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An Evaluation of the Potential Use of Non-Nuclear Density Gauges for Asphalt Concrete Acceptance

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16. Abstract:

This report describes the results of a study using non-nuclear density gauges (NNDGs) to measure the in-situ density of asphalt concrete (AC) material in Virginia. The study compared the NNDG results with those obtained from the use of two traditional AC density acceptance methods: the core method (AASHTO T 166) and the nuclear density gauge (NDG) method. Although these two methods are the most widely used methods of accepting AC density, the core method is time-consuming and destructive and involves bulky test setups and the NDG method, although portable and non-destructive, is associated with safety concerns related to the presence of radioactive materials in the gauge. The purpose of the study was to evaluate the use of two NNDGs as a potentially safe, portable, and expedient method of measuring AC density—a key indicator of pavement performance. The direct comparison of NNDG and core density and the acceptance rates with the use of NNDGs and NDGs were the focus of the study.

Extensive field and laboratory tests were conducted to determine AC density using two models of NNDGs (i.e., the Troxler PaveTracker Plus and the TransTech Model PQI 301) and one model of an NDG (i.e., the Troxler Model 4640-B). Density measurements of AC cores/plugs taken at gauge testing locations were conducted in the laboratory in accordance with AASHTO T 166 for comparisons. The results of the field testing showed that NNDG measurements were not well correlated with core density or NDG measurements. However, there was good agreement between readings from NNDGs and NDGs in terms of identifying core cutting locations (67%), control strip acceptance (75%), and test section acceptance (95%). This apparent contradiction between the acceptance rate among the gauges and the poor correlation could be explained by the relatively low ranges in measured field density (0-5 lb/ft^3), which is within the precision ranges of the gauges used.

The results of additional laboratory testing of 10 AC slabs with air void contents ranging from about 3% to 20% confirmed the results of the field testing. Specifically, they demonstrated that compared with NDGs, NNDGs were less sensitive, with an average relative bias of 19.6 lb/ft^3 and 9.6 lb/ft^3 for the PQI 300 and the PaveTracker Plus, respectively, compared with 2.2 lb/ft^3 for the NDG. The results also showed that results from use of the NNDGs were not well correlated with core density measured in accordance with AASHTO T 166, which is generally accepted as the most accurate method of measuring density.

The study concludes that NNDGs of the types used in the study are not suitable for measuring AC density for acceptance purposes and thus are not recommended for use as density acceptance tools in Virginia.

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FINAL REPORT

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ABSTRACT

This report describes the results of a study using non-nuclear density gauges (NNDGs) to measure the in-situ density of asphalt concrete (AC) material in Virginia. The study compared the NNDG results with those obtained from the use of two traditional AC density acceptance methods: the core method (AASHTO T 166) and the nuclear density gauge (NDG) method. Although these two methods are the most widely used methods of accepting AC density, the core method is time-consuming and destructive and involves bulky test setups and the NDG method, although portable and non-destructive, is associated with safety concerns related to the presence of radioactive materials in the gauge. The purpose of the study was to evaluate the use of two NNDGs as a potentially safe, portable, and expedient method of measuring AC density—a key indicator of pavement performance. The direct comparison of NNDG and core density and the acceptance rates with the use of NNDGs and NDGs were the focus of the study.

Extensive field and laboratory tests were conducted to determine AC density using two models of NNDGs (i.e., the Troxler PaveTracker Plus and the TransTech Model PQI 301) and one model of an NDG (i.e., the Troxler Model 4640-B). Density measurements of AC cores/plugs taken at gauge testing locations were conducted in the laboratory in accordance with AASHTO T 166 for comparisons. The results of the field testing showed that NNDG measurements were not well correlated with core density or NDG measurements. However, there was good agreement between readings from NNDGs and NDGs in terms of identifying core cutting locations (67%), control strip acceptance (75%), and test section acceptance (95%). This apparent contradiction between the acceptance rate among the gauges and the poor correlation could be explained by the relatively low ranges in measured field density (0-5 lb/ft^3), which is within the precision ranges of the gauges used.

The results of additional laboratory testing of 10 AC slabs with air void contents ranging from about 3% to 20% confirmed the results of the field testing. Specifically, they demonstrated that compared with NDGs, NNDGs were less sensitive, with an average relative bias of 19.6 lb/ft^3 and 9.6 lb/ft^3 for the PQI 300 and the PaveTracker Plus, respectively, compared with 2.2 lb/ft^3 for the NDG. The results also showed that results from use of the NNDGs were not well correlated with core density measured in accordance with AASHTO T 166, which is generally accepted as the most accurate method of measuring density.

The study concludes that NNDGs of the types used in the study are not suitable for measuring AC density for acceptance purposes and thus are not recommended for use as density acceptance tools in Virginia.

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INTRODUCTION

Density is considered one of the most important indicators of asphalt pavement performance (Brown, 1990). Monitoring density during pavement construction is therefore a key quality control / quality acceptance (QC/QA) activity undertaken by contractors and highway agencies. Common methods for monitoring density can be grouped into two categories: (1) those based on cores or plugs taken from newly constructed pavement (core method), and (2) those based on density gauges (nuclear density gauges [NDGs] and non-nuclear density gauges [NNDGs]).

It is generally agreed that measuring core density in accordance with AASHTO T 166 (American Association of State Highway and Transportation Officials [AASHTO], 2007) or a similar procedure is the most accurate method of obtaining material density. However, the method involves taking samples from newly constructed layers. Because of this, the method is considered destructive and therefore undesirable. Another disadvantage of the core method is that it is time-consuming and results are often not available until several tons of pavement material have already been placed.

NDGs have been used in attempts to address some of the issues concerning the core method (Burati and Elzoghbi, 1987; Kennedy et al., 1989; Maupin, 1988). Unlike the core method, NDGs are non-destructive and are comparatively faster, requiring minutes instead of hours to determine density.

As with the core method, NDGs have drawbacks. A major issue is that they contain small amounts of radioactive materials. This means stringent safety, security, and regulatory requirements must be met in order to own and operate the gauges. Owning and operating devices containing radioactive materials require strict accounting and monitoring by regulatory bodies such as the Nuclear Regulatory Commission (Vacca et al., 1997). Owners and/or operators of NDGs face severe penalties for loss or theft of the devices. Another issue with the use of NDGs is that compared to core density measurements, NDG measurements are more variable and therefore require regular calibration with core density. The NDG method could also be operator dependent, especially when operated in the back-scatter mode. Alternative non-destructive density gauges, especially those without radioactive-based sources, are therefore being evaluated as attractive alternatives to NDGs.

One common class of density gauges without radioactive-based sources, i.e., NNDGs, use measurement of the dielectric constant of asphalt material to estimate density. As with NDGs, NNDGs were introduced and marketed as fast, portable, and non-destructive density measuring tools, but without most of the safety and regulatory issues associated with NDGs. For more than a decade, evaluation of NNDGs as QC/QA tools for measuring asphalt concrete (AC) density during construction has been the subject of many studies (Hauseman and Buttlar, 2002; Hurley et al., 2004; Rao et al., 2007; Smith and Diefenderfer, 2008; Williams and Hall, 2008).

Many previous studies have focused on direct comparisons of core density with NNDG density and/or NDG density and developed regression models to describe the association (Hauseman and Buttlar, 2002; Hurley et al., 2004; Rao et al., 2007). Correlations between NNDG and core/NDG density were developed in most of these studies (Choubane et al., 1999; Hauseman and Buttlar, 2002; Williams and Hall, 2008). The results have, however, been mixed. Although some studies reported a good correlation, most found no evidence of a consistent link between NNDG density and AC core density in either field or laboratory studies. A review of the literature suggested no consensus on the ability of the gauges to be used as QC/QA tools. Thus, there is still a need to evaluate the potential of NNDGs for AC density acceptance.

