Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-04/0-4577-1		

4. Title and Subtitle EVALUATION OF NON-NUCLEAR DENSITY GAUGES FOR HMAC: YEAR 1 REPORT	5. Report Date October 2003 6. Performing Organization Code
7. Author(s) Stephen Sebesta, Marvin Zeig, and Tom Scullion	8. Performing Organization Report No. Report 0-4577-1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-4577
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Technical Report: September 2002-August 2003 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Further Development of NDT Devices to Identify Segregation in HMAC

16. Abstract

This report describes research efforts to determine if commercially available non-nuclear density gauges can be used for TxDOT's density profile and joint density testing procedures. Researchers conducted testing with a Troxler 3450 nuclear gauge (operated in the thin-lift mode) and the Pavetracker (PT) and Pavement Quality Indicator (PQI) non-nuclear gauges. In a laboratory setting, research showed all the gauges could be affected by mix temperature, where gauge readings typically decreased with decreasing mix temperature. All gauges' readings were also impacted by moisture, with the nuclear gauge least impacted. The precision of all gauges in the lab was good, with standard deviations below 0.5 pcf with the non-nuclear gauges and less than 1.0 pcf with the nuclear gauge. Field-testing showed the PQI was a suitable alternative to the nuclear gauge for density profiling and joint density testing. The Pavetracker performed erratically and should only be used for density profiling if it is calibrated to the mix; this gauge should not be used for testing joint density acceptance. All the gauges could exhibit bias in the field, and due to the sporadic nature of observed mean errors, gauge bias could not be estimated. *If the gauges were unbiased*, the following average levels of accuracy were indicated from the projects tested: Troxler 3450 nuclear gauge (in thin-lift mode): ±4.1 pcf; Pavetracker: ±5.7 pcf; PQI: ±2.6 pcf. All the gauges should be modified to include a slope calibration function for better accuracy. The Pavetracker performed erratically in the field; no additional testing should be performed with this gauge unless an upgraded model is obtained.

17. Key Words	18. Distribution Statement
Hot Mix Asphalt, Density Gauges, HMA, PQI, Pavetracker, Density Profile, Joint Density	No restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	84	

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

EVALUATION OF NON-NUCLEAR DENSITY GAUGES FOR HMAC: YEAR 1 REPORT

by

Stephen Sebesta
Associate Transportation Researcher
Texas Transportation Institute

Marvin Zeig
Student Technician II
Texas Transportation Institute

and

Tom Scullion, P.E.
Research Engineer
Texas Transportation Institute

Report 0-4577-1
Project Number 0-4577
Project Title: Further Development of NDT Devices to Identify Segregation in HMAC

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

October 2003

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation. The engineer in charge was Tom Scullion, P.E. (Texas, # 62683).

ACKNOWLEDGMENTS

This project was made possible by the Texas Department of Transportation in cooperation with the Federal Highway Administration. Many personnel made possible the coordination and accomplishment of the work presented herein. Special thanks must be extended to Magdy Mikhail, P.E., for serving as the project director. Tony Barbosa and Arif Chowdhury made the laboratory samples and collected the laboratory data.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

Table **Page**

EXECUTIVE SUMMARY

Over the past several years, one of the most urgent priorities within state DOT's has been finding suitable alternatives to the use of the nuclear density gauge. Additionally, achieving and being able to measure uniformity of new hot-mix asphalt overlays has been a major goal in the quality control/quality assurance area. As part of TxDOT project 0-4126 (completed in 2002), research work showed that both infrared imaging and ground-penetrating radar could effectively be used to evaluate uniformity and detect segregation in hot-mix asphalt (HMA) paving operations. In the process of project 0-4126, several non-nuclear density gauges were introduced for HMA applications. Thus, ongoing efforts were initiated to evaluate if these non-nuclear gauges could be used in place of the nuclear density gauge for TxDOT's density profile and joint density test procedures.

This report describes the results from the first year's research work of TxDOT project 0-4577, "Further Development of NDT Devices to Identify Segregation in HMAC." The work performed in the first year focused on evaluating the ruggedness, repeatability, and accuracy of the Troxler 3450 nuclear gauge and the Pavetracker and Pavement Quality Indicator (PQI) non-nuclear gauges. The first phase of the work evaluated how mix temperature, the presence of moisture on the HMA, and gauge battery voltage may affect the readings from the density gauges in a laboratory setting. In addition, researchers investigated the lift thickness function on the PQI, and the precision of the devices. Chapter 1 describes these results, and Appendix A of this report presents all the laboratory data. The laboratory testing indicated all devices could be affected by mix temperature, where gauge readings typically decrease with decreasing mix temperature. All gauge readings were also impacted by moisture. The nuclear gauge was impacted least by moisture. However, unless the test location is excessively wet, both non-nuclear gauges provided stable readings. Testing the effect of battery voltage with the PQI was not practical due to this gauge's auto-shutdown function. The Pavetracker is supposed to be recharged when the battery level drops below 9.0 V, and this gauge was tested down to a battery level of 8.2 V with no effect on density readings. The input lift thickness on the PQI was observed to marginally influence the gauge reading. The precision of all gauges in the lab was good, with standard deviations of repeat readings below 0.5 pcf with the non-nuclear gauges and less than 1.0 pcf with the nuclear gauge. The laboratory slabs were found unsuitable for evaluation of gauge accuracy.

Chapters 2 through 6 of this report describe the second and final phase of the first year's work plan. Researchers used all three gauges on TxDOT projects. The gauges were first calibrated to the job, and then researchers performed density profiles and collected field cores. This work served two purposes: first, the research team evaluated if the non-nuclear gauges could be used in place of the nuclear gauge for density profiles and joint density measurements; second, the accuracy of the gauges was evaluated in a field setting. Researchers tested the gauges on several projects, representing a spectrum of mix types including Type D, two projects with Type C, and SFA. The field-testing supported the following findings:

- The PQI, whether calibrated or not, could be used in place of the nuclear gauge for both density profiles and joint density evaluations.
- The Pavetracker could be used in place of the nuclear gauge for density profiles if calibrated to the mix. The Pavetracker should not be used for joint density evaluations.
- Rather than taking three 1-minute readings with the nuclear gauge oriented the same direction, density profiles with the nuclear gauge can be performed by only taking two 1-minute readings and rotating the gauge 180° between readings.
- While all the gauges could exhibit bias, the non-nuclear gauges seem very sensitive to slight changes in the HMA produced from day to day. Despite being calibrated one day prior to conducting density profiling, these gauges often exhibited bias, indicating a new calibration was needed. It appears the non-nuclear gauges need to be calibrated to the mix every day for that day's production if accurate results are desired.
- No gauge consistently performed best. Overall, the calibrated nuclear thin-lift was the most accurate, followed by the PQI, then the Pavetracker. There is room for improvement with all the gauges.
- The Giesel and Associates' Pavetracker seems to either have a glitch or requires unreasonably tedious testing procedures, as results with this gauge oftentimes seemed to bounce all over even though true core values changed little.
- All of the gauges should include a slope calibration function, where the user can input multiple true core densities and corresponding gauge readings over a range of values.
- *If the gauges were unbiased*, the following average levels of accuracy were indicated from the projects tested:

    - Troxler 3450 nuclear gauge (in thin-lift mode): ±4.1 pcf
    - Pavetracker: ±5.7 pcf
    - PQI: ±2.6 pcf

Despite the fact that none of the gauges performed flawlessly, there are some beneficial changes TxDOT can make based upon the results of this work. Given the promising results of using the PQI, whether calibrated to the mix or not, for density profiling and joint density testing, Appendix B and Appendix C of this report contain revised test procedures incorporating the use of this gauge. The PQI is much faster to use than a nuclear gauge. In addition, the procedure of taking only two readings with the nuclear gauge worked well and would reduce the time required for testing. Ongoing efforts in Year 2 of this project should include testing utilizing these procedures to verify the findings described in this report.

