Non-Nuclear Methods for HMA Density Measurements

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Final Report

by

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ABSTRACT

Non-nuclear methods for the measurement of hot-mix asphalt (HMA) density offer the ability to take numerous density readings in a very short period of time, without the need for intensive licensing, training, and maintenance efforts common to nuclear gauges. The Pavement Quality Indicator™ (PQI) and the PaveTracker™ use electrical impedance to estimate density. Early models of these gauges were deemed inadequate for quality control and quality assurance testing, but improvements have been made to each.

In this project, a number of field sites were used to evaluate the non-nuclear gauges in terms of ruggedness, accuracy, and precision. A thorough investigation of calibration methods was also performed.

In the ruggedness study, three pavement sites were used to determine potential procedural factors that significantly affected the non-nuclear density results. Moisture, the presence of sand or debris, gauge orientation, gauge type, and presence of paint markings were determined to significantly impact the accuracy of non-nuclear gauge readings.

Four calibration methods were investigated, including screed offset, core offset, two-point, and data pair techniques. None were found to possess all of the necessary components for generating significant correlations with field core densities. A screed-core method was developed as a method to more comprehensively adjust the magnitude of the offset as well as the sensitivity of the device over a large range of true densities.

Overall, neither non-nuclear gauge was able to predict core densities as accurately or precisely as the nuclear gauge. Of the non-nuclear devices, the PQI generated more consistent results but was less sensitive to actual changes in density. The PaveTracker was more sensitive to actual changes in density, but exhibited a higher level of variability. Existing specifications for use of non-nuclear devices should be edited to include guidance on gauge orientation during testing, as well as calibration procedures for a screed-slope type of technique.

ACKNOWLEDGMENTS

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INTRODUCTION

In-place density is a key indicator used to judge the quality of hot-mix asphalt (HMA) pavements. Traditionally, this property has been measured by determining the density of cores cut from the compacted pavement, or by the use of a nuclear gauge. Core densities are typically believed to provide the most accurate results, but this process is destructive to the newly compacted pavement. Nuclear technology offers a non-destructive method for density measurements, but is burdened with intense regulations associated with the handling, storage, and transportation of radioactive materials.

Within the last decade, non-nuclear technology has been developed for the purpose of measuring the density of in-place HMA materials. These devices operate based on the principles of electrical impedance for a current passing through the HMA material. These devices have many advantages in that they are capable of providing density measurements very quickly and in a completely non-destructive manner, are easy to handle, and are not subject to complicated regulations.

In order to adopt a new test method, certain advantages must be realized. The accuracy of the new method should be equivalent to, or better than existing technology. Other justifications relate to efficiency, in terms of time, effort, and money. There are a number of practical reasons to move toward the non-nuclear technology, but the method must first be proven to perform adequately.

In this project, the use of two non-nuclear gauges, the Pavement Quality Indicator™(PQI) and the PaveTracker™ were investigated in order to determine whether non-nuclear technology was appropriate for use in quality control and quality assurance (QC/QA) applications. A ruggedness study was performed in order to determine the effects of a number of factors on the results obtained by the non-nuclear devices including temperature, moisture, gauge type, gauge orientation, and presence of debris. The accuracy and precision of the gauges were assessed by comparisons with traditional methods of density measurement, including field cores and the nuclear gauge. In addition, a thorough consideration of calibration procedures was conducted, and suggestions were made for incorporation into existing specifications.

BACKGROUND

In-place density of asphalt pavement is a vital property which can indicate the long-term performance of a flexible pavement. It is also a primary characteristic used to measure quality during construction. Traditionally, the in-place density of HMA pavements was measured from core samples cut from the pavement after compaction. While this method offered a measure of density that was believed to be accurate, the process was time-consuming, labor-intensive, and destructive to the pavement. Nuclear technology was later developed as a non-destructive alternative for density determinations. This advancement was significant because a nuclear density measurement could be completed in less than five minutes, which provided the contractor with reasonably accurate information for "real-time" quality control. The greatest disadvantage of the nuclear device was that it contained radioactive materials, which required significant efforts relating to training, licensing, calibration, maintenance, handling, storage, and transportation. During the last decade, non-nuclear technology has been developed, which uses the impedance of an electrical current to measure dielectric constant and estimate pavement density. These devices do not require intensive safety procedures, are lightweight and easy to handle, and provide density measurements within a few seconds. Early models of these devices demonstrated poor correlations with traditional density measurements, and were significantly affected by factors such as temperature and moisture.

Core Method

Density from field cores is determined by cutting the core from the compacted pavement, then measuring bulk specific gravity the saturated-surface-dry method specified in AASHTO T166 or similar, as shown in Figure 1. *(1)* The bulk specific gravity is then divided by the maximum theoretical density (MTD) of the mix and density is expressed as a percentage of MTD. This measure of density has traditionally been accepted as the best available estimate of "true" density. Concerns have been expressed regarding the accuracy of this method, especially for coarse-graded and large NMAS mixes; however, this test is still the most commonly specified method for QA measures of field density.

Figure 1. AASHTO T 166

Nuclear Method

Nuclear density gauges measure density by emitting gamma rays from a Cesium source. These rays pass through the compacted material to detectors. For a densely compacted material, the gamma rays do not easily pass through to the detector, resulting in a low number of counts. Lower density materials allow the gamma rays to pass through to the detectors more readily, resulting in a higher number of counts. The density of the mat is inversely proportional to the counts, and can be expressed as a unit weight or as a percentage of MTD. Standard procedures for tests performed on HMA pavements are outlined in ASTM D 2950. *(2)* A Troxler Model 3430 nuclear gauge is shown in Figure 2. Although the nuclear method is a relatively quick and non-destructive method for obtaining field densities, poor correlations between nuclear and core densities have been documented. *(3, 4, 5)* As a result, most states require field cores for QA purposes.

Figure 2. Troxler Model 3430 Nuclear Gauge

Non-Nuclear Methods

Non-nuclear gauges estimate density by measuring the change in electromagnetic field when an electrical current is transmitted through an asphalt pavement. Specifically, an electrical current passes from the transmitter, is forced around an isolation ring, through the pavement, and is detected by the receiver. The impedance, or resistance to electrical flow, is measured and used to determine the dielectric constant. *(6)* A schematic of this process is shown in Figure 3.

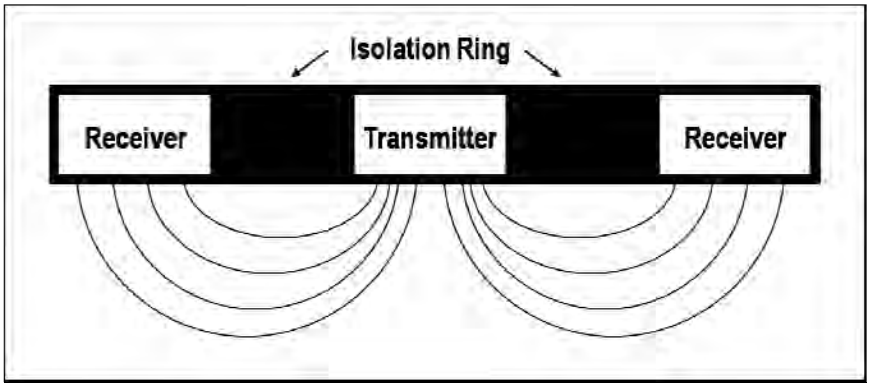

Figure 3. Schematic of Non-nuclear Gauge Function

The overall dielectric constant of an asphalt pavement is directly proportional to its density. *(6)* The dielectric constant of air is approximately 1.0, and that for aggregate and asphalt cement is in the range of 5 to 6. Because air has a smaller dielectric constant than the other HMA components, higher air void levels (i.e., lower densities) are indicated by a lower overall dielectric constant. Water has a very high dielectric constant (approximately 80), and small amounts of water can significantly impact the measured overall dielectric constant, such that densities estimated by dielectric constant are higher when water is present. Because the dielectric constant of air is less than that of HMA, and that of water is greater than HMA, the presence of a small amount of water can have the same numerical effect as a large decrease in air void spaces. *(7)*

The first impedance-type density gauge, the Pavement Quality Indicator (PQI), was developed by TransTech, Inc. in 1998 as part of the NCHRP-IDEA Program. *(6, 8, 9, 10)* The earliest model of the device, the PQI 100, did not have a moisture sensor, which created obvious problems with accuracy. This gauge did not correlate well with other measures of density and was not recommended for use. The next model (PQI 200) was capable of measuring moisture and temperature, and improved accuracy was reported. Subsequent improvements have been made to the PQI since that time, resulting in the PQI 300, PQI 301, PQI 302, and PQI 303. The PQI 301 is shown in Figure 4. Additions to the device have included settings for layer type, depth settings for layer thickness, and updated algorithms. *(11)*

Figure 4. Pavement Quality Indicator™ (PQI) Model 301

The PaveTracker is another non-nuclear density gauge, which was developed in 2000 and is currently marketed by Troxler Electronic Laboratories, Inc. *(8, 12)* This device is based on the same principles as the PQI, and is shown in Figure 5.

Figure 5. Troxler PaveTracker™ Model 2701-B

Non-nuclear gauges have primarily been used for determining mat density during construction, and results have been varied. *(6, 8, 13, 14)* Additional uses for these gauges have also been investigated, including density profiling, longitudinal joint density testing, and the quantification of segregation in compacted pavements. *(15, 16, 17)*

Calibration
A critical step in using impedance gauges effectively is to calibrate them in a manner that will increase the accuracy of results. Density measurements are relative measures of compaction, and can thus be adjusted mathematically in order to more accurately represent the "true" density of the pavement. Although an "absolutely true" measure of pavement density cannot be reasonably achieved, the most accurate measures are typically believed to result from the bulk specific gravity measurement of a pavement core cut from the compacted mat. Therefore, an alternative measure of density is believed to be accurate if it can produce results similar to those generated by core densities.

A number of methods are available for use in calibrating impedance gauges. The AASHTO TP 68 method, "Density of In-Place Hot-Mix Asphalt (HMA) Pavement by Electronic Surface Contact Devices", outlines three such methods. *(1)* The first is a relative method, which is recommended primarily for establishing rolling patterns during field compaction. In this method, the density of the mat is recorded after each of a series of roller passes. This process continues until the density no longer increases, and the number of roller passes is recorded. The second method is a screed calibration, in which the density behind the screed is estimated and used to generate an offset for the mix. The density behind the screed is typically in the range of 75 to 85 percent, and the actual value is usually based on operator experience. The third method involves a core calibration, and is the method recommended by AASHTO. In this procedure, one to five locations are chosen and impedance gauge readings are taken at each location. The offset is calculated based on the average differences in the gauge and core densities.

A method for non-nuclear density measurements has also been published as ASTM D 7113, "Standard Test Method for Density of Bituminous Paving Mixtures in Place by the Electromagnetic Surface Contact Methods". *(18)* This specification acknowledges that a number of calibration methods are available, but recommends a core calibration method in which three to ten locations are selected. A minimum of four non-nuclear gauge readings are taken at each location and compared to corresponding core densities. The average of the differences serves as the calibration offset.

Manufacturer's instructions for each gauge also provide insight to appropriate calibration procedures. TransTech recommends a core calibration procedure using five core locations and five gauge readings at each location. *(19)* A one point method is also described, which utilizes an offset based on the estimated density of the mat immediately behind the screed. An offset is determined based on the difference in the estimated screed density and the average of five gauge readings. In addition, a two-point method is described, which utilizes an estimate of density behind the screed as well as an estimate of density after the mat has been 'peaked' (i.e., the density no longer increases with additional roller passes). TransTech suggests that the density of an HMA pavement behind the screed is approximately 82 percent, and that the typical density of a peaked mat is approximately 95 percent. Based on linear modeling, the estimated and measured values are used to generate slope and intercept calibration constants.

Troxler recommends either a density offset method or a mix calibration method. *(12)* For the offset method, a series of readings can be taken with the non-nuclear gauge and compared to values generated by some other method, such as core densities, nuclear gauge densities, or gyratory-compacted core densities. The average difference is taken to be the offset. The mix calibration method involves taking pairs of density readings at a series of three to ten locations such that the range of density is at least 3 pcf. The non-nuclear gauge densities are paired with density readings from another method (in which the other method is assumed to provide 'true' results) such as core densities or nuclear gauge density readings, and linear modeling is employed as a means to generate slope and intercept calibration constants.

A calibration method seeks to reconcile the differences between two measures of the same property. In graphical form, if two measures are plotted against each other and agree perfectly, then the resulting relationship will follow the line of equality, which is a straight line having an intercept at the origin and a slope of 1 (see Figure 6). In most cases, perfect agreement is not present, and coefficients of regression (i.e., slope and intercept values) are used to transform measurements by one method to an equivalent measure by the second method.

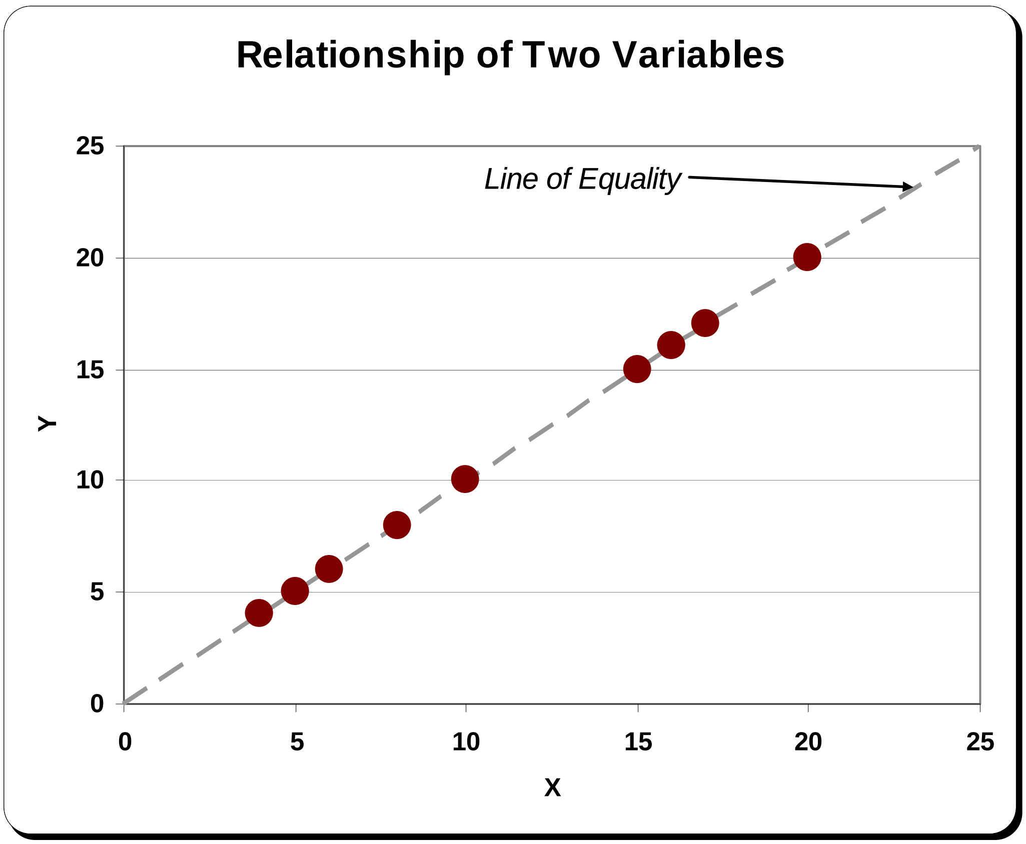

Figure 6. Relationship of Two Variables Having Perfect Agreement

An offset method of calibration is used to shift data vertically in order to create a dataset that most closely follows the line of equality. In Figure 7, the relationship of the original data is shown, as well as the corrected data after an offset calibration has been applied. In order to correct data using an offset calibration, a constant is added to the original data value.

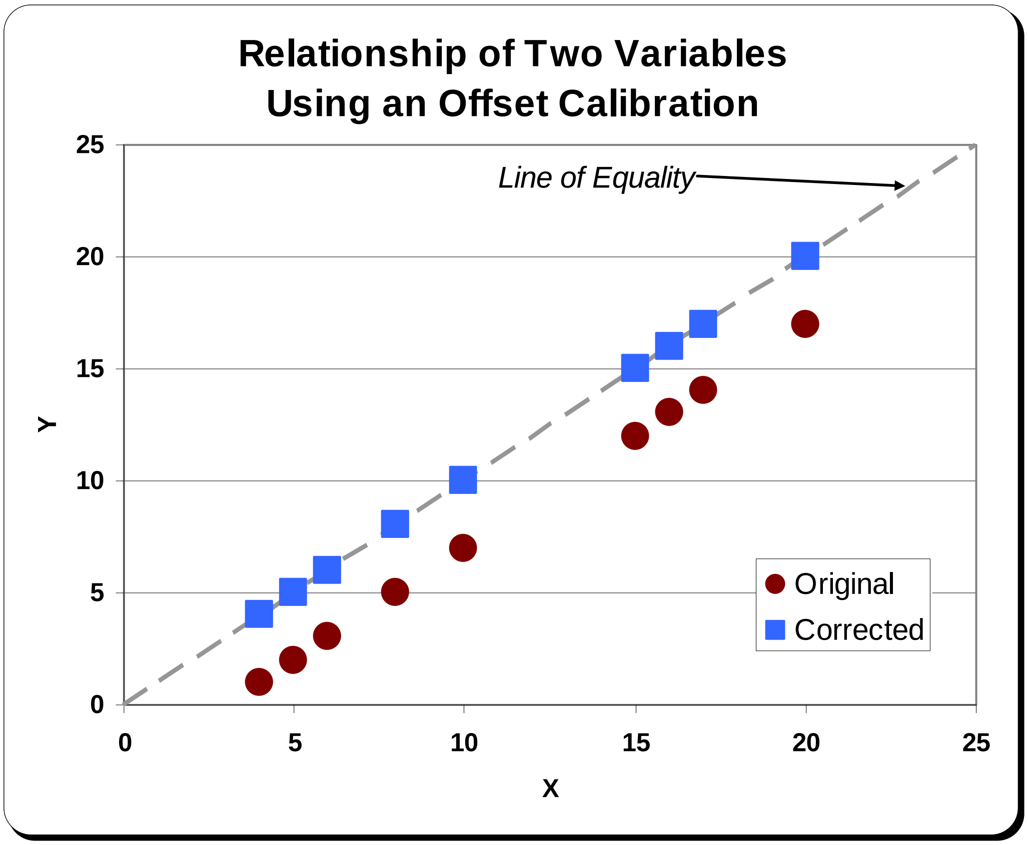

Figure 7. Relationship of Two Variables Using an Offset Calibration

A slope calibration is used to change the slope of a relationship to create a dataset that most closely follows the line of equality. In essence, the slope calibration will “twist” the relationship about the origin. In Figure 8, the relationship of the original data is shown, as well as the data after a slope calibration has been applied. In order to correct data using a slope calibration, the original data value is multiplied by a constant.

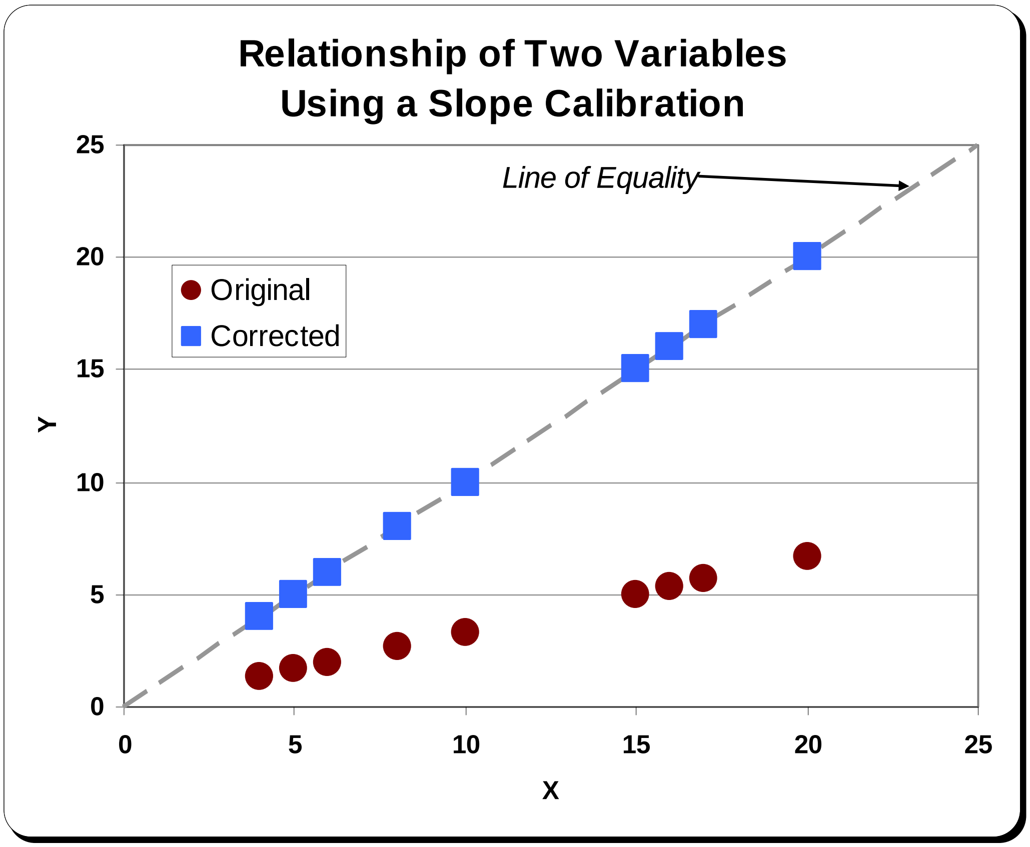

Figure 8. Relationship of Two Variables Using a Slope Calibration

To account for errors in the vertical position and slope of the relationship concurrently, a slope-intercept calibration should be used. This type of calibration method will "twist" the data to match the line of equality, and then apply an offset, or intercept, to shift the data vertically toward the line of equality. By including the both the slope factor and vertical offset, the data appears to be twisted about a point other than the origin. In Figure 9, the relationship of the original data is shown, as well as the data after a slope-intercept calibration has been applied. In order to correct data using a slope-intercept calibration, the data value is multiplied by a factor (slope) and then a constant (offset) is added to the result. The slope-intercept is the most difficult method to compute, but is usually able to provide a more complete adjustment to a dataset.

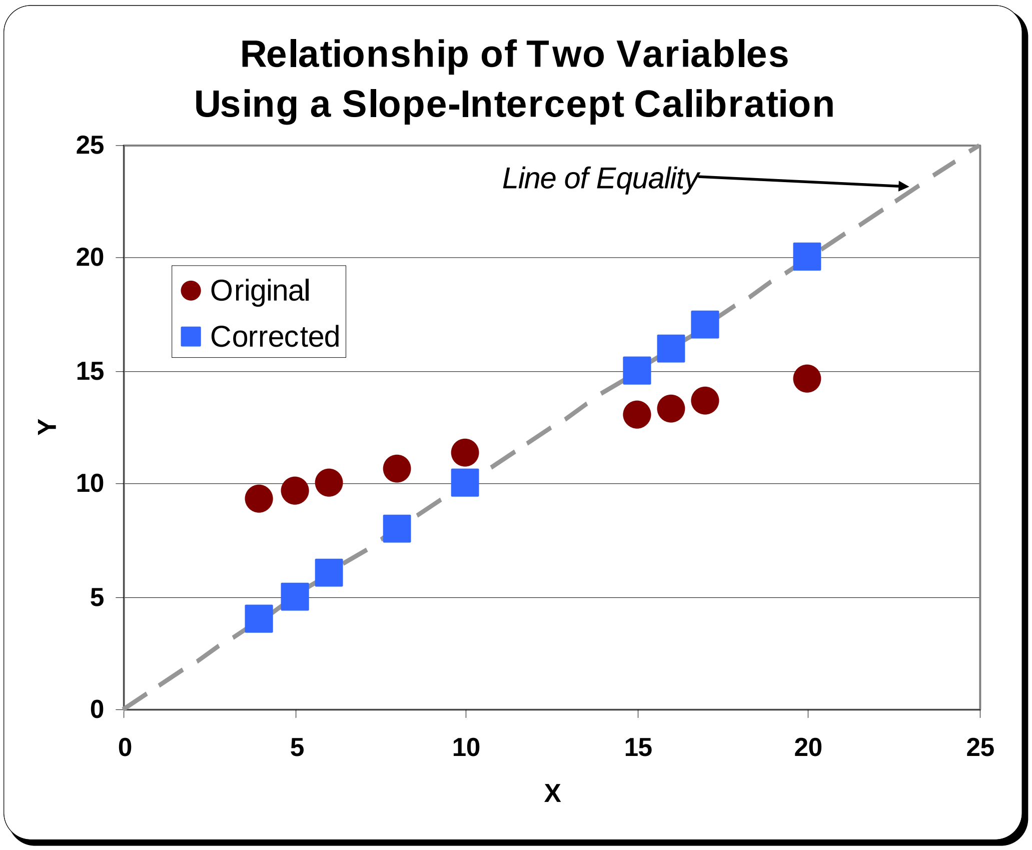

Figure 9. Relationship of Two Variables Using a Slope-Intercept Calibration

Cost

The costs associated with performing field density tests vary according to method. The term "cost" can include money, time, or effort, but these factors are typically assessed by some equivalent monetary value. In general, the non-nuclear devices have been advertised to provide significant savings as compared to the nuclear gauge. The initial cost of the non-nuclear devices is similar or slightly less than a nuclear gauge (depending on the model), but the majority of the savings is generated through the elimination of costs associated with licensing, training, and maintenance. One source reported that the annual operating cost of the PQI was $210 per year, as compared to $3075 per year for the nuclear gauge. *(7)* Another source reported that over a 5 year period, the non-nuclear devices could save as much as $50318. *(20)*

LITERATURE REVIEW

Rogge and Jackson

A number of studies have been performed to determine the ability of the non-nuclear devices to accurately and precisely measure in-place density of asphalt pavements. One of the earliest was performed in Oregon in 1999. *(21)* In this study, a Humboldt nuclear gauge and the original PQI model were compared to field cores in order to assess the compaction and field density for open-graded asphalt pavements having a nominal maximum aggregate size (NMAS) of 25mm and a typical air void range of 17 to 26 percent. Six projects were tested such that nuclear and non-nuclear densities were measured in 45 locations for each. Cores were also cut in each location, resulting in 270 cores and corresponding density measurements. Although a large amount of data was collected, it was reported that neither nuclear nor non-nuclear densities correlated well with core densities, and neither method was determined to be adequate for controlling field compaction.