PURPOSE AND SCOPE

In Virginia, NDGs are currently used to accept AC density once the gauges have been calibrated in accordance with Virginia Test Method 114 (VDOT, 2010), even though as discussed previously, density measured with NDGs has not shown a very consistent correlation with core density in previous studies (Burati and Elzoghbi, 1987; Choubane et al., 1999; Maupin, 1988). In this study, it was hypothesized that if the rate at which an NNDG accepts or rejects a pavement section was similar to the rate at which an NDG accepted or rejected a pavement section under similar conditions, that NNDGs could be used in a manner similar to NDGs even if the correlation between NNDG and core density was poor. The purpose of this study, therefore, was to evaluate the potential use of NNDGs for AC acceptance in Virginia. The direct comparison of NNDG and core density and the acceptance rate of NNDGs and NDGs was the focus of the study.

Field testing involving the use of both NNDGs and NDGs was conducted at 12 asphalt paving project sites located across Virginia. Laboratory testing of 10 compacted slabs, with varying air void contents (3%-20%) was also conducted. The results of the density gauges were compared with those obtained from cores in accordance with AASHTO T 166.

METHODS

The study objective was accomplished by a combination of field and laboratory testing using density gauges and laboratory equipment during the Virginia Department of Transportation's (VDOT's) 2009 construction season. A survey of state departments of transportation was also conducted to determine interest in the evaluation of NNDGs as QC/QA tools for field density measurements during AC placement. The results of the survey are reported elsewhere (Apeagyei et al., 2010).

Two models of NNDGs (Figure 1) and one model of NDG were used in the study. The NNDG models were (1) the PaveTracker Plus manufactured by Troxler Electronic Laboratories, Inc., of Raleigh, North Carolina (Troxler PaveTracker Plus), and (2) the Model PQI 301 manufactured by TransTech Systems, Inc., of Schenectady, New York (TransTech PQI 301). The NDG used was a Model 4640-B manufactured by Troxler Electronic Laboratories, Inc. (Troxler 4640-B), which was owned and operated by each participating contractor who took part in the study.

Figure 1. Non-Nuclear Density Gauges Used in Study: *Left:* PQI 301 manufactured by TransTech Systems, Inc.; *right:* PaveTracker Plus manufactured by Troxler Electronic Laboratories, Inc.

Field Testing

Contractor Training

Eight paving contractors volunteered to take part in the field testing for this study. Each contractor received a TransTech PQI 301 or Troxler PaveTracker Plus NNDG for use. The contractors were trained on the use of NNDGs by a team from VDOT and the Virginia Center for Transportation Innovation and Research, who were themselves trained by the gauge manufacturers. During the training, the contractors were asked (1) to collect density and moisture readings of 10 random locations using both an NNDG and their own NDG; (2) to determine the average density at the 10 random test locations for each gauge type; and (3) to collect cores at the 3 locations nearest the average (of those 10 random locations) for each gauge type.

Because each contractor had a different amount of VDOT contract work during the testing period, the amount of data submitted by individual contractors varied depending on the amount of projects they had during the 2009 paving season. Overall, usable density data were obtained from 12 control sections and the accompanying test strips. Since VDOT does not allow offset (Maupin, 1988) to be applied to NDG measurements, density gauge data values reported in this report consist of uncorrected density data reported by the contractors. Core density measurements were conducted in accordance with VDOT specifications (VDOT, 2008) and AASHTO T 166 on specimens collected from the 12 paving projects considered.

Control Strip and Test Sections

The control strip testing was conducted so that the contractor could do the following: (1) validate an acceptable roller pattern, (2) determine a target density for use during test section testing, and (3) obtain core samples for field testing. The *roller pattern* is the number of passes of selected compactors to give the maximum AC density as measured with an NDG. The target density is the average NDG measurements of 10 randomly selected locations on the control strip. It should be noted that NNDGs were not used during the establishment of roller patterns in this study because of contractual issues.

Each project site was divided into control strips and test sections for density testing. At each control strip, which was typically about 300 ft long per lane width, two density measurements were taken at 10 randomly selected locations, one with the NNDG and the other with the NDG. Next, for each gauge type, cores were taken at the 3 locations having a gauge-density value closest to the average of the 10. With this testing approach, between three and six cores were collected, depending on the agreement between the two gauge types. The term *agreement* is used here to mean the same identified core cutting location based on the locations closest to the average of the 10 gauge readings. For acceptance purposes, VDOT defines a test section (lot) as a portion of the day’s production consisting of 5,000 linear feet of paving train pass (VDOT, 2008). Each test section (lot) consists of about five sublots.

Field Cores From Control Strip

The cores were weighed in the field for density measurement in accordance with AASHTO T 166. Under current VDOT specifications (VDOT, 2008), if the ratio of the measured core density compared to the maximum theoretical density of the AC mixture exceeds 92.2% (92.5% for surface mixtures containing PG 64-22 asphalt binder), the control strip and the roller pattern are adopted for the remaining sections of the project (test sections). Acceptance of the rest of the paving is then based on contractors achieving between 98% and 102% of the control strip average NDG measurements. With the acceptance of the control strip, two NDG/NNDG readings are taken every 1,000 ft (sublot) of remaining pavement length.

The results of the field testing were evaluated in two steps: the first compared the density measured by each gauge type (NNDG and NDG) with the respective core density; the second involved a determination of whether each gauge type similarly identified acceptable/ unacceptable test sections.

Laboratory Testing

Fabrication of Slabs

A vibratory slab compactor was used to fabricate 10 slabs of dimensions 500 by 180 by 78 mm. The slabs were designed to have air void contents ranging from 3% to 20%. It was anticipated that such large ranges in air void contents would enable better correlations, compared with the field data, between core density and gauge density. In addition, the field testing showed few if any locations where the density was less than that required by the VDOT specifications (VDOT, 2008). Therefore the laboratory testing was designed to encompass most density levels achievable for AC materials.

Testing of Slabs with Gauges

The 10 laboratory-fabricated slabs were tested in such as a way that extraneous influences that could affect the results were reduced to a minimum. To ensure this, each slab was placed in a wooden mold and laid over a 1-in-thick piece of Styrofoam placed over three layers of ¼-in-thick plywood before the entire assembly was placed on the laboratory floor for testing. The aforementioned setup (Figure 2) was used to provide some assurance that the influence of the portland cement concrete floor in the laboratory did not adversely influence the density readings from the gauges.

For each density gauge, three readings were taken: one at each end of the slab and the third at the mid-section of the slab. The bulk specific gravity of the slabs was measured in accordance with AASHTO T 166. A CoreLok device was used to verify the results. Cores were taken from the slabs at the same location the gauges were placed. The density data for the cores were also compared with those of the entire slab and were found to be comparable.

Figure 2. Test Setup for Evaluating Density Gauges in Laboratory

RESULTS AND DISCUSSION

Identifying Core Cutting Locations on Control Strips

As previously indicated, a major reason for using NDGs on control strips during AC placement is to determine a target density to be used for acceptance purposes. Several steps are involved in determining the target density, as specified in Virginia Test Method 76 (VDOT, 2010).

1. Ten locations are selected for NDG testing using a stratified random sampling technique.

2. The average NDG reading for all 10 readings is computed.

3. The core cutting locations are identified as the 3 locations for which the density is closest to the computed NDG average density from the 10 locations.

4. Cores are taken at these 3 locations for density testing in the field in accordance with AASHTO T 166 to obtain the target density.

Therefore, the use of NDGs is critical in the acceptance process as they directly dictate where cores for target density will be taken for testing. As a result, one objective of the control strip testing in this study was to determine if core cutting locations identified by NNDGs and NDGs were similar.