CHAPTER 1

LABORATORY ASSESSMENT OF RUGGEDNESS, REPEATABILITY, AND ACCURACY OF DENSITY GAUGES

SUMMARY

Researchers conducted a laboratory investigation to evaluate how mix temperature, the presence of moisture on the HMA, and gauge battery voltage may affect the readings from the PQI, Pavetracker, and Troxler 3450 nuclear gauge with thin-lift operational mode. In addition, researchers investigated the lift thickness function on the PQI and the precision and accuracy of the devices. The laboratory testing indicated all devices could be affected by mix temperature, where gauge readings typically decrease with decreasing mix temperature. All gauges' readings were also impacted by moisture. The nuclear gauge was impacted least by moisture. However, unless the test location is excessively wet, both non-nuclear gauges provided stable readings. Testing the effect of battery voltage with the PQI was not practical due to this gauge's auto-shutdown function; the manufacturer states the PQI should provide at least 13 hours of run time on a charge. The Pavetracker is supposed to be recharged when the battery level drops below 9.0 V, and this gauge was tested down to a battery level of 8.2 V with no effect on density readings. The PQI lift thickness function was observed to have minimal influence on the gauge reading.

The precision of all gauges in the lab was good, with standard deviations of repeat readings below 0.5 pcf with the non-nuclear gauges and less than 1.0 pcf with the nuclear gauge. None of the gauges performed very well with respect to accuracy in the laboratory testing. It is thought the test slabs were too small, and a better assessment of accuracy can be developed by first calibrating each gauge in the field to a mix, then returning to the project to test the calibrated gauge. Appendix A to this report presents the complete data collected in the laboratory; the remainder of this chapter details the methods and the important findings from the laboratory work.

LABORATORY METHODS

Researchers' goals from the laboratory test phase were to:

- evaluate the effect of mix temperature on gauge readings
- evaluate the effect of the presence of free moisture on the HMA on gauge readings
- evaluate the effect of battery voltage on readings with the non-nuclear gauges
- evaluate which device is most precise
- evaluate the accuracy of the gauges in a controlled setting

To accomplish these goals, researchers selected two mix types (1 inch SFA and Type C) from which they prepared HMA slabs in the laboratory with a linear kneading compactor, shown in Figure 1.1. Table 1.1 shows the mixture designs for these mixes. For each mix type, project personnel prepared test slabs of varying densities and thickness. The length and width of the slabs were 18 inches × 12.5 inches. Table 1.2 shows the laboratory data for each test slab. Researchers measured both the bulk density of the entire slab and, after completing all testing, cored a 6 inch diameter sample from the center of each slab and measured the density of this center core.

Figure 1.1. Preparation of Laboratory Slabs with Linear Kneading Compactor.

Table 1.1. Mixture Design of HMA Used in Laboratory Testing.

1" Stone Filled		**Type C**	
Sieve Size	% Passing	Sieve Size	% Passing
1	100.0	7/8	100.0
¾	85.9	5/8	100.0
½	54.5	3/8	84.9
3/8	41.4	#4	59.0
#4	31.9	#10	39.2
#8	22.6	#40	22.5
#16	14.6	#80	9.7
#30	10.4	#200	5.3
#50	7.4		
#100	5.2		
#200	2.3		
Design Binder Percent: 4.1		**Design Binder Percent:** 4.4	
Measured Rice Gravity (pcf): 156.2		**Measured Rice Gravity (pcf):** 152.1	

Table 1.2. Laboratory Data on Test Slabs.

Mix Type	Slab Thickness (in.)	Slab Bulk Density (pcf)	Slab Air Voids (%)	Center 6" Core Density (pcf)	Center Core Voids (%)	Slab I.D.
SFA	2.5	152.0	2.6	153.5	1.7	SF-2.5-1
		150.4	3.7	151.6	2.9	SF-2.5-2
		148.6	4.8	149.9	4	SF-2.5-3
		145.4	8.9	145.8	6.6	SF-2.5-4
	3.0	148.6	4.8	150.9	3.3	SF-3-1
		144.4	7.5	144.8	7.2	SF-3-2
Type C	2.0	147.6	2.9	148.3	2.5	C-2-1
		144.7	4.8	145.9	4	C-2-2
		141.5	6.9	142.1	6.5	C-2-3
		137.8	9.3	141.8	6.7	C-2-4
	2.5	146.0	3.9	148.4	2.4	C-2.5-1
		138.2	9.0	135.8	8.3	C-2.5-2
		137.7	9.4	139.4	10.7	C-2.5-3
	3.0	145.7	4.1	147	3.3	C-3-1
		138.7	8.7	140.5	7.6	C-3-2

To conduct testing, each slab was placed on a sand test box (3 ft. × 3 ft. × 1.5 ft.), as shown in Figure 1.2, after compaction. As the slabs cooled, researchers measured the slab temperature with an infrared temperature gun and then measured the densities of the slabs with the various density devices as described below:

- PQI and Pavetracker: Researchers collected four readings with the device in the center of the slab by rotating the device 90° between readings. The average of the four readings was recorded as one measurement.
- Nuclear gauge: Due to its size, researchers collected two 1-minute readings with the nuclear gauge rotated 180° between readings. The average of the two readings was recorded as one measurement. The test slabs were not large enough to rotate the nuclear gauge 90° between readings.

Figure 1.2. Laboratory Slab on Sand Box for Density Testing.

To evaluate the effect of moisture, researchers recorded density measurements after spraying moisture on the top of the HMA with a spray bottle. To evaluate the effect of battery voltage on density readings, researchers left the Pavetracker turned on and periodically referenced the gauge to its case, recorded the battery voltage, then recorded the measured density on a slab of HMA. The outline of the Pavetracker was drawn on the slab with a crayon to ensure the gauge was placed in the same location for each reading. Similar testing was found impractical with the PQI, as this gauge automatically turns itself off after a set time. The PQI is supposed to operate for at least 13 hours on a full charge.

The research team made an extra 2.5 inch thick slab of the Type C material to examine the repeatability of the devices. The density was read 40 times with the non-nuclear devices and 20 times with the nuclear gauge, yielding a total of 10 measurements with each device (one measurement is the average of four readings with the gauge rotated 90° between readings for the non-nuclear devices and the average of two readings with the gauge rotated 180° between readings for the nuclear gauge). Researchers conducted this testing with the slab at approximately 230 °F then examined the standard deviation of the test results.

To investigate the accuracy of the devices, the research team compared gauge measurements to the measured density of the center cores taken from the slabs. To approximate field conditions, researchers used the gauge readings with the slab temperature closest to 140 °F.

