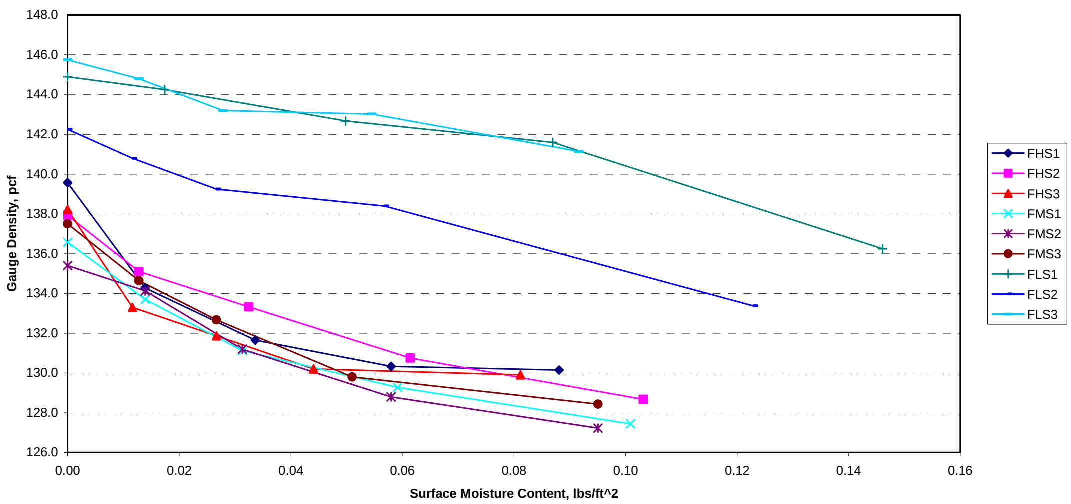

Figure 15. Effect of the Combination of Surface and Internal Moisture on the Gauge Density (Fine Mix, Partial Saturation)

Internal moisture created by partial saturation changed the relationship between the gauge reading and core density compared to that of a dry specimen. As shown in Figures 16 and 17, the gauge reading decreased with an increase of core density. Their relationships also became nonlinear. The nonlinearity of the relationship may be due to a disproportionate amount of internal moisture among high and low core density samples. Specimens with lower core density have larger air voids and will retain more internal moisture during 24 hours of water soaking. Consequently, the gauge readings on these mixes will be affected more by the internal moisture.

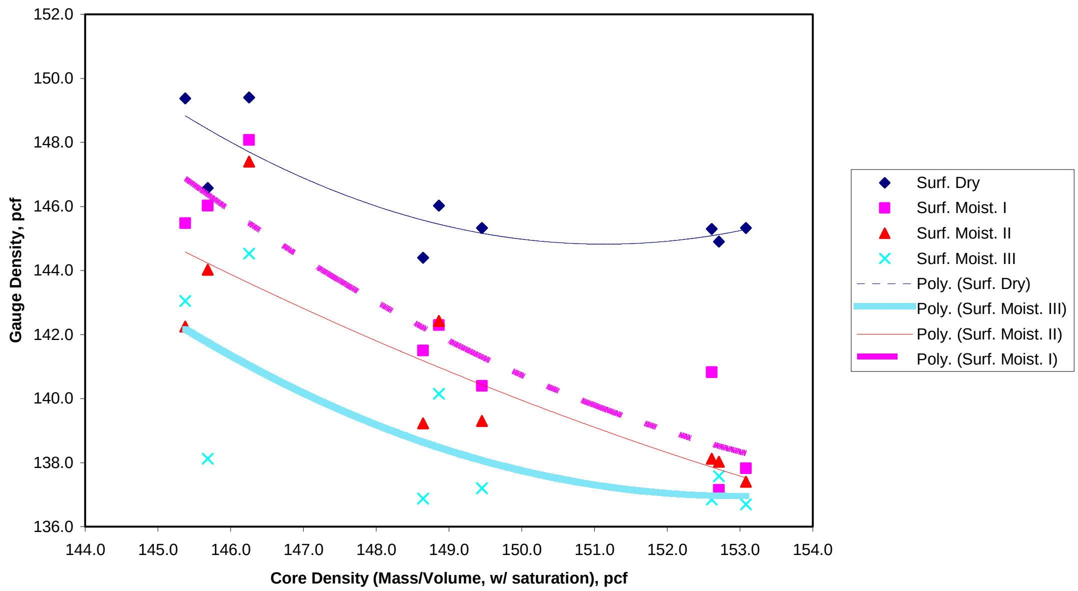

Figure 16. Effect of the Combination of Surface and Internal Moisture on the Gauge Density as a Function of Core Density for Coarse Mixtures

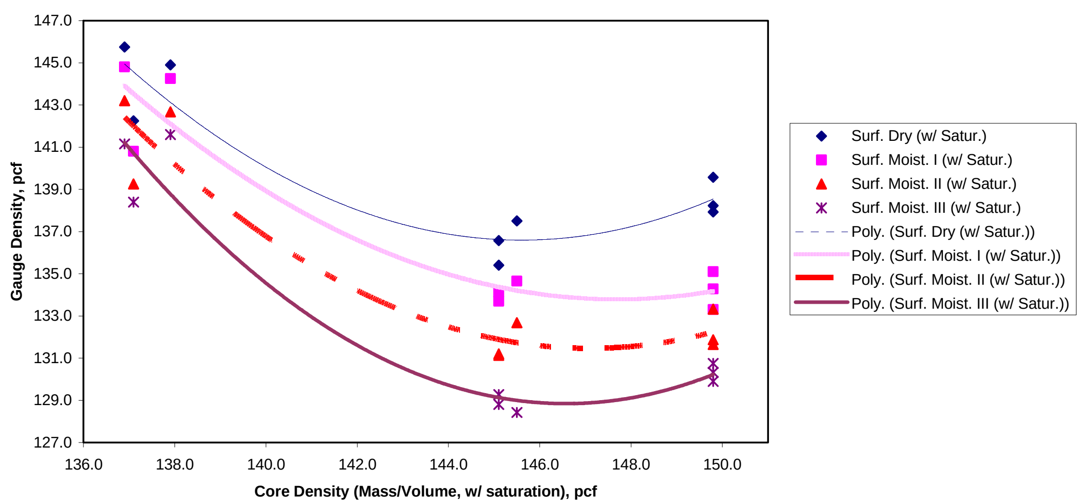

Figure 17. Effect of the Combination of Surface and Internal Moisture on the Gauge Density as a Function of Core Density for Fine Mixtures

Total unit weights of the partially saturated surface dry specimens (instead of dry unit weight as defined as core density) were used to find the relationship between the gauge reading and the core density as shown in Figures 17 and 18. Unlike the surface moisture that lowered the PaveTracker^{TM} gauge readings, the internal moisture caused higher gauge readings. Furthermore, the relationship between the gauge reading and core density (total or dry unit weight) deviates from the one developed using dry specimens. As shown in Figures 18 and 19, the effects of the internal moisture on PaveTracker^{TM} performance were especially significant for mixes with larger air voids (or mixes with low densities in the figures). For these mixes, the 24 hour soaking increased the unit weight by about 3 pcf (48 kg/m^3) while the gauge reading increased by 10 pcf (160 kg/m^3) or more.

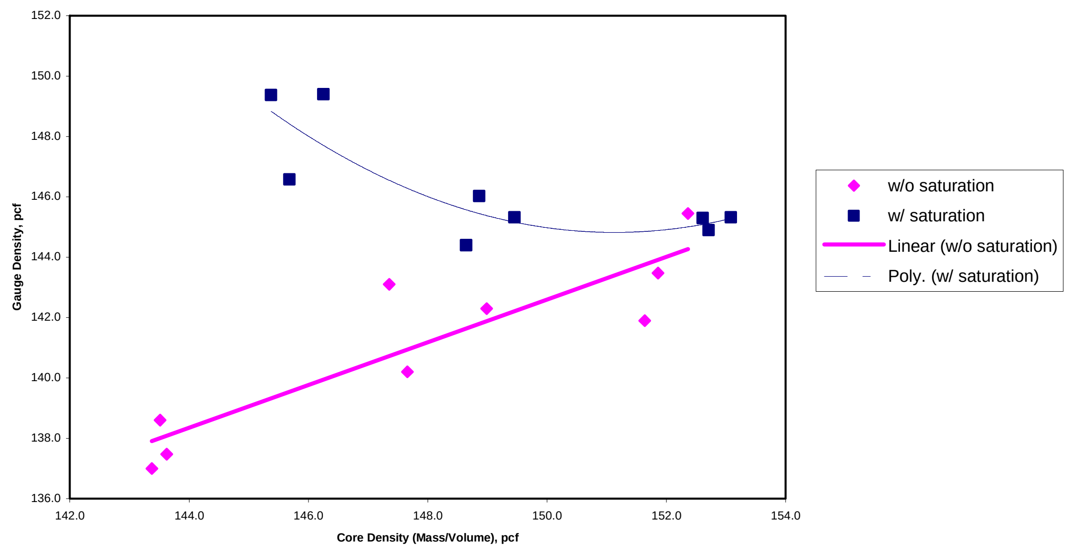

Figure 18. Effect of Internal Moisture on the Relationship Between Gauge Density and Core Density for Coarse Mixtures