Figure 3 shows typical results of control strip testing showing core cutting locations. As shown, the NNDG in this case identified 2 of the same locations for core sampling identified by the NDG (locations 4 and 8). In general, the results for all project sections indicated that the core cutting locations identified by the NNDGs and NDG agreed about 67% of the time. In those cases where the NNDGs identified different core cutting locations, most appeared to be at locations near the beginning or end of the control strips, where the variability in material density caused by the conventional compaction process is expected to be highest.

Correlation Between Gauges Regarding Density on Control Strips

Figure 4 shows sample results obtained when core density measured in accordance with AASHTO T 166 was compared with that obtained by the density gauges used in this study. The results represent data from control strips of 12 pavement sections tested during VDOT's 2009 paving season. As seen in Figure 4, there was no consistent correlation between core density and gauge density at any project site. Regression coefficients computed for the data from 12 project sections ranged from about 0.00 to 1.00. However, for most of the pavement sections tested, the regression coefficients were less than 0.40.

Given the variable levels of correlation between core density and NNDG density for individual projects (composed of three to six core density readings at each control strip), the researchers thought that a better correlation might be realized if a larger set of data was used for

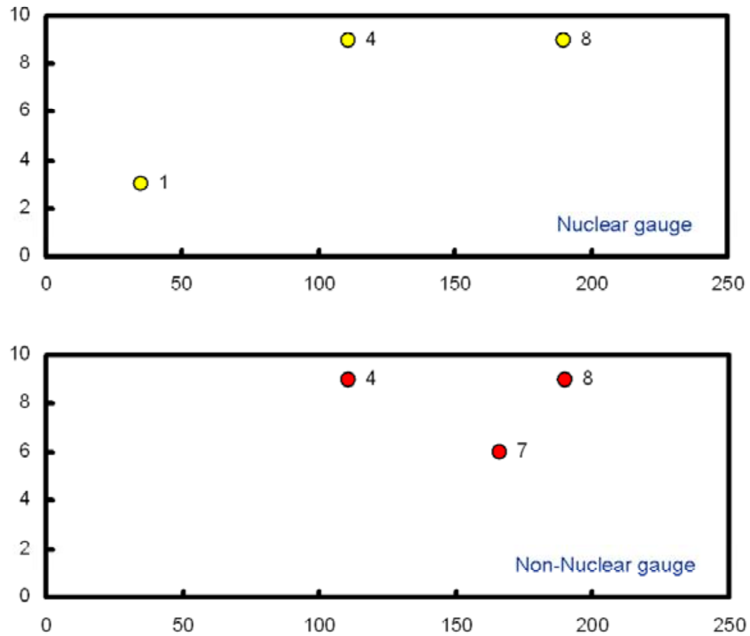

Figure 3. Typical Core Cutting Locations Identified by Nuclear and Non-Nuclear Density Gauges on 250-ft-long Control Strip (where the numerical values represent which of the 10 control strip test locations was selected)

the comparison. Therefore, density data taken from cores collected on control strips and test sections for the 12 projects were aggregated and compared. Figure 5 shows the comparison of core density versus NNDG density, core density versus NDG density, and NNDG density versus NDG density for the 12 projects combined. The regression coefficient improved when the data from all projects were analyzed together. However, there were no consistent correlations between the gauges and the cores. The correlations between NDG density and core density and between Troxler PaveTracker Plus density and core density were similar ($R^2 = 0.50$), whereas that between TransTech PQI 301 density and core density was quite low ($R^2 = 0.12$).

The analysis would suggest that density as measured by the gauges evaluated in this study showed little correlation with core density measured in accordance with AASHTO T 166. Similar results were reported in previous studies (Burati and Elzoghbi, 1987; Choubane et al., 1999; Hauseman and Buttlar, 2002; Hurley et al., 2004; Maupin, 1988; Smith and Diefenderfer, 2008). Therefore, previous work involving density gauges support the field data obtained in this study for both NDGs and NNDGs in terms of gauge correlation with core density.

Acceptance Rates for Control Strips

Under current specifications, a paving section is accepted (for 100% pay) by VDOT if the contractor achieves density between 98% and 102% of the control strip average NDG measurements (VDOT, 2008). For this study, the NNDGs and NDGs were used similarly for acceptance by comparing the average gauge densities from test sections and control strips.

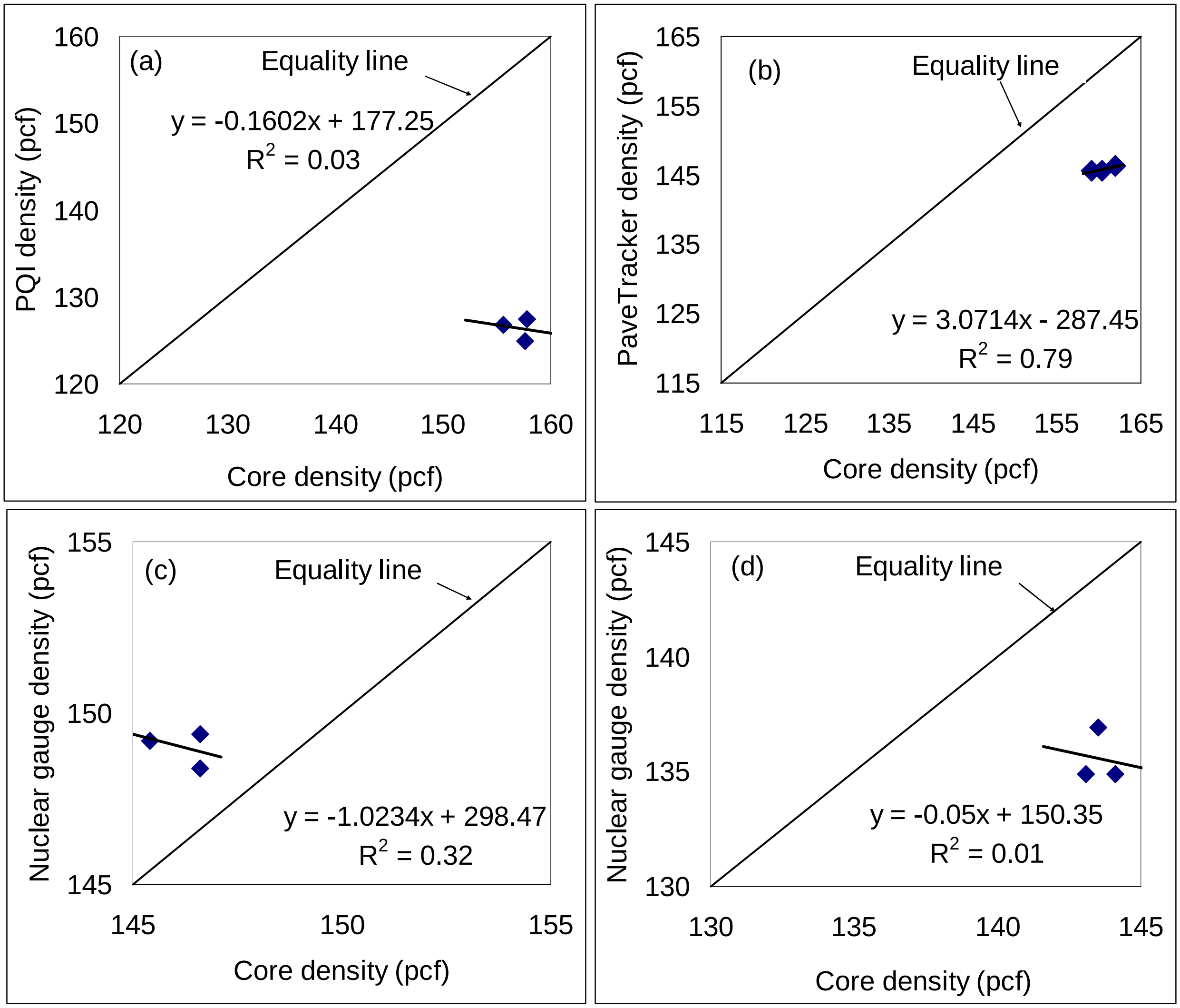

Figure 4. Sample Correlations Between Core Density and Gauge Density at Selected Project Sites, Control Strip Data Only. PQI = TransTech PQI 301 non-nuclear density gauge; PaveTracker = Troxler PaveTracker Plus non-nuclear density gauge. Nuclear gauge = Troxler 4640-B nuclear density gauge.