EFFECT OF SLAB TEMPERATURE ON GAUGE READINGS

With the SFA slabs both the PQI and the Pavetracker exhibited a general trend of an increasing gauge reading with increasing mat temperature, as illustrated in the example data set plotted in Figure 1.3. The nuclear gauge did not show any relationship between slab temperature and gauge reading with this mix. From the observations with the SFA mix, a 100 °F drop in temperature would be expected to result in a decrease in the density reading of the PQI by 1.8 pcf and a decrease in the Pavetracker reading of 5.2 pcf.

With the Type C slabs, only the nuclear gauge showed a trend of increasing gauge reading with increasing temperature. With all the Type C data, an increase in temperature of 100 °F would be expected to result in an increase in the nuclear gauge reading of 1.4 pcf. It is not understood why the results from the SFA and the Type C mixes contradict each other.

Based upon the tests investigating the effect of mix temperature on density readings, all the gauges tested could exhibit decreasing density readings as the mix cools. In general, the effect should not be too severe; typically if a relationship was observed a 100 °F drop in temperature would only be expected to impact the density reading by 1.5 to 2.0 pcf. However, with one mix the Pavetracker readings were influenced rather significantly, where a 100 °F drop in temperature would be expected to result in a drop in the density reading of over 5 pcf. Thus, regardless of which gauge is being used, readings should be taken when the mix is within a specified temperature range for maximum reliability. If testing is always conducted when the mat temperature is within a specific 30 to 40 °F window, the risk of significantly impacting test results should be relatively low.

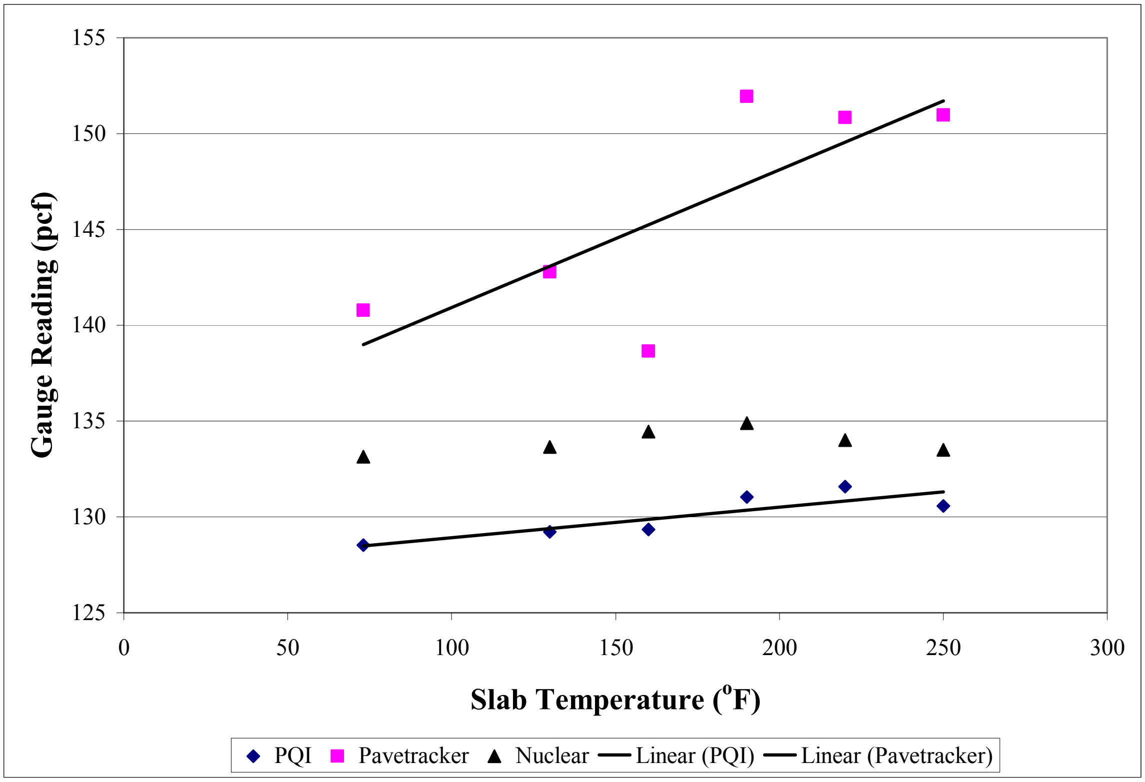


Figure 1.3. PQI and Pavetracker Readings Increase with Increasing Slab Temperature with SFA Mix.

EFFECT OF FREE MOISTURE ON GAUGE READINGS

Researchers suspected moisture would impact the density readings, especially with the non-nuclear gauges since the manufacturers warn against testing when excessive moisture is present. The non-nuclear gauges were impacted more severely by moisture than the nuclear gauge. Figure 1.4 illustrates the magnitude of the change in the average measured density value with the gauges when going from a dry to wet HMA condition. The figure uses the PQI moisture reading as an indicator of moisture, since in the thin-lift mode the nuclear gauge does not provide a moisture reading. Adding moisture to the slab resulted in an increase in the gauge-measured density. The nuclear gauge was impacted the least, followed by the PQI, then the Pavetracker. At a PQI moisture number of 7, the Pavetracker density value starts to climb. At a PQI moisture number of 10, the PQI density value starts to climb. It should be noted that when the PQI moisture number was 10, the HMA surface was visibly wet and water was starting to pond on the surface. Therefore, the research team concluded that all the gauges should be relatively insensitive to water as long as the operator uses good judgment and does not test on an excessively wet test location. The PQI gauge, however, does have an advantage over the Pavetracker because the PQI provides a numeric moisture number for the operator's reference. The PQI moisture number must be less than 10 or else the reading should be disregarded.