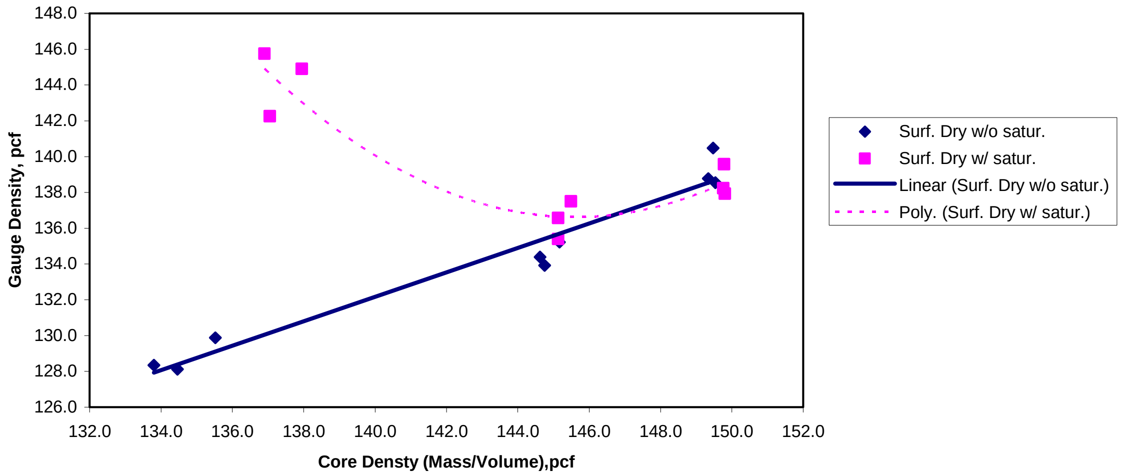

Figure 19. Effect of Internal Moisture on the Relationship Between Gauge Density and Core Density for Fine Mixtures

5.2.4. Effect of Maximum Size of Aggregate on Gauge Readings

From Figures 8 and 9, the gauge reading and core density relationship at ambient temperature is plotted in Figure 20 again for easy comparison. Both 19 mm coarse mix and 9.5 mm fine mix have similar slopes. However, their intercepts are significantly different for the given range of density. As shown previously in Table 2, both mixes consist of the same local limestone and natural sands. The 19 mm coarse mix also contains 30% RAP. The coefficient of determination (R^2) for fine mix (0.94) is larger than that of coarse mix (0.81). That is believed that the smoother surface texture of the fine mix allows better contact with the PaveTracker™ during measurement.

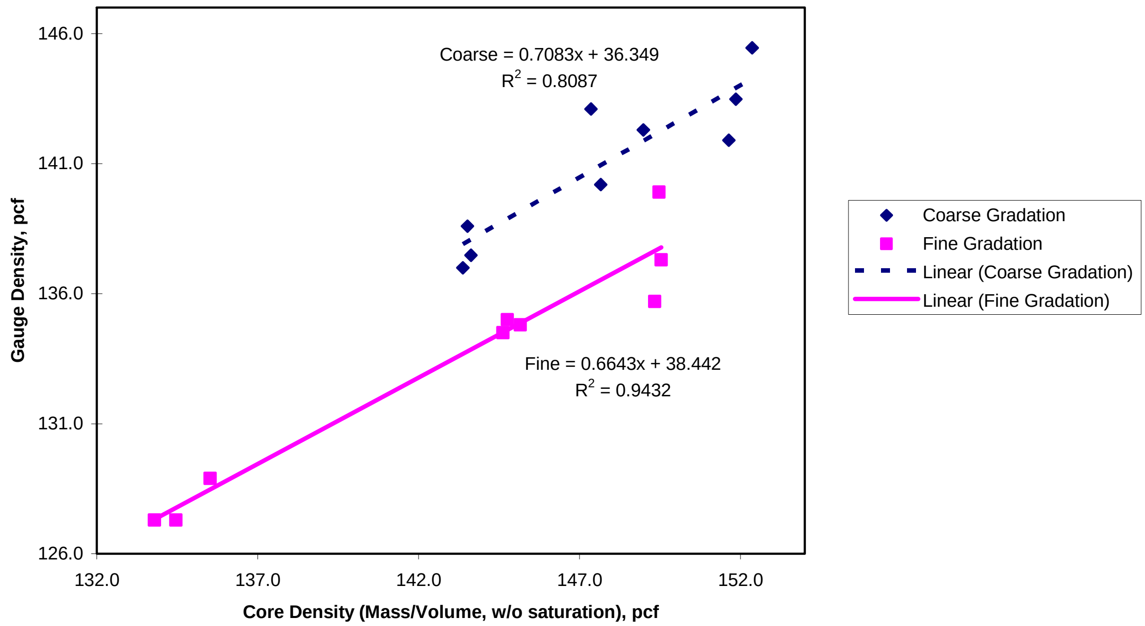

Figure 20. Effect of Aggregate Gradation on the Relationship Between Gauge Reading and Core Density Without Surface or Internal Moisture

5.2.5. Accuracy of PaveTracker^{TM} Gauge Readings

The gauge readings taken from the PaveTracker^{TM} on dry specimens at room temperature and core densities determined following AASHTO test procedure T-166 are summarized in Table 5. The largest difference between core density and gauge density was -5.9 pcf (-95 kg/m^3) (higher gauge reading) for CMS3. For the coarse mixes, the average difference between core density and gauge density was -3.4 pcf (-55 kg/m^3) and the standard deviation was 1.7 pcf (27 kg/m^3). The accuracy of the gauge with fine mixes is better; the average difference was -1.4 pcf (22 kg/m^3) and the standard deviation was 2.3 pcf.(37 kg/m^3) Based on all gauge densities from both types of mixes, the average difference was -2.6 pcf (-42 kg/m^3) and standard deviation was 2.0 pcf (32 kg/m^3). This also demonstrated that PaveTracker^{TM} works better with fine-graded mixes than coarse-graded mixes.

Table 5. Summary of the Accuracy of Gauge Measurement by PaveTracker™

Mix ID	Gauge Density (pcf)	Core Density (pcf)	Gauge Density after calibration (pcf)	Measurement Difference (pcf)	Average Difference (pcf)			Standard Dev. of Diff (pcf)		
FHS1	140.5	149.5	150.7	-1.2		-1.4	-2.6		2.3	2.0
FHS2	138.8	149.3	149.0	0.4						
FHS3	138.6	149.5	148.8	0.8						
FMS1	134.4	144.6	144.6	0.0						
FMS2	133.9	144.8	144.1	0.6						
FMS3	135.2	145.2	145.4	-0.3						
FLS1	129.9	135.5	140.1	-4.6						
FLS2	128.1	134.5	138.3	-3.9						
FLS3	128.4	133.8	138.6	-4.8						
CHM1	137.6	145.6	147.8	-2.2	-3.3	-3.4		1.4	1.5	
CMM1	139.3	147.6	149.5	-1.9						
CHM2	133.7	139.7	143.9	-4.1						
CMM2	138.3	143.7	148.5	-4.8						
CHS1	141.9	151.6	152.1	-0.5	-3.4			1.7		
CHS2	145.5	152.4	155.7	-3.3						
CHS3	143.5	151.9	153.7	-1.8						
CMS1	140.2	147.7	150.4	-2.7						
CMS2	142.3	149.0	152.5	-3.5						
CMS3	143.1	147.4	153.3	-5.9						
CLS1	138.6	143.5	148.8	-5.3						
CLS2	137.0	143.4	147.2	-3.8						
CLS3	137.5	143.6	147.7	-4.1						

5.2.6. Effect of Sample Area on PaveTracker™ Gauge Readings

According to the principle of operation of the PaveTracker™, the surface area of the material being measured is supposed to be somewhat larger than the area of contact plate of the PaveTracker™. It is rationalized that the surface area of specimens would to some extent affect gauge readings. To this end, an experiment was designed to measure slab density with slabs having three different surface areas. First, 22.5 in. x 22.5 in. (57.2 cm x 57.2 cm) slabs with 1.5 in. (3.8 cm) and 2.15 in. (5.46 cm) thicknesses were compacted and densities were measured. Then the slabs were cut to 12 in. x 12 in. (30 cm x 30 cm) and densities were measured again at same location. Finally, they were cut to 6 in. x 6 in. (15 cm x 15 cm) square slabs and densities were measured at the same location. These data were used to examine if an effect due to sample area exists since the only change on this process was the area of the specimen being measured. The data are shown in Table 6 and plotted in Figure 21. In order to double check the effect size, the cut slabs after all gauge readings were reassembled to one size larger, the process of which is called “reassembly”, in comparison with the process of cutting the slab down to a smaller size. Then, the densities were measured again. The reassembly data are also included in Table 6 and Figure 21. The significant effect of area on the gauge reading exits when the size of the mat changes from 12 in. x 12 in. (30 cm x 30 cm) to 6 in. x 6 in. (15 cm x 15 cm) for all mixes, which leads to an average decrease of 2.4 pcf (38 kg/m^3). Most of reassembly densities are virtually same as the original cut densities. For slab CMM1, however, reassembly density is always smaller than the original cut density. We believe that the gaps between cut pieces in the reassembling process cause the observed difference in density values.