Figure 6 depicts a summary of gauge density test results from 21 test sections compared with corresponding target density values from the respective control strip using NNDGs and NDGs. The figure compares test strip density and control strip density and shows how close the two sets of density measurements are and suggests a possible reason why the acceptance rates for all gauges were similar.

The figure is grouped into two parts according to NNDG type. Figure 6a shows data from the TransTech PQI 301, and Figure 6b shows data from the Troxler PaveTracker Plus. The correlation between control strip density and test section density was very high, as seen in the figure. One likely reason might be related to the ranges in density measured and the sensitivity of the gauges used. On any given project, the range in gauge readings never exceeded about 5 lb/ft^3. It important to note that this value is very close to the precision of most existing density gauges (ASTM D2950 [ASTM International, 2009a]; ASTM D7113 [ASTM International 2009b]). The implication of this on acceptance rate is discussed later.

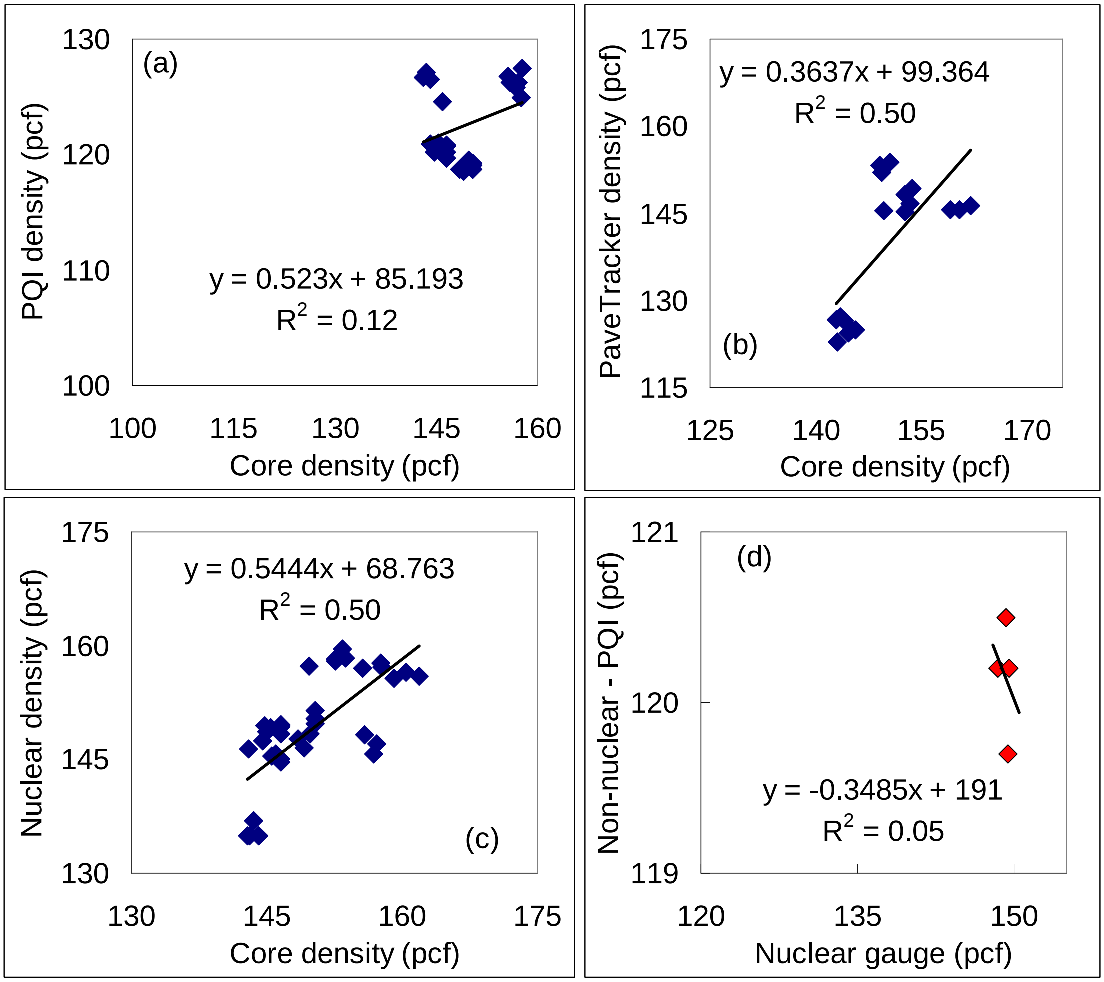

Figure 5. Correlation Between Core Density and Gauge Density for 12 Project Sites. PQI = TransTech PQI 301 non-nuclear density gauge; PaveTracker = Troxler PaveTracker Plus non-nuclear density gauge; nuclear = Troxler 4640-B nuclear density gauge.

Acceptance Rates for Test Sections

As discussed previously, each test section consisted of about five sublots. For each sublot, density testing was conducted in at least two locations. Several gauge readings were taken at two locations on each sublot, and the results used to compute the average gauge reading for the test sections. The result for a test section was compared with the target density from the corresponding control strip (relative density) to determine whether the section should be accepted (for 100% pay) or not. A test section was accepted if the relative density (ratio of the test section density to the target density) was in the range of 98% to 102%. Therefore, for the purposes of this study, *acceptance rate* was defined as the number of test sections having a relative density within the 98% to 102% range divided by the total number of test sections. One of the objectives of this round of testing was to compare the acceptance rates of NNDGs and NDGs.