Sully-Miller

In 2000, the Sully-Miller Contracting Company reported on a study in which the PQI was compared to a Troxler 3440 nuclear gauge. The variability was compared for the two gauges, and standard deviations of 0.95, 0.79, and 0.84 were reported for the PQI, and standard deviations of 1.51, 2.12, and 0.90 were reported for the nuclear gauge. The results of the nuclear gauge were widely varied, and it was concluded that these effects were due to surface texture. The PQI, however, did not appear to be affected by surface texture. Overall, it was determined that the PQI was reliable and accurate for measuring the in-place density of compacted HMA.

Henault

In another early study, the PQI 300 was evaluated in conjunction with the nuclear gauge in thin-lift mode, and the two were compared to field core densities with the intention of determining whether the PQI could be used for quality assurance (QA) testing. *(6)* Ten sites were tested, and a 5-core offset method was used to calibrate the PQI. Correlations between the PQI and core densities were poor, averaging 0.28, which was suspected to be due to moisture from the roller. Correlations between the nuclear gauge and core densities were better, but not good, having an average R^2 value of 0.55. Additionally, PQI densities did not correlate well with the nuclear gauge. Overall, the QA testing with the PQI was not recommended.

Pooled Fund Study

By 2002, the results of several non-nuclear gauge studies were published, including a pooled fund study. *(8)* In this study, laboratory and field evaluations of the PQI 300 were performed. The laboratory study sought to determine the effects of several factors, including density, NMAS, aggregate source, temperature, and moisture. Three aggregate sources and three aggregate sizes were used to compact slabs in the linear kneading compactor at varying densities. The results indicated that PQI readings were sensitive to temperature and moisture, even though improvements to the device had been made in an effort to combat these effects. Small amounts of moisture were not significant provided the moisture level remained fairly constant, and NMAS was not significant. The PQI 300 was recommended for use to indicate changes in density under constant temperature and humidity conditions, as long as a mixture specific calibration was used. A slope and intercept method of calibration was recommended.

As part of the pooled fund study, two field evaluations were performed. The first took place during the 2000 construction season, in which a nuclear gauge and PQI were evaluated with respect to field cores. It was found that nuclear gauge density readings provided the stronger correlation to field core densities. Although this relationship was merely fair, it was suggested that PQI readings were probably as reasonable as nuclear gauge readings, which are currently accepted by industry, and many practical reasons for using the PQI were cited. Due to poor correlations, the PQI was not yet recommended for field use; however, updated algorithms were recommended to further improve the device.

A second field study was held in the 2001 construction season, with five states participating. The PaveTracker, marketed by Troxler, was available at this time and was included in the study. In Pennsylvania, the PQI 300+ (improved) demonstrated the better performance, providing density values similar to that of cores for 6 of 9 projects. The PaveTracker demonstrated significant similarities to field cores in just 3 of 6 projects. The Pennsylvania project was regarded as highly successful, and part of the success was attributed to the experience of the technicians who made the decision to use a calibration based on an assumed density behind the screed of 87 percent.

In contrast, testing performed in Maryland indicated that the PQI was unable to sufficiently correlate with field cores in two of two projects. The PaveTracker was tested on three projects, and was able to successfully correlate with field cores in two of the three. Minnesota also reported greater success with the PaveTracker, which demonstrated high correlation with field cores for 4 of 7 projects and no poor correlations. The PQI performed poorly in 2 of 5 projects, and very well in 1 of the 5 projects. Similar results were generated for one project in Oregon in which the PaveTracker demonstrated a much stronger correlation to core densities than the PQI. In New York, similar results were achieved for the PQI and PaveTracker devices.

Overall, the PaveTracker demonstrated a somewhat better correlation to core densities than did the PQI, but neither performed as well as the nuclear gauge. It was noted that the PQI did not appear to be sensitive to actual changes in density in spite of its recent improvements. The non-nuclear devices were recommended for QC or supplemental testing, but not for QA testing.

Romero

Because several groups were analyzing the differences in non-nuclear density measurements, Romero offered guidance on the most appropriate ways to statistically analyze a dataset of this type. *(22)* T-tests were demonstrated to be inappropriate for comparing non-nuclear density data because the t-test can be misleading for highly variable data. The correlation coefficient was cited as the most accurate way to compare test methods because it provides an idea of the sensitivity of each parameter; however, small sample sizes can be detrimental to the reliability of this method. This is important to remember because small sample sizes are often an unfortunate side effect of a testing regime that involves destructive testing.

Prowell and Dudley

In 2002, the results of a similar type of comparison were reported for the PQI and nuclear methods. *(23)* Weak correlations existed between the PQI and field cores, but better correlations were exhibited by the nuclear gauge using the core calibration offset method, which was validated. The PQI readings were very consistent, but perhaps too consistent because PQI densities did not increase proportionally as core densities increased.

Hausman and Buttlar
Another comparison of the PQI and nuclear density gauge was performed in Illinois, and several factors were investigated in the laboratory portion of the study. *(11)* These factors were base coverage, moisture, slab thickness, and use of mineral filler. Base coverage was defined as the percent area of the base plate that is in contact with the HMA at each of 5 points along the longitudinal centerline of the slab. The results of the analysis showed that the PQI 300 was determined to still be sensitive to moisture, although not to the same extent as the PQI 100. Thus, the previous improvements to the device were beneficial. Mineral filler did not affect the measured density results.

The PQI 300 results did not correlate well with core densities. This was partially attributed to the density gradient created by the rolling wheel compactor used in the laboratory. The general conclusion of this study was that the accuracy and variability of the PQI was too high, and nuclear gauge results correlated better with core densities. As a result, density tests for pay were specified to be based on core densities tested according to AASHTO T 166, while nuclear gauge readings were deemed acceptable for QC/QA purposes.

Allen, Schultz and Willett
This Kentucky study was limited in scope to a single objective – to compare density measurements made by the nuclear and non-nuclear gauges. *(24)* Readings from a Troxler 4640-B thin layer gauge and two PQI 300 gauges were compared to approximately 150 field cores from a single 1.5-inch overlay project. The mix was a 12.5mm Superpave mixture containing PG 76-22 binder. A great deal of testing was performed and the distributions of values for each of the test methods were examined. A 5-core average offset calibration was used for the PQI devices. The density values obtained from the cores were taken to be true, and the distributions of the gauges were statistically compared to the distribution of the core values. The average percent densities were 92.9 and 92.1 percent for the PQI gauges, 92.7 percent for the thin lift gauge, and 92.8 percent for the cores. It was determined that the distribution of one of the PQI devices overlapped that of the cores by 88 percent; the other by 78 percent. The thin lift gauge distribution overlapped the core distribution by 83 percent. The core distribution was steeper than the others, which indicated that density values obtained from cores were less variable than the gauge methods. The data was then evaluated in terms of contractor pay. If the PQI devices had been used for pay factors, 100 percent pay would have resulted, while only 95 percent pay would have resulted from the use of the nuclear gauge. It was recommended that the PQI be allowed for QC purposes.

Sebasta, Zeig and Scullion
In Texas, a laboratory study was performed using the Troxler 3450 nuclear gauge and the PQI and PaveTracker non-nuclear devices to evaluate the effects of temperature, moisture and gauge battery voltage on densities generated by the PQI and PaveTracker non-nuclear devices. *(16, 17)* This data was used to assess the ruggedness, repeatability, and accuracy of the gauges. The results indicated that all gauges were sensitive to changes in temperature; specifically, density decreased as temperature decreased. All gauges were also affected by moisture, with the nuclear gauge exhibiting the least sensitivity to this factor. It was noted that unless the mat was excessively wet,

both non-nuclear gauges provided stable readings. For the battery voltage analysis, only the PaveTracker was used, and the effects of low voltage were not significant. The PQI was not included in this portion of the study because it performs an automatic shut off when the battery is low. Another observation noted was that the PQI, which requires the user to input the lift thickness, was marginally sensitive to this input value. As the input lift thickness increased, the measured density slightly decreased. The precision of the gauges in the laboratory was determined to be good, with standard deviations below 0.5 pcf for the non-nuclear gauges and less than 1.0 pcf for the nuclear gauge.

In the second phase of the project, a field study was performed. A 5-core calibration offset method was used, and data for the various gauges was compared to data generated from corresponding field cores. In terms of accuracy, no gauge consistently performed the best. With proper calibration, the nuclear gauge was selected as the best performer, followed by the PQI, then the PaveTracker. If all of the gauges were assumed to be unbiased (which was not likely to be true), then the PQI was the better performer. The authors cautioned, however that the PQI did not always adequately reflect true changes in mat density. The non-nuclear gauges were more sensitive to daily changes in the mix, and thus a daily mix calibration was recommended.

Experiments were also performed to determine whether the PQI and / or PaveTracker were suitable for use in density profiling and for testing the quality of longitudinal joints. The PQI was found acceptable for density profiling even without calibration, because the purpose of profiling is to detect relative changes. The PaveTracker was found to require calibration for profiling. The PQI was also found to be suitable for testing longitudinal joint density, but the PaveTracker was not. As a result of the concluding recommendations from this study, the PQI has been implemented by the Texas Department of Transportation for density profiling and longitudinal joint testing. *(17)*

Killingsworth

The PQI was used as a tool for measuring in-place density as a part of project NCHRP 9-15, which was an effort to relate measures of quality to performance-related specifications. *(25)* For dense-graded mixes in main line construction applications, the PQI exhibited very good performance when compared to nuclear and core density measurements. Average coefficients of variation on density were reported to be 0.90, 1.60, and 1.18 percent for the PQI, nuclear gauge, and field cores, respectively. These methods were also employed for evaluating longitudinal joints, and similar levels of variability were reported for each method.

Hurley, Prowell and Cooley

As additional improvements were made to the non-nuclear devices, further studies were performed in order to evaluate the effectiveness of the changes. In 2004, a report was published based on another study comparing the non-nuclear and nuclear devices. *(F)* In this evaluation, field projects having various NMAS and gradation types were chosen, and the gauge-measured densities were compared to core densities. The PQI was evaluated on 20 projects, and was found to have a fair to strong correlation to core densities for 16 of the 20. The PaveTracker was used on 10 projects, and displayed a fair to strong correlation for 7 of the 10. The conclusion of the analysis was that while the non-nuclear gauges had improved significantly, the nuclear gauge was still superior for field density measurements.

This study also included a discussion of calibration methods. Most users perform a simple offset calibration based on the average difference between gauge and core densities. However, this practice is based on the assumption that the two measures of density are correlated by a line having a slope of 1. The offset method was compared to a slope-offset method, however neither was successful at improving the correlation between the non-nuclear and core densities. Further study was recommended regarding calibration methods that included both a slope and offset.

Sargand, Kim and Farrington

This study was performed in Ohio with intentions similar to that of previous laboratory and field studies involving non-nuclear gauges. *(7, 27)* The statistical shortcomings of the previous evaluations were discussed, which included 1) a failure to account for random factors such as sampling error, 2) a lack of recognition for the variability within a single project (i.e., exact test locations were not documented), 3) the analysis of individual project datasets rather than a large, combined dataset, and 4) the unintentional introduction of bias resulting from failure to perform daily mix calibrations. Thus, this study attempted to account for all potential sources of error by performing statistically robust computations.

The laboratory study involved the PaveTracker non-nuclear gauge, and focused on the possible effects of temperature, moisture, aggregate size, sample area, and mat thickness. A fine-graded 9.5mm mix and a coarse-graded 19mm mix were used, and more consistent relationships between PaveTracker and AASHTO T166 densities were present for the fine-graded mix.

Two moisture conditions were used, including one that simulated roller water on the surface of the mix, and another that represented a partial saturation of the pavement layer. Moisture was found to be significant in that as surface moisture increased, the density decreased, but as internal moisture increased, the density increased. Since the dielectric constant of water is much greater than the other constituent components of HMA, the reasonable trend would have been for density to increase in the presence of moisture. Thus, the practical implication could be that either surface characteristics were not significant to the densities measured by the PaveTracker, or some other complicating factor affected the results. Temperature was not a significant factor.

Relative to mat thickness, the PaveTracker was reported to measure density to a constant depth of 1.75 inches. Thus, it seems reasonable that any measurements taken for pavements having a lift thickness of less than 1.75 inches, the resulting density is actually a composite measure of the layers existing within the measuring depth of the device. The effect of this factor was evaluated by measuring the density of thin pavement layers placed on bases of widely varying density. Mat thickness was determined to be significant, but only when the mat thickness was less than the 1.75 inch measurement depth of the PaveTracker.

Finally, the surface area was evaluated by testing a large slab (22.5 in. x 22.5 in.), then cutting the slab into progressively smaller sections and performing subsequent density measurements. Density readings were significantly impacted when the surface area of the test sample was less than 2 times the contact area of the gauge. As sample size decreased, density decreased. The practical implication of this was the fact that using 6-inch diameter gyratory-compacted specimens for calibration, as recommended by Troxler, is not appropriate.

In the field portion of the study, 24 projects were chosen, and 10 random locations were tested during two seasons using the nuclear gauge, the PQI 300, and the PaveTracker. Cores were also cut for density determinations in the laboratory. No gauge calibrations were performed, and all analyses were based on relative changes in density. The nuclear gauge and PaveTracker densities were similar in terms of sensitivity to changes in core density, but neither gauge detected the full range of actual changes in core density. The PQI, was more sensitive to changes in density, with the regression line relating the two having a slope of 0.924. Thus, a mix-specific daily offset calibration method was deemed appropriate for the PQI. Using a simple offset calibration factor, the PQI was able to generate density measurements that were statistically similar to core densities; the PaveTracker was not. The final recommendation resulting from the study was that the PQI could be implemented for QC and QA purposes if a daily mix-specific calibration was used. The PaveTracker was not recommended for QA purposes, regardless of calibration, but could be used for QC purposes.

Sawyer, et al

In 2005, the North Carolina Department of Transportation published the results of a study in which the PQI, PaveTracker, Troxler 4640-B nuclear gauge, and field cores were used to evaluate various types of asphalt rollers. *(28)* In this effort, the analysis of densities generated by each method were based comparisons to target density, which was defined as the ratio of the average density of the gauge readings to the average density of the cores, expressed as a percentage. When density measurements were compared for the various methods at a specific location, the results often differed. However, averaging the results over a given area tended to improve the correlations between gauge and core densities. A ratio of 5 non-destructive tests to 1 core value was recommended, and a control strip was recommended for calibrating the gauges to core densities.

Schmitt, Rao and Von Quintas

In Wisconsin, three non-nuclear devices were tested (PQI 300, PQI 301, and PaveTracker 2701-B) and compared to a nuclear gauge. *(29)* When no calibration offsets or slopes were used, the raw data showed that all non-nuclear gauges produced density readings that were lower than the nuclear readings. The PQI 300 values were 4.2 to 26.6 pcf lower, the PQI 301 was 11.2 to 27.2 pcf lower, and the PaveTracker was 1.8 to 17.7 pcf lower. This bias existed consistently, but the magnitude of the bias varied between days and mixture types. In terms of variability, the standard deviation of the nuclear readings was greater than that of the non-nuclear readings for a large portion of the sites tested.

Several factors were reported to affect the results measured by both the nuclear and non-nuclear gauges. The gradation was cited as significant, in that coarse-graded mixes having less than 40 percent passing the #4 (4.75mm) sieve had lower densities. Pavement thickness affected the difference in the nuclear and non-nuclear readings. As pavement thickness increased, the difference in nuclear and non-nuclear densities increased.

Since several factors affect gauge results, it was recommended that a calibration should be done for each project. Also, a daily calibration to the nuclear density gauge using 10-point calibration with the slope-intercept method was suggested. In this project, the slope and slope-intercept calibration methods were both successful in reducing error for non-nuclear devices, however the slope method was recommended as the most practical so that field technicians are not required to perform linear regression calculations in the field.

Sample size was also investigated in order to determine a testing frequency that would provide reliable density measurements by the non-nuclear methods. The existing specification in Wisconsin required a nuclear density sample size of 7, which corresponded with a 95 percent confidence interval of ± 1.5 pcf. The recommended sample size for non-nuclear testing was suggested to be 30 test sites, which yielded a 95 percent confidence interval of ± 1.0 pcf.

The recommended daily calibration procedure of comparing the non-nuclear devices to the nuclear gauge offers several practical advantages: it is quick and easy to perform, it is non-destructive to the pavement, and the entire calibration process can take place in the field. However, the intended purpose of the non-nuclear gauges is to replace the nuclear gauge and provide a safe, quick, and simple alternative for density measurements. Requiring the nuclear gauge as a part of the daily calibration procedure for the non-nuclear devices negates many of the advantages of using non-nuclear technology. Additionally, the variability of the nuclear device has been demonstrated to be greater than that of the non-nuclear device. Thus, calibrating the non-nuclear gauge based on a more variable method may not improve the true accuracy of the subsequent density measurements. Although the measured density of a field core cannot be proven to be “true”, it is generally accepted as the most correct value. If the non-nuclear gauges were calibrated based on field cores, greater accuracy would be expected. However, requiring 10 cores for calibration, or requiring a daily core calibration, is not a practical solution.

Kvasnak, et al

A recent study in Iowa was performed to assess the performance of the PQI and PaveTracker devices in the laboratory and the field. *(20)* In the field portion of the study, readings were procured after various numbers of roller passes in order to assess the sensitivity to the gauges to actual changes in density. Both non-nuclear devices were sensitive to these changes, which verified that they were able to detect densities with some significance. A large number of factors were analyzed using regression techniques and to determine which factors were significant to non-nuclear density measurements. The significant factors cited for the PaveTracker were roller pass, pavement moisture condition, contractor, aggregate type, NMAS, and traffic level. Significant factors affecting the PQI were station roller pass, distance across the pavement width, site, contractor, aggregate type, binder content, and pavement width. Based on observation, it also was believed that slag in a mix could significantly alter non-nuclear density results.

In general, the variability of the PQI-measured densities was greater than that for the PaveTracker or field cores. In terms of QA, the results generated by the PQI would have resulted in the same contractor pay as the results based on the field cores. However, penalties would have been assessed to the contractor if the PaveTracker data had been used.

In the laboratory study, a number of factors were analyzed, including moisture, sample thickness and sample area. The presence of moisture was significant in that density values were higher when moisture was present. Sample thickness was not a factor, however all samples were 2 inches in thickness, which is greater than the measurement depth of 1.75 inches reported for the PaveTracker. Sample size was determined to be insignificant. Specifically, the results obtained when the footprint of the PQI exceeded the area of the specimen were equivalent to those obtained when the PQI did not exceed the specimen area. The only exceptions to this result were for the mixes containing slag.

The primary conclusion of this study was that since mixture and project factors were significant to non-nuclear density measurements, the use of test strips should be investigated as a way to properly calibrate non-nuclear gauges.

Smith and Diefenderfer
In 2008, the results were presented for a study that investigated the effects of moisture on non-nuclear gauge measurements. *(30)* Although it has been firmly established that moisture does affect non-nuclear density measurements, these effects have been difficult to quantify. The study involved the PQI 301 and a Troxler 4640-B nuclear gauge to compare to laboratory density measurements on dense-graded HMA field cores. A number of statistical methods were employed to develop a regression-based correction for moisture content using a qualitative moisture index. A specific relationship was developed for each of 8 jobs, and the results showed that using this technique improved the PQI measurements such that PQI data correlated better with field cores than the nuclear gauge did for 7 of the 8 projects. Unfortunately, the relationships were project specific, and should not be applied for general use.

Precision and Bias
A study was performed in New York to develop a precision and bias statement for non-nuclear gauges according to ASTM E 691. *(31)* In this procedure, statistical techniques are used to assign levels of variability to the specific sources with which they are associated. This method is typically used for laboratory methods and materials, but was adapted for the field study. The ASTM procedure calls for “laboratories” which were assumed in this case to be the individual gauges used for testing. The “materials” were the various pavement test sections. It is recommended that at least 6 laboratories and 6 materials be tested in order to develop the precision and bias statements. In this experiment, 6 PQI gauges, 4 PaveTracker gauges, and 7 nuclear gauges were used, resulting in a total of 17 laboratories. Four pavement test strips were constructed, with each strip being subdivided into 9 sections, each section having a different density. Thus, a total 36 materials were used.

The four test strips each consisted of a different NMAS mix (9.5mm, 12.5mm, 19mm, and 37.5mm). Each strip was compacted such that the first roller pass was applied to the entire length of the strip and each successive roller pass was limited to a shorter distance, resulting in sections having a total of nine separate densities. Six density tests were performed and 4 cores were cut for each strip/section combination. The generated data was such that separate precision and bias statements were developed for the nuclear and non-nuclear devices. The PQI and PaveTracker devices produced results that were statistically similar enough to be grouped, so one precision and bias statement was developed for both non-nuclear devices. Practically speaking, grouping the similar devices is desirable for the implementation of a broadly-applicable specification.

The precision and bias statement is intended to provide a measure of repeatability and reproducibility. Repeatability is the ability of the test method itself to provide the same results when the same “laboratory” performs replicate tests on a particular “material”. Reproducibility is the ability of different “laboratories” to generate the same results when a particular material is tested. The precision statement developed was:

Gauge Type	x	s_r	s_R	r	R
Non-nuclear	136.91	0.17	3.27	3.27	9.15
Nuclear	137.28	0.53	4.15	4.15	11.63

where:

where:	x	average of study data
	s_r	repeatability standard deviation
	s_R	reproducibility standard deviation
	r	repeatability acceptable range of two test results (1s: 95% limit)
	R	reproducibility acceptable range of two test results (d2s: 95% limit)

Summary

In general, the progression of the non-nuclear gauges is evident. Early models were determined to be affected by various parameters, and subsequent improvements to the gauges have been made a result of the continued research on this topic. In spite of the improvements, researchers have voiced common themes including 1) insensitivity to actual changes in density, 2) poor correlations with other measures of density, and 3) the need for a better calibration procedure. The current consensus appears to be that while the non-nuclear gauges offer a great number of practical advantages, their results are significantly affected by a number of factors and thus the accuracy and precision of non-nuclear gauges is not sufficient for QA purposes. However, most agree that when properly calibrated, they can a viable solution for contractor use as a QC tool.

ANALYSIS AND DISCUSSION

In this project, the PQI™ Model 301and the Troxler PaveTracker Plus™ Model 2701-B were the non-nuclear gauges investigated. A Troxler Model 3430 nuclear gauge was also used. Densities of field cores were determined according to AASHTO T 166.

A series of experiments were conducted involving various aspects of the non-nuclear gauges. The first was a ruggedness study, which was used to determine factors that significantly affected non-nuclear gauge results, and what procedures should be followed in order to avoid unintentionally introducing error into density measurements. The second set of considerations involved a number of comparisons of density measurement according to the various test methods. The third topic of investigation involved calibration procedures for non-nuclear devices.

Ruggedness Study

A ruggedness study is a designed experiment used to identify potential factors that generate significant effects on a measurement. Several ruggedness-type studies have been performed for non-nuclear gauges, both in the laboratory and in the field. The primary thrust of the field studies, however, was to develop correlations among the various testing methods. Since the non-nuclear gauge is intended for field use, it was believed that a more accurate measure of the ruggedness of the devices could be assessed through a field ruggedness study. Although considerable field work has been done, no single field study had encompassed a comprehensive set of experimental factors likely to be encountered in common practice, and no evidence was found in the available literature regarding the completion of a true ruggedness study performed in accordance with ASTM E 1169.

The global objective of this portion of the project was to assess the effects of a considerable number of factors potentially affecting the density measurements generated by two non-nuclear devices. The desired result was to create a statistically robust evaluation of potential influences, and to develop a practical solution for each situation relative to these factors.

The ruggedness study was performed in two distinct phases. In Phase I, seven potential factors were chosen for a ruggedness, or screening, test according to ASTM E 1169, Standard Guide for Conducting Ruggedness Tests. As a result, significant factors were identified for further study. Next, the factors presenting the greatest likelihood for significance were investigated further. Phase 2 of the ruggedness study focused on these factors in a more statistically complete examination.

<u>Phase 1</u>

In the first phase of the ruggedness study, ten separate locations on a 12.5mm dense-graded Superpave mix containing a limestone / sandstone aggregate blend were tested. A calibration offset for each gauge was determined using field cores according to AASHTO TP 68, Method C. Seven experimental factors were chosen that were believed to have the potential to impact the density measurements obtained by the non-nuclear devices. The factor selection was based on information found in the available literature, as well as a consideration of practical and procedural deviations that could take place during field testing (even within the parameters of the state testing procedures). A Plackett-Burman design for N = 8 (fractional factorial) was used, which requires 7 experimental factors. The factors chosen were gauge type, mat temperature, presence of moisture, presence of sand, gauge orientation, number of readings used to generate one test “result”, and gauge placement. Each factor was varied at two levels (termed ‘low’ and ‘high’). A summary of the experimental factors and levels is presented in Table 1. The experiment was replicated in 10 locations on the compacted HMA mat.

Factor	**Low Level**	**High Level**
GAUGE	PQI	PaveTracker
TEMP	Approx. 100F	Approx. 180F
WATER	No Water	Water
SAND	No Sand	Sand
ORIENT	Parallel	Perpendicular
REPS	1	4
PICKUP	No Pick Up	Pick Up

Table 1. Ruggedness Study Phase 1 Experimental Factors and Levels

Gauge Type

Two gauge types were used – the TransTech PQI 301 and the Troxler PaveTracker Plus. The purpose of including this factor was to determine whether the two gauge models could be used interchangeably. In order to develop a generic construction specification which allows non-nuclear technology, the various gauge models should provide similar results. Other research project have investigated the use of both gauges, and though correlations have been mentioned, most of the analyses have focused on the ability to each to correlate with core densities or nuclear density measurements rather than to correlate with each other.

Mat Temperature

In early studies, the temperature of the mat was shown to significantly affect the performance of the non-nuclear devices. Specifically, decreases in temperature created decreased density readings. *(16)* Although product modifications have been performed to compensate for this factor, it was included in the experiment to ensure that its effects were no longer significant. The high temperature used was the temperature of the mat immediately behind the finish roller (approximately 180 degrees F) and the low temperature was tested after the mat had cooled considerably (approximately 100 degrees F). The exact testing locations were marked so that the same locations could be tested after the mat had cooled. It was recognized that a greater temperature differential could have been more informative. However, testing at higher temperatures (i.e., prior to final rolling) would have been confounded by actual differences in pavement density.

Moisture

Modifications were also made by the manufacturers to compensate for the effects of moisture. This factor was included in the experiment in order to assess the success of such modifications. In the manufacturer’s instructions for the PQI, the user is cautioned to ensure that no visible signs of moisture are present on the testing surface. However, the PaveTracker manual does not include a warning of this type. *(12, 19)* Current standard specifications, AASHTO TP68 and ASTM D 7113, state that the surface should be free from excess moisture, but that roller water is allowable. In this study, the “dry” condition was tested when the mat had no visible signs of moisture present. To achieve the “wet” condition, a spray bottle was used to wet the surface until the surface voids were essentially filled with water, then a towel was used to blot the surface. In the “wet” state, the mat resembled a saturated-surface dry (SSD) condition. Basically, the moisture comparison evaluated the effect of excessive roller water on the mat’s surface.