Table 6. Effect of Sample Area on PaveTracker^{TM} Gauge Reading (1 pcf = 16.0 kg/m^3).

Mix ID	Gauge Density (pcf)@ dimension					
	Original cut			Reassembly		
	22.5 x 22.5	12 x 12	6 x 6	22.5 x 22.5	12 x 12	6 x 6
CHM1	137.6	N/A	133.1	134.9	N/A	133.4
CMM1	139.3	138.7	135.4	137.5	137.3	135.1
CHM2	132.8	132.2	130.8	132.4	132.6	130.6
CMM2	138.4	137.7	135.3	138.1	137.6	135.6

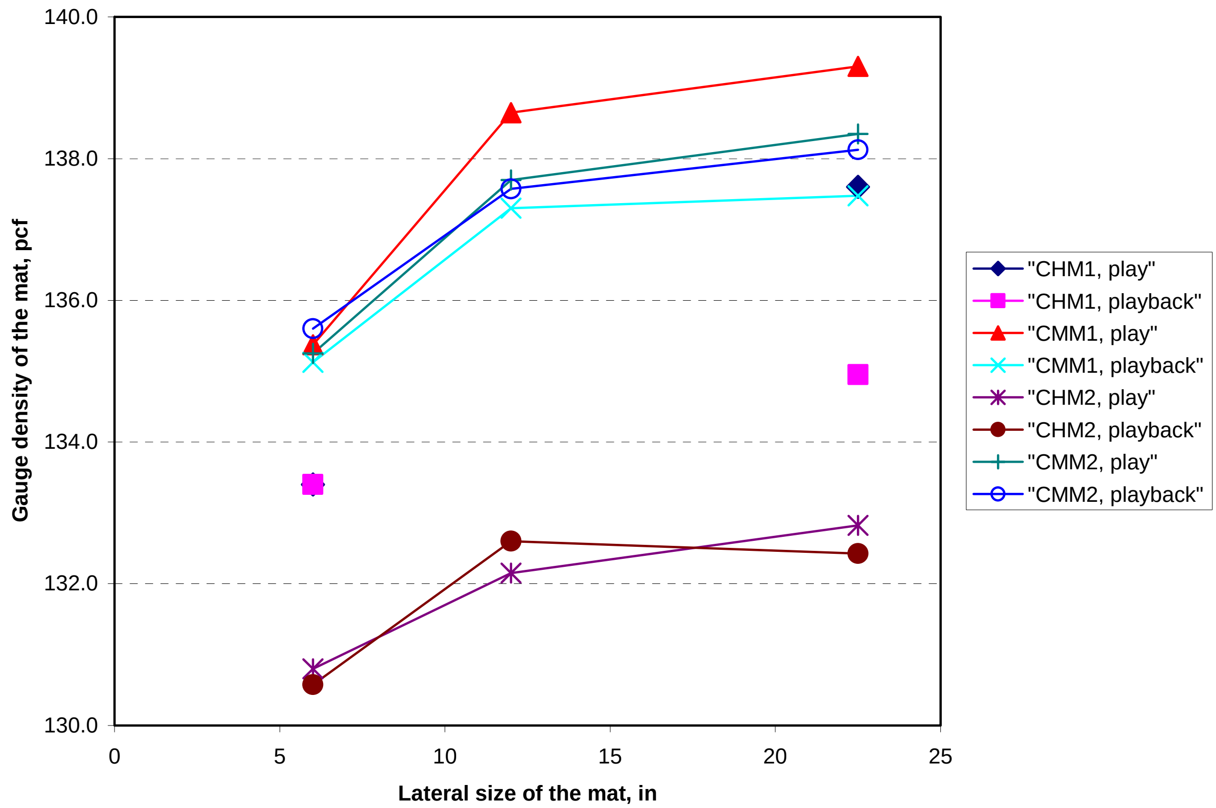

Figure 21. Effect of Lateral Size on PaveTracker^{TM} Gauge Reading (1 in =2.54 cm, 1 pcf = 16.0 kg/m^3)("play"= original cut, "playback" = reassembly).

It is concluded that the area of the specimen affects the PaveTracker™ gauge readings when the surface area of the materials being measured is less than two times of the area of the contact plate of the PaveTracker™. Therefore, calibration with a 6 in. (15 cm) core or SGC sample is not recommended.

5.2.7. Effect of Measuring Depth of the PaveTracker™ on Gauge Readings

In the field, the lift thickness of asphalt layer is sometimes less than 1.75 inches (4.45 cm), the measuring depth of the PaveTracker™ used in this study. Application of the PaveTracker™ to measure the density of such thin HMA is of great concern. Since the measuring depth of the PaveTracker™ used in this study is 1.75 in. (4.45 cm), slabs with thicknesses of 1.5 in. (3.81 cm) and 2.15 in. (5.46 cm) were compacted to experiment with the PaveTracker™. To see if base material on which HMA slab is lying on has an effect on gauge reading, three types of base materials were used including, timber wood, other HMA with different density, and Portland cement concrete. To determine how much effect there was, the density of each base material was measured using the PaveTracker™. The results are illustrated in Table 7 and Figure 22.

Table 7. Effect of Slab Thickness Relative to Measuring Depth of the PaveTracker™ (1 pcf = 16.0 kg/m^3).

Sample size	Gauge Density, pcf							
	Base	CHM1 (1.5 in., 3.8 cm)	Base	CMM1 (1.5 in.)	Base	CHM2 (2.15 in., 5.46 cm)	Base	CMM2 (2.15 in., 5.46 cm)
6”x6”	Wood (87.0)	133.6	87.0	135.4	87.0	130.8	87.0	136.1
	ACC (135.5)	135.4	135.4	137.3	135.5	131.1	133.4	136.6
	PCC (142.9)	136.2	159.9	138.1	160.3	131.3	160.2	137.0
12”x12”	Wood	-	87.0	138.7	87.0	132.2	87.0	137.7
	ACC	-	135.4	140.0	135.5	132.8	133.4	138.1
	PCC	-	159.9	140.7	160.3	132.8	160.2	138.0

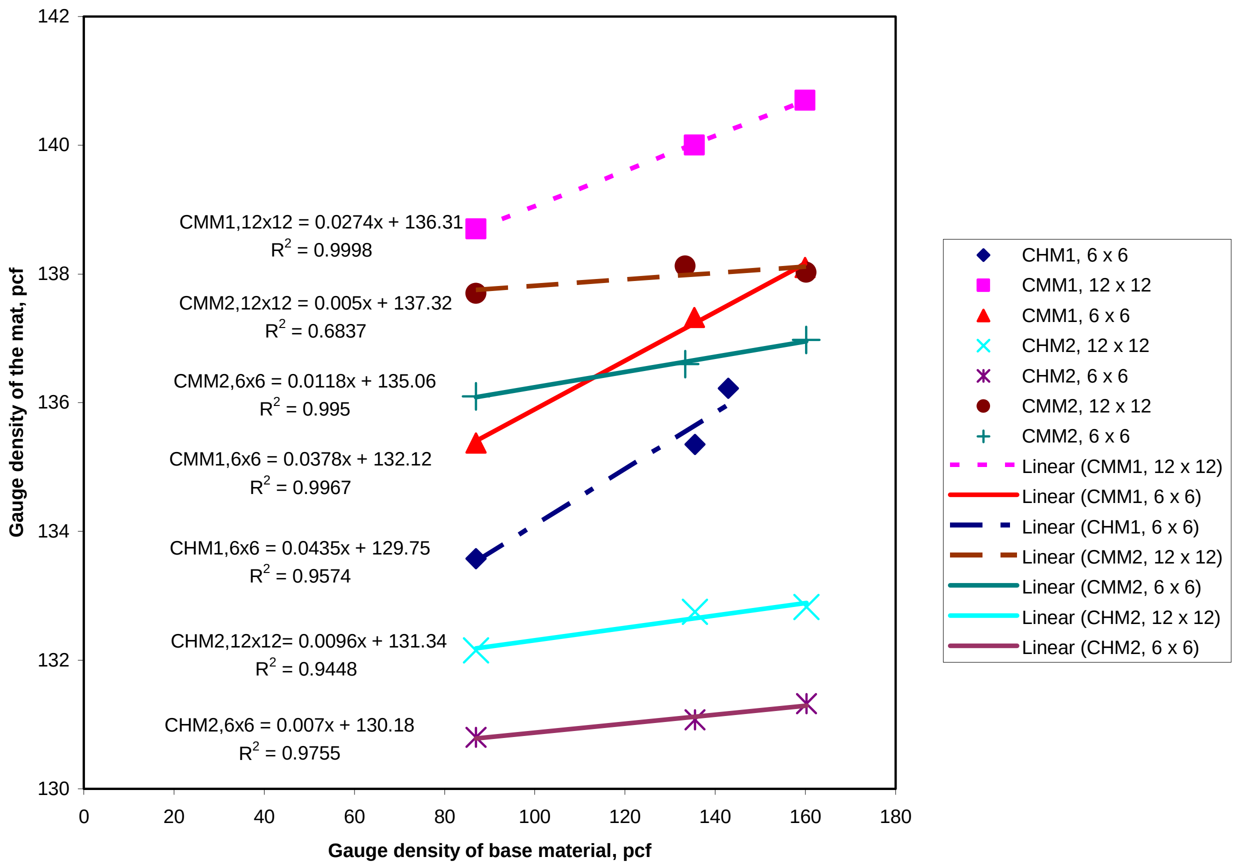

Figure 22. Effect of Slab Thickness Relative to Measuring Depth of the PaveTracker^{TM}