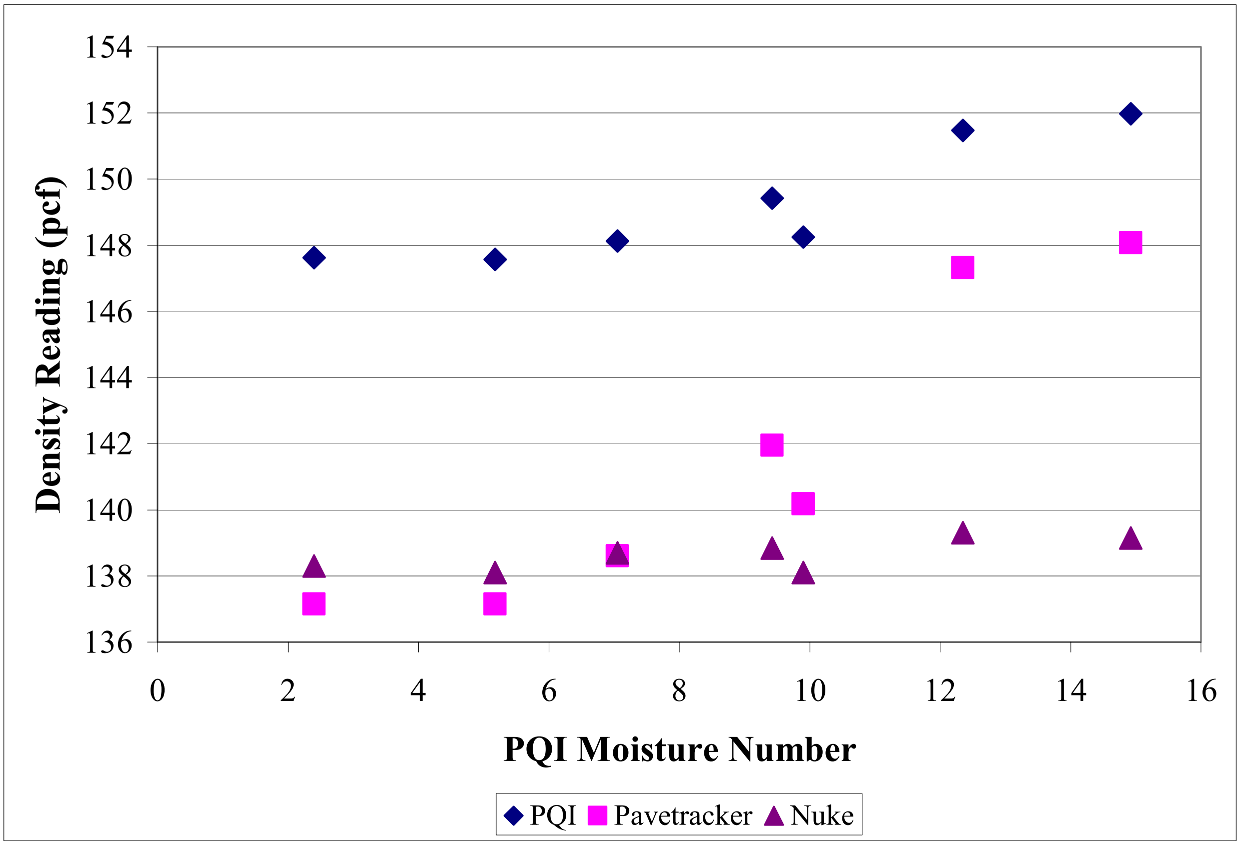


Figure 1.4. Level of Change in Average Density from Dry to Moist Slab Condition.

EFFECT OF BATTERY VOLTAGE ON READINGS WITH NON-NUCLEAR GAUGES

Table 1.3 shows the results from testing the same location with the Pavetracker as the battery voltage dropped. The operating instructions for this gauge recommend recharging when the battery level drops below 9.0 V. Researchers tested this gauge down to a battery level of 8.2 V. Statistical tests reveal there is no correlation between battery voltage and the density reading within the voltage range tested. Thus, the data indicate this gauge could be used down to a battery level as low as 8.2 V before recharging. This finding is especially advantageous, since if the gauge were to be recharged at 9.0 V the data reveal the user would only get one hour of use before a recharge is needed. In contrast, the PQI is supposed to provide at least 13 hours of use on a full charge.

Table 1.3. Effect of Battery Voltage on Pavetracker Readings.

Battery Voltage	Gauge Reading	Time (hrs:mins)
9.52	152.8	0:00
9.38	152.5	0:10
9.25	152.6	0:20
9.18	152.7	0:30
9.10	152.5	0:45
9.03	152.3	1:00
8.98	152.4	1:15
8.78	152.3	2:15
8.60	152.5	3:30
8.46	153.7	4:10
8.37	152.8	4:35
8.21	152.7	5:15

EFFECT OF INPUT LIFT THICKNESS ON PQI READINGS

Figure 1.5 shows the average PQI reading with varying input lift thickness on two test locations. The figure illustrates that, although the PQI reading slightly decreases with increasing input lift thickness, the overall impact of the function is negligible. In fact, at most the difference in the PQI reading when changing the input lift thickness from 1 inch to 8 inches was 0.3 pcf.

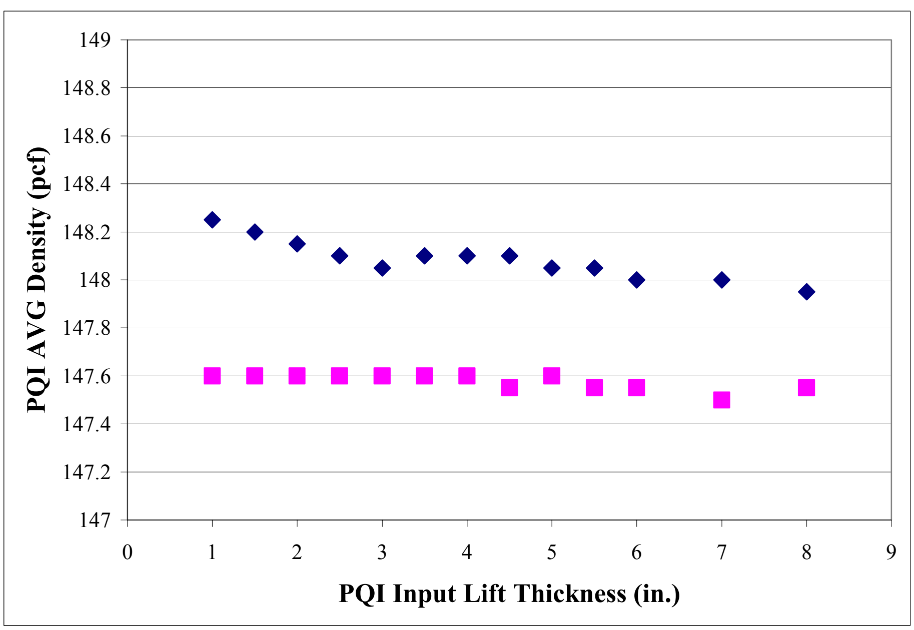


Figure 1.5. Impact of Input Lift Thickness on PQI Readings.

REPEATABILITY PERFORMANCE OF DENSITY GAUGES

Figure 1.6 and Table 1.4 show the results from repeatability testing. With the gauge oriented the same way on the slab with repeat readings, the Pavetracker is the most repeatable, followed by the PQI, then the nuclear gauge. If the average reading from all gauge orientations used is considered as one measurement, the PQI performed best, followed by the Pavetracker, then the nuclear gauge. The standard deviation of the 10 average measurements for the PQI, Pavetracker, and nuclear gauge were 0.14, 0.16, and 0.40 pcf, respectively. All of the observed standard deviations were low, less than 1 pcf.