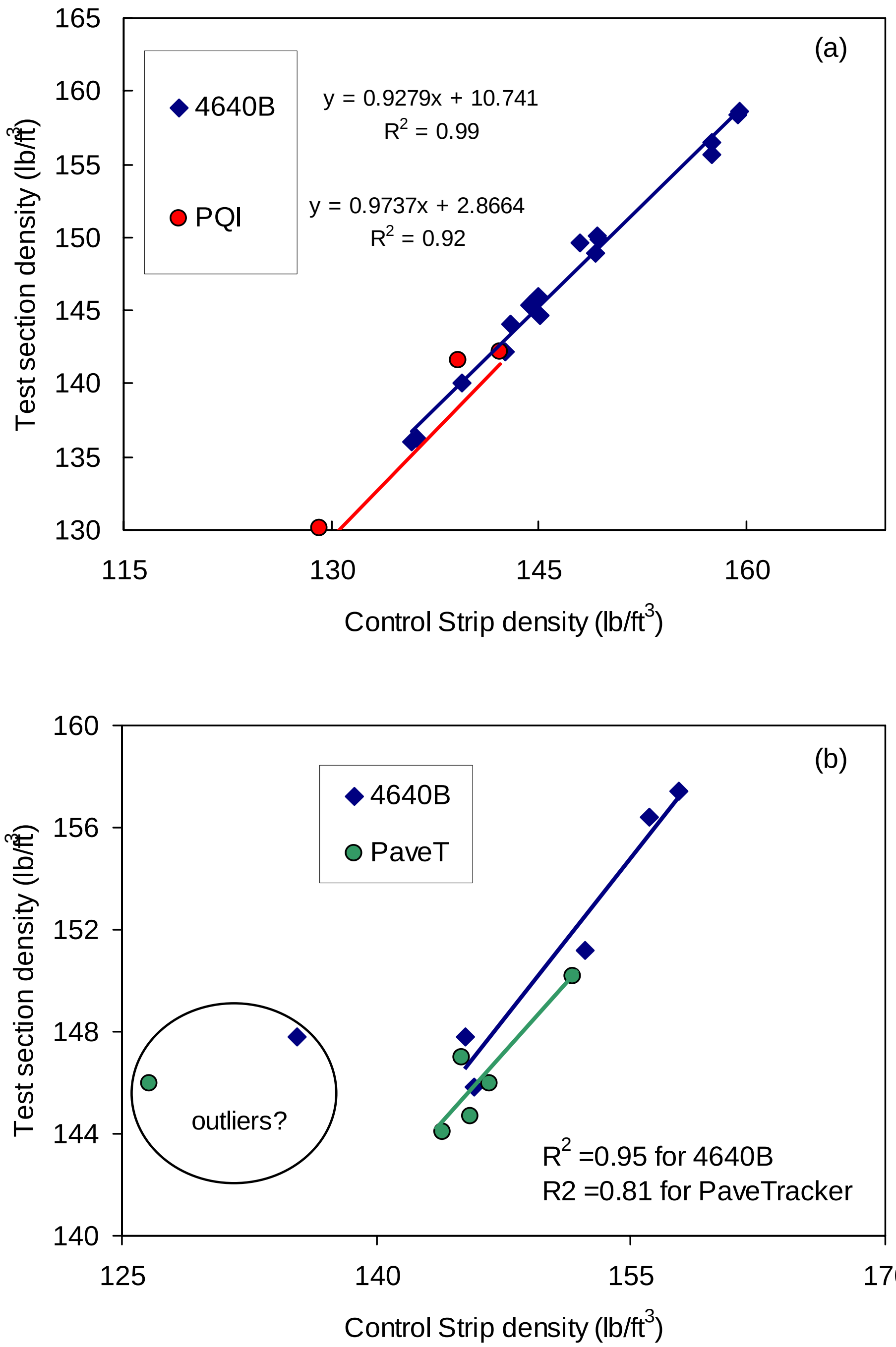

Figure 6. Control Strip Versus Test Strip Density Obtained with Nuclear and Non-Nuclear Density Gauges

Relative density values for 21 test sections were computed, and the results used to estimate and compare the acceptance rates of the gauges. The results showed that relative density ranged from 95.6% to 115%. Most of the results (more than 95%) were in the acceptance range of between 98% and 102% of the control strip average gauge density values.

The acceptance rate for sections where the Troxler PaveTracker Plus NNDG was used was in perfect agreement with that of the NDG (Troxler 4640-B). In other words, the

PaveTracker Plus and the NDG accepted or rejected the same test sections. It is worth noting that in the single case where a test section was rejected by the PaveTracker Plus, the NDG rejected the same section.

There was agreement on acceptance rate between the TransTech PQI 301 NNDG and the NDG in all but one instance. The acceptance rates were similar in about 94% of the cases considered.

Overall, the results showed that the acceptance rates for all gauges (NNDG and NDG alike) were similar; about 95% of the test locations were identified as acceptable by all gauges. The excellent agreement for the test sections is in contrast to the poor correlation between gauges and between gauges and cores for the control strips presented earlier (Figures 4 and 5). As discussed previously, the acceptance rate was computed as the ratio between test section density and control strip target density.

Based on the data from the field testing, it could, therefore, be argued that the density gauges are outputting the same density values irrespective of where they were used (control strip or test section) or that the actual material densities lie within a very narrow range (within the precision of the gauges). There was a very high correlation ($R^2 = 0.93$) between test section density and control strip density measured by the PQI 301 and the 4640-B and by the PaveTracker Plus and the 4640-B, which appears to support the assertion that field densities lie in a narrow range.

Statistical Analysis of Field Data

To gain additional insight into the apparent contradiction regarding acceptance rate among the gauges on the test sections, further analysis was conducted. Statistical analysis (at the 0.05 significance level) of the data revealed interesting trends. First, when target density data from the NDG (Troxler 4640-B) from the control strips were compared with the average density for the test strips, there was no statistically significant difference (p-value = 0.75). Second, no statistically significant difference was found between target density readings and test section data for the two NNDGs (p-value = 0.41 for the Troxler PaveTracker Plus and 0.83 for the TransTech PQI 301).

In general, when density data from all 12 projects were considered, the following could be said with 95% confidence: (1) density readings from NDGs were in the range of 146.1 to 150.4 lb/ft^3; (2) the PaveTracker Plus readings were in the range of 140.7 to 148.7 lb/ft^3; and (3) the PQI 301 readings were in the range of 122.88 to 131.6 lb/ft^3. Thus, since pavement density data are expected to be within a narrow range of density values, it is not surprising that all gauges were accepting test sections equally even though the data from the gauges themselves did not correlate well with core data. The data obtained in this study suggested the need for gauges with a high enough sensitivity or accuracy to capture the relatively narrow range of asphalt material density encountered in the field. The analysis indicating narrow ranges in gauge readings may explain why the acceptance rate for the gauges are similar for the test sections considered in this study.

In the absence of gauges with a precision better than 5 lb/ft^3, a decision was made to evaluate mixtures with larger ranges of density values. This was a major motivation for conducting the additional laboratory testing of slabs discussed later.

Laboratory Testing

Density Measurements

Table 1 provides a summary of density test results from testing 10 laboratory-compacted slabs. For the three density gauges, each data point in Table 1 represents the average of three measurements taken on each slab. Three cores were taken from each slab and tested to determine its density and air void content. The average of the three core density values and the maximum theoretical density values were used to compute air void content for each slab. Figure 7 summarizes the air void contents for the 10 slabs, which varied from about 3% to 20%.

Table 1. Density (lb/ft^3) of Laboratory-Compacted Slabs by Gauge Type

Specimen ID		Test Method			
		PQI	**PaveT**	**4640-B**	**Core**
A-1	Mean	126.2	140.7	151.8	151.6
	COV	0.24	1.93	0.09	0.18
A-2	Mean	125.7	136.9	150.9	152
	COV	0.68	1.67	0.98	0.59
B-1	Mean	126.9	137.7	150.9	150.7
	COV	0.30	2.31	0.00	0.12
B-2	Mean	126.4	136.5	149.7	150
	COV	0.12	4.23	1.94	0.10
C-1	Mean	125.1	134.6	141.4	146.8
	COV	0.44	3.41	1.40	0.25
C-2	Mean	124.7	137.2	147.8	146.4
	COV	0.81	3.62	0.34	1.06
D-1	Mean	127.6	139.5	145.8	144.5
	COV	0.24	1.13	0.58	0.65
D-1	Mean	127.3	137.5	146.5	144.3
	COV	0.21	1.73	0.14	1.02
E-1	Mean	124.7	132.3	138.8	133.4
	COV	0.29	1.06	0.10	0.72
E-1	Mean	125.4	132.1	139.4	134.9
	COV	0.24	1.58	0.25	0.17

PQI = TransTech PQI 301 non-nuclear density gauge, PaveT = Troxler PaveTracker Plus non-nuclear density gauge; 4640-B = Troxler 4640-B nuclear density gauge; Core = core density measured in accordance with AASHTO T 166; COV = coefficient of variation (%).