With the mat with a thickness of 1.5 in. (3.8 cm) (CHM1 and CMM1), the gauge reading can change as much as about 2.5 pcf (40 kg/m^3) with different base materials. In comparison with the change of gauge reading of the mat with a thickness of 2.15 in. (5.46 cm) (CHM2 and CMM2), a conclusion can be drawn that if the measuring depth of the PaveTracker^{TM} is larger than the thickness of the mat being measured, the gauge reading is a composite of the target HMA material and the underlying base material. On average, the gauge reading of 1.5 inch (3.8 cm) thick slab was influenced by the underlying material's density at a rate of 0.03 pcf/pcf (0.03 (kg/m^3)/(kg/m^3)) and the gauge reading of 2.15 inch (5.46 cm) thick slab at a rate of about 0.01 pcf/pcf (0.01 (kg/m^3)/(kg/m^3)). When the thickness of the mat being measured is reasonably larger than measuring depth of the PaveTracker^{TM}, the effect of base material on gauge reading will be small and may be neglected without any loss of measurement accuracy.

5.2.8. Statistical Analysis of Measurement Results

Among the density measurement results, those from the laboratory method AASHTO T-166 are viewed as controls with which others can be compared. Two measures of evaluating the applicability of the PaveTracker^{TM} to determine HMA density, the coefficient of correlation and the analysis of variance, were computed to analyze density measurement results.

5.2.8.1. Coefficient of Correlation

The coefficient of correlation in statistics can be used to study the nature of the relations between variables. When there is a correlation, one of variables can be inferred on the basis of the other. Mathematically, the correlation coefficient is defined as

$$R = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{Control - Control\_Aver}{STDEV\_Controls}\right)\left(\frac{Gauge - Gauge\_Aver}{STDEV\_Gauges}\right)$$

Where

R = correlation coefficient
Control = density from laboratory testing of control samples
Control_Aver = average density from all control samples
Gauge = density from gauge measurement
Gauge_Aver = average density from gauge measurement
STDEV_Controls = standard deviation of density from all control samples
STDEV_Gauges = standard deviation of density from all gauge measurements

The value of the correlation coefficient is usually given in the form of R^2, called the coefficient of determination. The closer the R^2 is to 1, the better correspondence there is between gauge measurement and core density. If R^2=0.80, that means 80 percent of the sum of squares of differences of gauge readings and their mean is due to differences in core density. The reliability of the value of coefficient of correlation is proportionally based on the size of samples. Table 8 collectively lists the coefficients of determination, R^2, and the corresponding linear equations.

Table 8. Summary of Regression Equations in this Study.

Condition			Mix	R^2	Equation
Dry & Room Temperature			Coarse (Gyratory Sample)	0.8087	$y = 0.7083 \cdot x + 36.349$
			Fine (Gyratory sample)	0.9432	$y = 0.6643 \cdot x + 38.442$
			Coarse (mat sample)	0.8563	$y = 0.6842 \cdot x + 38.852$
Temperature	Hot	w/CHS1	Coarse (Gyratory Sample)	0.4653	$y = 0.5039 \cdot x + 66.957$
		w/o CHS1		0.8351	$y = 0.7009 \cdot x + 38.453$
	Intermediate	w/CHS1		0.6741	$y = 0.581 \cdot x + 55.284$
		w/o CHS1		0.7872	$y = 0.6774 \cdot x + 41.391$
	Room	w/CHS1		0.8086	$y = 0.7104 \cdot x + 36.055$
		w/o CHS1		0.8513	$y = 0.7838 \cdot x + 25.459$
	Hot		Fine (Gyratory sample)	0.9715	$y = 0.6743 \cdot x + 39.222$
	Intermediate			0.9825	$y = 0.6915 \cdot x + 36.069$
	Room			0.9539	$y = 0.6833 \cdot x + 36.51$
	Hot		Coarse (mat sample)	0.9188	$y = 0.6973 \cdot x + 37.963$
	Intermediate			0.9057	$y = 0.6904 \cdot x + 38.389$
	Room			0.8557	$y = 0.6802 \cdot x + 39.168$
Surface Moisture	Dry		Coarse (Gyratory Sample)	0.8087	$y = 0.7083 \cdot x + 36.349$
	Level I			0.8959	$y = 0.9966 \cdot x - 9.0606$
	Level II			0.7238	$y = 1.0739 \cdot x - 23.327$
	Level III			0.8054	$y = 0.5417 \cdot x + 52.366$
	Dry		Fine (Gyratory sample)	0.9432	$y = 0.6643 \cdot x + 38.442$
	Level I			0.9449	$y = 1.0786 \cdot x - 22.446$
	Level II			0.8068	$y = 0.5177 \cdot x + 55.534$
	Level III			0.7854	$y = 0.8012 \cdot x + 7.2401$
Mat Thickness	1.5 in (3.8 cm)		CHM1, 6"x6"	0.9574	$y = 0.0435 \cdot x + 129.75$
			CMM1, 12"x12"	0.9998	$y = 0.0274 \cdot x + 136.31$
			CMM1, 6"x6"	0.9967	$y = 0.0378 \cdot x + 132.12$
	2.15 in (5.46 cm)		CHM2, 12"x12"	0.9448	$y = 0.0096 \cdot x + 131.34$
			CHM2, 6"x6"	0.9755	$y = 0.007 \cdot x + 130.18$
			CMM2, 12"x12"	0.6837	$y = 0.005 \cdot x + 137.32$
			CMM2, 6"x6"	0.9950	$y = 0.0118 \cdot x + 135.06$

Note:

- With respect to the conditions of 'Dry & Room Temperature', 'Temperature', and 'Surface Moisture', variable x represents the core density of the sample being measured and variable y means the gauge density measured by PaveTracker™.
- With respect to the condition of 'Mat Thickness', variable x means the gauge density of base material on which the sample being measured lies and variable y is the gauge density of the sample being measured.

5.2.8.2 Analysis of Variance

The effect of some factors discussed previously can be examined from another perspective – the Analysis of Variance (ANOVA). In this report, one-way ANOVA was conducted to see if the effect of temperature and moisture levels on the gauge readings is significant. The results of the ANOVA are tabulated in Table 9.

The P-value in the table is the probability whether the difference between the sample means are different on a predefined risk level. The risk level in this analysis was chosen to be 0.05. Therefore, any P-value that is less than 0.05 indicates that the difference is significant and accordingly the effect of the factor being considered is significant. As can be seen in Table 9, all P-values from both temperature levels are larger than 0.05, which means that the surface temperature of specimens does not affect the gauge reading for both coarse and fine gradation mixes significantly. For the factor of surface moisture, the P-value is less than 0.05 for Moisture Levels II and III for coarse graded HMA, and fo Moisture Level III for fine graded HMA. Thus, the accuracy of the gauge would be affected significantly by surface moisture in excess of 0.05 lbs/ft^2 (0.24 kg/m^2).

Table 9. Summary of Analysis of Variance (ANOVA)

Gradation	Factors	P-value
Coarse	Hot temperature	0.780
	Intermediate temperature	0.940
	Moisture Level I	0.121
	Moisture Level II	0.001
	Moisture Level III	0.000
Fine	Hot temperature	0.518
	Intermediate temperature	0.740
	Moisture Level I	0.578
	Moisture Level II	0.067
	Moisture Level III	0.001

5.3. Laboratory Study Conclusions

- The performance of the PaveTracker^{TM} was not significantly influenced by HMA mix surface temperature. In general, gauge readings slightly dropped with decreasing mix temperature.
- The presence of surface moisture significantly affects gauge readings. With an increase in surface moisture without internal moisture, gauge readings decrease appreciably. But with the introduction of internal moisture without the application

of surface moisture, gauge readings increase. The increased amount is far larger than that of core density. The results given by the PaveTracker^{TM} must be interpreted carefully when moisture is present. From the Analysis of Variance, the maximum surface moisture level at which moisture is not a significant factor is 0.05 lbs/ft^2 (0.24 kg/m^2).

- The PaveTracker^{TM} performed better with fine mixtures than with coarse mixtures.
- The area of the specimen being measured does affect the accuracy of the PaveTracker^{TM}. In this study, the average decrease in gauge density was 2.4 pcf (38 kg/m^3) while the mat was cut from 12 in. x 12 in. (30 cm x 30 cm) down to 6 in. x 6 in. (15 cm x 15 cm) An increase in mat size from 12 in. x 12 in. (30 cm x 30 xm) to 22.5 in. x 22.5 in. (57.1 cm x 57.1 cm) caused the PaveTracker^{TM} reading to increase by 0.4 pcf (6.4 kg/m^3) on average.
- The relation between measuring (probing) depth of the PaveTracker^{TM} and the thickness of the material being measured is critical to the accuracy. If the measuring depth of the gauge is larger than thickness of the material, the base material would affect the gauge reading, which would be a composite density value of the HMA and the base material. This effect seems to be linearly related to the density of base material.