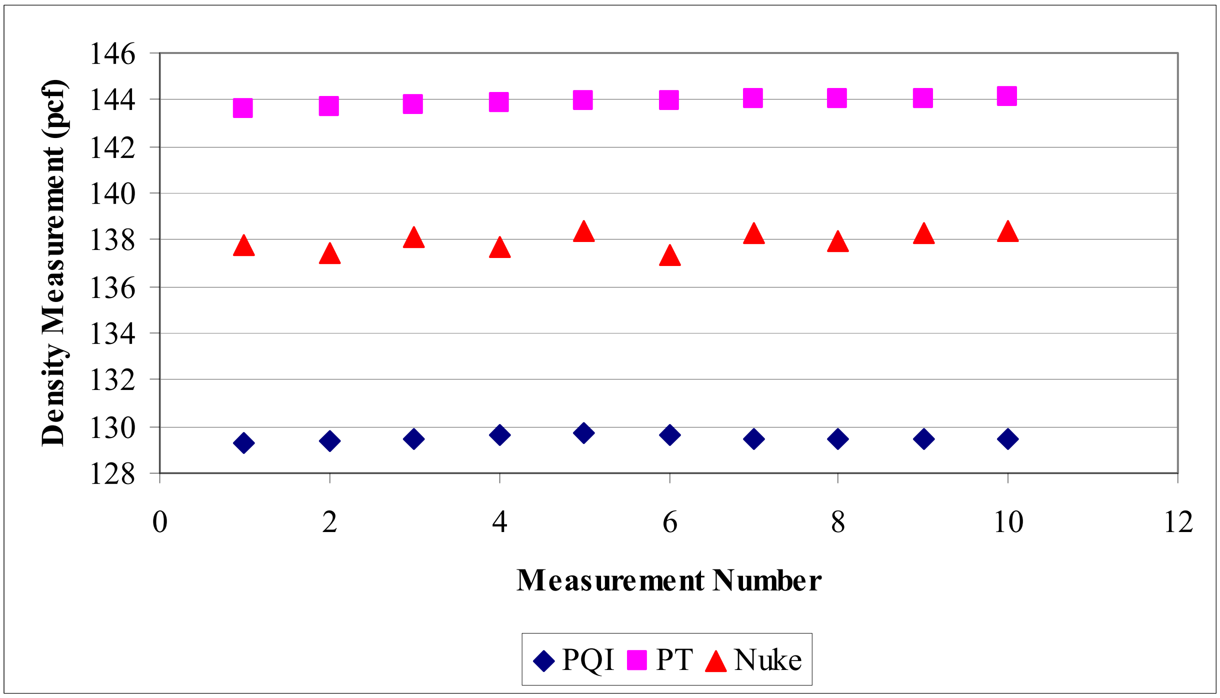


Figure 1.6. Test Results from Repeatability Investigation.

Table 1.4. Laboratory Repeatability Test Results.

	Transtech (PQI)					Pave Tracker					Nuclear		
Test #	1	2	3	4	Avg	1	2	3	4	Avg	1	2	Avg
1	127.9	130.1	129.3	129.7	129.3	142.2	143.0	144.5	144.8	143.6	136.9	138.7	137.8
2	128.1	130.3	129.6	129.6	129.4	142.5	143.0	144.5	144.8	143.7	136.2	138.6	137.4
3	128.5	129.6	129.7	129.9	129.4	142.6	143.0	144.5	144.9	143.8	138.1	138.1	138.1
4	128.4	130.7	129.5	129.8	129.6	142.7	143.0	144.6	145.0	143.8	137.2	138.2	137.7
5	128.6	130.8	129.9	129.6	129.7	142.7	143.3	144.6	145.0	143.9	138.2	138.6	138.4
6	128.9	130.5	129.5	129.7	129.7	142.7	143.3	144.6	145.1	143.9	136.6	138.0	137.3
7	128.8	130.3	129.1	129.5	129.4	142.7	143.4	144.7	145.2	144.0	137.3	139.2	138.3
8	128.7	130.2	129.3	129.7	129.5	142.8	143.4	144.7	145.3	144.1	136.7	139.1	137.9
9	128.6	130.2	129.2	129.8	129.5	142.7	143.4	144.7	145.4	144.1	137.5	139.1	138.3
10	128.6	130.3	129.3	129.6	129.5	142.8	143.3	144.8	145.5	144.1	138.3	138.5	138.4
Average	128.5	130.3	129.4	129.7	129.5	142.6	143.2	144.6	145.1	143.9	137.3	138.6	138.0
Standard Deviation (pcf)	0.31	0.33	0.25	0.12	0.14	0.18	0.19	0.10	0.24	0.16	0.72	0.43	0.40

ACCURACY OF GAUGES ON LABORATORY SLABS

As a whole, none of the gauges performed very well in the laboratory tests with respect to accuracy. Figures 1.7 through 1.9 show the results with the stone-filled mix. With this mix, the PQI had the slope closest to 1.0. The slope of the nuclear gauge data was almost double that of the perfect-fit line. In general all the gauges read low with this mix, probably a result of the combined effects of the mix type (coarser texture) and the relatively small size of the test slabs.

Figures 1.10 through 1.12 show the results of the gauges with the Type C mix. With the Type C mix, the nuclear gauge had the closest slope to 1.0 in the relationship between core density and gauge measurement. However, as evident in Figure 1.11, all the nuclear readings are low. The cause of this is probably air around the slabs; the slabs do not adequately represent a mat of HMA.

Given the problems with attempting to evaluate the accuracy of the gauges with test slabs in the lab, researchers believe a better assessment of gauge accuracy can be made through field measurements and coring. Laboratory slabs were relatively small as compared to the gauge sizes; the amount of air around the slabs likely influenced the gauge results. Furthermore, for optimum accuracy gauges need to be calibrated to the mix before recording "official" readings. In these tests none of the gauges had been calibrated prior to testing.

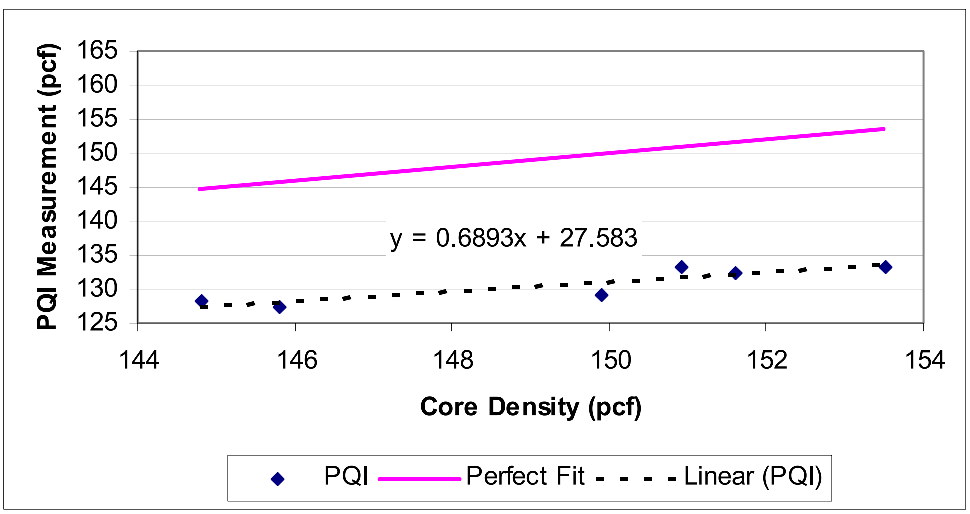


Figure 1.7. PQI Results with SFA.

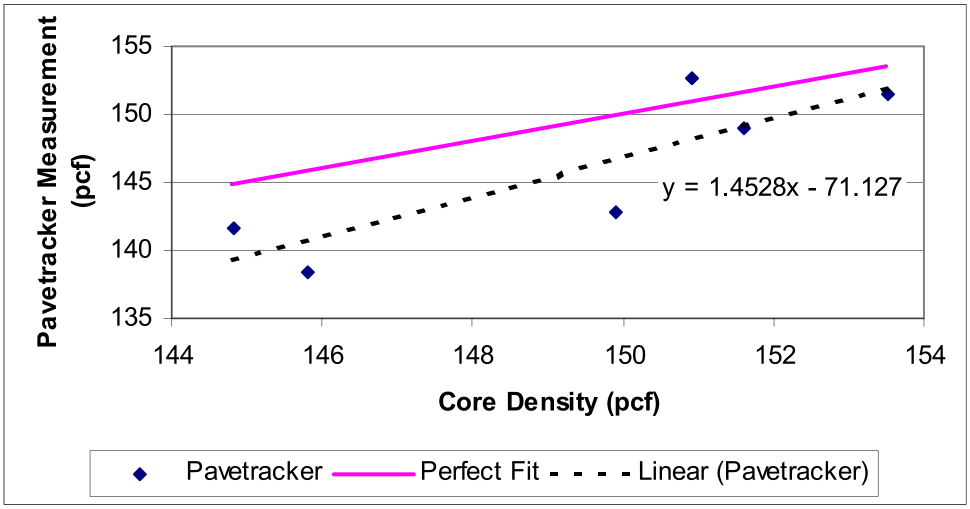


Figure 1.8. Pavetracker Results with SFA.