Regression Analysis

Figure 8 compares slab density measured with the TransTech PQI 301 NNDG (Figure 8a), the Troxler PaveTracker Plus NNDG (Figure 8b), and the Troxler 4640-B NDG (Figure 8c). The figure shows poor correlations (typified by the low R^2 values) between NNDG and core density measured in accordance with AASHTO T 166. The results agree with the field testing data with one minor exception: the NDG predictions in the laboratory were better than those in

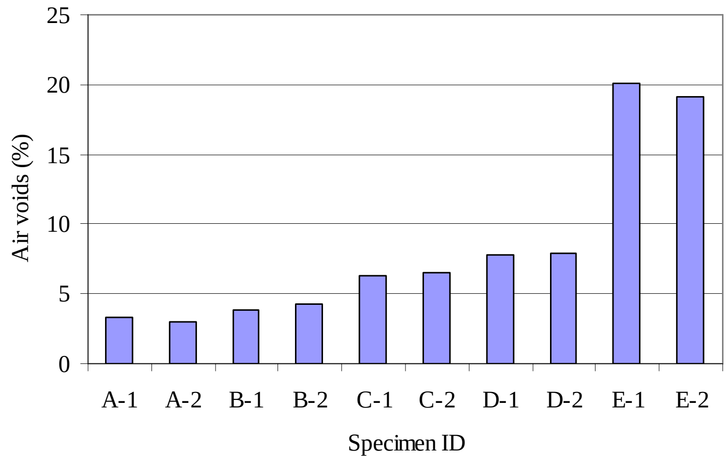

Figure 7. Air Void (From Core Testing) Distribution for 10 Laboratory-Compacted Slabs

the field. The results are also in agreement with previous studies described earlier. The correlation was best with the 4640-B with an R^2 of 0.82 followed by the PaveTracker Plus with an R^2 of 0.58; the PQI 301 had the worst correlation, with an R^2 of 0.13.

Average-Discrepancy Plots

The use of regression analysis for evaluating NNDGs has been questioned by some (see, e.g., Colosimo's "Discussion" in Hurley et al., 2004). An alternative method to regression analysis involving the use of average-discrepancy plots was suggested by Altman and Bland (1983). An attempt was made to evaluate the laboratory test results using their approach.

When comparing two methods of measurements, e.g., A and B, Altman and Bland (1983) recommended plotting the arithmetic difference between the methods (A - B) against the average of the methods (A + B)/2 to determine if differences varied or were consistent over the range of measurement values. Figure 9 shows one such plot for the slab data. In Figure 9a, the difference between the PQI 301 density and core density is plotted against the average of the core density and PQI 301 density. Similar plots are shown for the Troxler PaveTracker Plus NNDG and the Troxler 4640-B NDG (Figure 9b and Figure 9c, respectively). In Figure 9a, a clear relationship ($R^2 = 0.91$) between the difference in PQI 301 and core density and the magnitude of the average PQI 301 and core density can be seen. This would suggest that the difference increases as core density increases and, therefore, that the PQI 301 appears to be insensitive to changes in core density. The PaveTracker Plus showed a relationship ($R^2 = 0.69$) that was similar to but smaller than that with the PQI 301. Unlike with the PQI 301 and the PaveTracker Plus, no clear trends are seen in Figure 9c for the 4640-B. Thus, density measurements from the 4640-B appear to be independent of the magnitude of core density, suggesting that NDGs may be comparatively more sensitive than either the PQI 301 or PaveTracker Plus NNDG.

Relative Error and Bias

One important advantage of using the Altman and Bland (1983) approach is the ability to estimate the magnitude of agreement between measuring two devices/methods. The magnitude of agreement (error and relative bias) between the gauges and the measured core density values

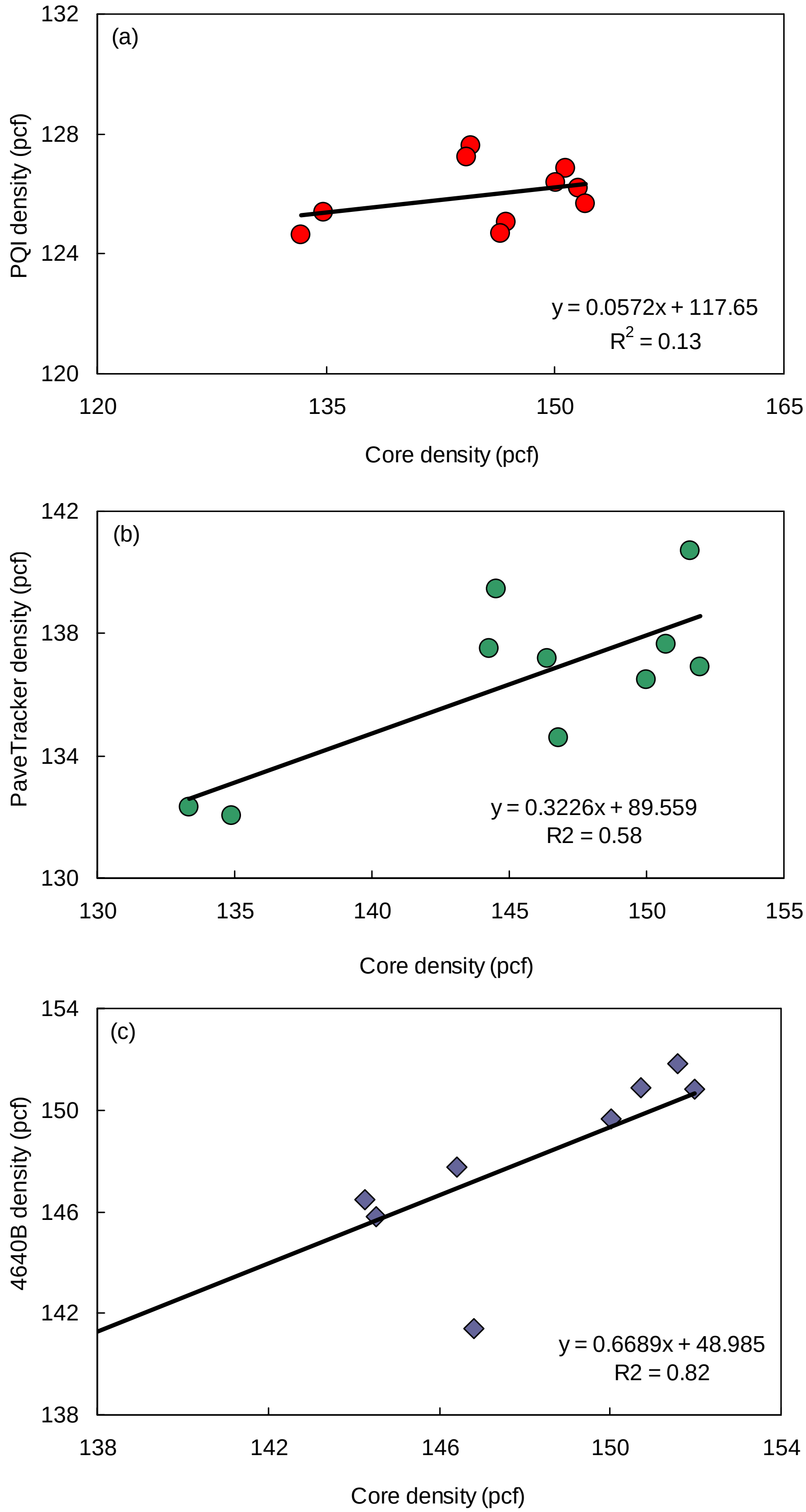

Figure 8. Comparison of Density From Nuclear and Non-Nuclear Density Gauges With Core Density: (a) TransTech PQI 301 non-nuclear density gauge; (b) Troxler PaveTracker Plus non-nuclear density gauge; (c) Troxler 4640-B nuclear density gauge.