6. Field Study

6.1. Experimental Procedures

For the field study, pavements were measured on 24 different projects. Details of each project are given in Table 10. The ODOT Engineer on each project identified and marked 10 random sample locations within each lot. The locations varied throughout the pavement to include edges, center, wheel paths, etc. The contractors then performed coring to extract the ten samples and send them to the ODOT laboratory for analysis. Contractors also performed the field nuclear gauge measurements during both construction seasons and the PQI Model 300 measurements during the first construction season. OU students performed the PaveTracker^{TM} (PT) measurements during both seasons and the PQI Model 300 measurements during the second season.

The PQI instrument is referenced to a test plate made of a controlled composition material prior to making pavement density measurements. Neither the PT nor the PQI instruments were otherwise calibrated in the field or against laboratory core results.

Table 10. Details of Projects Included in Field Study

Proj	Weather	Temp (°F)	Location	Contractor	Supplier	Sur/Int	Thick (in)	Mix	Binder	Gmm	NMS	%AC	%air	JMF
1	night	70	Rt 161/Licking	Kokoshing	Kokoshing	sur	1.5	I	70-22Latex	2.421	12.5	5.6	3.5	B412414
2	night	70	Rt 161/Licking	Kokoshing	Kokoshing	sur	1.5	I	70-22Latex	2.421	12.5	5.6	3.5	B412414
3	night		I-270	Kokoshing	Kokoshing	sur	1.5	12.5SP	70-22	2.465	12.5	5.9	4.0	B412460
4	sunny		Lancaster bypass	Kokoshing	Kokoshing	int	1.75	II	64-22	2.469	19	4.81	3.5	B412115
5	night	90	I-270/Rt33	Shelly&Sands	Shelly&Sands	sur	1.5	I	70-22		12.5			
6	cloudy		I-270	Shelly&Sands	Shelly&Sands	int	2	II	64-28	2.475	19	4.6	4.0	B412300
7	cloudy		I-670	Shelly&Sands	Shelly&Sands	sur	1.5	1 H	64-28	2.457	12.5	5.6	3.5	B412318
8	sunny	90	Rt 16	Shelly	Shelly	int	1.5	II	70-22	2.459	19	4.9	4.0	B411390
9	sunny	90	Rt 17	Shelly	Shelly	sur	1.5	I	70-22	2.413	9.5	6.2	3.5	B411466
10	sunny	90	Jeffersonville	Valley A C	Valley A C	int	1.75	II	64-22	2.467	19	5.3	4.0	B411074
11	sunny	90	Jeffersonville	Valley A C	Valley A C	sur	1.75	I		2.461				B411075
12	rain	90	Rt35 Jeffersonville	Valley A C	Valley A C	int	1.75	446-2H	70-22	2.487	19	5.2	4.0	B411255
13	sunny	75	Rt67 Seneca Co	SE Johnson	Kokoshing	sur	1.5	12.5SP	70-22	2.468	12.5	5.6	4.0	B412318
14	cloudy	75	Rt33/Lancaster	Kokosing	KMI	sur	1.5	446-1H	70-22PM	2.438	12.5	5.8	3.5	B413204
15	sunny	85	Rt33/Lancaster	Kokosing	KMI	sur	1.5	446-1H	70-22PM	2.438	12.5	5.8	3.5	B413204
16	sunny	85	Rt33/Lancaster	Kokosing	KMI	sur	1.5	446-1H	70-22PM	2.438	12.8	5.8	3.5	B413204
17	cloudy	80	I670/Columbus	Shelly	Shelly	sur	1.5	448-1	70-22	2.439	9.5	6.1	3.5	
18	cloudy	75	Rt35/Chillicothe	Shelly	Melvin Stone	int	1.5	19 SP	64-22	2.502	19	5.3	4.0	B411528
19	cloudy	75	Rt35/Chillicothe	Shelly	Melvin Stone	int	1.5	19 SP	64-22	2.507	19	5.3	4.0	B411528
20	sunny	80	Rt35/Chillicothe	Shelly	Melvin Stone	int	1.5	19 SP	64-22	2.498	19	5.3	4.0	B411528
21	cloudy	80	Rt35/Chillicothe	Shelly	Melvin Stone	int	1.5	19 SP	64-22	2.506	19	5.3	4.0	B411528
22	cloudy	88	Rt35/Chillicothe	Shelly	Melvin Stone	int	1.5	12.5SP	70-22	2.478	9.5	5.7	3.5	B411529
23	cloudy	88	Rt35/Chillicothe	Shelly	Melvin Stone	int	1.5	12.5SP	70-22	2.466	9.5	5.7	3.5	B411529
24	cloudy	65	Rt23/Delaware	Kokosing	KMI	int	1.5	type II	70-22	2.438	19	4.9	4.0	

6.2. Results

Table 11 summarizes the field and laboratory results from each project in the study. Blank cells exist in some columns of the table where no field measurements were obtained by the method corresponding to the column.

Table 11. Summary of Field Measurement Densities in pcf (1 pcf = 16.03 kg/m^3).

		Mean Value				Standard Deviation			
Project	N	Lab	Nuclear	PT	PQI	Lab	Nuclear	PT	PQI
1	10	142.3	141.7	140.9		1.7	2.9	2.4	
2	10	142.6	141.8	140.1		2.0	3.1	3.0	
3	10	146.5	144.2	144.7		1.2	1.3	0.8	
4	10	144.8	143.4	139.4		1.8	2.4	1.9	
5	5	144.8	147.4	145.5		1.5	2.3	3.2	
6	10	142.4	144.9	144.3		2.5	4.1	3.3	
7	10	144.7	146.2	143.7		2.4	3.0	2.3	
8	10	143.7	145.2	139.6		2.3	2.8	2.7	
9	10	144.0	145.3	142.3		2.4	1.8	2.1	
10	10	141.7		137.3	139.3	1.8		2.5	1.2
11	10	141.2		139.6	145.5	1.5		1.8	1.4
12	2	144.7	145.4	142.9	146.4	3.3	0.7	0.0	2.7
13	7	142.5	141.5	146.2		2.3	2.3	1.6	
15	10	144.9	145.2	143.1	154.5	2.2	2.4	2.8	3.1
16	10	145.9	145.8	144.8	152.4	2.1	2.0	1.9	3.3
18	10	147.1	147.8	146.4	155.3	1.4	1.1	1.4	3.1
19	10	147.3	145.3	145.8	158.3	1.2	1.1	4.1	3.5
20	10	146.5	146.2	145.0	158.4	1.6	1.4	1.6	3.1
21	10	146.7	146.5	146.6	158.7	1.7	1.2	1.3	2.5
22	10	145.9	145.6	140.0	149.1	0.5	0.5	1.7	0.9
23	10	145.5	145.0	141.8	147.6	0.5	0.7	1.2	2.3
24	10	144.5	141.6	142.4	151.5	1.9	4.4	2.5	2.5

Note: PT=PaveTracker

6.3. Statistical Analyses

6.3.1. Correlation

Regression analysis was conducted using data from all specimens from all projects and again using project average data. In contrast to previous studies, we intentionally included results from several different projects with different mix designs in the analysis of correlation to provide planned variation in the actual density, rather than a small range of mere random variability within a single mix. Figures 23 and 24 below present gauge density measurements plotted versus core density measurements, with a line of least squares fit for each of the three gauges. The regression results are summarized in Table 12.

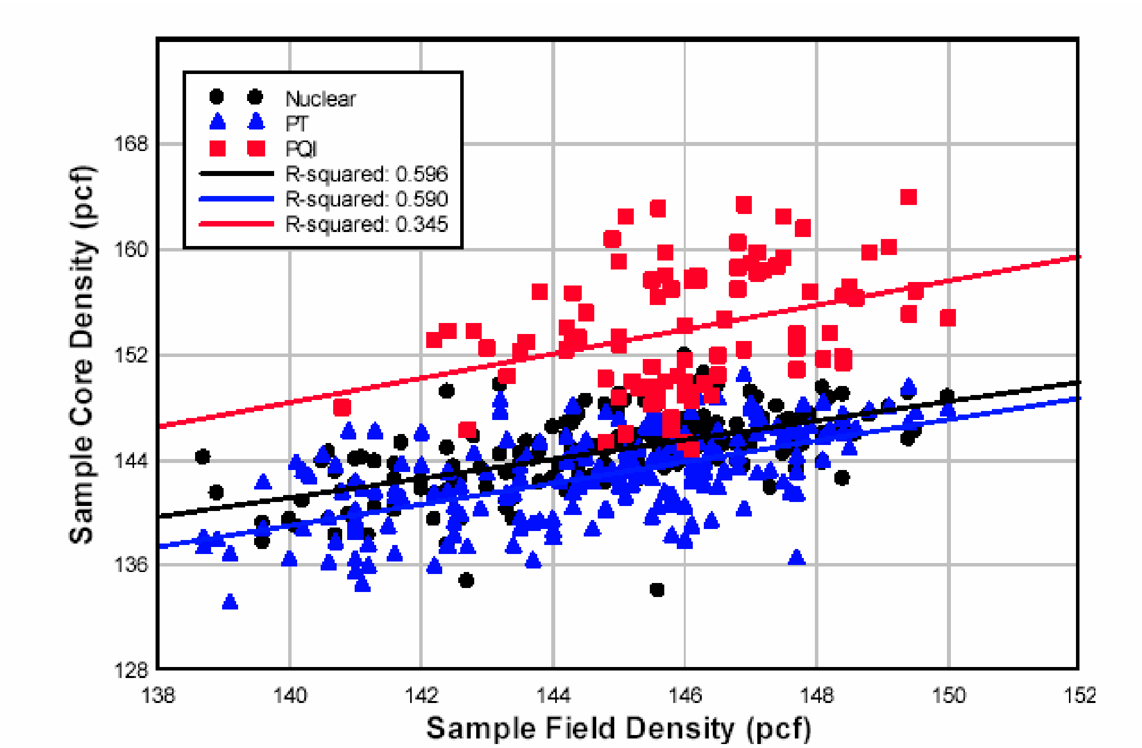

Figure 23. Correlation Between Gauge and Core Densities Based on Individual Specimens From All Projects (1 pcf = 16.03 kg/m^3).