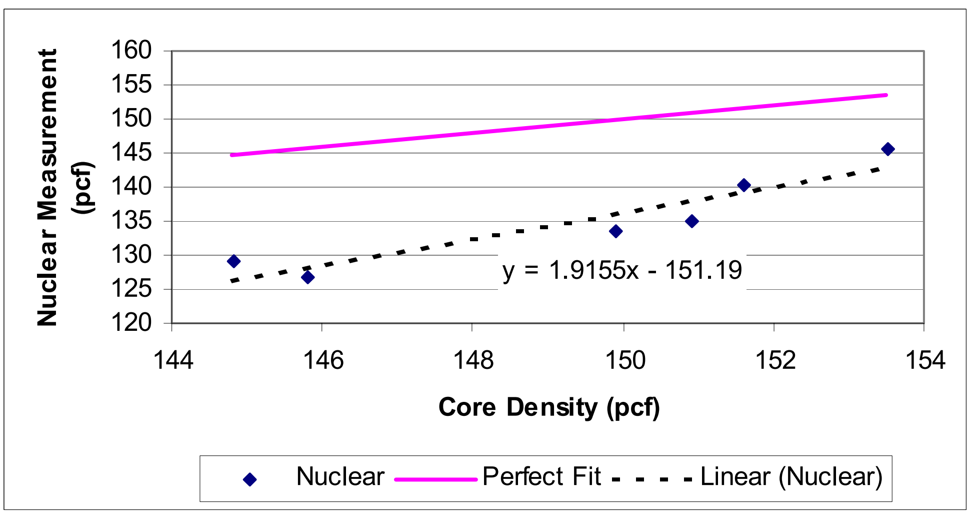


Figure 1.9. Nuclear Gauge Results with SFA.

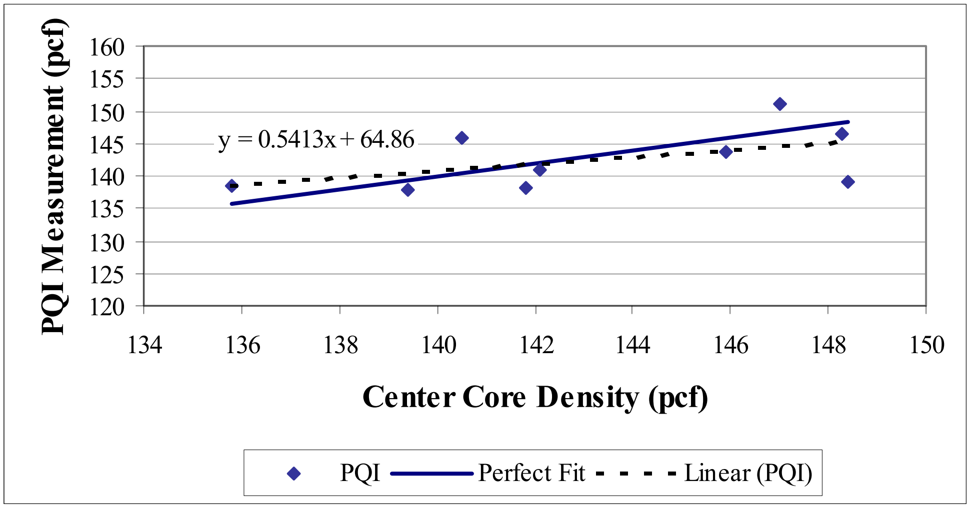


Figure 1.10. PQI Results with Type C Mix.

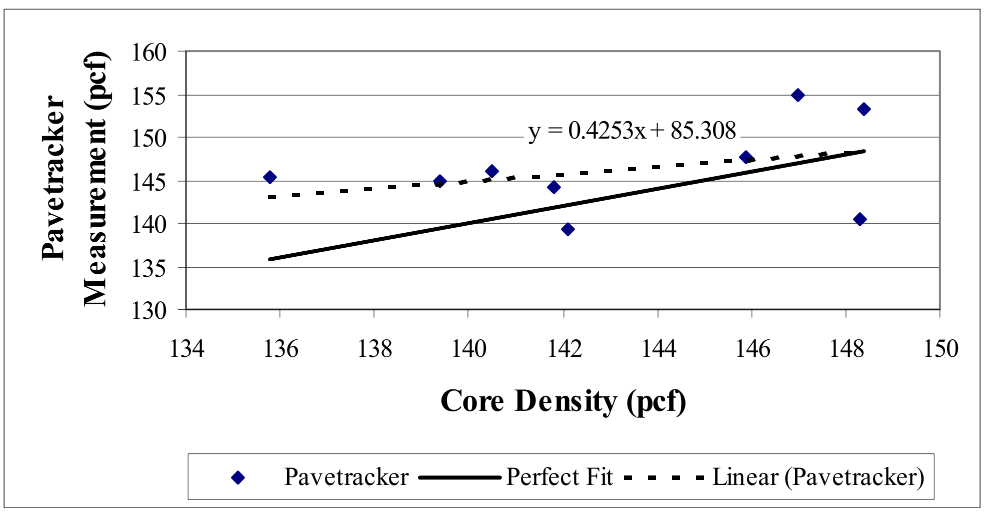


Figure 1.11. Pavetracker Results with Type C Mix.

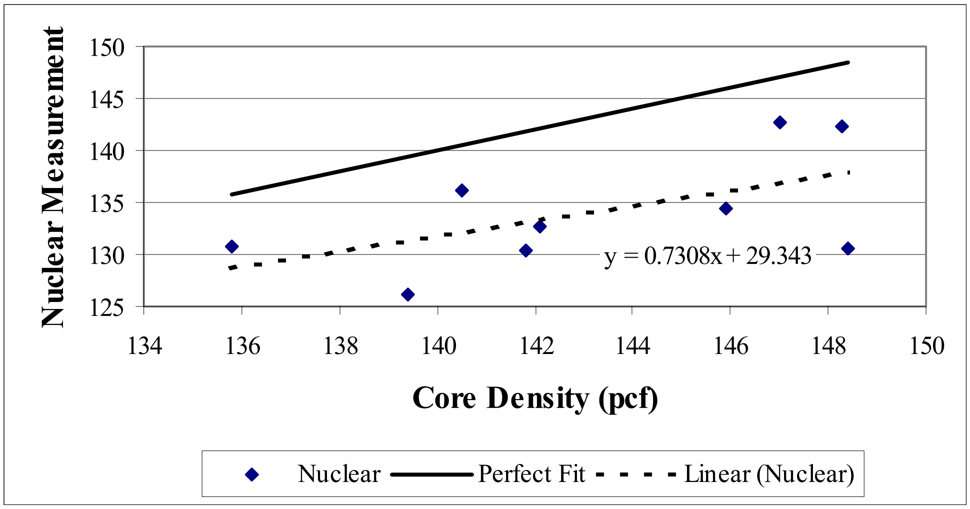


Figure 1.12. Nuclear Gauge Results with Type C Mix.