Presence of Sand

The non-nuclear gauges rely heavily upon the quality of contact with the surface of the HMA. Therefore, sand particles or debris could disrupt the contact between surfaces. Construction debris is often present at job sites and could affect readings, especially if the density measurements are not taken immediately after paving. If the surface of the mat contains a large number of voids, however, the measured dielectric constant could be excessively affected, indicating a lesser density. To remove the effects of surface defects when using the nuclear density gauge, fine sand is often used to fill the surface voids. If this same technique were applied to the non-nuclear gauge, it is possible that the same benefit could be realized. In order to perform testing with “no sand”, the surface was thoroughly brushed (if necessary) to remove all visible signs of debris. In some cases, vigorous brushing was necessary. Samples tested “with sand” were prepared by sprinkling a small amount of fine natural sand (passing the #30 (0.600mm) sieve) and then lightly brushing it so that only the surface voids were filled.

Gauge Orientation

The standard convention for taking nuclear density readings is to place the gauge parallel to the direction of paving. However, the gauge orientation is not specified in the manufacturer’s instructions or in AASHTO TP68 or ASTM D 7113. ASTM D 7113 also recommends rotating the gauge to obtain maximum contact between the gauge and the surface. Thus, a technician could place the gauge in any orientation and still abide by the stated procedures. Density readings were taken both parallel and perpendicular to the direction of paving. Because the contact areas of the gauges are round, parallel orientation was defined such that a technician facing the direction of paving could read the gauge display screen directly. Parallel and perpendicular orientations are shown in Figure 10.

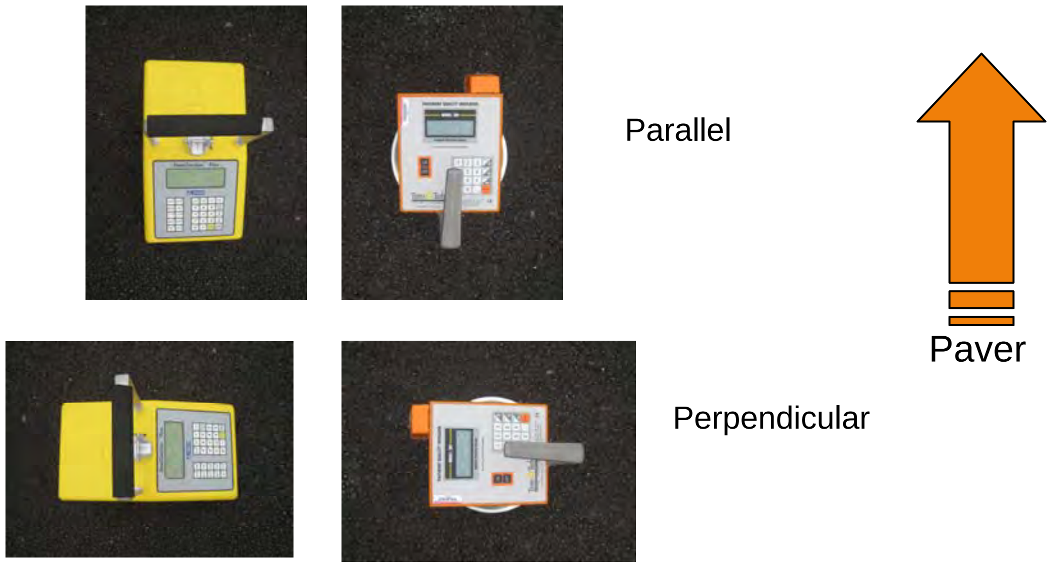

Figure 10. Parallel and Perpendicular Gauge Orientation

Number of Readings
For calibration purposes, non-nuclear gauge manufacturers recommend using the average of multiple readings (four or five) to generate one reported value. For general use, however, the number of readings required to obtain a reported value is not explicitly stated in the currently specifications. In general, increasing the number of readings is expected to improve the overall results. In this study, one reading and four readings were used to generate a reported value. Because the intention was to assess the gauges' ability to repeatedly measure a density and not to assess the variability of the mat, all replicate readings were taken in the exact same location, thereby removing the confounding effects of variation in mat density.

Gauge Placement
As stated previously, non-nuclear gauges require firm contact with the HMA surface for maximum effectiveness. In addition, it is generally desirable to report the average of multiple readings as the in-place density for a given location. It is reasonable, then, to ask the question: when taking multiple readings for a given location, should the user "pick up" the gauge between readings, or ensure a single firm placement and leave the gauge in place for all readings? This factor was included to assess the effect of picking up the gauge between successive readings.

<u>Phase 1 Analysis</u>
The results of the testing performed in this portion of the experiment are given in graphical comparison for each factor as shown in Figures 11 through 17, such that average values are presented for each testing location.

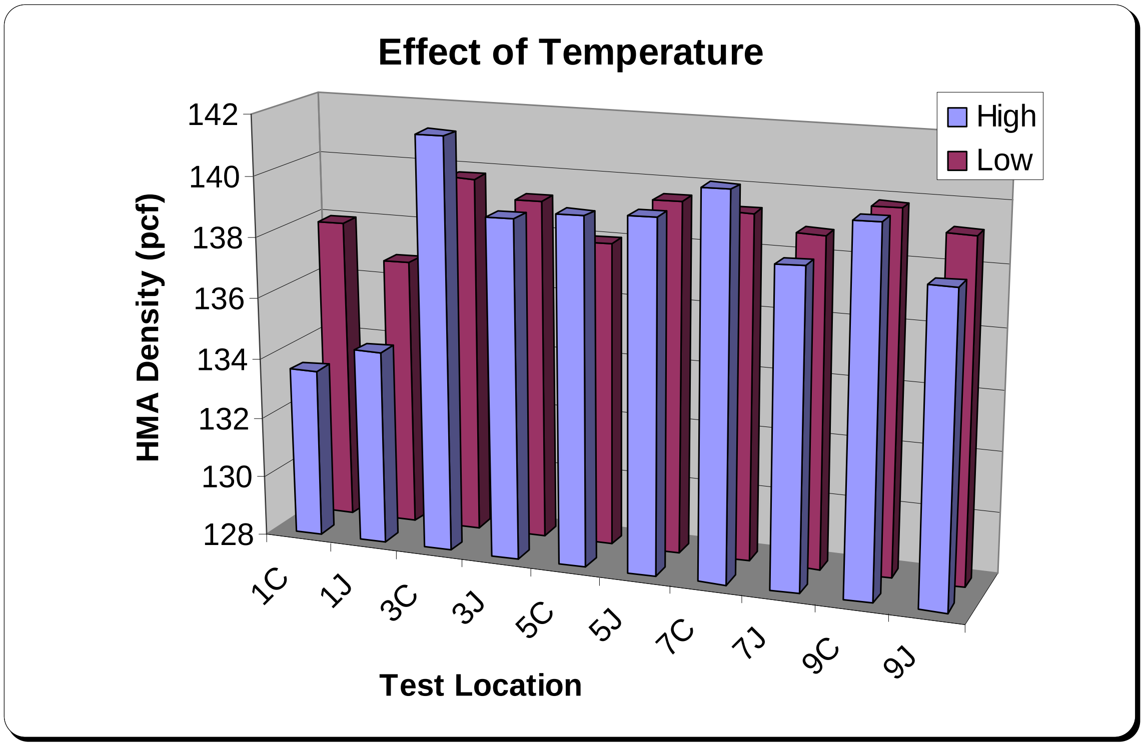

Figure 11. ASTM E 1169 Analysis – Effect of Temperature

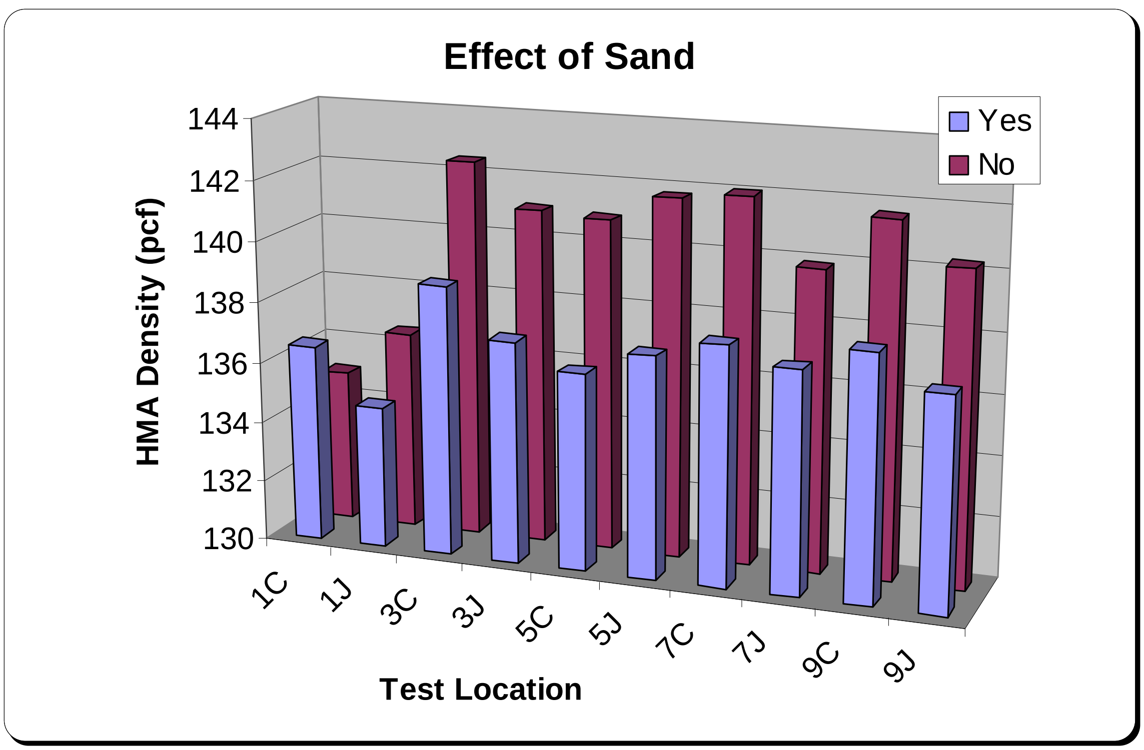

Figure 12. ASTM E 1169 Analysis – Effect of Sand

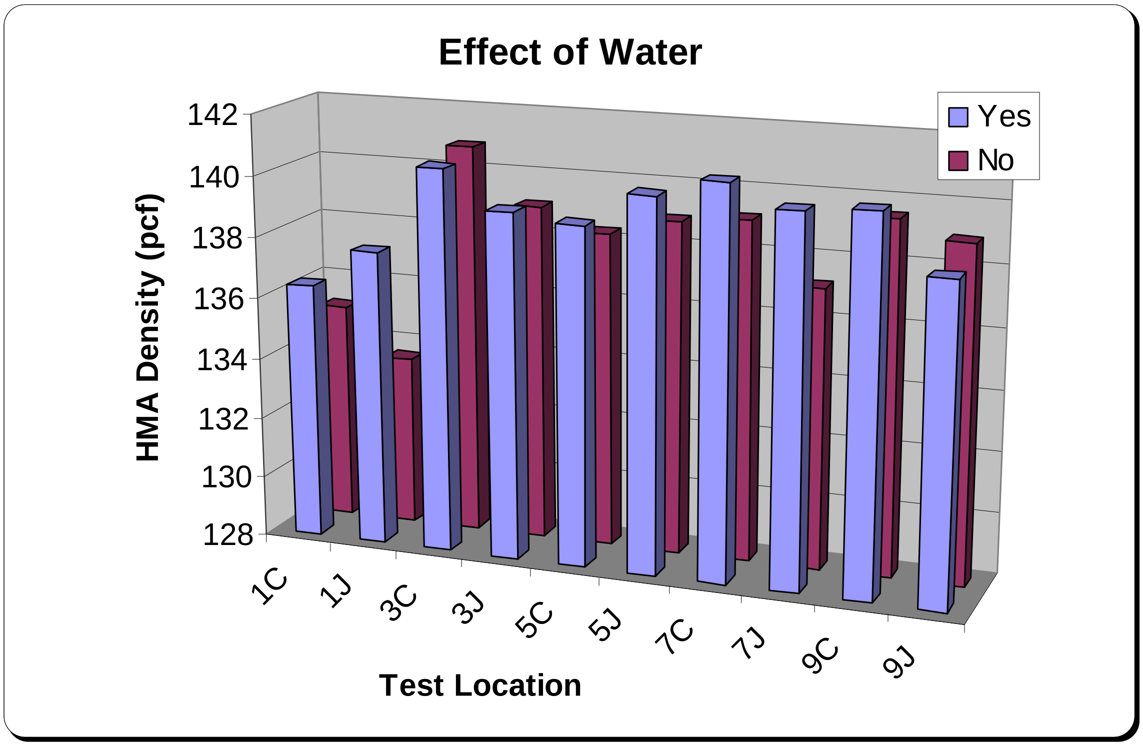

Figure 13. ASTM E 1169 Analysis – Effect of Water

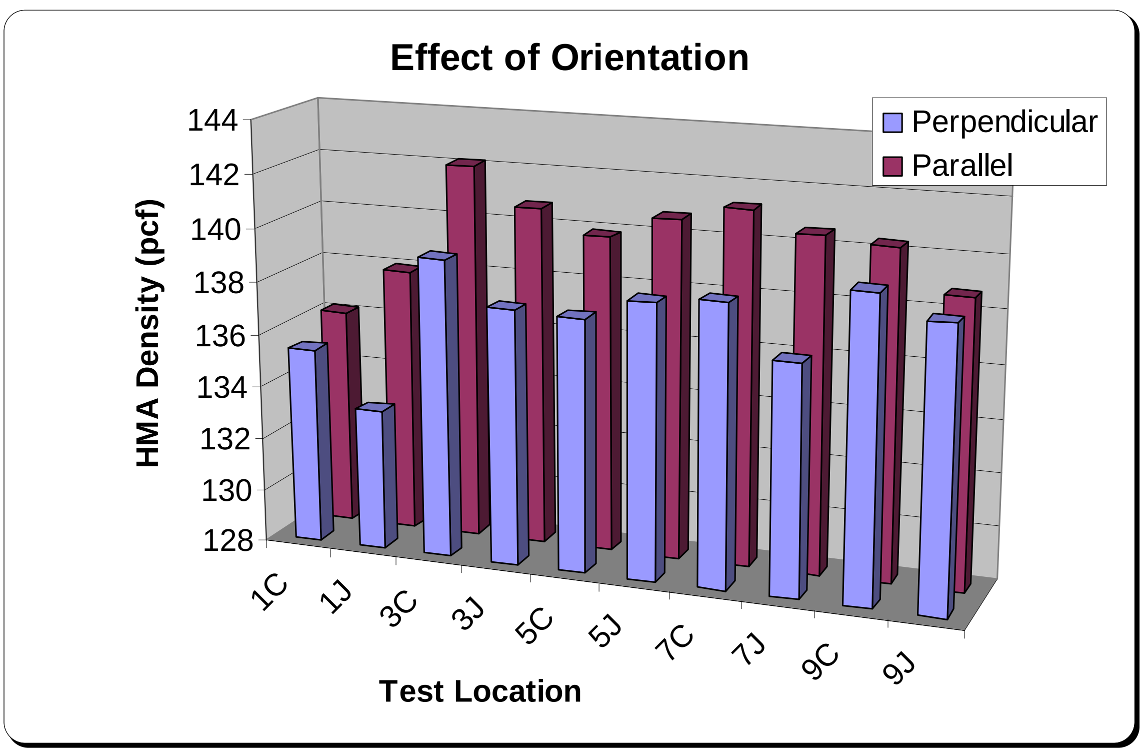

Figure 14. ASTM E 1169 Analysis – Effect of Gauge Orientation

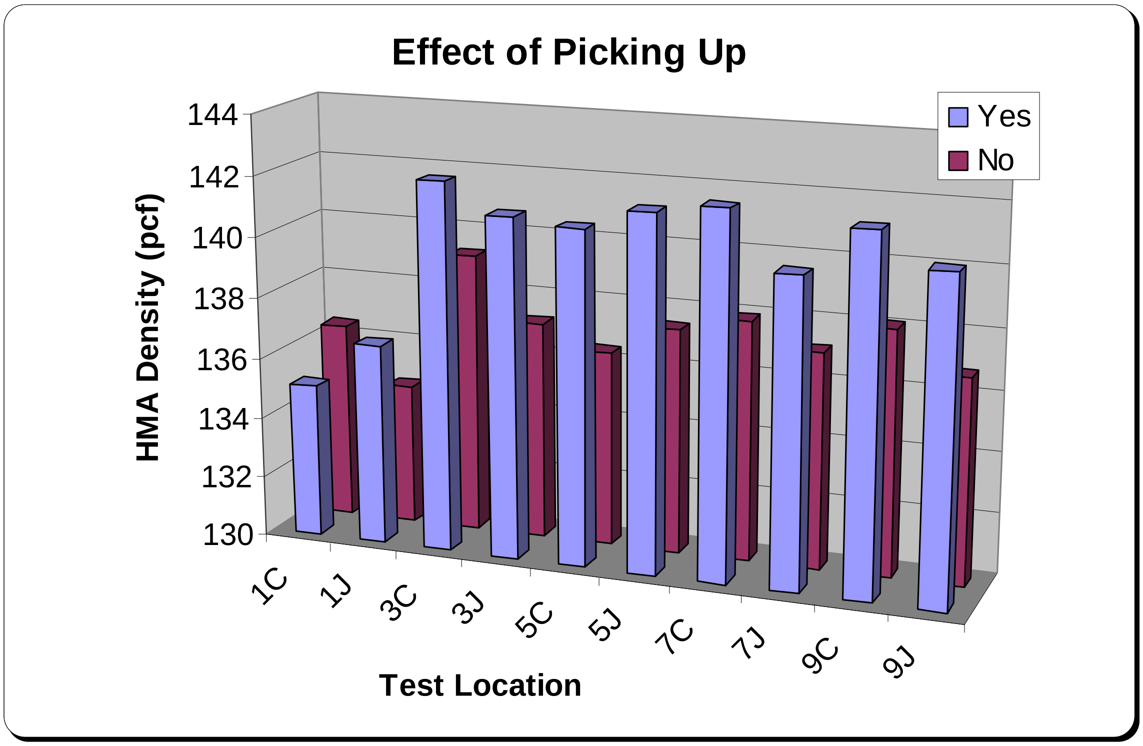

Figure 15. ASTM E 1169 Analysis – Effect of Picking Up the Gauge

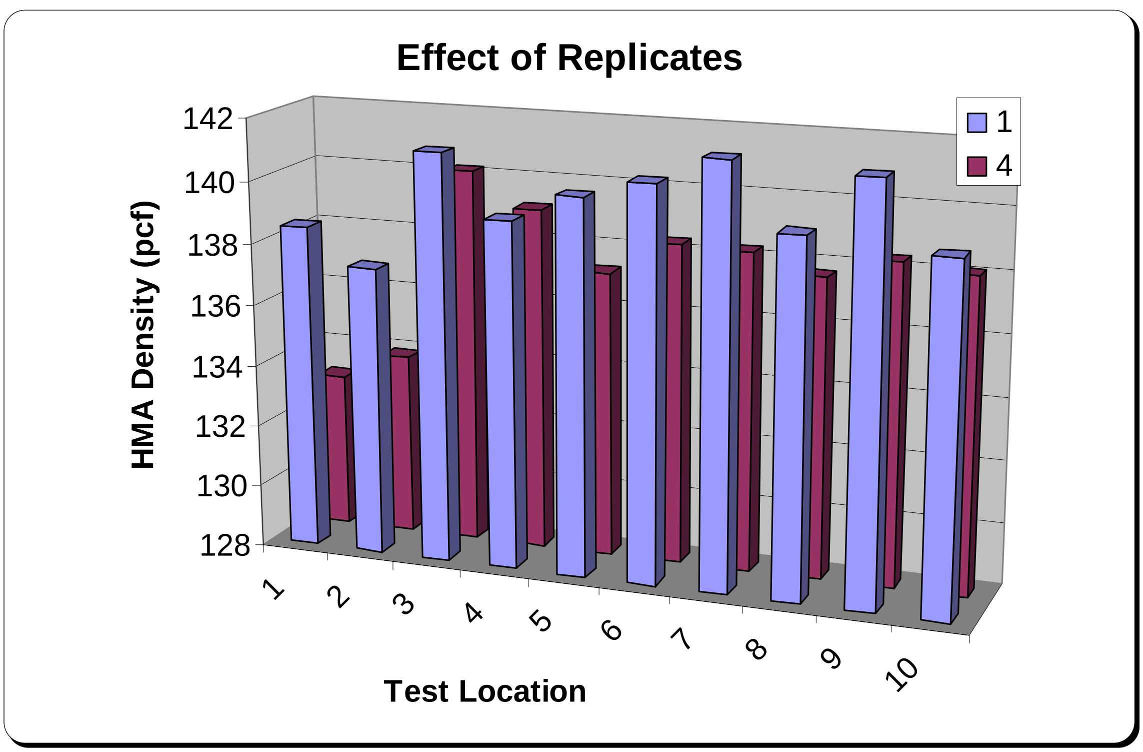

Figure 16. ASTM E 1169 Analysis – Effect of Number of Replicate Readings

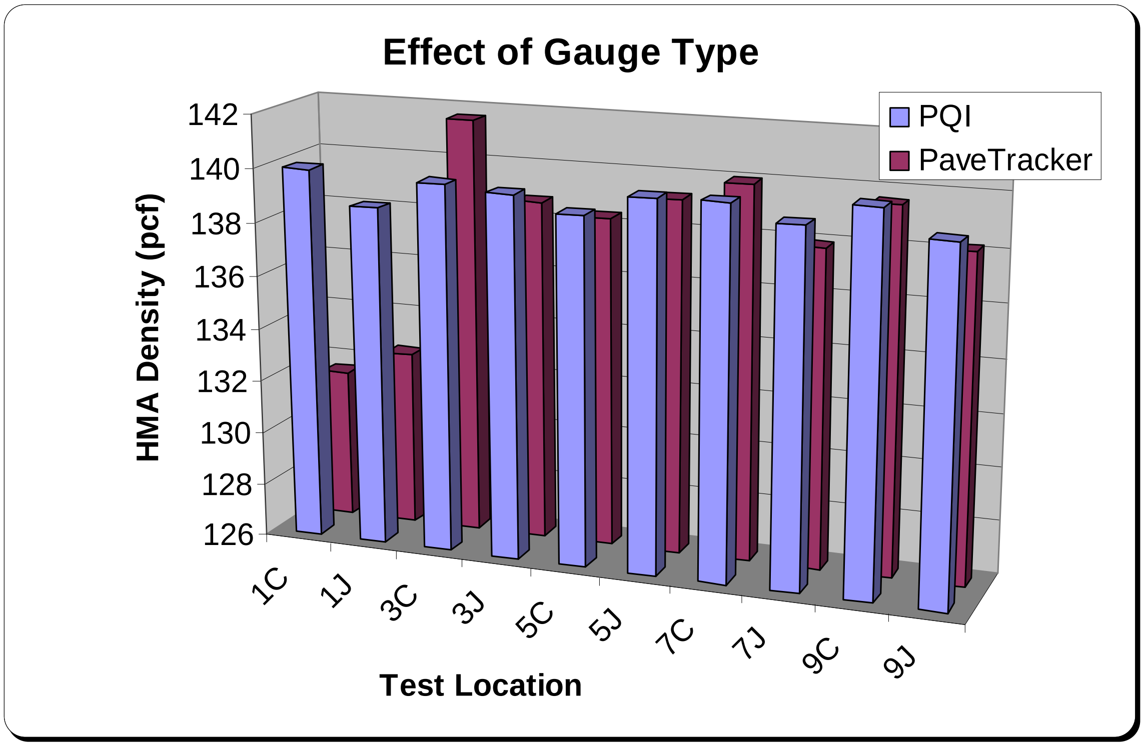

Figure 17. ASTM E 1169 Analysis – Effect of Number of Gauge Type

Field test data was initially analyzed using the procedures outlined in ASTM E 1169. Because the analysis was replicated in ten locations, a series of 10 sets of calculations were performed. The results are provided in Table 2. Significant effects are in bold type.

	LOCATION										Average
Factor	1	2	3	4	5	6	7	8	9	10	Effect
TEMP	-2.30	1.33	-0.58	0.73	0.52	-0.42	**4.79**	**2.45**	-0.59	-0.34	-0.4
SAND	-0.26	**-4.52**	**-2.73**	**-4.06**	**-4.09**	**-5.90**	**-12.84**	**-5.49**	**-4.27**	**-5.03**	**-3.1**
WATER	1.79	0.19	0.93	0.43	0.96	1.37	2.19	0.52	**2.43**	**2.90**	1.1
ORIENT	-1.78	**-2.62**	-1.95	**-2.80**	**-3.02**	**-4.36**	**-5.77**	**-3.38**	**-5.59**	**-4.52**	**-2.4**
PICKUP	0.29	**4.02**	**3.10**	**3.99**	**3.82**	**5.64**	**12.16**	**4.81**	**4.46**	**5.09**	**3.0**
REPS	**-2.83**	**-2.81**	-1.34	-1.47	-1.53	-1.34	**-9.91**	**-3.46**	-0.82	**-2.93**	**-2.5**
GAUGE	**-4.55**	0.61	-1.13	-0.73	-0.06	-0.93	0.37	1.57	-1.76	-1.37	**-1.7**

Note: The critical t-value is 2.36

Table 2. Calculated t Values and Average Effects for Experimental Factors

Phase 1 Conclusions

Based on the ASTM E 1169 analysis, the following conclusions were made.

- Non-nuclear density measurements were largely unaffected by the range of temperatures tested. Of the ten locations, temperature was significant for only two, and the average effect was relatively small.