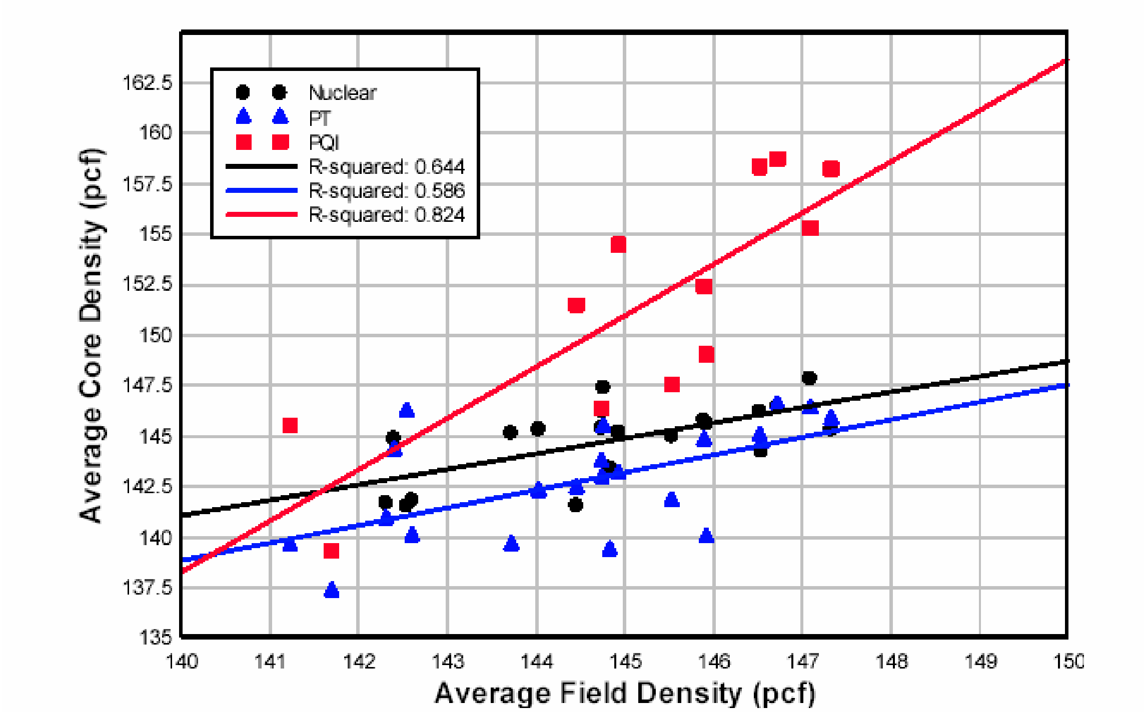

Figure 24. Correlation Between Gauge and Core Densities Based on Average of Specimens From Each Project (1 pcf = 16.03 kg/m^3).

Table 12. Regression Model Coefficients and Correlation for Individual Specimens and Project Averages (1 pcf = 16.03 kg/m^3).

	Individual Samples			Project Averages		
Gauge	Nuclear	PT	PQI	Nuclear	PT	PQI
Intercept (pcf)	38.8	26.1	19.1	33.9	16.7	-217.6
Slope	0.731	0.807	0.924	0.766	0.873	2.542
R^2	0.596	0.590	0.345	0.644	0.586	0.825

Note: PT=PaveTracker

Table 12 shows the regression model coefficients and R^2 value for both individual specimen densities aggregated from all projects, and project average densities. Field gauge results were regressed against laboratory core results. The results indicate the nuclear gauge responded best to variability in laboratory-determined core density for all specimens aggregated, but the PQI Model 300 responded best to variation in project average laboratory-determined core density.

6.3.2. Tests of Hypotheses

The project generated data quadruplets for each sample (nuclear, PT, PQI, and laboratory). This allowed paired statistical tests such as t tests to be performed to compare methods. A useful framework for using paired tests to compare methods is null hypothesis testing, which tests the claim that there is no statistically significant difference between a new methodology (e.g., PT or PQI) and a reference methodology (e.g., nuclear or laboratory). More specifically, we state the null hypothesis (H0) as “the mean of the population of differences between the two methods is zero ($\mu=0$).” The null hypothesis can be evaluated against the alternative hypothesis (HA:$\mu\neq0$): the mean difference is not equal to zero. On the basis of the random sample we have obtained from the population, we decide whether to accept or reject the null hypothesis.

Both parametric and non-parametric tests exist for the purpose of hypothesis testing, and the applicability of each type depends on the distribution of the population, as inferred from the distribution of the random sample obtained. The Student’s t test is a parametric test of paired data used to test hypotheses about the mean of a population. The Student’s t test is only applicable to a population that is near normal or can be transformed to a normal distribution. In cases where the population of differences is not normally distributed, and the differences of log concentrations are also not normally distributed, a non-parametric test should be performed. The Wilcoxon Signed Rank test, also known as the Wilcoxon Matched Pairs test, is the most powerful non-parametric test and applies if the population is symmetric. If the population is asymmetric, a sign test can be performed.

The process of hypothesis testing begins with calculating paired differences by subtracting the reference method result from the field method (nuclear, PQI or PT) result. Next, assumptions about the normality of the distributions of paired differences are tested by application of the Kolmogorov-Smirnov (K-S) test. At a 90% confidence, the two-tailed K-S test will reject the assumption that the data are normally distributed when the p-value associated with the test statistic is less than 0.05. Normality testing was performed on the paired difference data set for each measurement method of interest. In cases where the assumption of normality held (i.e., $p > 0.05$), we applied a one-sample t-test to the null hypothesis that the mean of the differences was equal to zero (H0:$\mu=0$) against the alternative hypothesis that the mean was not equal to zero (HA:$\mu\neq0$). In cases where the assumption of normality did not hold (i.e., $p < 0.05$), we applied the non-parametric Wilcoxon Signed Rank test to the differences (testing the null hypothesis that the median of the differences is equal to zero, against the alternative hypothesis that the median is not equal to zero).

Results from our hypothesis testing on the paired results at the 90% confidence level are summarized in Table 13. The key metric in the table is the P value, which relates to the probability of being wrong if the null hypothesis is rejected. At P values above 0.10 the null hypothesis is accepted. In practical terms, this means that there is no statistically significant difference between the results of the two methods.

Table 13. Results of Statistical Tests of Hypothesis

Difference Tested	N	Mean	St. Dev	Test	p	Conclusion
Nuclear-Core	180	-0.106	1.675	Wilcoxon	0.227	Accept H0
PT-Core	204	-1.290	1.959	Student's t	0.000	Reject H0
PQI-Core	112	4.506	3.492	Wilcoxon	0.000	Reject H0
PT-Nuclear	184	-1.570	2.943	Student's t	0.000	Reject H0
PQI-Nuclear	92	8.354	4.537	Student's t	0.000	Reject H0

Note: PT=PaveTracker

6.3.3. Additional Hypothesis Tests

The manufacturers of both the PQI and PaveTracker^{TM} recommend calibrating the gauges at the beginning of each day by applying an offset to the readings based on comparison to a laboratory core result. The field staff did not perform this calibration because we wanted to evaluate the effect of the calibration by comparing methods both with and without it. To evaluate the effects of applying the calibration procedure, we repeated the statistical tests of hypothesis on results that were post-processed to add an offset based on the difference between the gauge reading and the first core result of each day. The statistical results from testing on the calibrated readings are summarized in Table 14.

Table 14. Results of Statistical Tests of Hypothesis on "Calibrated" Gauge Data

Difference Tested	N	Mean	St. Dev	Test	p	Conclusion
Nuclear-Core	184	-0.165	2.42	Wilcoxon	0.227	Accept H0
PT-Core	204	-1.703	2.70	Wilcoxon	0.000	Reject H0
PQI-Core	112	-0.050	4.41	Wilcoxon	0.808	Accept H0
PT-Nuclear	184	-1.706	3.04	Student's t	0.000	Reject H0
PQI-Nuclear	92	-0.407	3.90	Student's t	0.320	Accept H0

As the results in Table 14 show, performing the manufacturer recommended calibration procedure dramatically improved agreement between the PQI gauge and both the nuclear gauge and laboratory method, resulting in acceptance of the null hypothesis for comparisons to both, whereas uncalibrated results had led to universal rejection of the null hypothesis.