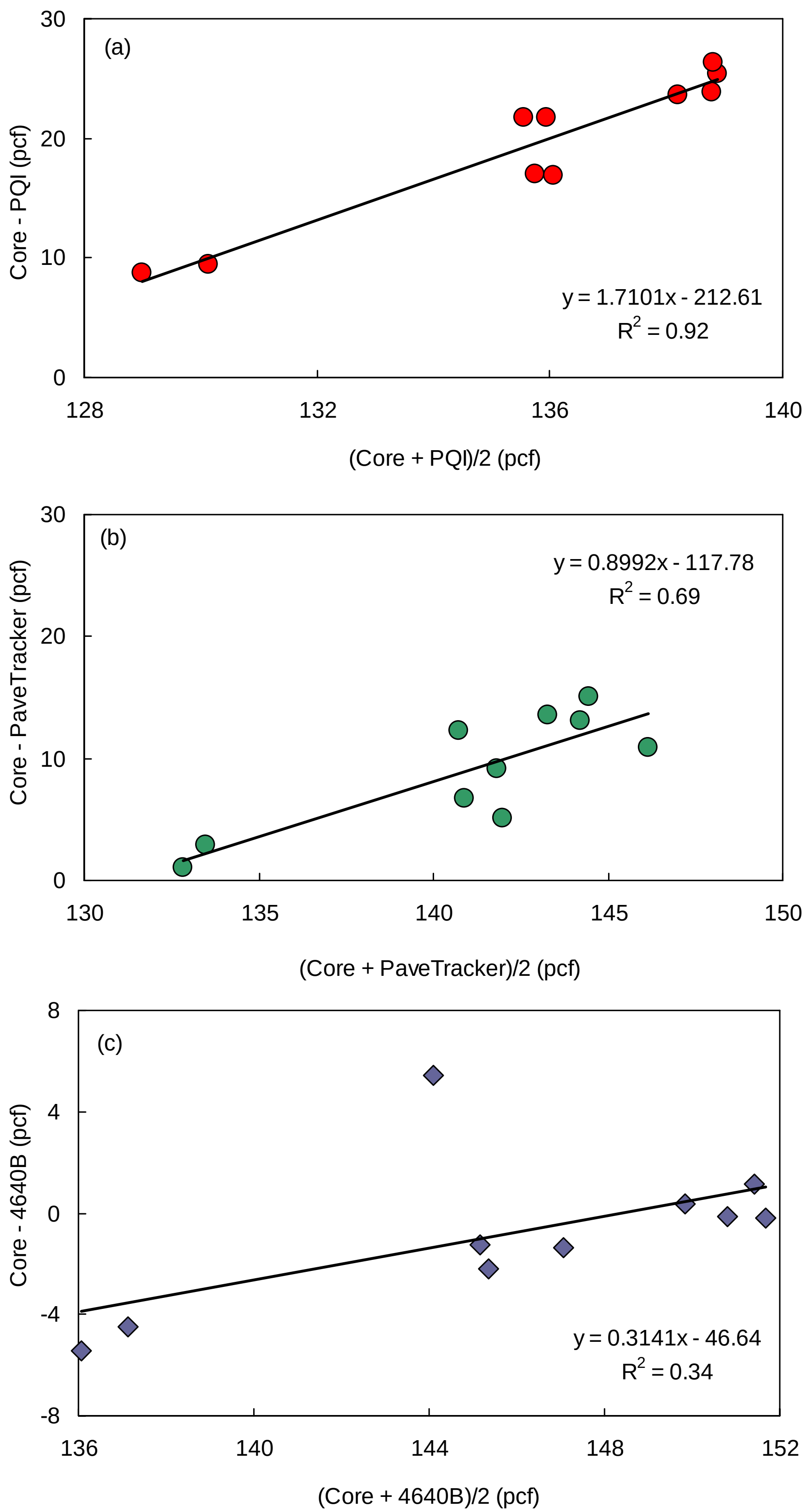

Figure 9. Average-Discrepancy Plots: (a) TransTech PQI 301 non-nuclear density gauge, (b) Troxler PaveTracker Plus non-nuclear density gauge, (c) Troxler 4640-B nuclear density gauge.

was estimated using data plotted in Figure 10. The error of each method, computed as the standard deviation of the average difference between the methods, ranged from 3.0 to 6.3 lb/ft^3 as shown in Figure 10a. The results suggest that for the gauges considered, the TransTech PQI 301 NNDG had the largest error followed by the Troxler PaveTracker Plus NNDG. The NDG (Troxler 4640-B) had the lowest relative error, which was about one-half that of the PQI 301.

The results for relative bias were, however, significantly different for the three gauge models. As shown in Figure 10b, relative bias values, computed as the average of the difference between each gauge and the core density, ranged from 2.2 to 19.5 lb/ft^3. The bias in the three gauges differed tremendously among the gauges, with the NDG having the lowest bias of all the gauges evaluated. The relative bias also varied even for the same gauge type used on slabs with different air voids. Therefore it might not be possible to use a single bias value to characterize each gauge consistently. The relative bias of the PQI 301 was about 2 times that of the PaveTracker Plus and almost 9 times that of the 4640-B. Thus for the laboratory slabs tested, on average, the PQI 301 measurement differed by about 20 lb/ft^3 compared with core density

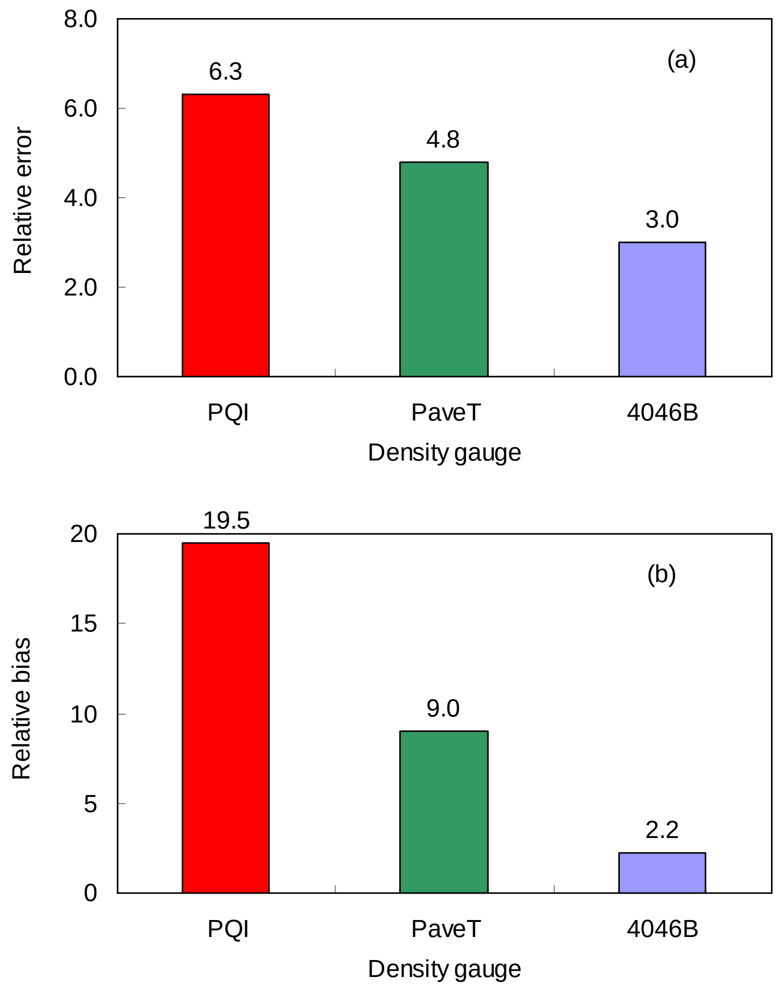

Figure 10. Magnitude of agreement between density gauges and core method: (a) relative error, (b) relative bias. PQI = TransTech PQI 301 non-nuclear density gauge; PaveT = Troxler PaveTracker Plus non-nuclear density gauge; 4046B = Troxler 4046-B nuclear density gauge.

measured in accordance with AASHTO T 166. Even though the PaveTracker Plus had a lower bias than the PQI 301, it still differed by about 9 lb/ft^3 compared to core density. These results suggest that NNDGs might not be sensitive enough, compared with NDGs or core density measured in accordance with AASHTO T 166, which is generally accepted as the most accurate method of measuring density. Similar results were obtained when NNDG-measured densities were compared with CoreLok measurements for the 10 slabs tested.