- Nine of ten locations were significantly affected by the presence of sand. Introducing sand to the mat decreased the average density reading by approximately 3 pcf. Based on this result, it is believed that the sand is more likely to prevent solid contact between the gauge and the mat, than to alleviate the detection of a disproportionate number of surface voids.
- Water was found to be significant in only 3 of the 10 locations. Thus, blotting surface moisture from the mat (as per specifications) may be an adequate procedure. It was noted that the average effect was greater than 1 pcf.
- Gauge orientation was significant in 8 of 10 locations. Overall, placing the gauge in a direction parallel to the direction of paving creates a density approximately 2.4 pcf higher than when placed perpendicular to the direction of paving. Thus, rotating the gauge to obtain maximum contact is not acceptable.
- Picking up the gauge between readings was significant in 9 of 10 locations. Interestingly, placing the gauge repeatedly in the exact location increased the density readings by 3 pcf. It is suspected that the repeated placement may have "seated" the gauge in its place, increasing the quality of the contact with the mat. It could also be due to the operator unintentionally placing slightly more pressure on the gauge each time it was placed.
- The number of readings used to generate one reported value was significant in 5 of 10 locations. In general, the values consisting of 1 reading were significantly higher than those consisting of 4 readings. Though no explanation for this phenomenon was determined, it was noted that the practical purpose for including this factor was to provide the required number of factors necessary to properly perform the procedures outlined in ASTM E 1169.
- Overall, gauge type was not found to be significant. In general, the PQI generated slightly higher densities, however the average difference was statistically significant in only one of the ten locations tested. Because the non-nuclear density readings are relative, a proper calibration and offset should be sufficient to create similar density data.

An analysis of variance (ANOVA) was used to evaluate all of the data in a single analysis. However, since each location tested could, in theory, have a different actual density, it was necessary to block on the location factor. And because the dataset did not have the ability to provide full orthogonal contrasts and interactions, only the main effects were tested. While this technique is not sufficiently robust for a detailed investigation, it is acceptable for use in a screening experiment, such as this. The results of the ANOVA are given in Table 3. At the 95 percent level of significance (a = 0.05), all experimental factors are at least marginally significant with the exception of temperature. The presence of moisture was significant at the 92.5 percent level of significance, and was considered to be significant. Overall, these results appeared to be fairly consistent with those derived from the ASTM E 1169 procedure.

Source	df	Mean Square	F-Value	P-Value
LOCATION	9	21.907	2.82	**0.0074**
TEMP	1	2.521	0.32	0.5707
SAND	1	191.581	24.7	**<0.0001**
WATER	1	25.765	3.32	0.0731
ORIENT	1	114.290	14.73	**0.0003**
PICKUP	1	182.468	23.52	**<0.0001**
REPS	1	123.654	15.94	**0.0002**
GAUGE	1	56.113	7.23	**0.0091**
Error	63	7.756		

Table 3. ANOVA Table for Ruggedness Experiment - Phase 1

From these results, the least critical factors were eliminated from further study. Temperature was eliminated from the testing matrix due to the conclusive evidence that non-nuclear density measurements were not significantly affected by changes in that factor for the range tested. The number of readings used to generate a reported value was also eliminated from the testing matrix. Although this factor was significant, it is generally recognized that increasing the number of readings will decrease the overall variability. Because the difference in one reading and four readings was statistically significant, it was concluded that multiple readings should be used for the measurement of density by non-nuclear methods. This evidence was considered sufficient for a conclusive recommendation, and was therefore not included in the phase 2 ruggedness experiment.

The gauge placement factor was also removed from the experiment. Although significant, this factor lacked practical significance. In most applications, the gauge is picked up between readings. It was noted that there was very little, if any, variation in readings taken consecutively without moving the gauge. When lifting the gauge between measurements, the variability of consecutive readings was considerably greater. This supports the fact that non-nuclear gauges are very sensitive to the quality of contact between the gauge and the mat.

The factors remaining in the experiment included gauge model, gauge orientation, the presence of sand, and the presence of water. Though gauge model was not largely significant in the ASTM E 1169 analysis, it was determined to be significant in the ANOVA. And, both gauges were intended to be used in the study, so this factor was retained. Gauge orientation and the presence of sand were clearly significant in the analysis, and were selected for further testing in phase 2. While the presence of water was only marginally significant in the phase 1 analysis, it has bee reported in several other studies to have a significant effect on non-nuclear density readings. Therefore, it was also included in the phase 2 study.

<u>Phase 2</u>

Two dense-graded Superpave mixes having NMAS of 12.5mm and 37.5mm were chosen for testing in phase 2. For each of the mixes, the experiment was repeated in 16 locations, and two replicates of the experiment were performed at each of the 16 locations. A full four-factor factorial analysis was performed including the high and low levels of the remaining factors. Consistent with AASHTO TP 68, Method C, the non-nuclear density devices were calibrated for each mix using field cores in order to generate appropriate offset values.

12.5mm Mix

For the 12.5mm surface mix, results of the ANOVA are presented in Table 4. Significant factors included sand and water, as well as the interactions of sand and water, gauge and sand, and gauge and water. The 3-way interaction of gauge, sand, and water was significant, in that the interaction of sand and water was slightly more prominent for the PaveTracker than the PQI. The differences were not practically significant, however, having differences in the interactions of less than 0.5 pcf. Therefore, only the 2-way interactions were considered.

Source	df	Mean Square	F-Value	P-Value
LOCATION	15	47.404	53.9	**<0.0001**
GAUGE	1	0.343	0.39	0.5323
ORIENT	1	0.671	0.76	0.3827
GAUGE*ORIENT	1	0.710	0.81	0.3695
SAND	1	177.496	201.83	**<0.0001**
GAUGE*SAND	1	72.105	81.99	**<0.0001**
ORIENT*SAND	1	0.007	0.01	0.9272
GAUGE*OR*SAND	1	0.317	0.36	0.5485
WATER	1	155.695	177.04	**<0.0001**
GAUGE*WATER	1	16.124	18.33	**<0.0001**
ORIENT*WATER	1	0.002	0	0.9647
GAUGE*OR*WATER	1	0.313	0.36	0.5510
SAND*WATER	1	7.158	8.14	**0.0045**
GAUGE*SAND*WATER	1	4.108	4.67	**0.0312**
ORIENT*SAND*WATER	1	0.242	0.28	0.5998
GAUGE*OR*SAND*WATER	1	0.016	0.02	0.8928
Error	481	0.879		

Table 4. ANOVA Table for Ruggedness Study Phase 2 – 12.5mm Mix

The interaction of gauge model and sand is shown in Figure 18. For both gauges, the presence of sand reduced the measured density, suggesting that the sand particles do, in fact, partially interrupt the contact between the gauge and the mat. The PaveTracker appeared to be more sensitive to this phenomenon.

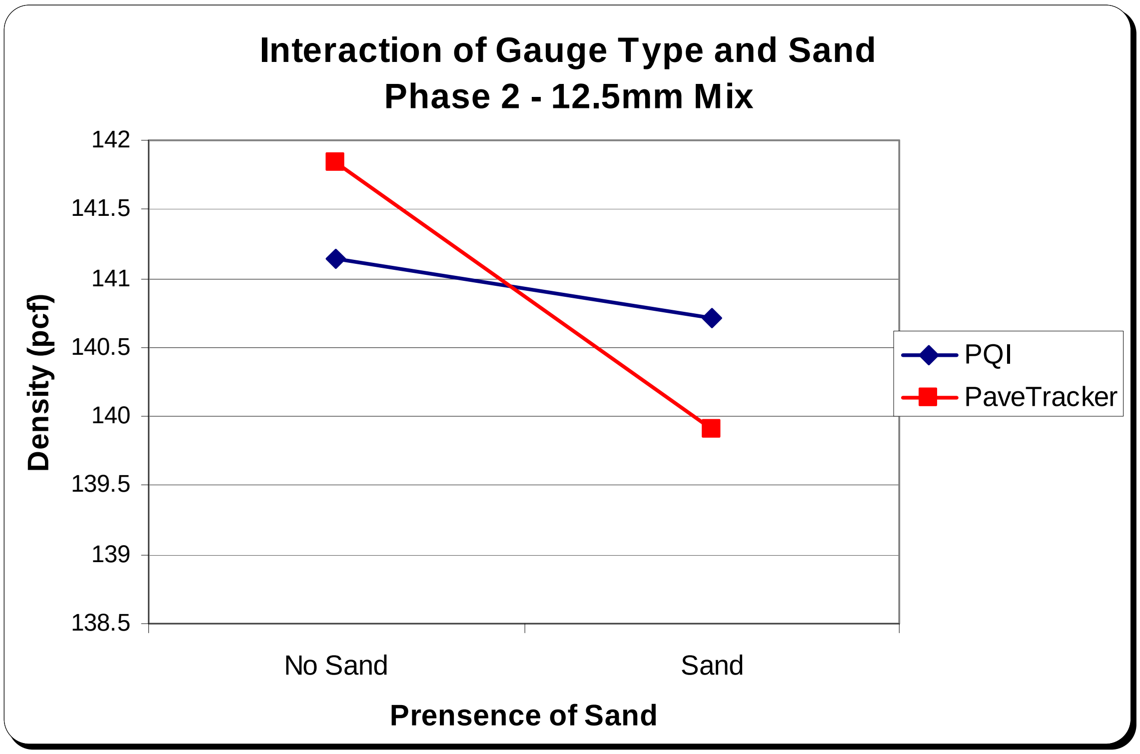

Figure 18. Phase 2 Ruggedness – Interaction of Gauge Type and Sand for 12.5mm Mix

The interaction of gauge type and water is given in Figure 19. In general, density increases when water is present. This outcome is reasonable based on the known dielectric constant for water. However, the significance of this parameter indicates that the gauges are still unable to accurately account for moisture in their internal algorithms. The PaveTracker appears to be slightly more sensitive to this change than the PQI.

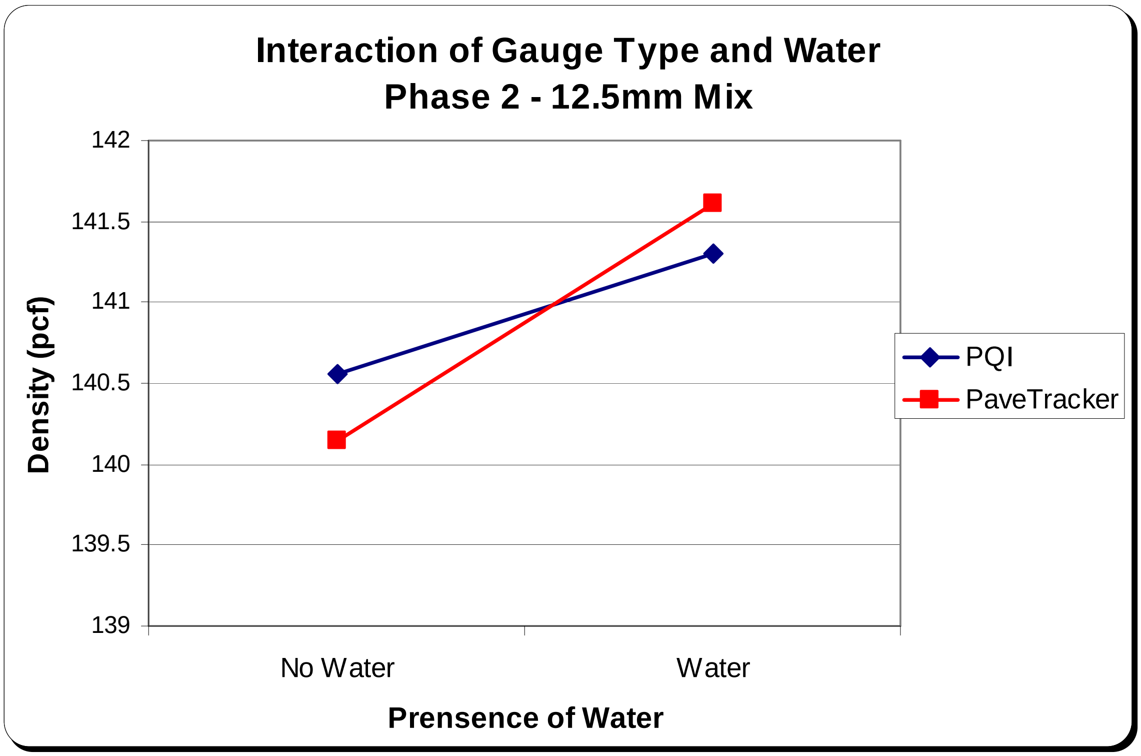

Figure 19. Phase 2 Ruggedness – Interaction of Gauge Type and Water for 12.5mm Mix

The interaction graph for the effects of sand and water are shown in Figure 20. The general trend indicated that the effects of water, such that density increases in the presence of water, were slightly more pronounced when no sand was present.

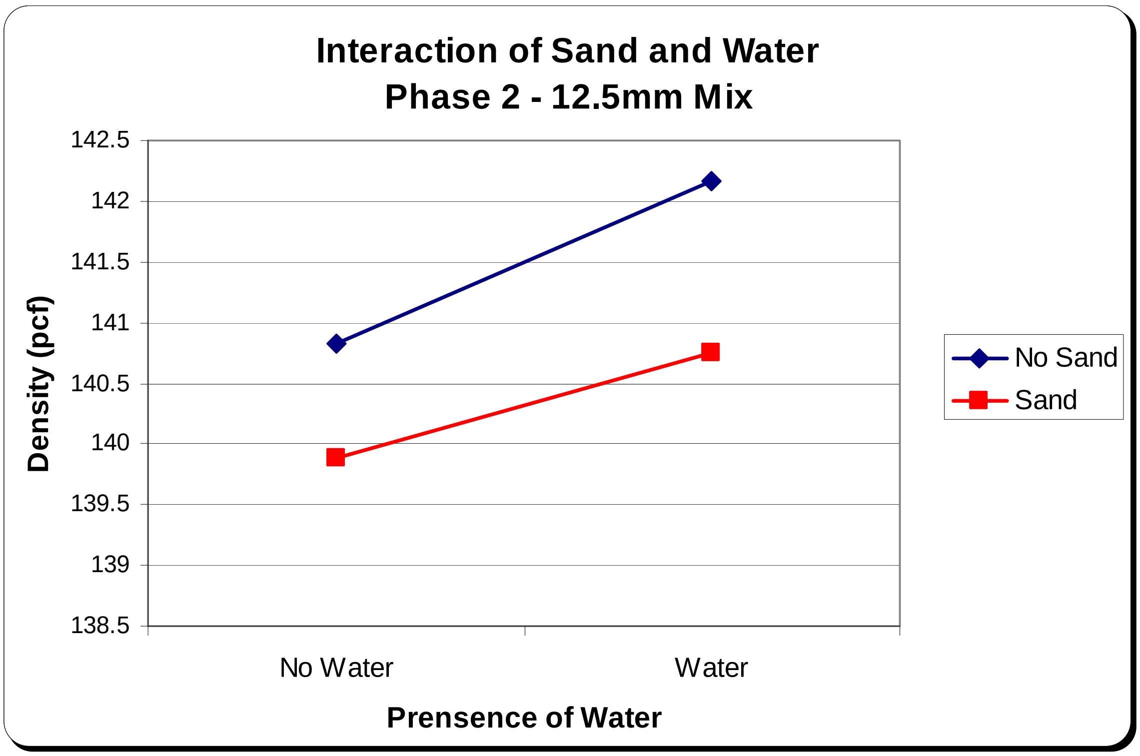

Figure 20. Phase 2 Ruggedness – Interaction of Sand and Water for 12.5mm Mix

Interestingly, gauge orientation was not significant as a main effect or in any interaction with other factors. However, since it did present as a significant factor in the phase 1 screening test, there may be situations in which the orientation of the gauge could affect the estimation of mat density. Therefore, a direction should be chosen as standard, such as in the direction of paving.

37.5mm Mix

The phase 2 ruggedness testing was also performed on a 37.5mm mix. A summary of results of the ANOVA results are given in Table 5.

Source	df	Mean Square	F-Value	P-Value
LOCATION	15	136.156	10.00	**<0.0001**
GAUGE	1	429.062	31.50	**<0.0001**
ORIENT	1	15.022	1.10	0.2942
GAUGE*ORIENT	1	19.806	1.45	0.2285
SAND	1	0.335	0.02	0.8754
GAUGE*SAND	1	9.058	0.67	0.4152
ORIENT*SAND	1	4.902	0.36	0.5488
GAUGE*OR*SAND	1	0.199	0.01	0.9038
WATER	1	6721.477	493.49	**<0.0001**
GAUGE*WATER	1	2.325	0.17	0.6797
ORIENT*WATER	1	5.801	0.43	0.5143
GAUGE*OR*WATER	1	12.594	0.92	0.3367
SAND*WATER	1	265.795	19.51	**<0.0001**
GAUGE*SAND*WATER	1	55.981	4.11	**0.0432**
ORIENT*SAND*WATER	1	1.006	0.07	0.7859
GAUGE*OR*SAND*WATER	1	2.688	0.20	0.6570
Error	481	13.62		

Table 5. ANOVA Table for Ruggedness Study Phase 2 – 12.5mm Mix

Significant factors included gauge type and water, as well as the interaction of sand and water. The 3-way interaction of gauge, sane, and water, was marginally significant in that the PQI was slightly more sensitive to the interaction of sand and water than the PaveTracker. Again, the differences were not practically significant, however, having differences in the interactions of less than 1 pcf. Therefore, the two-way interaction was considered (shown in Figure 21). Although statistically significant, this interaction does not appear to be practically significant. The more influential factor affecting the density reading is the presence of water. Gauge model was significant for the 37.5mm mix such that overall, the PQI produced readings that were, on average, 1.83 pcf higher than those for the PaveTracker.

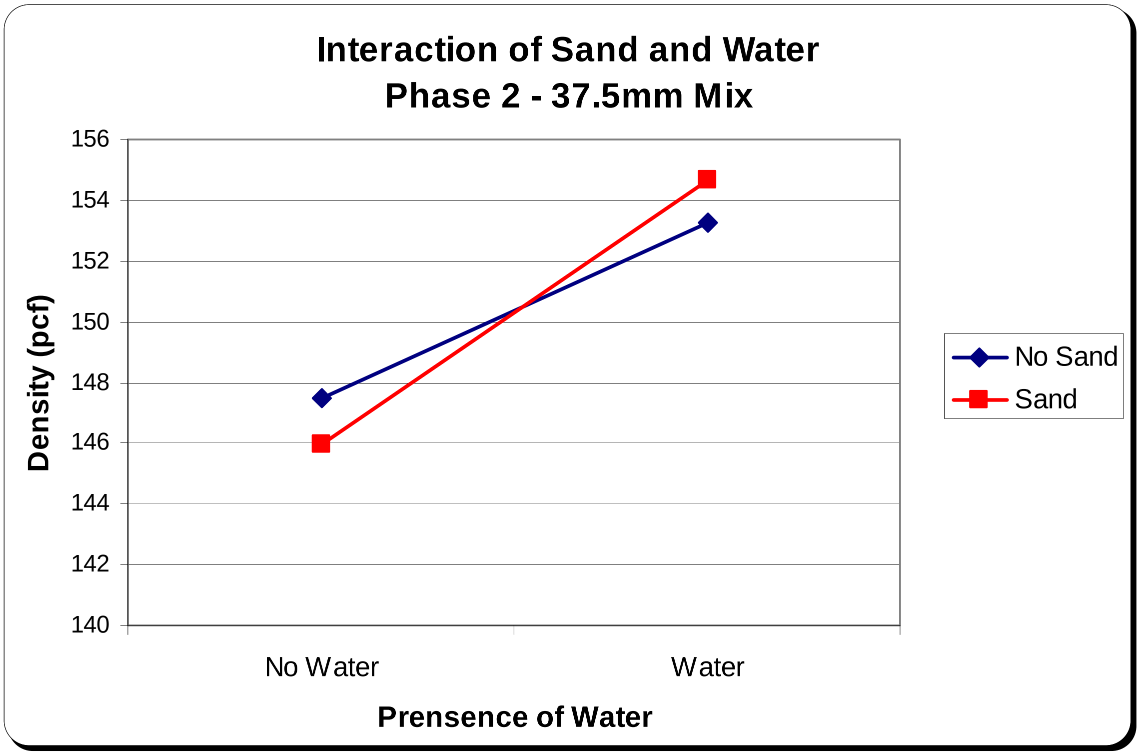

Figure 21. Phase 2 Ruggedness – Interaction of Sand and Water for 37.5mm Mix

Phase 2 Conclusions

Based on the analyses presented in the ruggedness study, the following conclusions were made.

- For the range tested, temperature did not significantly affect the density readings obtained by the PQI or the PaveTracker.
- The orientation of the gauge can be a significant factor, but is likely mixture dependent. Therefore, a consistent orientation, such as parallel to the direction of paving, should be required. Instructions and specifications should be edited to include this item.
- The presence of sand significantly affected non-nuclear density readings, and was especially pronounced for mixes containing smaller surface voids (i.e., 12.5mm surface mixtures). This effect was more significant for the PaveTracker than the PQI.
- The presence of water significantly affected density readings in some cases. For mixes with smaller surface voids (i.e., 12.5mm surface mix) the significant effects were only detected for the PaveTracker. However, both gauges were affected when tested on a 37.5mm mix. Care should be taken to remove all visible water from the surface prior to testing.
- The PaveTracker and PQI provided similar results for the 12.5mm mixtures, but displayed statistically significant differences for the 37.5mm mix. It should be recognized that a 37.5mm mix having large and irregular surface voids is likely to increase the variability of density readings, which can increase the likelihood of generating “different” results.

Overall, the results of the ruggedness study indicated that there are still factors that significantly affect the ability of the non-nuclear gauges to produce consistent readings. In order to combat these effects, procedures for use should include a requirement to place the gauge parallel to the direction of paving, to ensure that no sand or debris is present on the surface, and to remove as much surface water as possible, especially for coarse-graded and large stone mixes.

Influence of Surface Moisture

Although the presence of water was statistically significant for both the 12.5mm and the 37.5mm mixes, its effects appeared to be much more pronounced for the 37.5mm mix. Because the 37.5mm mix had a more irregular surface with larger surface voids, it is then logical that more water (i.e., greater moisture content) was necessary to fill the surface voids and create the "SSD" condition, thereby possibly enhancing the effects. In order to investigate the effects of water further, an additional study was performed.

A 12.5mm mix and a 37.5mm mix were tested to determine the effects of varying amounts of moisture in and on the surface of the mat. The relative water value, as measured by the PQI device, was used as the measurement for moisture. The original locations used in phase 2 of the ruggedness study were used for the 37.5mm mix. However, the 12.5mm mixture was no longer available for testing, so a similar site was chosen. At each location, a reading was taken with the PQI on the pavement with no visible surface moisture, and there had been no recent rainfall. The PQI density and relative water values were recorded, and then a corresponding density reading was obtained with the PaveTracker. This represented the "substantially dry" condition. Then, increments of water (approximately 2 mL) were misted onto the surface using a spray bottle and the density and moisture readings were recorded for each increment. For the 12.5mm mix, approximately 35 mL of water was sufficient to fill the surface voids such that water began to pond on the surface. This amount of water corresponded with PQI relative water values of approximately 25. For the 37.5mm mix, water began to pond after approximately 50 mL were applied, which corresponded with a PQI relative water value of about 35. The resulting correlations are presented in Figures 22 and 23.

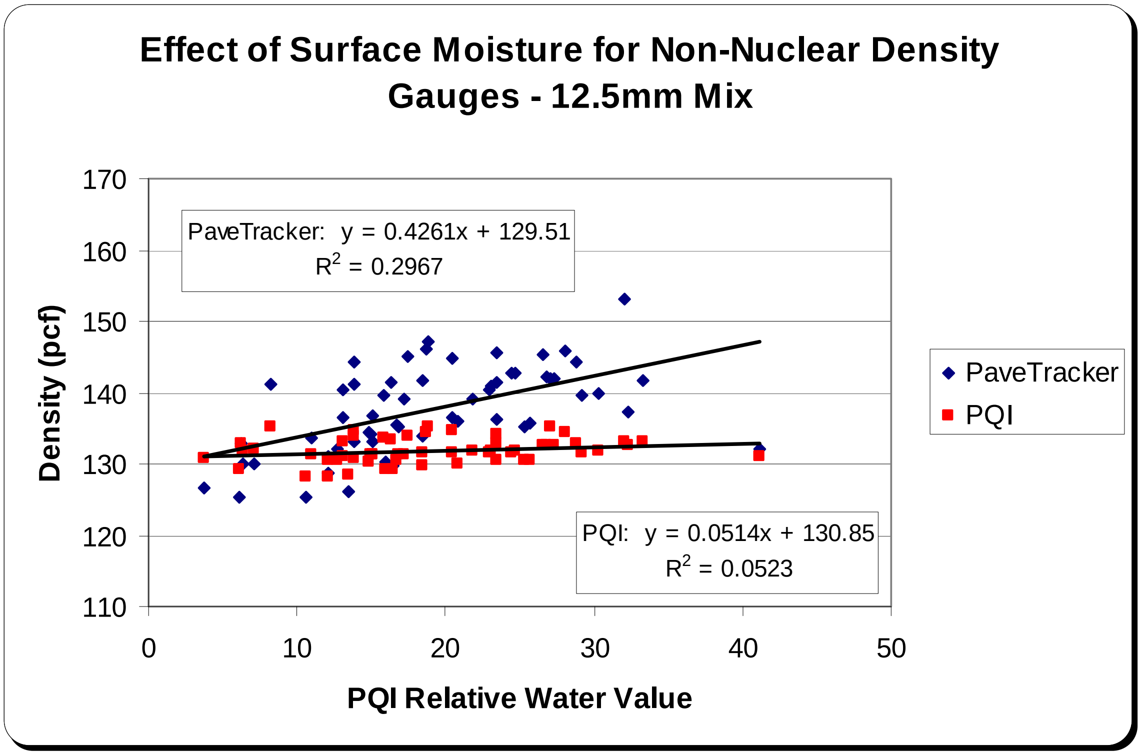

Figure 22. Relationship of Density and Relative Water Value – 12.5mm Mix

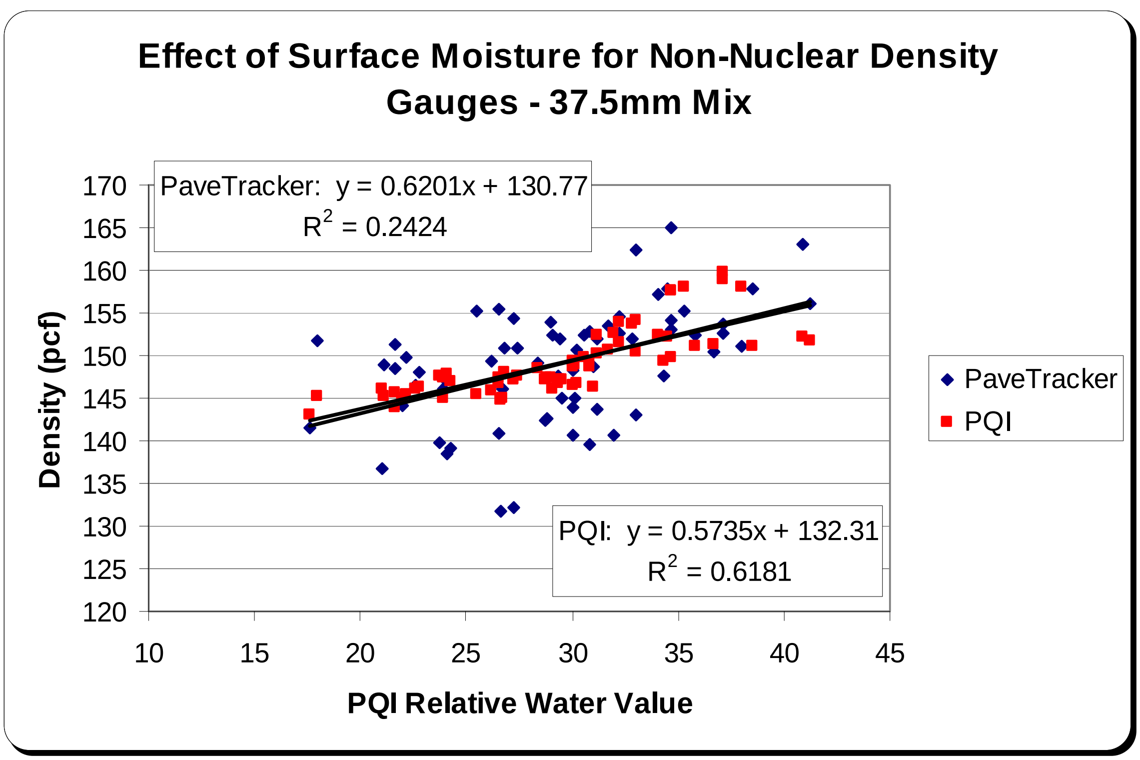

Figure 23. Relationship of Density and Relative Water Value – 37.5mm Mix

The correlations appear to be consistent with the results of previous analyses. For the 12.5mm mixture, the PaveTracker was clearly more sensitive to increases in moisture, whereas the PQI did not appear to be affected. Neither relationship showed good correlation. For the 37.5mm mixture, both gauges were affected by moisture; however, the PQI exhibited a more consistent relationship (as evidenced by the R^2 value of 0.62). It was noted that the relationships did not appear to change significantly as water began to pond on the surface.