6.4. Pay Factor Analysis

Pay factors on ODOT paving contracts are determined according to the criteria in the 2005 ODOT Construction and Material Specifications Section 446.05, excerpted in Table 15. A contractor can receive less than 100% of scheduled pay for either exceeding or falling short of the desired in-place density range, but can also earn a 4% bonus for a surface course that is greater than or equal to 94% but less than 96% of the design density.

Table 15. Ohio DOT Pay Factors (from Ohio Department of Transportation (2005)).

Mean of Cores(1)	Pay Factor	
	Surface Course	Intermediate Course
98.0% or greater	(2)	(2)
97.0% to 97.9%	0.94	(2)
96.0 to 96.9%	1.00	0.94
94.0% to 95.9%	1.04	1.00
93.0% to 93.9%	1.00	1.00
92.0% to 92.9%	0.98	1.00
91.0% to 91.9%	0.90	0.94
90.0% to 90.9%	0.80	0.88
89.0% to 89.9%	(3)	(3)
Less than 89.0%	(2)	(2)

(1) Mean cores as percent of average MSG for the production day.

(2) For surface courses, remove and replace. For other courses, the District will determine whether the material may remain in place. If the District determines that the courses should be removed, the Contractor shall remove and replace this course and all courses paved on this course. The pay factor for material allowed to remain in place will be 0.60.

(3) The District will determine whether the material may remain in place. If the District determines that the course should be removed and replaced, the Contractor shall remove and replace this course and all courses paved on this course. The pay factor for material allowed to remain in place will be 0.70.

Since pay factors are determined on the basis of a ten-core average, an accurate analysis of the effects of non-nuclear gauges on pay factors is simplified by also performing the statistical tests on the basis of a ten-core average.

State transportation agencies generally determine pay factors based on the results of the laboratory analysis of core samples, so the essential question to the contractor is how the use of a non-nuclear density gauge will affect their ability to meet density requirements in the field. There is a greater cost to the contractor if the field instrument under-estimates in-place density than if it over-estimates, because the pay factors diminish more rapidly for over-compaction than for under-compaction with respect to changes in density. We conducted the present analysis assuming that contractors would achieve a density indicated by the non-nuclear gauge to be within the range corresponding to a pay factor of 1.00 or better. We then added the probability distribution of the random measurement error associated with the non-nuclear gauge to the target density and computed the cumulative probability of overpayment or underpayment as a result of this error.

6.5. Field Study Conclusions

We have reviewed numerous studies on the suitability of non-nuclear pavement density gauges for Quality Control (QC) and Quality Acceptance (QA) testing of pavements. Most of these studies have concluded that the current crop of non-nuclear gauges is suitable for contractor QC but not recommended for QA. While a few of these studies were very good, several have suffered from experimental design weaknesses which include: a) eschewing objective rigorous statistical evaluation of the data obtained, in favor of quasi-quantitative observations (e.g., failing to account for the possible role of random factors such as sampling error); b) relying on within-project density variations – expected to be minimal – as a basis for assessing correlation between field gauge results and laboratory core results; c) not combining data from multiple projects into a large enough sample set to assure adequate statistical power (and real pavement density variability); and d) following proper procedures for nuclear gauge operation but failing to a heed non-nuclear gauge manufacturer recommendations for applying mix-specific equipment calibrations to the equipment at the start of each day, thus biasing results.

We conducted a study that combined data from multiple projects into one large sample set to both maximize the power of the statistical hypothesis testing and provide real pavement density variability greater than that expected within a single project to better assess correlation between the non-nuclear gauge results and the laboratory core results.

Without daily calibration, we found both the PQI and PT results to differ from both laboratory reported core densities and nuclear density results with statistical significance.

Applying a daily mix-specific offset to gauge results as recommended by the manufacturers, hypothesis testing showed that the PT results remained statistically different from both nuclear gauge and laboratory results, but PQI results were not significantly different. In fact, as indicated by the greater P-value for PQI results than for nuclear gauge results, calibrated PQI results agreed better with laboratory core results than did nuclear gauge results.

6.6. Field Study Recommendations

Based on the results of statistical hypothesis testing, we recommend that use of the PQI Model 300 for both QC and QA testing provided the manufacturer’s recommendation to calibrate the device daily by applying a mix-specific offset is followed. We cannot recommend the use of the PQI for QA testing without conducting the recommended calibration.

Even following the manufacturer’s recommended calibration procedure for the PT, we cannot recommend it for QA testing, although contractors may find it useful for QC purposes.

In deciding whether or not to use non-nuclear pavement density gauges, contractors should evaluate the potential cost savings against the risk of receiving underpayment.

Taking a broader view of QA testing, we recommend future research attempting to measure stiffness instead of density. The use of in-place density to indicate pavement quality originated as a surrogate for stiffness, which could not at the time be measured in situ with practicality. However, advances in sensor capability, signal processing technology, and field data processing capability now enable the development of instruments that can determine in situ stiffness practically. Therefore, we recommend that QA standards and practices be adjusted to exploit this capability. The practicality and reliability of measuring stiffness instead of density should be investigated.

7. References

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Appendix: Field Data

Notes: Includes all data from all projects included in field study.
Contractors: 1 = Kokosing, 2 = Shelly & Sands, 3 = Shelly, 4 = Valley AC, 5 = SE Johnson
PT = PaveTracker
For additional details on projects, see Table 10 in text.

Year	Project	Contractor	**Coring**	**Nuclear**	**PT**	**PQI**
1	1	1	141.2	138.3	137.5	
1	1	1	140.7	138.3	137.7	
1	1	1	143.4	139.5	141.4	
1	1	1	142.6	139.5	139.8	
1	1	1	144.7	145.0	143.3	
1	1	1	143.5	143.6	143.5	
1	1	1	144.4	144.2	142.1	
1	1	1	139.6	139.2	138.7	
1	1	1	141.7	145.3	143.6	
1	1	1	141.3	143.9	141.5	
1	2	1	145.8	146.6	141.3	
1	2	1	142.5	142.1	138.2	
1	2	1	144.4	143.7	141.9	
1	2	1	140.0	139.5	136.4	
1	2	1	142.6	142.6	141.9	
1	2	1	140.6	139.5	136.1	
1	2	1	144.3	144.1	140.3	
1	2	1	142.4	137.6	137.3	
1	2	1	143.8	144.6	145.3	
1	2	1	139.6	137.8	142.2	
1	3	1	145.2	144.0	143.8	
1	3	1	147.6	144.8	146.1	
1	3	1	145.6	144.1	144.2	
1	3	1	145.3	142.5	144.7	
1	3	1	148.1	143.8	143.9	
1	3	1	145.7	143.4	144.1	
1	3	1	145.3	143.9	144.9	
1	3	1	147.7	143.3	144.2	
1	3	1	147.8	145.2	145.7	
1	3	1	147.1	147.4	145.9	
1	4	1	147.6	147.1	141.5	
1	4	1	146.5	144.1	141.8	
1	4	1	143.7	144.1	139.1	
1	4	1	147.7	146.9	141.3	
1	4	1	144.6	142.8	138.7	
1	4	1	142.2	139.5	135.9	
1	4	1	144.0	142.6	138.5	
1	4	1	144.8	143.7	140.1	
1	4	1	143.8	142.3	139.3	
1	4	1	143.4	141.1	137.4	
1	5	2	142.5	143.5	140.4	
1	5	2	144.4	147.5	144.4	
1	5	2	145.6	148.2	146.4	
1	5	2	144.8	148.2	147.5	
1	5	2	146.5	149.6	148.6	
1	6	2	142.0	142.4	143.5	

Year	Project	Contractor	**Coring**	**Nuclear**	**PT**	**PQI**
1	6	2	145.5	146.5	146.8	
1	6	2	145.4	148.6	146.4	
1	6	2	138.9	141.5	137.9	
1	6	2	146.0	152.0	148.9	
1	6	2	140.5	143.9	144.3	
1	6	2	143.2	149.7	147.6	
1	6	2	140.7	143.1	143.5	
1	6	2	141.6	140.2	141.2	
1	6	2	140.2	140.9	143.1	
1	7	2	141.0	144.1	142.3	
1	7	2	141.6	143.7	141.7	
1	7	2	145.1	148.5	144.5	
1	7	2	142.9	143.4	140.2	
1	7	2	144.2	146.8	143.9	
1	7	2	146.2	149.9	143.0	
1	7	2	148.1	149.5	148.3	
1	7	2	144.5	144.9	144.1	
1	7	2	147.3	141.9	143.1	
1	7	2	146.5	149.7	146.1	
1	8	3	143.5	144.5	139.5	
1	8	3	145.4	148.5	142.7	
1	8	3	146.6	145.2	142.9	
1	8	3	145.8	145.2	140.9	
1	8	3	140.6	144.6	139.5	
1	8	3	146.3	150.6	143.0	
1	8	3	141.6	142.6	136.8	
1	8	3	141.0	142.1	135.4	
1	8	3	142.4	141.7	137.4	
1	8	3	144.0	146.5	138.0	
1	9	3	145.0	149.0	142.5	
1	9	3	141.1	144.2	141.7	
1	9	3	138.7	144.2	137.3	
1	9	3	145.6	145.8	144.0	
1	9	3	146.4	146.5	144.9	
1	9	3	145.2	144.6	143.1	
1	9	3	144.1	143.6	142.3	
1	9	3	143.3	143.0	141.1	
1	9	3	146.3	147.3	143.7	
1	9	3	144.6	145.1	142.2	
1	10	4	141.5		138.9	139.0
1	10	4	141.1		134.5	137.4
1	10	4	144.3		141.4	141.0
1	10	4	139.1		136.8	140.8
1	10	4	141.0		138.4	138.7
1	10	4	143.7		136.3	140.4
1	10	4	141.2		135.9	139.3
1	10	4	142.5		139.2	139.9