The lower relative bias of the NDG data in Figure 10b was in agreement with the relatively good correlation between NDG density and core density presented in Figure 8c. To illustrate this further, NDG density was plotted against core air voids instead of density, which has been done in some previous studies (e.g., Hauseman and Buttlar [2002]). The results are shown in Figure 11 and indicate a good correlation ($R^2 = 0.77$) between NDG density and the laboratory-measured air void contents of the slabs. The strength of the correlation between NNDG and core density was lower ($R^2 = 0.17$ and $R^2 = 0.63$ for the PQI 301 and the PaveTracker Plus, respectively) than that between NDG and core density.

SUMMARY OF RESULTS

- Density measured with the NNDG was poorly correlated with core density measured in accordance with AASHTO T 116 in both the field and laboratory tests.
- Density measured with the NDG was poorly correlated with core density in the field trials but well correlated with core density in the laboratory studies.
- In the laboratory study, the NDG had the lowest relative bias of 2.2 lb/ft^3; the NNDGs had relative biases (9.0 lb/ft^3 for the Troxler PaveTracker Plus and 19.5 lb/ft^3 for the TransTech PQI 301) that were orders of magnitude higher than those of the NDG.
- Of the two NNDGs, the Troxler PaveTracker Plus performed better (in terms of correlation with measured core density, relative bias, and relative errors).

CONCLUSIONS

- NNDGs of the types used in this study are not suitable for measuring AC density for acceptance purposes.
- NNDG-measured density values correlated poorly with core density determined in accordance with AASHTO T-166, which is generally considered as a more accurate method for determining AC density. Therefore, NNDGs do not appear to be a suitable alternative for core density measurements.

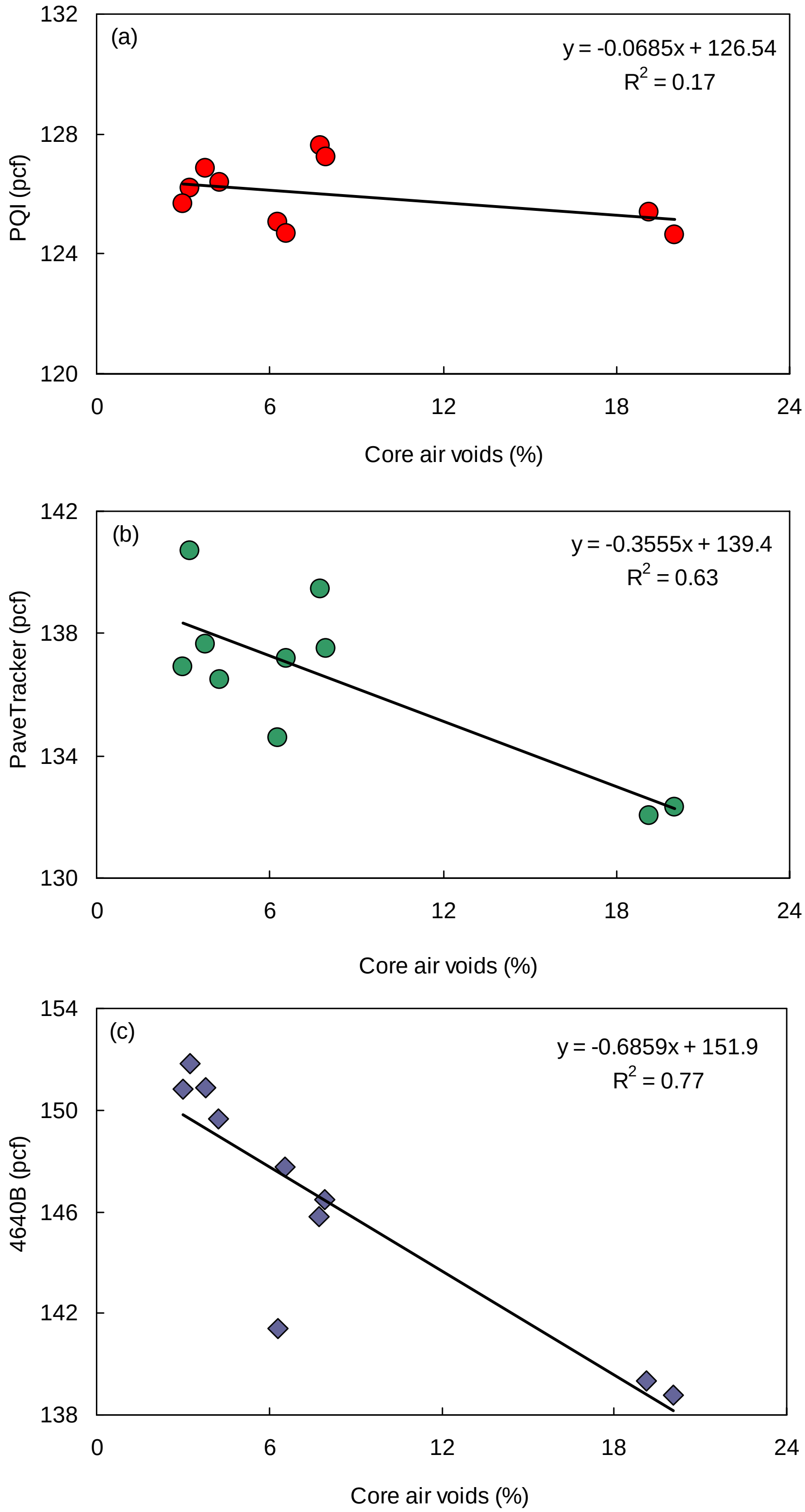

Figure 11. Relationship between NDG measurements and measured air voids in laboratory-compacted slabs: (a) TransTech PQI 301 non-nuclear density gauge, (b) Troxler PaveTracker Plus non-nuclear density gauge, (c) Troxler 4640-B nuclear density gauge.

- NNDGs appear to be less sensitive than NDGs. The NNDGs used had relative biases that were orders of magnitude higher (9.0 lb/ft^3 for the Troxler PaveTracker Plus and 19.5 lb/ft^3 for the TransTech PQI 301) than that of the NDG (2.2 lb/ft^3).

- Compared to traditional NDGs, NNDGs offer a safer and more expedient method for estimating AC density. In addition, NNDGs can be used to identify core cutting locations in a manner similar to that currently used with NDGs. However, as previously stated, the study did not find enough evidence to support their use as acceptance tools.

RECOMMENDATION

1. *VDOT's Materials Division should continue using NDGs for determining the density of AC materials when the core method (AASHTO T 166) is not used.* Until the rather large relative bias and lack of a good correlation between core density measured in accordance with AASHTO T 166 and NNDG-measured density are addressed, it is difficult to recommend their use as a comparable alternative to existing NDGs.

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