Effect of Paint

A common practice of field technicians is to use paint markings on the pavement to indicate testing locations. If non-nuclear devices are to be used for QA purposes, then they must either be insensitive to the effects of paint, or sampling locations must be marked in some other manner. For a single pavement type, having a 25.0mm NMAS and containing PG 70-22 binder, the effects of paint were tested. For tests performed with no paint, a crayon was used to lightly mark the testing locations, and non-nuclear density readings were taken with both the PQI and the PaveTracker. Then, a solid circle of paint was sprayed to simulate the marking of a 6-inch core location. After the paint dried, readings were taken with each gauge. The results of the paint study are shown in Figure 24. On average, the PQI readings were 1.1 pcf higher when paint was present, and the PaveTracker readings were 1.3 pcf higher when paint was present. Thus, a filled circle of paint should not be used for marking non-nuclear density test locations.

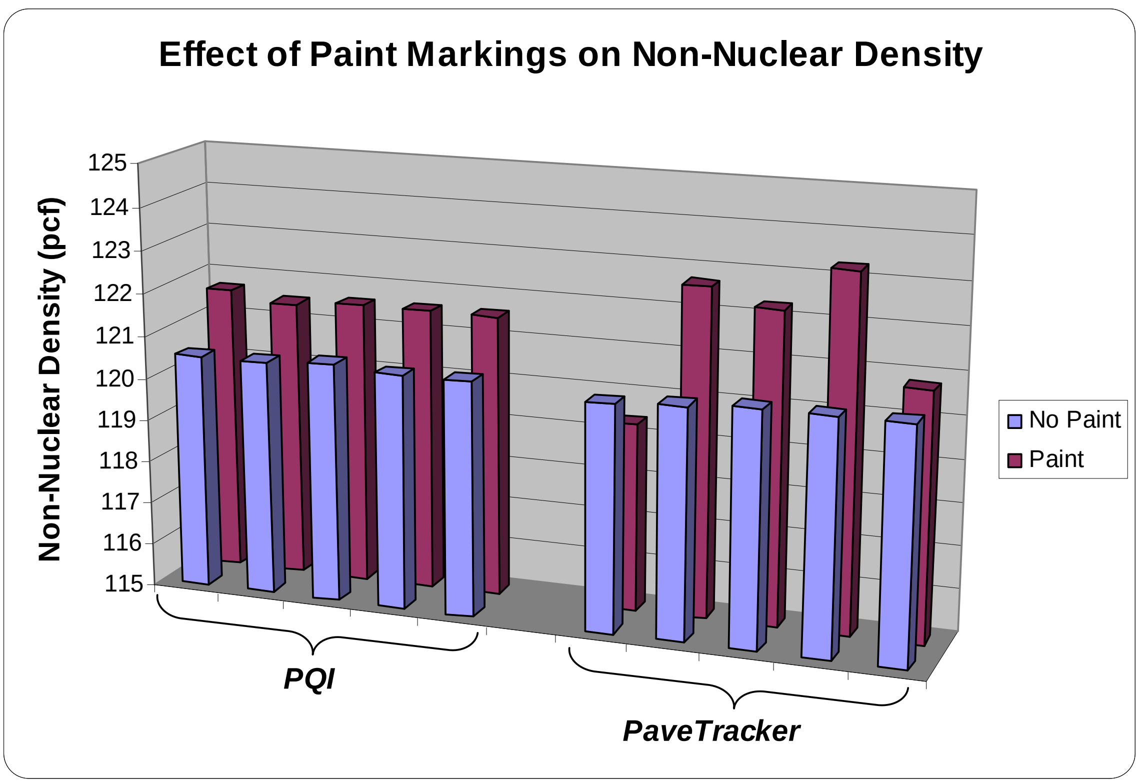

Figure 24. Effect of Paint Markings on Non-Nuclear Density

Method Comparisons

The next experiments performed with the gauges were intended to provide general data comparisons of density measurements by the various gauges. Two mixes were tested – a 12.5mm dense-graded mix and a 37.5mm coarse-graded mix. Both mixes contained a combination of limestone and sandstone aggregates, but the limestone materials associate with each mix were from different quarries. Both mixes contained PG 70-22 binders. For the locations tested in this experiment, each nuclear gauge result was based on a single gauge measurement, and each non-nuclear result represented the average of 5 readings performed at the center and at four points around the test location in an overlapping cloverleaf pattern, as shown in Figure 25.

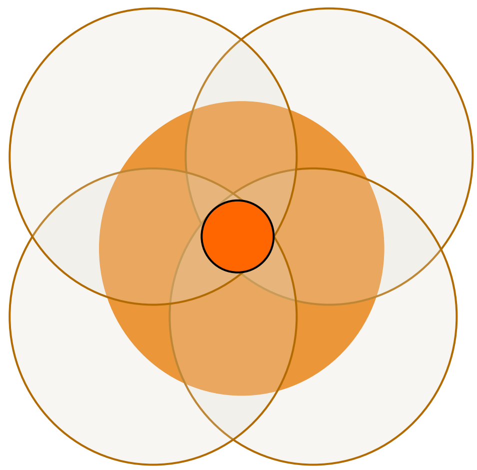

Figure 25. Non-Nuclear Testing Pattern Around a Marked Testing Point

For each location, thirty testing locations were marked and densities were tested using the nuclear gauge, PQI, and PaveTracker. No offsets or calibration factors were used, and consistent testing procedures were followed such that no sand or water was present on the surface, and gauge orientation was parallel to the direction of paving. A comparison of raw data from nuclear and non-nuclear tests for the 12.5mm and 37.5mm are shown in Figures 26 and 27, respectively.

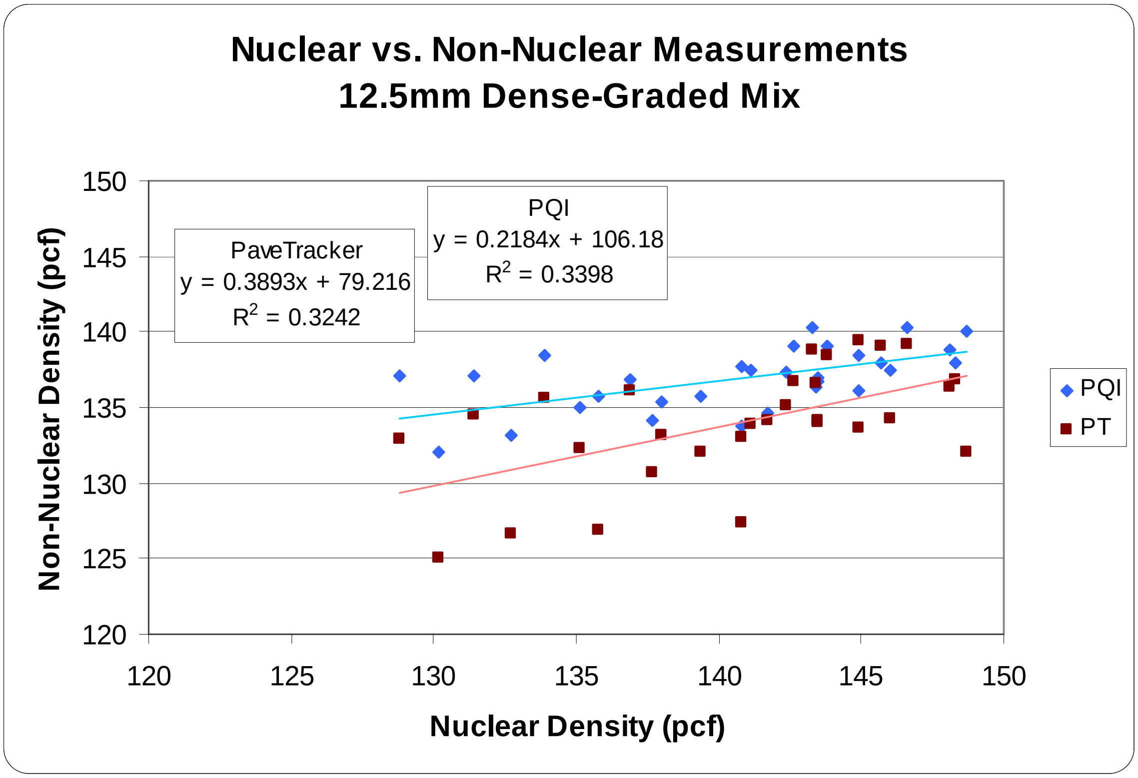

Figure 26. Comparison of Nuclear and Non-Nuclear Measurements – 12.5mm Mix

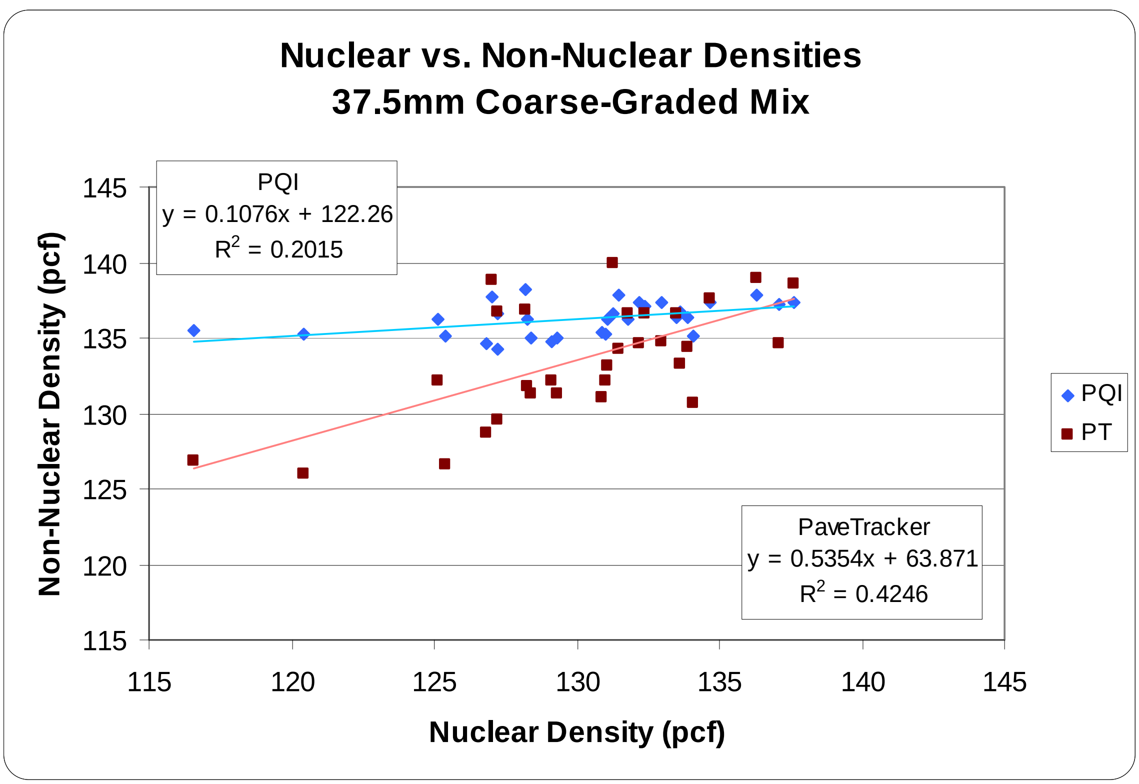

Figure 27. Comparison of Nuclear and Non-Nuclear Measurements – 37.5mm Mix

For the12.5mm mix, there was not a strong correlation between nuclear and non-nuclear density results, as indicated by the low R^2 values (0.34 and 0.32). The slopes of the relationships were quite flat, meaning that the nuclear gauge was more sensitive to changes in density than either the PQI or the PaveTracker. The PaveTracker was slightly more sensitive to density changes than the PQI, but the PQI was slightly more consistent than the PaveTracker.

For the 37.5mm mix, neither non-nuclear gauge exhibited a strong relationship to the nuclear gauge, however the PaveTracker appeared to be significantly more sensitive to density changes than the PQI. This is indicated by the difference in slope constants – 0.1076 for the PQI as compared to 0.5354 for the PaveTracker.

In order to more thoroughly investigate variability, additional testing was performed for the 37.5mm mix. Fifty testing point locations were identified and marked, and each non-nuclear gauge was used to obtain 3 replicate density measurements at each point. The testing sequence was such that all 50 points were measured by each gauge, and then subsequent replicates of the experiment were performed. A summary of results, including the mean, standard deviation, and coefficient of variation (COV), is presented in Table 6.

	PQI			PaveTracker		
Location	Mean (pcf)	Std. Dev.	COV(%)	Mean (pcf)	Std. Dev.	COV(%)
1	139.6	0.800	0.573	145.6	6.555	4.503
2	136.6	0.902	0.660	133.3	1.739	1.305
3	137.1	1.301	0.949	136.1	5.716	4.200
4	135.5	1.493	1.102	135.0	2.639	1.954
5	135.3	0.404	0.299	132.4	1.872	1.413
6	135.8	0.058	0.043	124.6	7.481	6.006
7	137.5	0.709	0.516	137.0	3.066	2.239
8	134.1	1.422	1.060	125.2	4.004	3.198
9	137.3	0.058	0.042	137.1	3.239	2.362
10	133.7	2.931	2.192	128.8	1.646	1.278
11	138.3	0.551	0.398	137.2	6.580	4.796
12	136.3	1.222	0.897	136.2	4.706	3.454
13	138.2	0.436	0.315	137.2	4.155	3.029
14	133.4	0.624	0.468	127.1	3.232	2.543
15	137.4	1.266	0.921	137.6	1.136	0.825
16	138.8	0.700	0.504	137.2	7.481	5.454
17	137.6	0.635	0.461	138.4	5.647	4.080
18	134.4	1.002	0.745	132.4	3.955	2.987
19	138.1	0.723	0.524	138.8	2.234	1.609
20	135.5	0.265	0.195	132.6	5.358	4.039
21	135.1	0.551	0.408	123.2	1.044	0.847
22	137.5	1.041	0.757	136.5	0.208	0.152
23	135.9	0.503	0.370	133.2	5.488	4.122
24	133.5	0.252	0.188	128.2	1.179	0.920
25	137.4	1.127	0.820	137.6	5.121	3.721
26	135.6	0.473	0.349	124.9	4.115	3.294
27	135.3	0.666	0.492	130.8	5.066	3.874
28	135.1	0.400	0.296	131.4	5.484	4.173
29	139.1	0.961	0.691	139.5	1.572	1.127
30	136.5	2.597	1.902	133.2	4.073	3.058
31	136.0	1.153	0.848	126.7	3.066	2.421
32	137.5	1.274	0.927	136.1	3.635	2.671
33	135.8	0.700	0.515	134.0	7.655	5.711
34	136.6	0.379	0.277	134.0	0.866	0.646
35	137.5	0.551	0.400	143.3	2.173	1.517
36	132.8	0.208	0.157	119.2	2.196	1.843
37	134.7	1.850	1.373	135.1	4.500	3.330
38	136.2	0.700	0.514	130.5	2.157	1.653
39	136.2	0.416	0.306	135.1	1.350	1.000
40	135.6	1.026	0.757	133.2	5.631	4.228
41	138.2	0.153	0.111	140.1	1.168	0.833
42	135.2	0.346	0.256	131.9	6.907	5.237
43	135.7	0.586	0.432	129.1	2.403	1.861
44	136.0	0.306	0.225	135.0	1.270	0.941
45	137.4	0.173	0.126	137.1	1.858	1.356
46	133.6	0.520	0.389	126.6	4.895	3.866
47	138.2	0.702	0.508	143.7	4.551	3.167
48	135.2	0.265	0.196	132.1	2.193	1.660
49	138.9	0.404	0.291	140.7	2.223	1.581
50	134.6	0.850	0.632	126.2	3.182	2.521
AVERAGE	**136.3**	**0.773**	**0.57**	**133.6**	**3.593**	**2.69**

Table 6. Variability Summary Data for PQI and PaveTracker – 37.5mm Mix

Based on measurements by the PQI, the range of densities detected was 132.8 to 139.6 pcf, with an average value of 136.3 pcf. The average standard deviation was 0.773 and the COV was 0.57 percent. A COV of less than 1 percent indicates that the PQI provides very consistent measurements.

From the PaveTracker measurements, the range of densities was 119.2 to 145.6 pcf, with an average of 133.6 pcf. The average standard deviation was 3.593 and the COV was approximately 2.7 percent. Although the PaveTracker appeared to be more variable than the PQI, but the relatively low COV suggests good repeatability for the PaveTracker. Also, the PaveTracker detected a much larger range of densities for the marked testing points than the PQI. Thus, it is likely that the PQI's true variability may be masked by its insensitivity.

Although the nuclear gauge has more of an established history, a comparison measure of variability based on the same mix was desirable for providing a fair comparison of the variability of the gauge methods. While some measures of variability have been reported in the literature for the nuclear gauge, this data is often based on a large number of tests performed on an entire project, or section of a project. Such a measure of variability is a measure of both the variability of the nuclear gauge *and* the variability of the HMA mat. For this experiment, the variability is based on replicate measures of density for an exact location, which includes no mat variability. Thus, the measures of variability can be attributed solely to the gauge. A limited amount of data was collected for this purpose, including triplicate measures of density at 10 locations. This data is given in Table 7.

	Nuclear Gauge		
Location	Mean	Std. Dev.	COV(%)
1	133.9	2.899	2.165
2	131.7	0.557	0.423
3	129.7	3.422	2.638
4	129.5	1.345	1.039
5	135.3	2.108	1.558
6	120.8	4.414	3.654
7	132.5	1.305	0.985
8	129.0	2.066	1.602
9	130.5	5.059	3.876
10	128.8	4.709	3.656
Average	**130.2**	**2.788**	**2.16**

Table 7. Variability Summary Data for Nuclear Gauge – 37.5mm Mix

The average standard deviation for the nuclear gauge was 2.788, and the average COV was 2.16 percent. This data indicated a higher level of variability for the nuclear device than the non-nuclear devices. However, it was previously shown that the nuclear gauge appeared to be more sensitive to actual changes in density, and a greater level of sensitivity typically exposes more of the true variability.

Next, three projects were chosen for the purpose of relating nuclear and non-nuclear gauge measurements to core densities. All mixes tested were 12.5mm dense-graded surface mixes containing PG 70-22 binder. Aggregate composition varied. For each project, 20 testing points were selected; in-place density measurements were performed using the PQI, PaveTracker, nuclear gauge, and core methods. In an attempt to generate a wide range of true density values, some testing points were located near longitudinal joints. At each testing point, a single reading was used to generate results by the nuclear and non-nuclear methods. In this way, the effects of mat variability were reduced. The resulting density readings by the gauges were compared to core densities, and the entire dataset is shown in Figure 28.

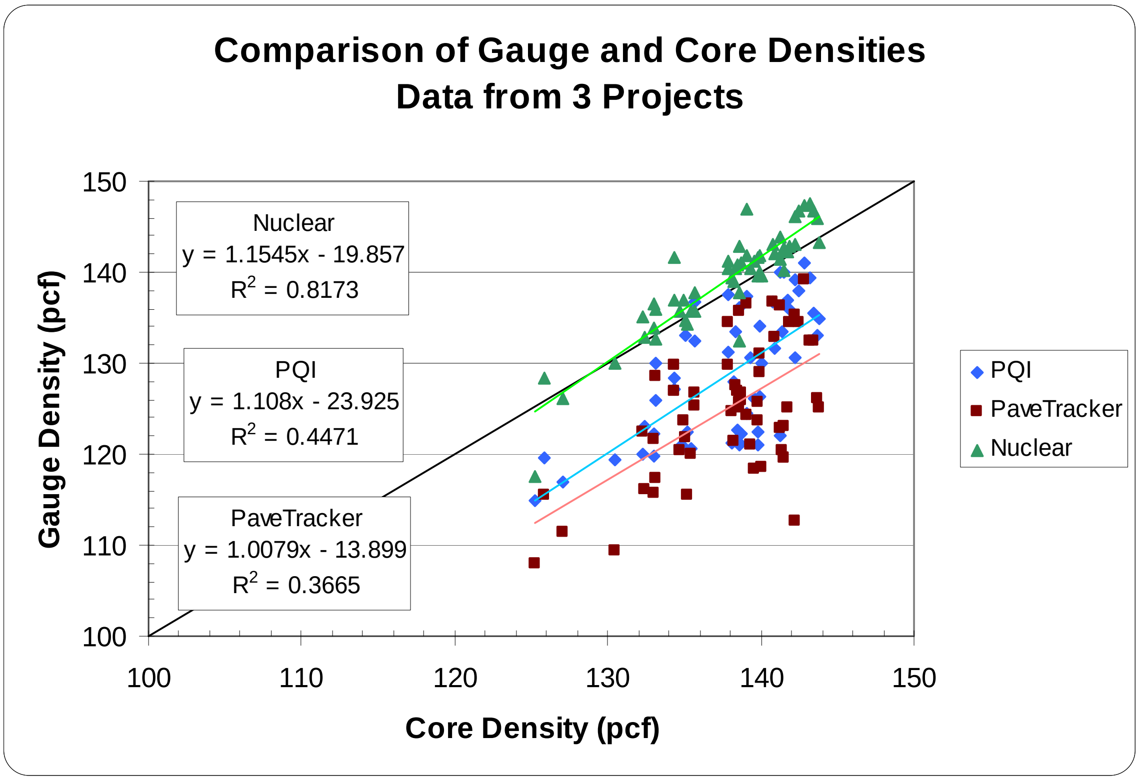

Figure 28. Comparison of Nuclear, Non-Nuclear, and Core Densities for 3 Projects

Overall, the nuclear gauge provided the best relationship, having an R^2 value of 0.82. The PQI and PaveTracker values were more variable, as indicated by the low R^2 values, and tended to underestimate core density. The trendlines for the three gauges were similar in slope, and were reasonably parallel to the line of equality. Based on this comparison, it appeared that a simple offset calibration could improve the accuracy of the non-nuclear gauges, but the variability would still be a concern.

Next, the relationships were separated by project to see if the correlations would improve. Several researchers had reported that relationships tend to be mixture specific, so plotting individual project data could prove beneficial. These graphs are given in Figures 29, 30, and 31.