Year	Project	Contractor	**Coring**	**Nuclear**	**PT**	**PQI**
1	10	4	143.5		138.7	139.1
1	10	4	139.1		133.1	137.9
1	11	4	140.2		138.7	145.2
1	11	4	141.7		141.1	147.1
1	11	4	143.4		141.3	147.5
1	11	4	138.7		138.0	144.5
1	11	4	144.0		139.4	143.7
1	11	4	140.3		142.7	146.4
1	11	4	141.0		139.3	145.8
1	11	4	141.0		140.1	145.2
1	11	4	141.0		138.8	146.3
1	11	4	141.0		136.4	143.5
1	12	4	147.1	145.9	142.9	148.3
1	12	4	142.4	144.9	143.0	144.4
1	13	5	143.2	144.4	148.5	
1	13	5	140.9	139.9	146.1	
1	13	5	141.3	140.4	146.1	
1	13	5	140.1	139.0	143.7	
1	13	5	143.3	140.3	145.4	
1	13	5	142.0	141.8	146.0	
1	13	5	147.0	145.1	147.9	
2	14	1	147.5	146.7	176.4	162.5
2	14	1	142.8	147.1	174.7	152.0
2	14	1	146.6	142.2	175.2	155.7
2	14	1	144.0	142.1	188.0	156.2
2	14	1	147.3	146.6	144.7	152.8
2	14	1	147.5	140.8	142.1	153.0
2	14	1	144.3	146.9	147.9	157.1
2	14	1	147.0	142.4	143.5	151.4
2	14	1	146.7	144.3	155.0	162.3
2	14	1	143.9	146.8	168.5	160.7
2	15	1	147.5	146.9	142.2	162.5
2	15	1	143.8	145.3	139.3	156.8
2	15	1	146.9	145.7	140.2	152.4
2	15	1	142.2	141.4	141.4	153.1
2	15	1	142.8	145.8	144.4	153.8
2	15	1	142.4	149.2	141.5	153.8
2	15	1	145.0	142.5	142.7	153.4
2	15	1	146.0	145.8	145.9	154.2
2	15	1	144.3	146.8	148.0	153.0
2	15	1	148.4	142.6	146.0	151.9
2	16	1	148.4	146.7	147.4	151.4
2	16	1	147.7	145.5	143.0	150.9
2	16	1	145.6	145.1	144.1	148.5
2	16	1	146.0	146.0	145.5	151.6
2	16	1	145.9	143.7	144.2	150.4
2	16	1	140.8	141.6	141.5	148.0

Year	Project	Contractor	**Coring**	**Nuclear**	**PT**	**PQI**
2	16	1	147.7	146.1	146.2	153.6
2	16	1	145.5	148.0	147.3	157.7
2	16	1	144.5	148.5	145.4	155.2
2	16	1	146.8	146.7	143.3	157.0
2	17	3		147.0	145.0	154.7
2	17	3		141.4	139.1	147.2
2	17	3		146.2	145.2	151.2
2	17	3		143.6	142.1	148.6
2	17	3		144.8	142.8	149.3
2	17	3		146.9	142.6	149.8
2	17	3		144.7	144.7	150.3
2	17	3		141.3	138.7	144.0
2	17	3		145.4	144.7	151.4
2	17	3		146.4	145.6	152.7
2	17	3		147.7	145.9	149.5
2	17	3		147.3	144.5	151.3
2	17	3		146.3	144.4	149.9
2	17	3		145.3	144.5	150.1
2	17	3		148.9	147.0	156.0
2	17	3		146.0	144.4	150.0
2	17	3		144.2	144.6	149.8
2	17	3		147.2	146.0	149.4
2	17	3		147.4	145.9	150.4
2	17	3		147.8	147.0	151.0
2	17	3		142.8	144.4	149.3
2	17	3		146.0	146.4	151.3
2	17	3		140.4	140.6	145.1
2	17	3		141.6	142.5	147.0
2	17	3		145.2	145.8	149.1
2	17	3		145.9	143.7	146.9
2	17	3		145.7	144.3	149.0
2	17	3		143.1	143.0	148.6
2	17	3		144.5	143.8	149.2
2	17	3		146.5	144.9	150.1
2	18	3	146.5	146.8	144.4	152.0
2	18	3	150.0	148.8	147.8	154.8
2	18	3	148.2	148.7	146.3	153.7
2	18	3	146.0	147.1	144.6	150.0
2	18	3	147.4	148.1	146.4	158.8
2	18	3	145.0	147.7	147.0	152.8
2	18	3	145.8	145.7	145.0	157.0
2	18	3	147.0	149.2	148.2	159.0
2	18	3	147.9	147.5	146.5	156.8
2	18	3	147.1	148.8	147.5	158.2
2	19	3	147.7	144.9	136.5	152.5
2	19	3	146.1	146.0	143.4	157.9
2	19	3	146.9	143.6	150.4	163.4

Year	Project	Contractor	**Coring**	**Nuclear**	**PT**	**PQI**
2	19	3	148.8	147.4	147.7	159.8
2	19	3	146.1	145.2	147.5	157.6
2	19	3	146.8	143.9	145.5	158.6
2	19	3	146.2	145.0	148.7	157.7
2	19	3	148.6	146.0	146.3	156.3
2	19	3	149.4	145.6	149.5	164.0
2	19	3	146.6	145.7	143.1	154.7
2	20	3	148.1	146.0	145.6	151.7
2	20	3	148.4	149.0	147.0	156.5
2	20	3	146.8	145.2	144.2	160.5
2	20	3	149.1	148.0	148.0	160.2
2	20	3	145.6	145.1	143.8	156.4
2	20	3	147.2	147.1	146.5	158.4
2	20	3	145.1	145.5	143.7	162.5
2	20	3	145.7	146.5	143.9	159.8
2	20	3	144.9	145.0	143.2	160.8
2	20	3	144.3	144.8	144.4	156.7
2	21	3	145.0	148.8	148.6	159.1
2	21	3	147.5	144.5	145.6	159.4
2	21	3	149.5	146.2	147.5	156.9
2	21	3	144.2	145.7	145.7	154.1
2	21	3	145.6	146.3	147.0	163.1
2	21	3	146.2	146.8	145.2	158.0
2	21	3	145.7	145.3	146.4	158.0
2	21	3	147.8	147.4	148.1	161.6
2	21	3	148.5	146.0	144.8	157.2
2	21	3	147.1	147.6	146.9	159.8
2	22	3	146.4	145.5	139.3	148.9
2	22	3	146.1	145.7	139.0	148.5
2	22	3	145.7	145.6	141.5	150.0
2	22	3	145.8	145.6	138.2	147.2
2	22	3	145.5	146.0	139.6	149.5
2	22	3	146.3	145.7	142.0	149.8
2	22	3	146.1	146.2	138.8	148.5
2	22	3	146.5	146.0	141.9	150.5
2	22	3	145.0	145.7	141.9	148.8
2	22	3	146.0	144.2	137.8	148.9
2	23	3	145.5	145.8	143.8	151.1
2	23	3	145.3	145.9	142.9	149.5
2	23	3	144.8	144.8	140.2	145.4
2	23	3	146.0	144.0	140.4	145.4
2	23	3	145.5	146.0	142.5	148.2
2	23	3	145.8	144.0	140.5	146.3
2	23	3	145.1	145.0	141.1	146.0
2	23	3	146.1	144.5	142.5	144.8
2	23	3	145.2	145.2	142.0	150.0
2	23	3	146.1	144.8	142.2	149.1

Year	Project	Contractor	**Coring**	**Nuclear**	**PT**	**PQI**
2	24	1	142.7	134.8	137.3	146.3
2	24	1	144.2	141.7	143.7	152.4
2	24	1	143.6	145.4	144.2	153
2	24	1	143.5	142.4	142.5	152.3
2	24	1	143.3	140.9	141.4	150.4
2	24	1	145.6	134.1	140.3	149.5
2	24	1	144.8	142.3	142.8	150.2
2	24	1	143.0	141.9	142.9	152.5
2	24	1	149.4	149.1	146.7	155.1
2	24	1	144.4	143	142.5	153.3

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