CONCLUSIONS FROM LABORATORY WORK

Based upon the results from the laboratory test phase, researchers made the following observations:

- All of the gauges were influenced by mix temperature at some time. In general, gauge readings dropped with decreasing mix temperature. Readings should be taken at a specified temperature or when the mix is within a specified temperature range for maximum reliability.
- All of the gauges could be influenced by the presence of moisture on the HMA. The presence of moisture typically resulted in an increase in gauge readings. In these laboratory tests, the PQI was affected the most and the nuclear gauge was affected the least.
- If needed, users should be safe operating the Pavetracker at battery levels down to 8.2 V. Due to its auto-shutdown feature, testing the impact of battery level on the PQI was not practical.
- In the laboratory tests of repeatability, all of the gauges performed well. The standard deviation of repeat readings was less than 1.0 pcf for all the gauges. Both non-nuclear gauges performed better than the nuclear gauge in repeatability testing. For best precision, multiple readings should be collected then averaged to constitute one measurement.
- Attempting to assess the accuracy of the gauges with the laboratory slabs did not work well. The slabs were deemed too small, and no gauge consistently exhibited the best relationship with core density. Gauge calibration should be performed in the field.

CHAPTER 2

FIELD TEST PLAN

SUMMARY

To consistently and effectively collect field data useful for analyzing the performance of each density gauge, Texas Transportation Institute (TTI) researchers developed written guidelines for use by project personnel describing proper methods for gauge placement, gauge calibration, and subsequent testing. Researchers formatted gauge placement and calibration guidelines from the manufacturers' recommendations. Project personnel formatted testing guidelines as appropriate to evaluate whether the non-destructive test (NDT) devices result in findings consistent with the nuclear gauge when used for density profiles (Tex-207-F Part V) and joint density (Tex-207-F Part VII) specifications.

METHODS

PQI

General Information

- PQI is non-nuclear and has several operating modes and calibration modes
- Mode is changed by pressing the "mode" key
- "Menu" key is used to access mix information (Rice gravity, lift thickness, max particle size), displayed measurement units (metric/English), etc.
- Calibration modes include linear offset and a slope/offset calibration
- Ideally, collect project data with both 3-second mode and continuous mode (for comparison purposes)
- Ideally, collect project data both with only a linear offset and with the slope/offset calibration
- Battery voltage is displayed in the continuous mode. Charge unit when battery voltage is below 11.5 V

Gauge Placement

- Ensure no significant protruding stones are on the surface (to avoid an air gap between gauge and HMA)
- Do not test any location where there is water visible on the HMA
- Verify the bottom of the gauge is not damp or wet. Wipe dry any damp components
- Place gauge directly over location of interest
- Trace an outline of the gauge with a marking crayon
- Start the measurement. Do not touch the gauge while reading. Record the reading

- Take and record four additional readings at 2, 4, 8, and 10 o'clock positions relative to the original gauge position, for a total of five readings at each test location, as shown in Figure 2.1 (bold line is position one; see User's Manual for additional info).
- Average the five readings as the "official" gauge measurement at the test location

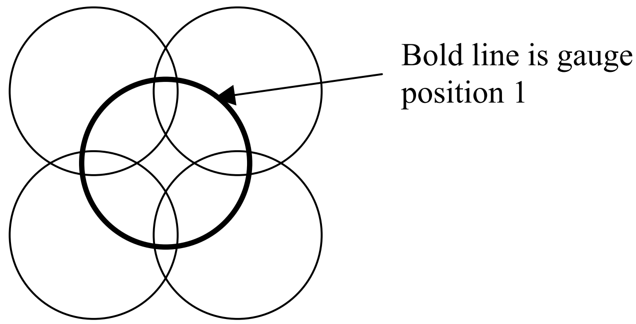


Figure 2.1. PQI Positions for Each Test Location

Gauge Calibration-Data Collection

- Verify gauge is adequately charged (>11.5 V)
- **Make sure all gauge calibration factors are at factory settings before taking readings for calibration**
  - Offset should be 0.00
    - Press "CAL"
    - Select "Normal"
    - If current "Offset" is negative, select "PQI reads to lo"
    - If current "Offset" is positive, select "PQI reads to hi"
    - Input the absolute value of the current offset at the "Offset Adjustment" screen and press "Enter"
    - The "New Offset" should now read 0.0
    - Select "Use this value"
  - Slope should be 1.00
    - Press "CAL"
    - Select "Special"
    - Select "Manual Slope"
    - At the "Set Slope" screen, if the current slope is not 1.00, select "Enter a new value"
    - Input 1.00 and press "Enter"
- Take calibration readings in the single-reading mode
- Record single readings as described in *Gauge Placement* on at least three calibration test locations (typically eight to 10 readings are taken then core locations selected)
  - Infrared and/or GPR can be used to screen for potential calibration locations
  - One test location should be the lowest density reading
  - One test location should be the highest density reading
  - One test location should be a "normal" location

- Obtain cores from within the outline of gauge position 1 at each calibration location and measure the bulk density of the cores in the laboratory
- Either from project job mix formula (JMF) or lab test, obtain the Rice gravity of the HMA and determine the percent compaction of each calibration core

Gauge Calibration-Linear Offset Method

- Determine the **linear offset calibration** for the project as follows:
  - Average the readings from the five gauge positions at each calibration test location
  - Determine the error at each test location by subtracting the laboratory-determined density from the average gauge density at that location
  - Average all the errors to obtain the linear offset.
  - Input the offset into the PQI by pressing "CAL," "Normal," then select whether the PQI reads too high or too low. Input the offset value.

Gauge Calibration-Slope Method

- Determine the **slope calibration** as follows:
  - **Do not use the slope function unless the range of percent compaction from the high to low calibration cores is at least 4 percentage points**
  - Return all gauge calibration factors to factory settings (offset=0.00; slope=1.00)
  - Input the Rice gravity of the mix in the gauge
    - Press "Menu"
    - Select "Mix Information"
    - Select "Set MTD"
    - Select "Enter a new value"
    - Input the desired Rice gravity value and press "Enter"
  - Enter the calibration menu by pressing the "CAL" button
  - Press "2" for Special Calibration
  - Select "3" for Two-Point Method
  - When prompted, enter the "Low Reading." This is the lowest PQI reading from the calibration locations
  - When prompted, enter the "High Reading." This is the highest PQI reading from the calibration locations
  - When prompted, enter the "Lo Estimate." This is the percent compaction of the calibration core (from laboratory density test and Rice gravity) that corresponds with the lowest PQI reading
  - When prompted, enter the "Hi Estimate." This is the percent compaction of the calibration core (from laboratory density test and Rice gravity) that corresponds with the highest PQI reading.
  - The PQI will display a new slope. Record this value, and select to use this value.