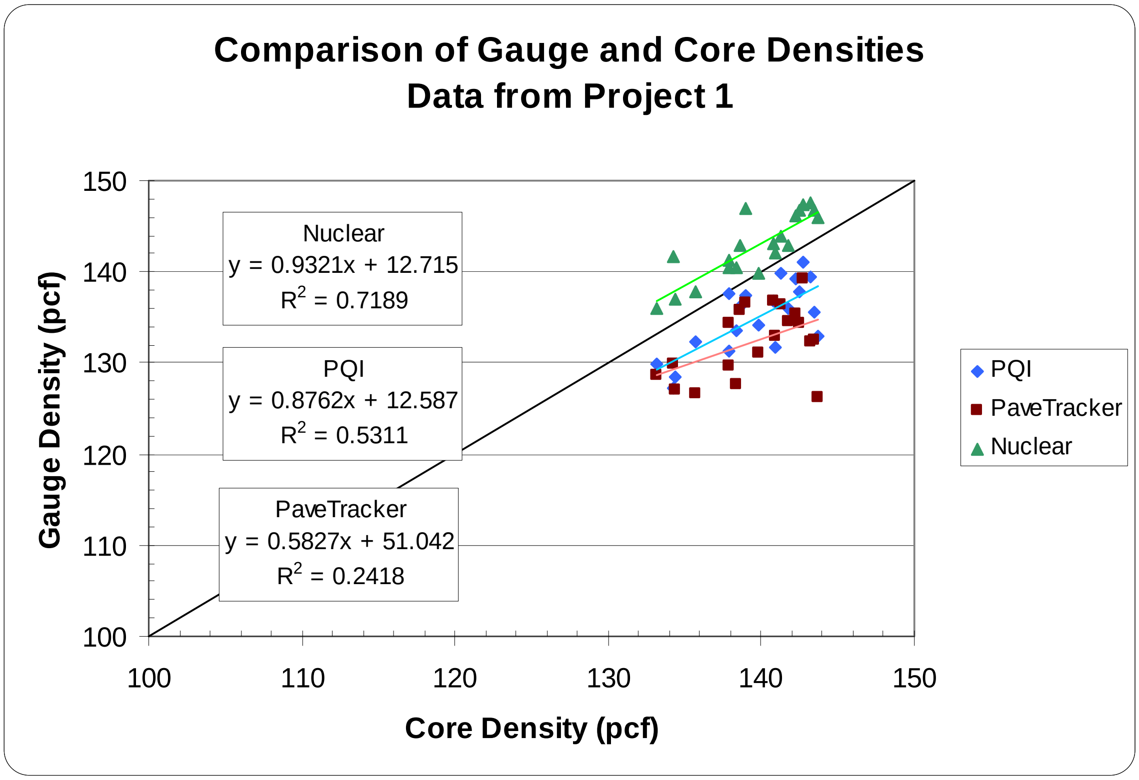

Figure 29. Comparison of Nuclear, Non-Nuclear, and Core Densities for Project 1

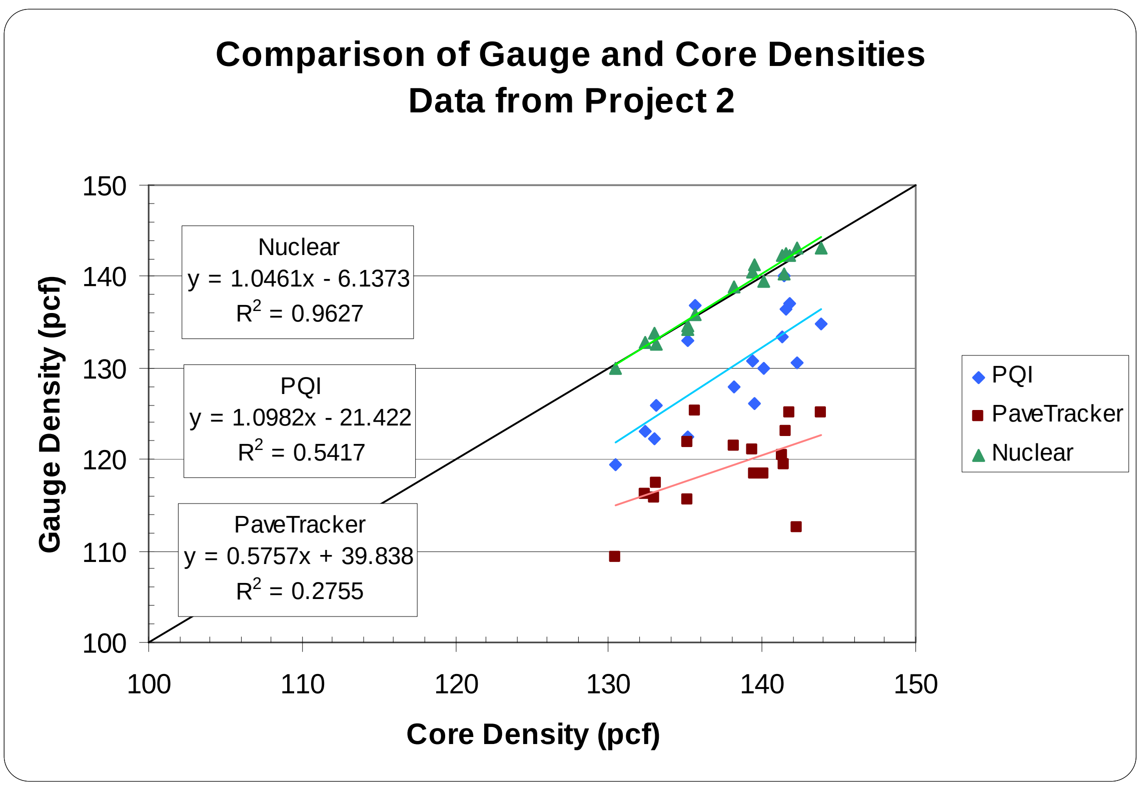

Figure 30. Comparison of Nuclear, Non-Nuclear, and Core Densities for Project 2

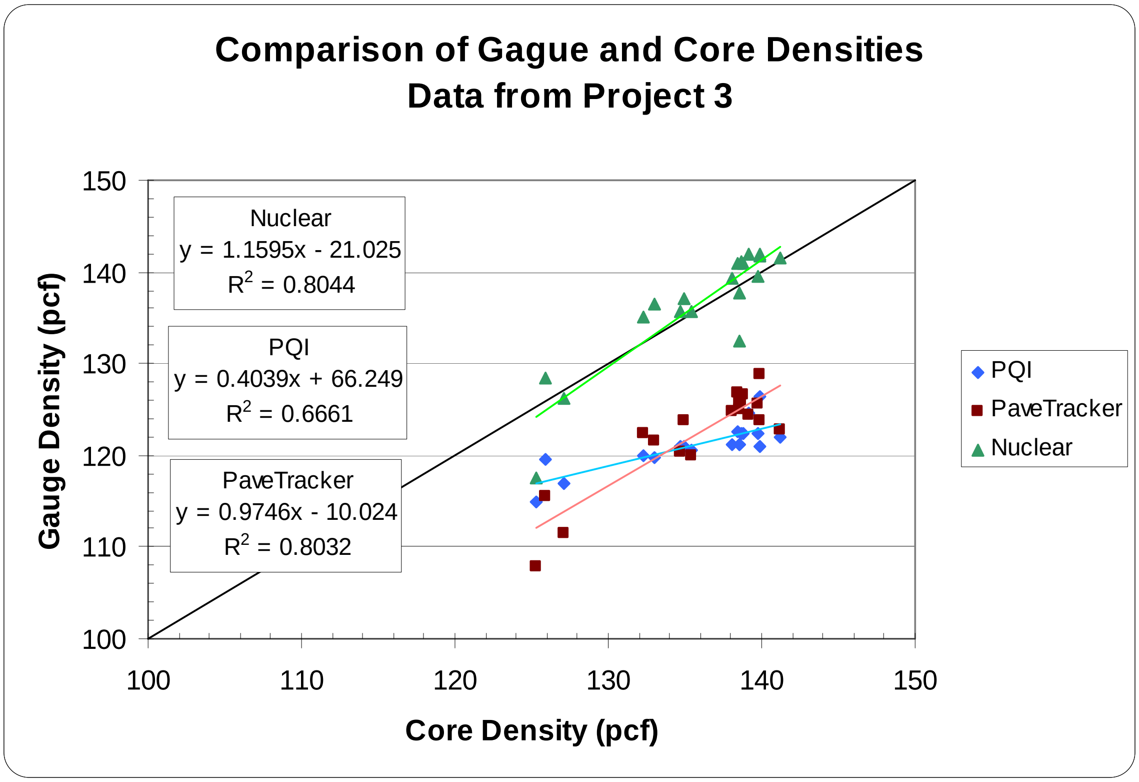

Figure 31. Comparison of Nuclear, Non-Nuclear, and Core Densities for Project 3

For projects 2 and 3, the nuclear gauge displayed excellent correlation with core densities. For project 1, this relationship was similar in slope, but was slightly offset from the line of equality such that core densities were overestimated.

The PQI relationships for projects 1 and 2 demonstrated a consistent bias in that density was underestimated, but exhibited a slope that was somewhat parallel to the line of equality. For project 3, the PQI showed a significant tendency to underestimate density, and the magnitude of the underestimation increased with increasing density. Correlations were fair for all 3 projects.

The PaveTracker results were most consistent for project 3, and the slope was nearly equal to the line of equality. However, this device was generally the worst offender in terms of underestimating density, especially as core density increased. Correlations for the PaveTracker were poor for projects 1 and 2, but good for project 3.

Because significant variability was present, and did appear to be somewhat mixture dependent, a thorough investigation of calibration methods was used in an attempt to account for sources of variability.

Calibration

The focus of this portion of the project was to review and evaluate various methods of calibration, and to determine the most advantageous for routine use. In this evaluation, a Troxler Model 3430nuclear gauge, the PQI 301, and the PaveTracker Plus 2701-B were used on three HMA pavements of similar aggregate composition having NMAS of 12.5mm, 25.0mm, and 37.5mm.

For each of the 3 pavements, non-nuclear gauge and nuclear gauge densities were measured during the compaction process. Densities were measured immediately behind the screed (i.e., before rolling) and after each roller pass. In order to complete the testing scheme in a timely manner between roller passes without interrupting the routine compaction process, a 15-second count was used for the nuclear gauge. Densities were also measured after the completion of finish rolling and after the mat had cooled considerably. This process was completed for each mix in a number of locations. The following day, a number of separate locations were identified for further testing with the nuclear and non-nuclear devices, and cores were cut from each of the locations.

Evaluation of Methods

Four calibration methods were used to derive calibration constants, and these constants were then applied to density results for additional testing locations. Next, cores were cut from each additional testing location in order to judge the accuracy of gauge measurements.

The first, or 'Screed Method', involved the determination of a calibration offset based on density readings immediately behind the screed, and the assumption that the density at this location was approximately 82 percent of the maximum theoretical density (MTD). *(10)* The average difference in the estimated and measured density behind the screed was based on multiple locations, and a calibration offset was determined for each impedance gauge as well as the nuclear gauge for each of the three mixes.

The 'Core Method' involved a similar offset calculation, but was based on the actual measured density of several cores. The average difference in the core densities and gauge densities at each location was determined to be the calibration offset for each mix. Again, offsets were determined for each of the three gauges.

The 'Two-Point Method', as described by TransTech, was based on estimates of density prior to compaction (behind the screed) and after the mat had been peaked. Screed density was taken to be 82 percent of MTD, and the peak density was taken to be 95 percent of MTD. Linear regression procedures were used to determine the slope and intercept of the relationship between estimated and measured densities at each location. The average slopes and intercepts for each of the three gauges were used as the calibration constants for each mix.

The final method, termed the 'Data Pair' method, was performed as described by Troxler, assuming the nuclear gauge to be the true measurement. Because the core density is typically considered to be the best available "true" density, this method would have been best performed by comparing gauge readings to core densities after each roller pass. However, this is not practically feasible since cores cannot usually be cut between roller passes. Also, cores cut from relatively uncompacted material would probably not be suitable for laboratory testing. Thus, the nuclear gauge was taken as the truest measure of density. At each location, a test point was marked, and corresponding density measurements were taken with each of the three gauges after each roller pass. Linear regression was used to develop slope and intercept values for the relationships of each impedance gauge to the nuclear gauge. Average slopes and intercepts were used as the calibration constants for each mix.

Results and Discussion

In order to assess accuracy, each of the four calibration methods were used to generate calibration constants, and these constants were then applied to subsequent density measurements in order to assess the relative ability of each to provide correct results.

Screed Method

For each mix, the density at several locations was tested immediately behind the screed using the nuclear gauge (NG), the PQI, and the PaveTracker (PT). Based on an estimated 82 percent of MTD, an offset was determined for each gauge and each mix. The resulting calibration constants are given in Table 8.

Mix Type	Number of Locations	Gauge Type	Average Density Offset (pcf)
37.5 mm	5	NG	5.18
		PQI	10.90
		PT	14.96
25.0 mm	6	NG	5.85
		PQI	7.87
		PT	3.99
12.5 mm	6	NG	11.09
		PQI	7.67
		PT	10.79

Table 8. Summary of Calibration Constants for Screed Method

Next, these offsets were applied to density readings for each gauge at separate locations for a range of densities. The results of the impedance gauges were plotted against those of the nuclear gauge in order to assess how closely the results of the three gauges agreed. If the impedance and nuclear gauges provided similar density measurements, the points plotted on the graph lie along the line of equality. The results for the 12.5mm, 25.0mm, and 37.5mm mixes are shown in Figures 32, 33, and 34, respectively.

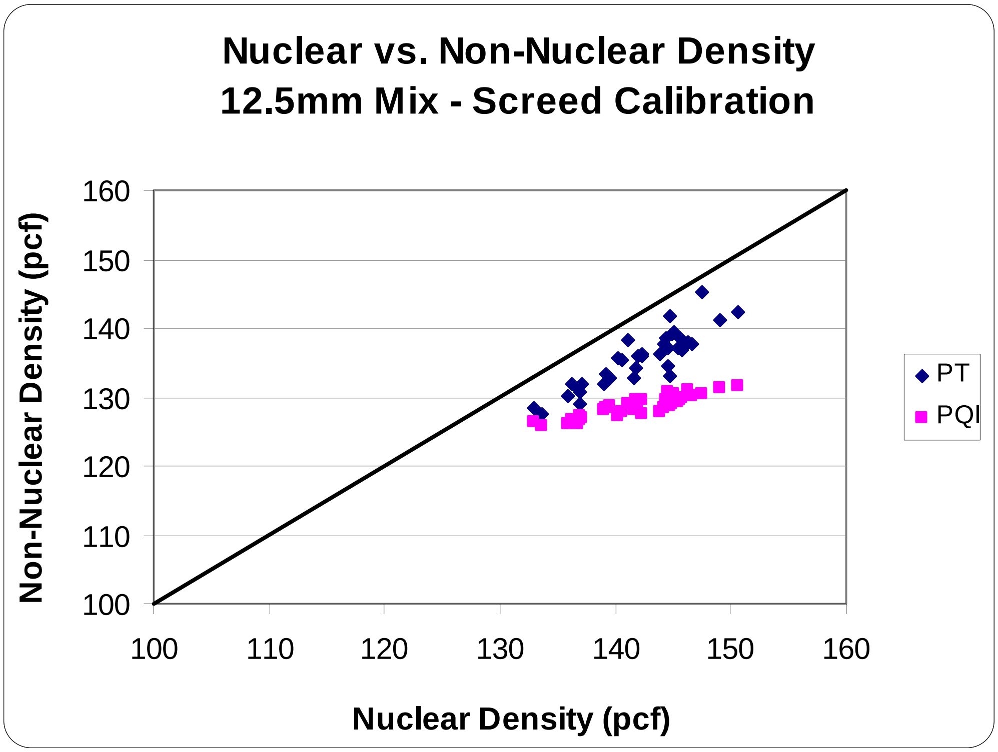

Figure 32. Gauge Comparison for Screed Method of Calibration – 12.5mm Mix

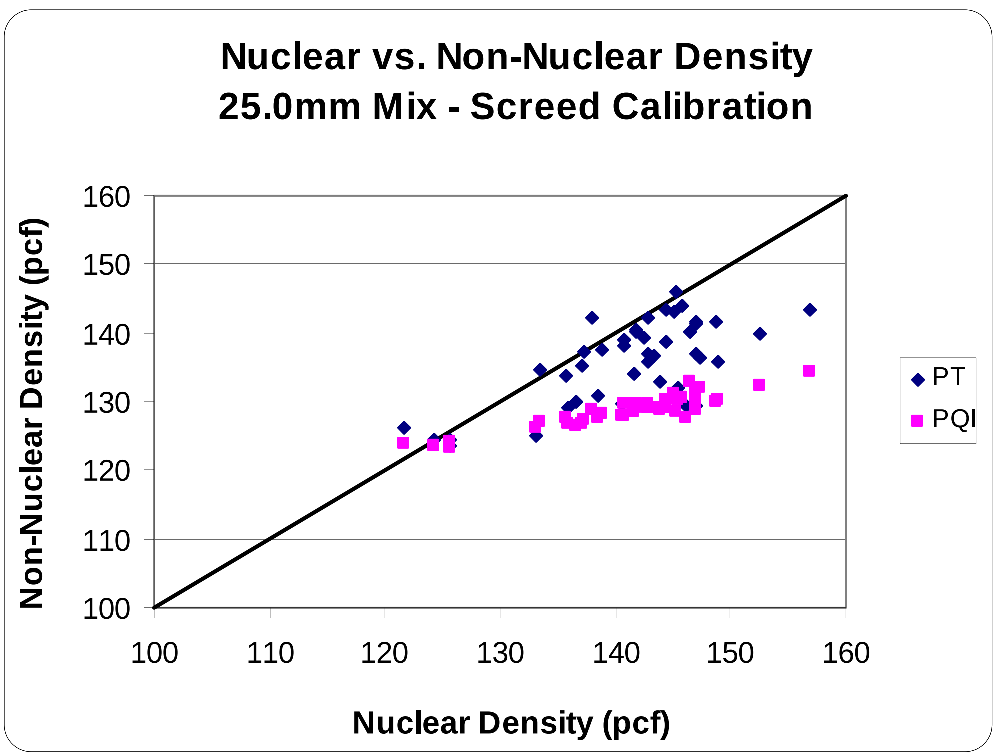

Figure 33. Gauge Comparison for Screed Method of Calibration – 25.0mm Mix

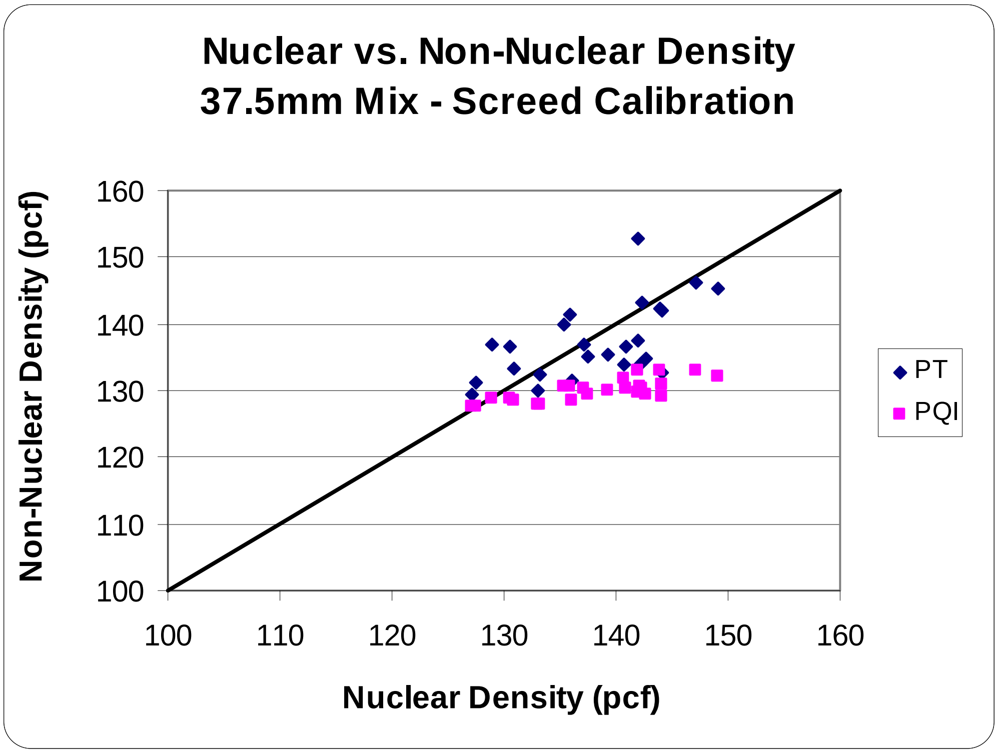

Figure 34. Gauge Comparison for Screed Method of Calibration – 37.5mm Mix

In general, results for the three methods were similar at low densities, but began to diverge as the density increased. This was not unreasonable because the calibration procedure was based on the density of the mat prior to compaction, which was very low. As the density increased, the impedance gauges were prone to underestimate the density as measured by the nuclear gauge. This trend was more pronounced for the PQI than the PaveTracker. Overall, it appeared that the nuclear gauge was most sensitive to changes in density, while the PQI was least sensitive.

Next, the calibration constants were applied to finished mat densities at several additional locations and compared to core densities. These results are given in Figure 35. The 37.5mm, 25.0mm, and 12.5mm mixes were tested in six, five, and four additional locations, respectively.

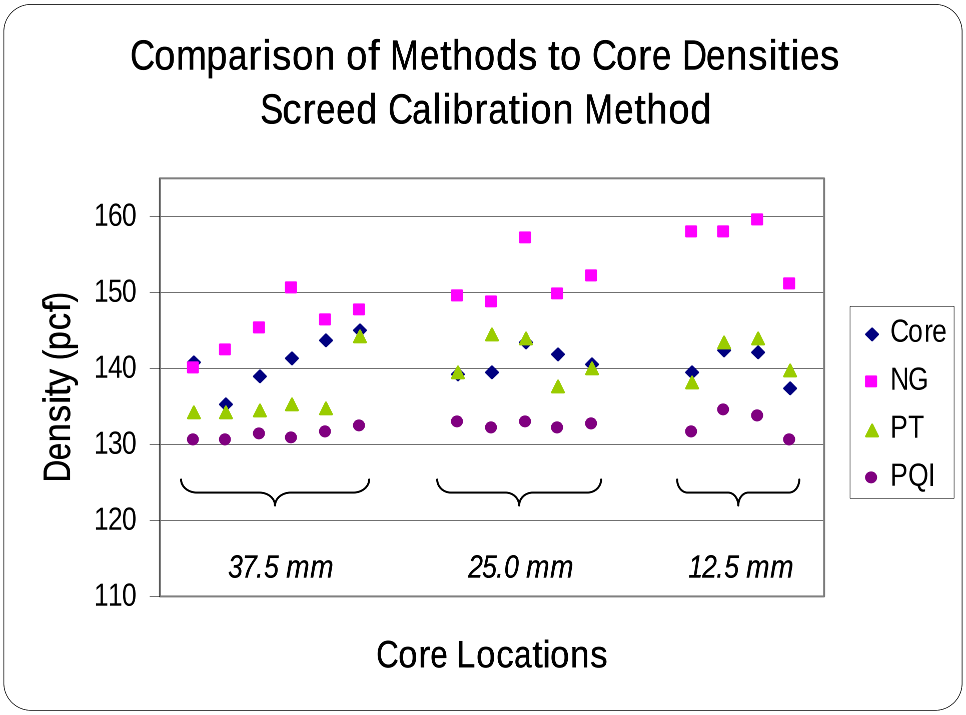

Figure 35. Comparison of Methods Using Screed Calibration Method

Based on the data presented in Figure 35, the following observations are made:

- In general, nuclear gauge densities were greater than core densities, especially for the 12.5mm mix. These differences were almost 20 pcf in some cases.
- In all cases, the PQI densities were less than core densities.
- There was less fluctuation among PQI densities than for the other methods.
- Densities measured by the PaveTracker were generally most similar to core densities.
- On average, the nuclear gauge provided densities 10.4 pcf greater than core densities, the PQI provided densities 8.6 pcf less than core densities, and the PaveTracker generated densities 1.2 pcf less than core densities.

Overall, this method is not believed to accurate enough for calibration in situations where impedance gauge data is to be used for quality control and/or quality assurance (QC/QA). Because the calibration constants were developed based on densities much lower than those expected to exist in the finished pavement, serious errors could result when using this method of calibration.

Core Method

Core densities were tested for each mix at a number of locations. Prior to cutting the cores, a series of corresponding density measurements were taken using the nuclear gauge, PQI, and PaveTracker. Based on the densities of the cores, an average offset was determined for each gauge. The resulting calibration constants are given in Table 9.

Mix Type	Number of Locations	Gauge Type	Average Density Offset (pcf)
37.5 mm	6	NG	0.53
		PQI	20.40
		PT	19.88
25.0 mm	5	NG	-4.46
		PQI	16.61
		PT	4.88
12.5 mm	4	NG	-3.78
		PQI	15.15
		PT	11.06

Table 9. Summary of Calibration Constants for Core Method

Next these offsets were applied to density readings for each gauge at a range of densities. The results of the impedance gauges were again plotted against those of the nuclear gauge in order to demonstrate the agreement of the three gauges. The results for the 12.5mm, 25.0mm, and 37.5mm mixes are presented in Figures 36, 37, and 38.

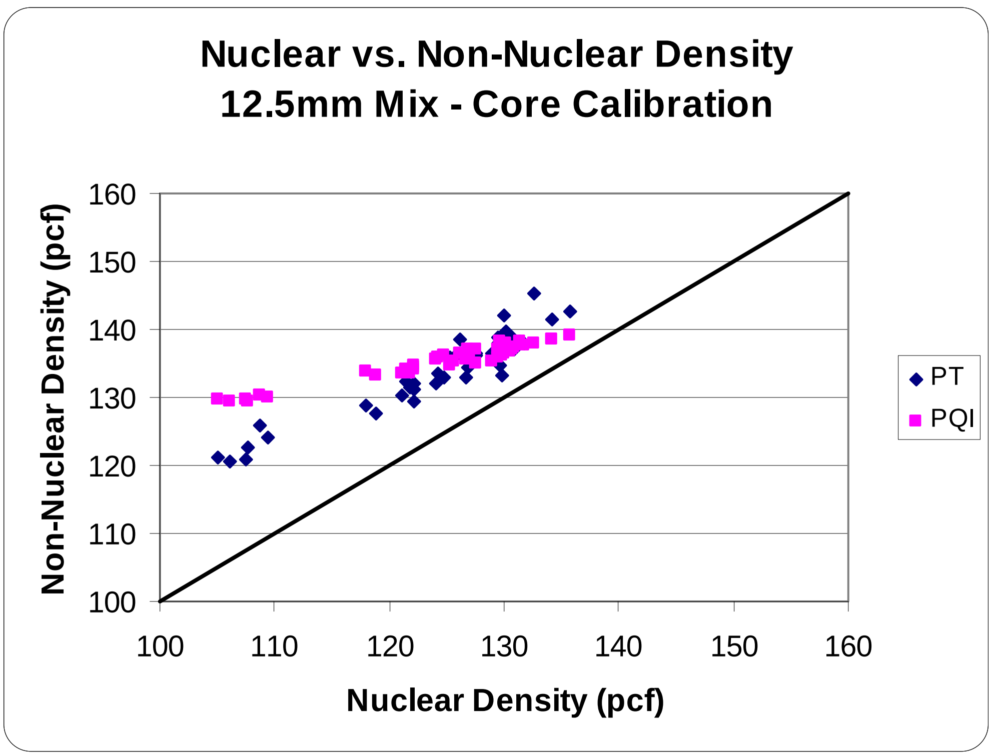

Figure 36. Gauge Comparison for Core Method of Calibration – 12.5mm Mix

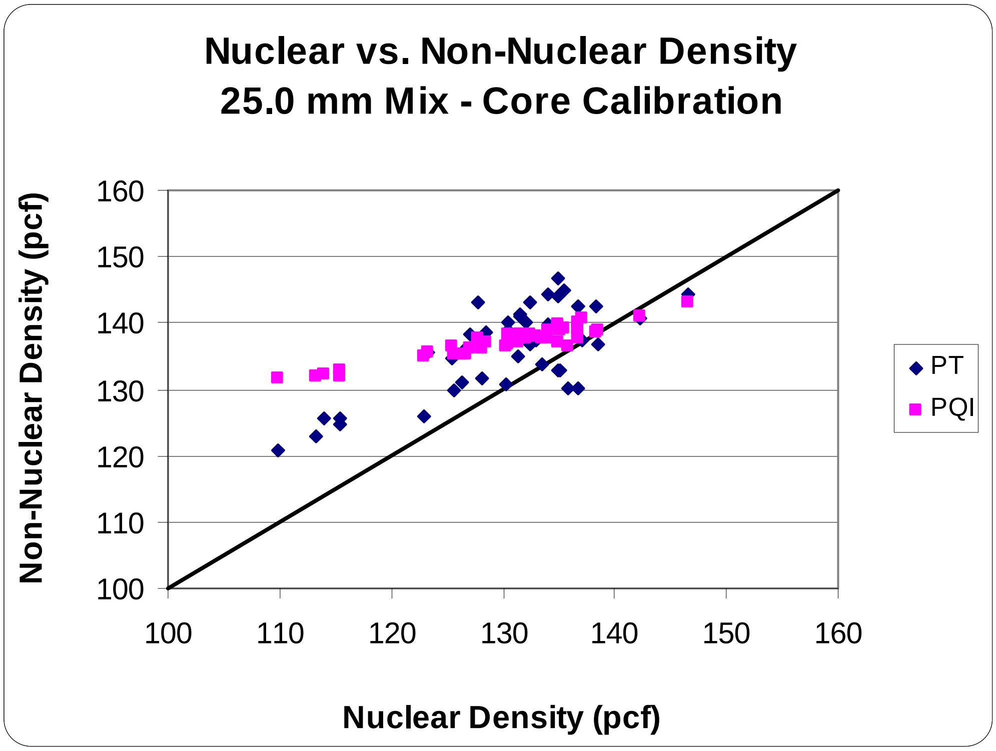

Figure 37. Gauge Comparison for Core Method of Calibration – 25.0mm Mix

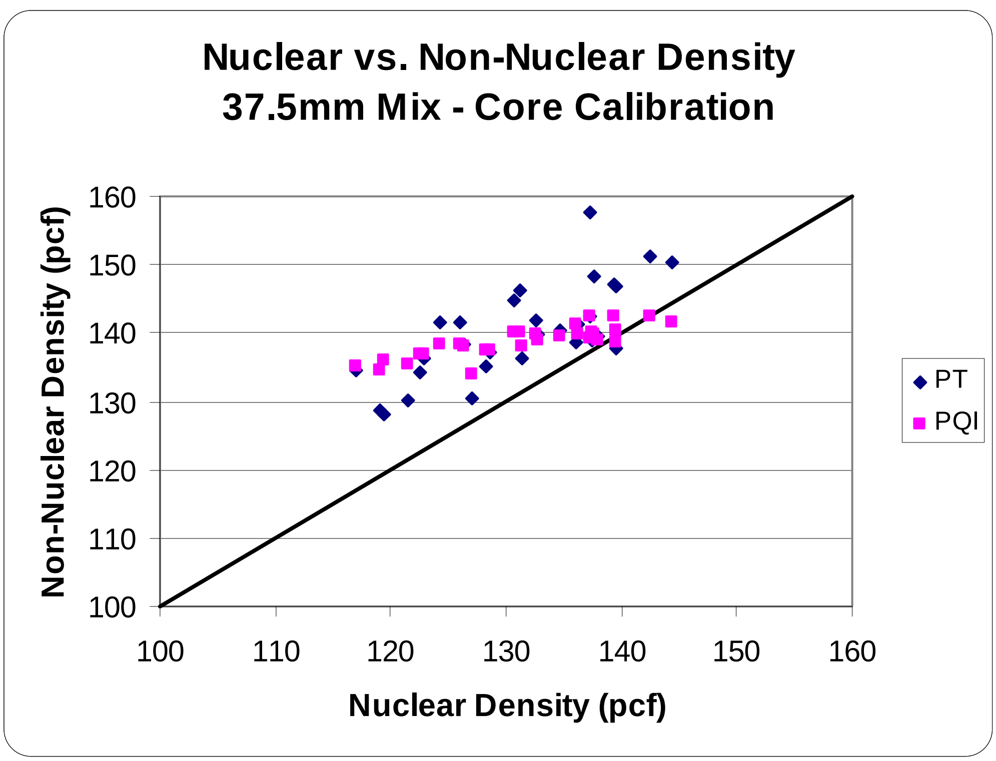

Figure 38. Gauge Comparison for Core Method of Calibration – 37.5mm Mix

Overall, the three methods correlated fairly well at higher densities, but not as well at lower densities. This was not unexpected because the correlations were developed at higher densities rather than lower densities. For this calibration method, the impedance gauges tended to overestimate density for lower levels of compaction. This trend was more clearly evident for the PQI than the PaveTracker. As seen with the screed calibration method, the impedance gauges did not appear to be as sensitive as the nuclear gauge to changes in density, and the PQI appeared to be least sensitive to such changes.

Next, the respective calibration constants obtained from the core method were applied to a number of testing locations for each mix. These results are given in Figure 39.

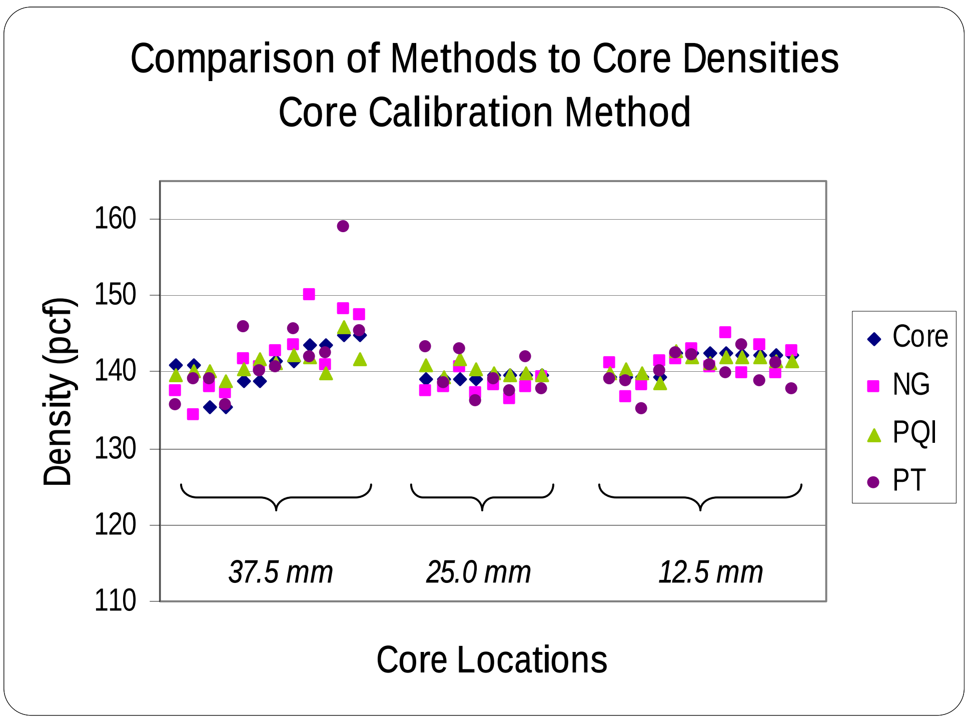

Figure 39. Comparison of Methods Using Core Calibration Method

Overall, reasonable agreement was achieved between the methods for the 25.0mm and 12.5mm mixes, while more 'scatter' of the data was displayed for the 37.5mm mix. On average, the nuclear gauge generated densities that were 0.04 pcf greater than core densities, the PQI generated densities 0.24 pcf greater than core densities, and the PaveTracker provided densities 0.22 pcf greater than core densities. In general, the PQI appeared to provide the closest agreement to the core densities, while the PaveTracker showed the greatest amount of fluctuation with respect to core density.

In general, the core method appeared to be more accurate than the screed method. This was most likely due to the fact that the calibration procedure was completed in a manner that is most similar to the material conditions and densities that were experienced during typical QC/QA activities. However, the accuracy of the gauges could have been significantly and adversely affected if a pavement having a wide range of densities were encountered. For example, suppose that QC efforts are based on the PQI calibrated by the core method, and QA tests are based on field core densities. If an area of the pavement had a very low density, the PQI might not be sensitive to this significant decrease, and may falsely indicate an acceptable level of density. If a core were cut for QA purposes from this area, a failing test result and subsequent pay reduction would likely result.

Two Point Method

In this method, the density behind the screed was estimated based on the assumption that the pavement density was approximately 82 percent of MTD. In addition, the 'peaked' density of the mat was estimated to be 95 percent of MTD. Corresponding density measurements were taken with each gauge, and this sequence was replicated in a number of locations for each mix. Based on the resulting data, regression analysis was used to generate slope and intercept values for each location. Then, final calibration constants were calculated as the average slope and average intercept for each mix. The results for the two point calibration method are presented in Table 10.

Mix Type	Number of Locations	Gauge Type	Average Slope	Average Intercept
37.5 mm	5	NG	1.83	-98.74
		PQI	4.45	-403.04
		PT	1.98	-92.82
25.0 mm	6	NG	0.88	19.53
		PQI	2.98	-221.58
		PT	1.32	-33.21
12.5 mm	6	NG	0.87	25.17
		PQI	2.68	-185.28
		PT	1.32	-24.58

Table 10. Summary of Calibration Constants for Two Point Method

After applying these calibration constants to additional density readings, the relationships of the nuclear and impedance gauges were plotted. These results are given in Figures 40, 41, and 42. Apparent differences were present based on NMAS. Clearly, as the NMAS decreased, the relationships between methods became more substantial. This suggested that the precision of the two point calibration method increased as the NMAS of the mix decreased.

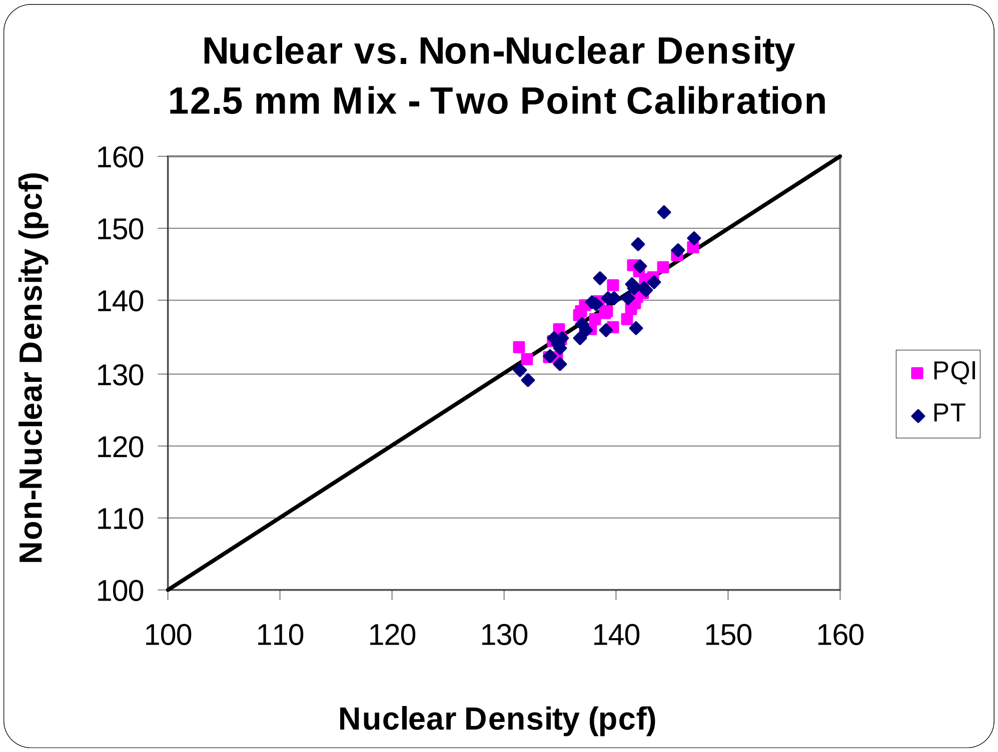

Figure 40. Gauge Comparison for Two Point Method of Calibration – 12.5mm Mix

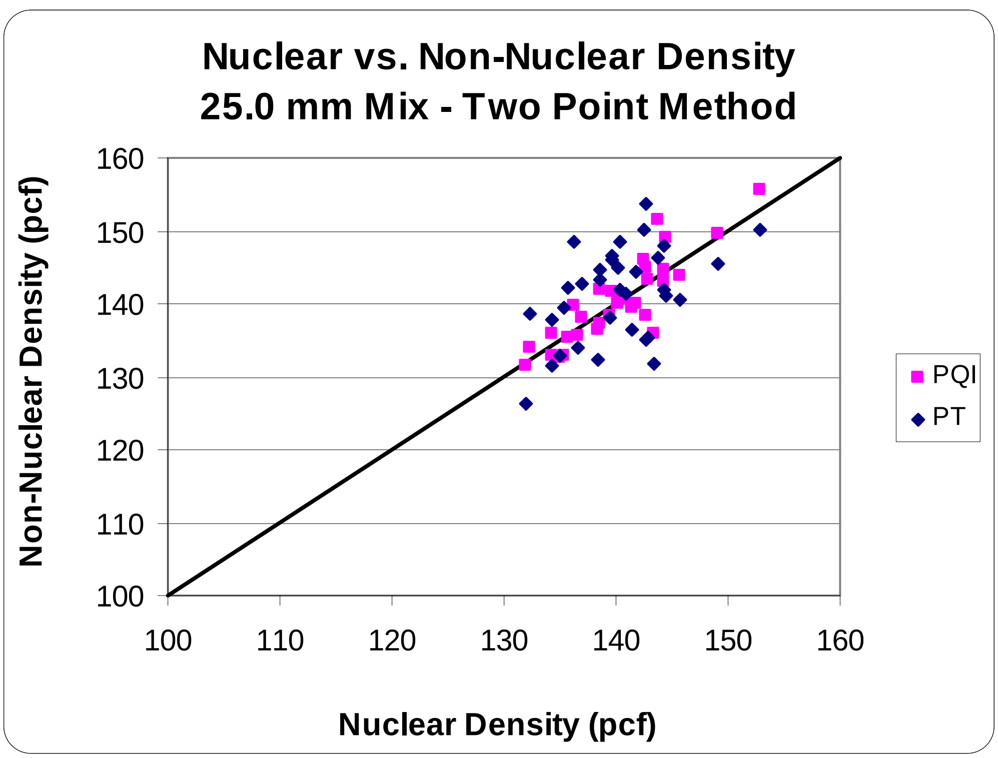

Figure 41. Gauge Comparison for Two Point Method of Calibration – 25.0mm Mix

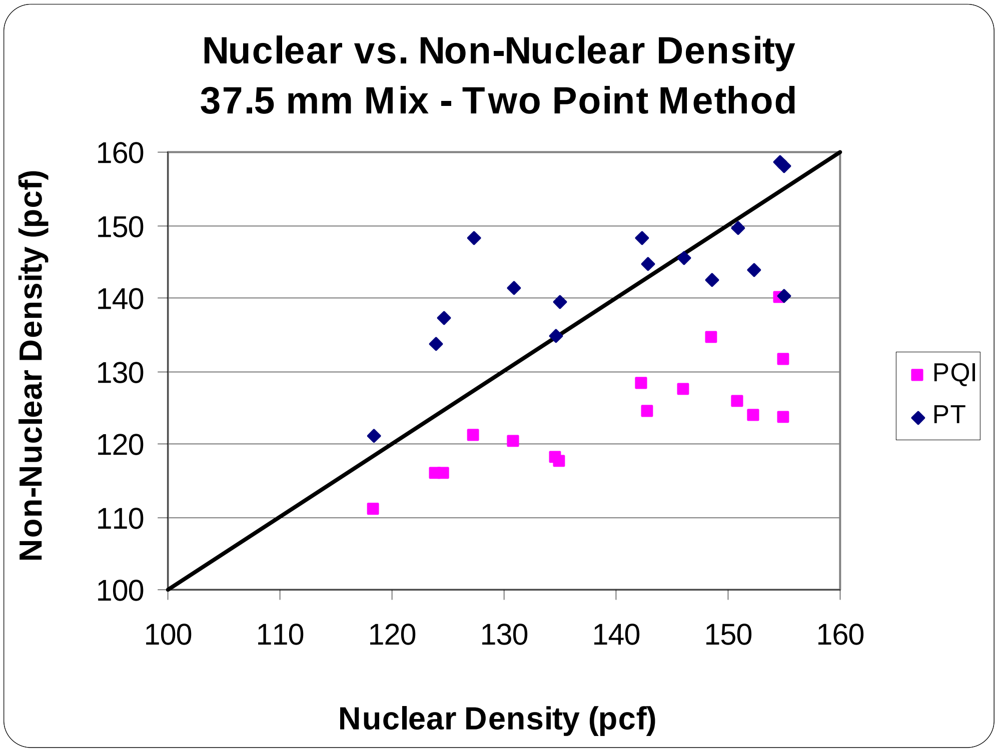

Figure 42. Gauge Comparison for Two Point Method of Calibration – 37.5mm Mix

Relative to the agreement between methods, the relationships appeared to be consistent over the range of densities tested. In other words, the slopes of the lines relating the test methods were relatively parallel to the line of equality. Thus, the slope-intercept calibration constants generated by the two point method should increase the accuracy of results for a broader range of densities. However, the accuracy was directly dependent upon the accuracy of the density estimates used during the calibration procedure.

As with the other methods analyzed, the calibration constants were applied to an additional set of data for each gauge and compared to core densities. These results are provided in Figure 43.

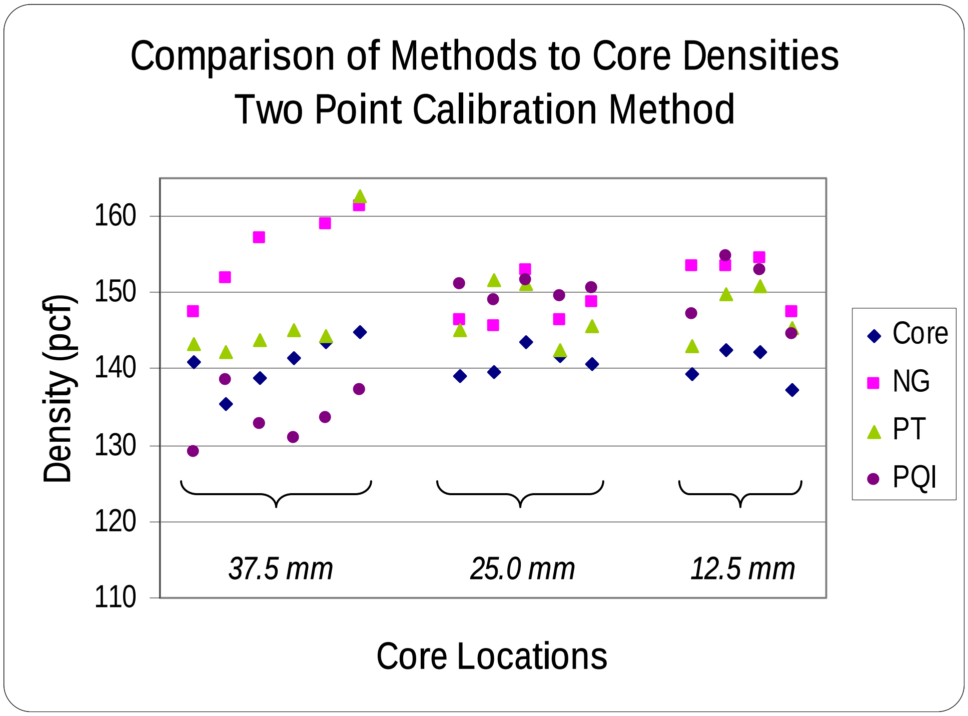

Figure 43. Comparison of Methods Using Two Point Calibration Method

Overall, the gauges tended to overestimate core densities, and this trend was especially true for the nuclear gauge. For the 37.5mm mix, however, the PQI underestimated density. On average, the nuclear gauge densities were 12.5 pcf greater than core densites, the PQI densities were 3.9 pcf greater than core densities, and the PaveTracker densities were 6.7 pcf greater than core densities. In general, the PaveTracker gauge appeared to most closely match the core density.

The greatest advantage of the two point calibration method is that it is able to account for differences in methods for a range of densities. In other words, a numerical adjustment can be applied to force the impedance gauges to be more sensitive to changes in density if necessary. The primary disadvantage is that the densities used to generate the calibration data is based on an estimation involving experience and judgment rather than the measurement of an actual property. For the mixes tested, the 'peaked' density was obviously less than 95 percent. Thus, a more accurate measure of density for the compacted material could increase the accuracy of this method.

Data Pair Method
In this method, regression analysis was employed for determining slope and intercept values over a range of densities. To generate the pairs of data, densities were measured using the PQI, PaveTracker, and nuclear gauge. The nuclear gauge was utilized as the best available "true" measure of density. Density measurements were taken before rolling and after each roller pass in order to generate data encompassing the largest possible range of densities. This process was replicated in a number of locations for each mix.

Based on the resulting data, regression procedures were used to generate slope and intercept values for each location. The final calibration constants were taken as the average slope and average intercept for each mix. The results for the data pair calibration method are presented in Table 11. Because the nuclear gauge data was used to generate the calibration constants, no slope or intercept values were produced for that method.

Mix Type	Number of Locations	Gauge Type	Average Slope	Average Intercept
37.5 mm	5	PQI	2.904	-213.14
		PT	0.956	15.66
25.0 mm	6	PQI	3.41	-276.35
		PT	1.31	-36.84
12.5 mm	6	PQI	3.01	-233.72
		PT	1.39	-42.73

Table 11. Summary of Calibration Constants for Data Pair Method

After applying the calibration constants to the density readings, the relationships of the nuclear and non-nuclear gauges were plotted, and these plots are given in Figures 44, 45, and 46. Although the nuclear gauge data was used to generate the calibration constants, there was still a large amount of scatter in the data. This indicated the fact that a relatively large amount of variability was present in the differences between the nuclear and non-nuclear methods.

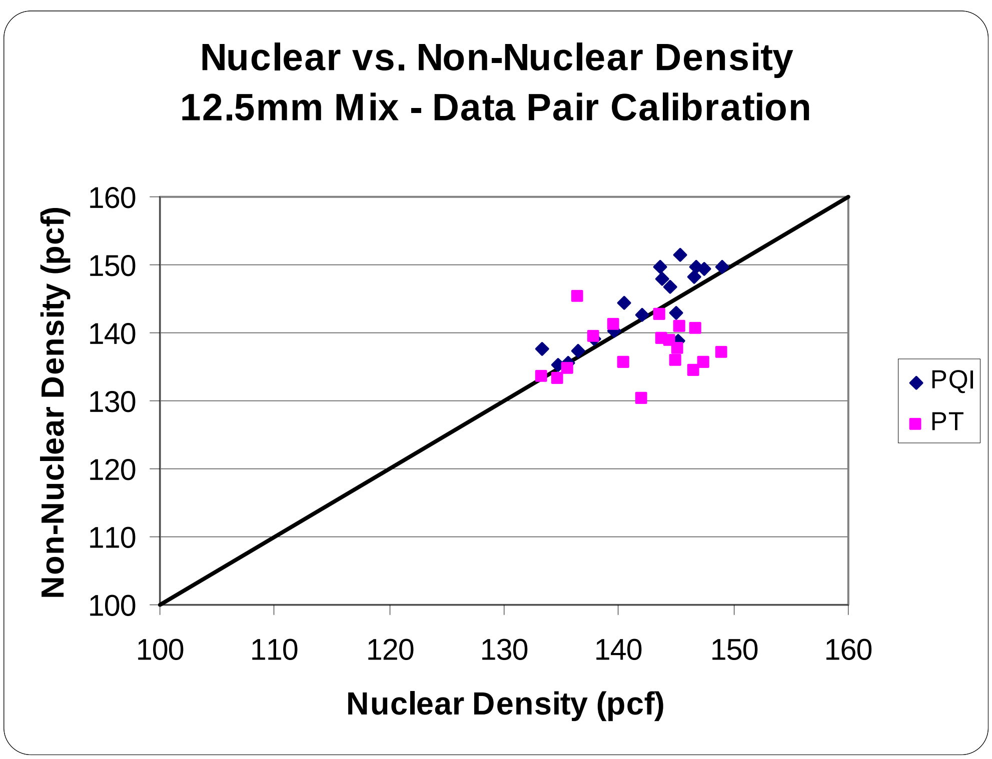

Figure 44. Gauge Comparison for Data Pair Method of Calibration – 12.5mm Mix

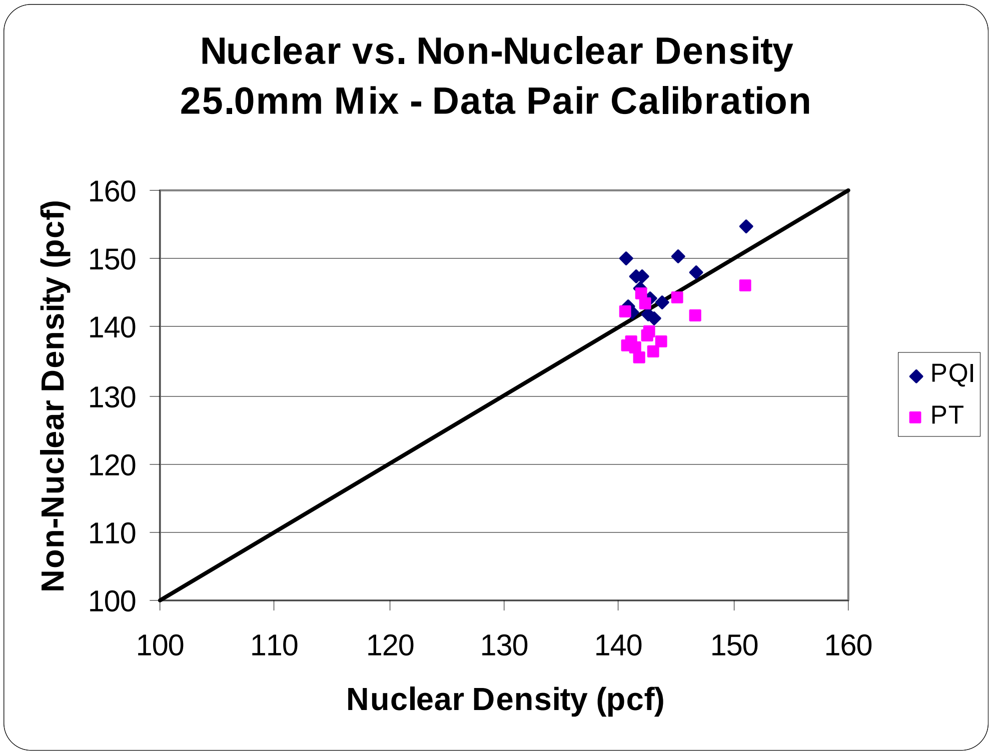

Figure 45. Gauge Comparison for Data Pair Method of Calibration – 25.0mm Mix

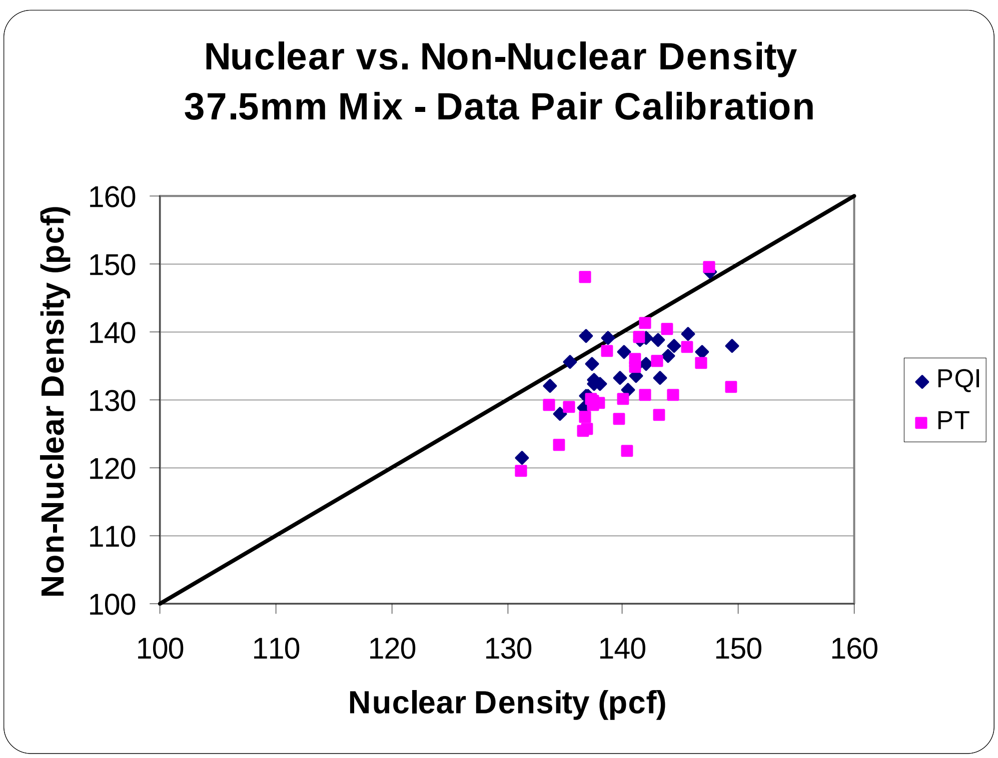

Figure 46. Gauge Comparison for Data Pair Method of Calibration – 25.0mm Mix

A second set of data was taken in order to compare the accuracy of the gauges with respect to actual core densities. This process was completed in several locations for each mix. The results are presented in Figure 47.

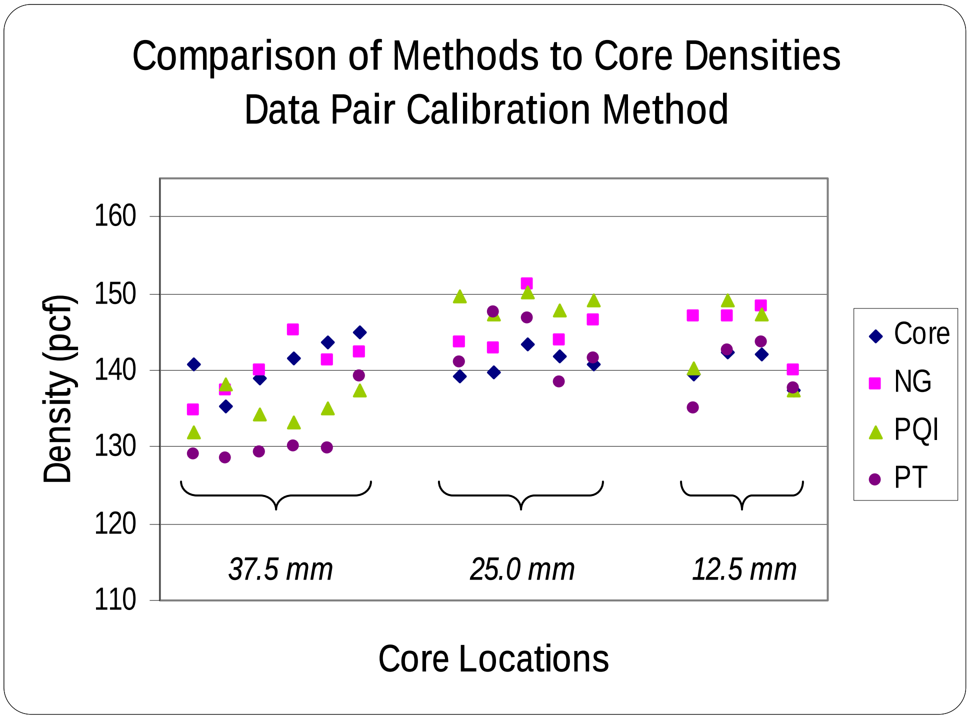

Figure 47. Comparison of Methods Using Data Pair Calibration Method

For the 12.5mm and 25.0mm mixes, the PaveTracker method most closely matched the core densities, while the PQI method provided the nearest approximation of core density for the 37.5mm mix. On average, the nuclear provided densities 2.7 pcf greater than core densities, the PQI provided densities 1.2 pcf greater than core densities, and the PaveTracker generated densities 3.4 pcf less than core densities. It is noted that no calibration factor, offset, or other correction was applied to the nuclear density readings because these measurements were taken as 'truth' for the calibration procedure.

The data pair calibration method has merit, but does not appear to be very precise. The scatter of data for the mixes is likely due to the fact that the nuclear gauge was used to generate the 'true' densities for each mix, which has been repeatedly been reported to correlate poorly with cores. *(3, 4, 5)* Thus, any inaccuracy or variability present in the nuclear gauges test method is projected into the calibration constants, which then affects the quality of all subsequent data generated. As previously mentioned, core densities would have been preferred for this method; and while this may have provided more accurate and/or precise calibration constants, this method is not practical for field implementation.

Variability

For each calibration method and mix, relationships were generated to relate the impedance gauge measurements to nuclear gauge measurements. In addition to relating the methods for a range of densities, the consistency of the relationships were assessed. Table 12 provides the R^2 values for the relationships developed from each calibration method for each mix. A higher R^2 value indicates a more consistent relationship between methods, and can be used as an indicator of precision. In other words, an R^2 value of .70 means that 70 percent of the variability in the data set can be explained by the correlation between methods. As more variability is explained by the correlation, the precision is increased.

Calibration Method	Relationship	37.5 mm Mix	25.0 mm Mix	12.5mm Mix
Screed	PQI vs. NG	0.62	0.85	0.82
	PT vs. NG	0.35	0.49	0.79
Core	PQI vs. NG	0.72	0.90	0.95
	PT vs. NG	0.54	0.55	0.90
Two Point	PQI vs. NG	0.74	0.76	0.83
	PT vs. NG	0.65	0.22	0.80
Data Pair	PQI vs. NG	0.51	0.41	0.72
	PT vs. NG	0.28	0.31	0.01

Table 12. R^2 Values for Nuclear / Non-Nuclear Relationships By Calibration Method

For all calibration methods, the relationships between the PQI and nuclear gauge were more consistent than those for the PaveTracker and nuclear gauge (i.e., possessed a higher R^2 value). This suggests that the PQI was less variable than the PaveTracker. Another notable observation is that the relationships tended to improve as the NMAS decreased. Based on the R^2 values, the best correlations were provided by the core calibration method.

Conclusions

When choosing a method for non-nuclear gauge calibration, it is desirable to select a method that provides accurate and repeatable results in such a way that can be practically implemented in the field. Of the four calibration methods, no single method possessed all of the desired advantages. The screed and core methods provide an offset, which is simple to calculate and easily implemented. However, these methods do not account for variations in sensitivity of the various gauges to actual changes in density. The two point and data pair methods do provide a consideration for the sensitivity of the gauges to changes in density. However, the two point method is strictly dependent upon the ability of the operator to “guess” the relative density of the mat behind the screed and after the mat has been peaked, and the data pair method is dependent upon the accuracy and precision of the nuclear gauge.

Based on the results of this study, the following conclusions were drawn:

- The screed calibration method was not adequate for determining a density offset for impedance gauges when measuring the density of the compacted mat.

- The core calibration method was capable of providing an adequate offset value for a small range of densities. Thus, the calibration applicable to materials having densities very similar to that which will be tested during QC/QA functions.
- The two point method of calibration was advantageous in that it considers the sensitivity of each method to actual changes in density. However, it is based on operator experience and can be detrimentally affected by incorrect estimations of screed and peak densities.
- The data pair method considered the largest number of factors affecting the impedance gauge measurements, but is dependent upon the accuracy of the nuclear gauge. Thus, the calibrations can only be as accurate as the nuclear gauge measurements.
- In terms of accuracy, the core calibration method provided results that most closely matched core densities.
- In terms of variability, the core calibration method provided the greatest consistency in terms of relationships between nuclear and non-nuclear gauge readings, but did not account for differences in sensitivity of the gauges over a range of densities.
- In general, the variability of non-nuclear gauge methods increased as NMAS increased.
- Overall, the nuclear gauge was much more sensitive to actual changes in density than the non-nuclear gauges.
- The PQI more consistently related to the nuclear gauge than did the PaveTracker.
- In general, the PQI appeared to be more precise than the PaveTracker, but the PaveTracker was the more accurate of the impedance-type gauges.

The concept of the data pair method appears to address the largest number of factors affecting the non-nuclear gauge measurements, and should therefore have the most promise. However, there was a large amount of scatter in the data using this data pair calibration method. Also, since the nuclear gauge may not adequately represent core density, any device calibrated to the nuclear gauge would be less likely to represent densities obtained from field cores.

Another consideration is that the intended purpose of the non-nuclear gauge is to provide an alternative to the nuclear gauge. If a nuclear gauge is required for the calibration process, then two gauges would be necessary to perform the function of one. As a result, many of the potential advantages of the non-nuclear devices would no longer be seen as benefits.

Screed-Core Calibration

From the previous analyses, a combination of the core calibration and two-point calibration methods was identified as a possible alternative for non-nuclear gauge calibration. In essence, this method involves a two point calibration in which measured core densities are used in place of the estimated peaked density. This method allows the calibration to encompass the greatest possible range of densities, making it more applicable to a variety of actual field data. This process was also hypothesized to be capable of accounting for differences in measured densities (i.e., magnitude), as well as sensitivity to changes in density.

For this method, the true density behind the screed was estimated to be 82 percent of MTD, and the measured density behind the screed obtained using the nuclear gauge and each non-nuclear gauge in 5 locations. These averages of these values were used as “low range” values, just as the screed values were used in the two point calibration method. Next, 5 core densities were measured and compared to the corresponding measurements by each gauge. The core and gauge densities were used as the “high range” values, similar to the ‘peak’ values in the process described for the two point method. Next, regression techniques were used to generate slope and intercept values for each location, and final calibration constants were calculated as the average slope and intercept for each mix. The results for the Screed-Core calibration method are presented in Table 13.

Mix Type	Number of Locations	Gauge Type	Average Slope	Average Intercept
37.5 mm	5	NG	0.78	31.88
		PQI	2.69	-182.29
		PT	1.63	-54.36
25.0 mm	5	NG	0.63	49.28
		PQI	2.02	-109.71
		PT	1.07	-6.02
12.5 mm	5	NG	0.55	61.60
		PQI	1.71	-74.24
		PT	1.02	8.97

Table 13. Summary of Calibration Constants for Screed-Core Method

After applying these calibration constants to additional density readings, the relationships of the nuclear and non-nuclear gauges were plotted. The results are given in Figures 48, 49, and 50. The resulting relationships between methods are shown as the dashed lines.

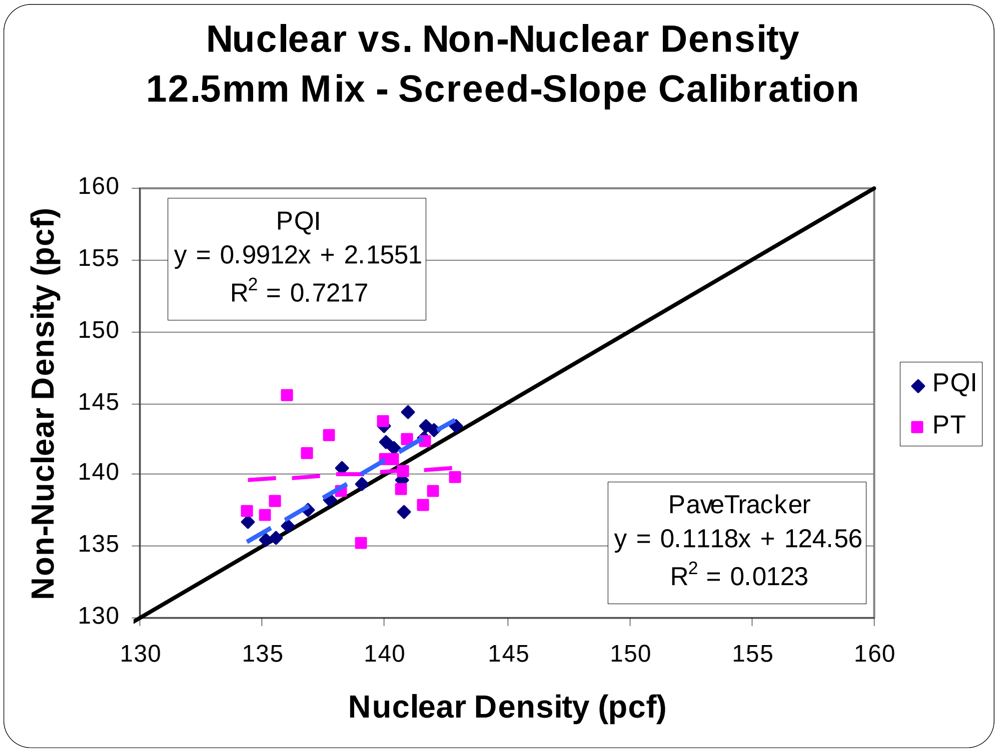

Figure 48. Gauge Comparison for Screed-Slope Method of Calibration – 12.5mm Mix

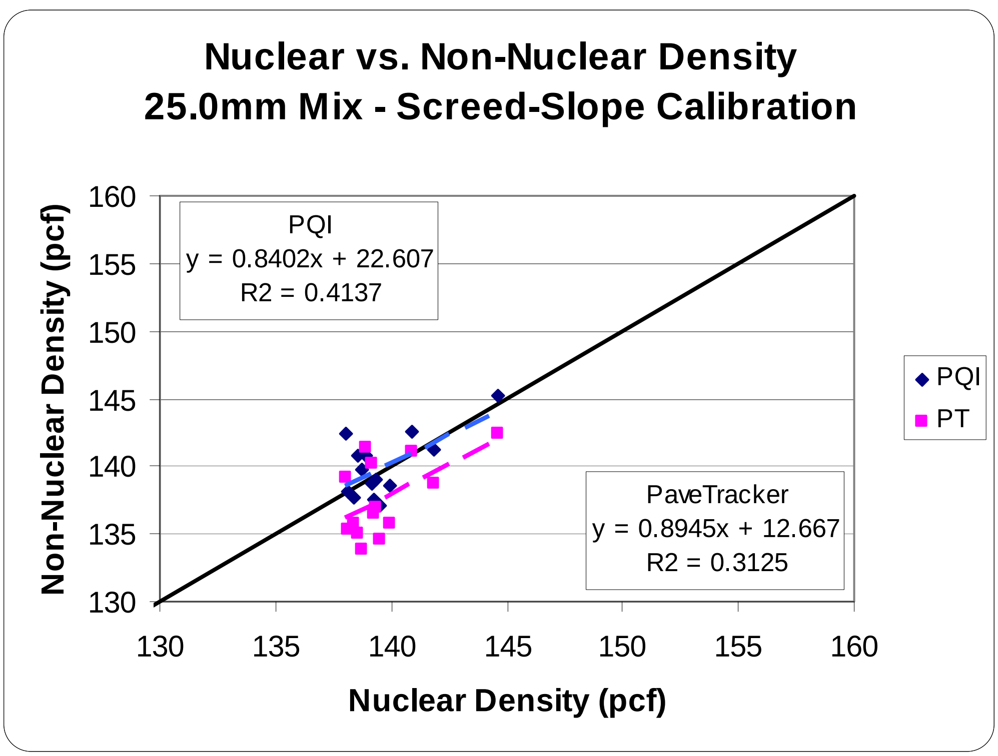

Figure 49. Gauge Comparison for Screed-Slope Method of Calibration – 25.0mm Mix

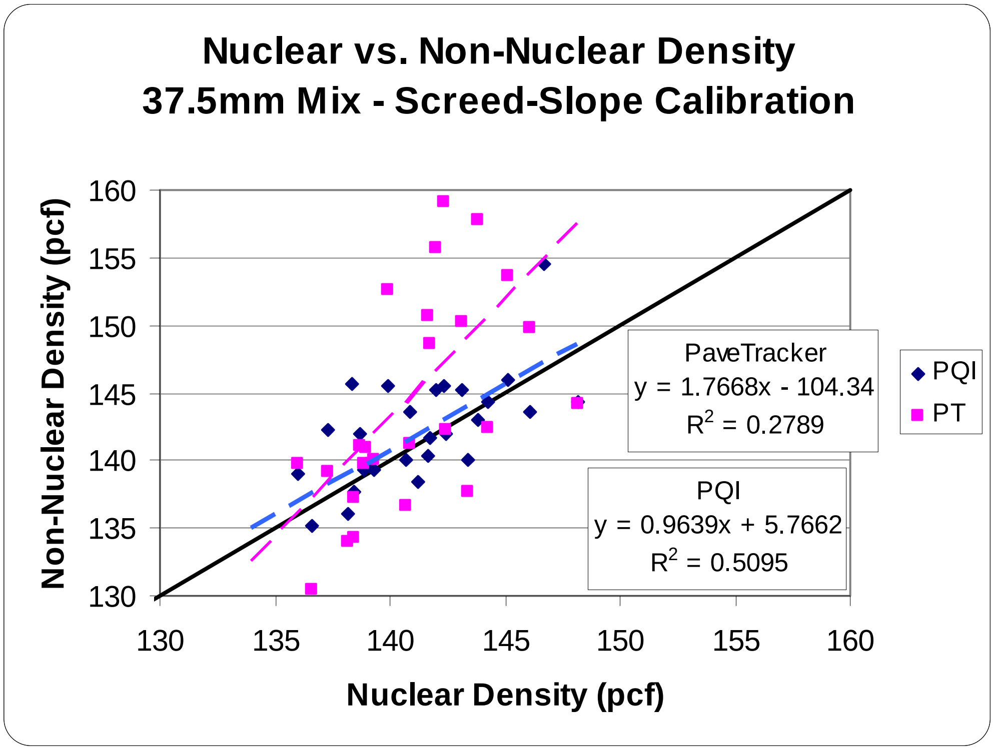

Figure 50. Gauge Comparison for Screed-Slope Method of Calibration – 37.5mm Mix

The application of the screed-slope calibration constants made a significant improvement to the relationship of the nuclear gauge and PQI. In fact, the trendlines describing the relationships were nearly equivalent to the line of equality for each mix type. The slopes of the trendlines were close to 1, meaning that the PQI was made sensitive to actual changes in density. Also, the vertical locations of the trendlines on the plot match that of the line of equality, indicating that the necessary offset has been provided. Although the trendlines show a desirable relationship, the R^2 values were not as high as had been hoped. The relationship was fair for the 12.5mm mix (R^2 = 0.72), but poor for the 25.0mm mix (R^2 = 0.41) and the 37.5mm mix (R^2 = 0.51) Thus, significant variability was exhibited by the individual data points. By forcing the PQI to become more sensitive to changes in density, a greater amount of actual variability was exposed. In other words, this method magnifies the sensitivity and the variability of the PQI.

The PaveTracker density measurements did not benefit significantly from the screed-slope calibration constants. The slope of the relationship for the 25.0mm mix was approximately equal to the line of equality. Overall, relationships were very poor, having R^2 values of 0.01, 0.31, and 0.28 for the 12.5mm, 25.0mm, and 37.5mm mixes, respectively. It appeared that the variability in the PaveTracker data was simply to great to be compensated by the screed-core calibration method.

Comparisons to core densities were not performed for this method. Rather, accuracy was assessed based on the relationships of the nuclear and non-nuclear densities. Though a direct comparison to core densities would have generated a more substantial validation of the calibration procedure, such an analysis would have been hindered by the fact that only a small range of densities would be available for the validation process. Cores can only be cut after final compaction, and if adequate compaction was achieved then a very small range of true densities would be available. By using the nuclear gauge data as a comparison, densities could be measured after each roller pass, which encompassed a wide range of densities. The nuclear gauge readings were calibrated to the core densities, thereby offering the best possible surrogate measure of “true” density along with a wide range of values for validating the calibration method.

Variability and Sample Size

Although a significant amount of variability still existed, a relatively large sample size would make this method work well for use in QC applications. Requiring a large sample size is normally a significant disadvantage for any test method. However, the non-nuclear devices are capable of returning density results within 3 seconds, so even a sample size as large as 30 can be completed in a very reasonable amount of time. Based on the standard deviations measured in this project and the magnification of variability generated by the screed-slope calibration method, a sample size of 25 would be required to detect a difference in density of 1 pcf.

Practicality

A calibration method should be accurate and practical. Calibration methods involving the nuclear gauge are not practical because the purpose of adopting new technology is to replace older methods with something more advantageous. Requiring the nuclear gauge for non-nuclear calibration would negate many of the reasons for using non-nuclear technology. It has been demonstrated that the most appropriate method for calibration should include an offset adjustment as well as a slope, or sensitivity, adjustment so that densities can be more accurately predicted for a wide range of values. To do this, linear regression techniques were used. It is not likely that technicians will feel that it is practical to perform linear regression in the field. Thus, it is recommended that non-nuclear gauge manufacturers add user-friendly input screens to the current gauge models so that this process can be handled internally by the device.

Conclusions

In conclusion, following conclusions were made regarding the screed-core calibration method.

- The screed-core method forced the PQI to become sensitive to actual changes in mat density.
- The variability associated with the PQI increased when the screed-core calibration constants were applied.
- A sample size of 25 is recommended for use with the PQI.
- The screed-core method was determined to provide a good relationship to true density for the PQI.
- The screed-core method was not appropriate for the PaveTracker.

The greatest advantage of the screed-core method is that is able to affect accuracy in terms of both magnitude and sensitivity for a wide range of density values. If the mathematical routines were incorporated into easy-to-use gauge menus, the screed-core calibration method would be feasible for implementation.

CONCLUSIONS AND RECOMMENDATIONS

This study of non-nuclear densities gauges was composed of a number of experiments designed to evaluate ruggedness, accuracy, variability, and calibration methods associated with the devices. TransTech's Pavement Quality Indicator™ (PQI) Model 301 and Troxler's PaveTracker™ Plus Model 2701-B were used in conjunction with a Troxler Model 3430 nuclear gauge and field cores.

Ruggedness

The ruggedness study was a field study designed to identify factors having a significant effect on density measurements made by the non-nuclear density gauges. Two 12.5mm NMAS mixes and one 37.5mm mix were used to test the effects of gauge type, mat temperature, moisture, presence of sand or debris, gauge orientation, number of readings used to generate one result, and gauge placement. The following conclusions were made.

- The PaveTracker and PQI provided similar results for the 12.5mm mixtures, but significant differences were present for the 37.5mm mix. Thus, the two types of gauges cannot be used interchangeably in all cases.
- The orientation of the gauge was significant in some cases, but appeared to be mixture dependent. A consistent orientation should be implemented to alleviate this problem.
- The presence of sand significantly affected both the PQI and PaveTracker, especially for the 12.5mm mixes. The PaveTracker was more sensitive than the PQI to this factor. All sand and debris should be thoroughly swept from the mat prior to testing.
- The presence of water significantly affected density readings in that the presence of moisture generated increased density readings. Although modifications to the non-nuclear gauges have attempted to account for moisture, they are still significantly affected.
- For the range tested, temperature did not significantly affect the density as measured by the PQI or PaveTracker.
- Paint caused non-nuclear testing devices to produce higher density readings.

Method Comparisons

Initial comparisons of the nuclear and non-nuclear gauges indicated weak correlations between them. Both non-nuclear gauges were significantly less sensitive to changes in density than the nuclear gauge. In terms of variability, the PQI was the least variable, followed by the nuclear gauge and PaveTracker devices.

When compared to core densities, the nuclear gauge demonstrated the strongest relationships, followed by the PQI and PaveTracker. Again, the non-nuclear gauges appeared to be insensitive to actual changes in density for some mixes. However, it was concluded that proper calibration may be able to account for these differences.

Calibration

Four calibration methods were evaluated, including the screed offset method, the core offset method, the two-point method, and the data pair method. None of these methods were able to provide non-nuclear devices with a way to estimate densities equivalent to core densities with respect to both magnitude and sensitivity. The following reasons were cited.

- The screed offset method provided values that were acceptable at very low densities, but was unable to accurately estimate high densities. An additional difficulty of this method was the fact that it is based on operator experience.
- The core offset method was successful at predicting high density levels, but was not sensitive to decreases in density. This could be detrimental a QC/QA application.
- The two-point method provided, reasonable estimates of density, and was sensitive to changes in density. However, it was based on operator experience.
- The data pair method considered the largest number of factors, but was dependent upon the nuclear gauge. Since the intended purpose of the non-nuclear gauge is to serve as a *replacement* for the nuclear method, this style of calibration does not provide a long-term solution.
- The variability of non-nuclear gauges increased as NMAS increased.
- The PQI appeared to be the more precise of the non-nuclear devices; however the PaveTracker was more precise.

A screed-core calibration was developed in order to combine the advantages of the core offset and two-point calibration methods. In this procedure, an estimate of density behind the screed was used to simulate low density, and cores were used to determine high density. Regression procedures were then used to generate calibration constants. This method was successful in correcting both the magnitude and sensitivity of the PQI readings; however, greater levels of testing variability were exposed, which necessitated a large sample size for accurate determinations. A sample size of 25 was determined to provide adequate discrimination. The PaveTracker readings did not benefit significantly from the screed-core calibration technique.

Recommendations

Although non-nuclear gauges have improved significantly since the early models were introduced, there are still factors that significantly affect densities measured by the PQI and PaveTracker. Existing specifications for non-nuclear density devices should be edited to require parallel orientation of the gauge when testing, and to stress the importance of ensuring that no sand or water is present on the mat.

Overall, the PQI was relatively insensitive to actual changes in density, and required a calibration procedure that forced the detection of density fluctuations. The PaveTracker was more sensitive to actual changes, but did not detect these changes consistently. The PQI appears to be a suitable tool for QC purposes when calibrated appropriately. However, neither the PQI nor the PaveTracker performed adequately for use as a QA tool.

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