Pavetracker

General Information

- Pavetracker is non-nuclear and only has a linear offset calibration
- Pavetracker is calibrated by changing the reference density when the device is inside its calibration/storage case
- Charge the Pavetracker if battery voltage is below 9.0 V. Check battery voltage by pressing the "battery" button

Gauge Placement

- Ensure no significant protruding stones are on the surface (to avoid an air gap between the gauge and HMA)
- Do not test any location where there is water visible on the HMA
- Verify the bottom of the gauge and the inside of the calibration case is not damp or wet. Wipe dry any damp components
- Perform testing with the Pavetracker in the "Fast" operating mode and on the "lbs" setting
- Allow the gauge to warm up for 1 minute before performing an testing
- Before testing a location, place Pavetracker in its calibration/storage case as shown in Figure 2.2 and press "Ref." Verify correct reference density value

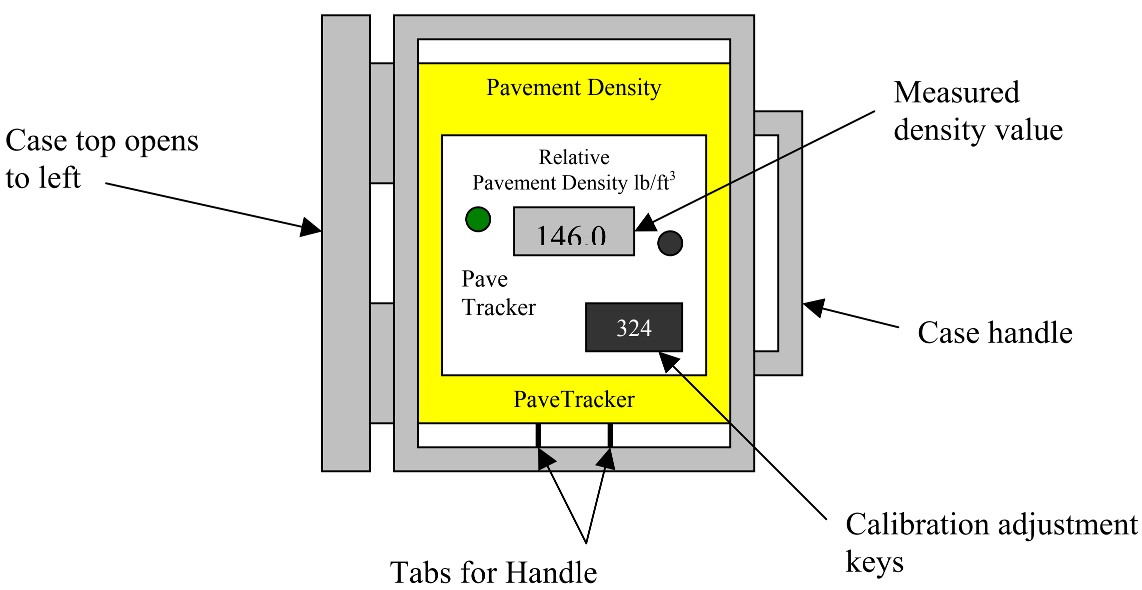


Figure 2.2. Proper Placement of Pavetracker in Case for Calibration Referencing.

- Place Pavetracker in the center of previous PQI position 1 and record the reading
  - Maintain a distance of at least 2 ft. between any objects and the Pavetracker
  - Do not touch the Pavetracker while recording measurements
  - If PQI is not used, outline the Pavetracker with crayon
- Record three additional readings at each test location by rotating the Pavetracker 90° between readings. The Pavetracker should be approximately centered inside the circle from the PQI for each reading.
- Average the four readings as the "official" Pavetracker measurement at the location

Gauge Calibration-Data Collection

- Verify gauge is adequately charged (>9.0 V)
- Allow the gauge to warm up for 1 minute
- Place the gauge inside its reference case as illustrated in Figure 2.2
- Press the "Ref" button and record the density value
- Record the three-digit number on the calibration adjustment keys
- Record readings as described in *Gauge Placement* on at least three calibration test locations (typically eight to 10 readings are taken then core locations selected)
  - Infrared and/or GPR can be used to screen for potential calibration locations
  - One test location should be the lowest density reading
  - One test location should be the highest density reading
  - One test location should be a "normal" location
- Obtain cores from within the gauge outline at each calibration location and measure the bulk density of the cores in the laboratory

Gauge Calibration

- Determine the offset calibration for the project as follows:
  - Average the readings from the four gauge positions at each calibration test location
  - Determine the error at each test location by subtracting the laboratory-determined density from the average gauge density at that location
  - Average all the errors to obtain the linear offset. A negative average error means the gauge is reading too low. A positive average error means the gauge is reading too high.
- Adjust the offset in the gauge as follows:
  - Place Pavetracker in its calibration case as shown in Figure 2.2
  - Press "Ref"
  - Record the current reference density value
  - If the gauge was reading too low, increase the three-digit calibration number with the calibration adjustment keys and press "Ref" by trial and error until the new reference density value has been increased by the required amount. If the gauge was reading too high, decrease the three-digit calibration number with the calibration adjustment keys and press "Ref" by trial and error until the new reference density value has been decreased by the required amount
  - Record both the new three-digit calibration number and the reference density.

Nuclear Density Gauge (Troxler Model 3450)

General Information

- When not taking a reading keep the source rod in standard position (all the way up)
- The nuclear gauge must be put into a calibration mode when taking measurements in order to calibrate to job. This is stored as a "partial calibration." After coring, the core densities are input into the gauge to complete the calibration
- Ideally, perform measurements at potential calibration core sites first in the thin layer measurement mode. Then after selecting core locations, enter the calibration mode and collect density measurements at these locations in the calibration mode
- Perform all normal measurements in the 1-minute count mode

Gauge Placement

- Ensure the site is smooth and the gauge does not rock
- Place the gauge centered over the area of interest
- Set the gauge to thin layer mode by pressing "Mode" then select "Thin Layer Mode"
- Enter the overlay thickness and press "Enter"
- Press "Start"
- Lower the source rod to the backscatter position (first click down) and make sure the rod latches in place
- If testing a location that has not been cored, center the gauge on the test location and take two readings by rotating the gauge 180° between readings
- If testing a previously cored location, take four readings as shown in Figure 2.3
- Press "Start" to begin the reading
- Record the reading, then lift the gauge by the source rod handle and move the gauge to the next test position or location, as appropriate

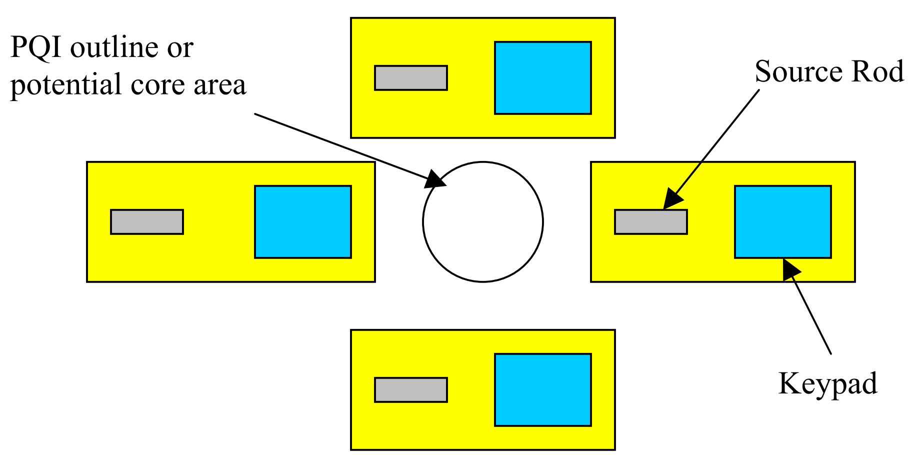


Figure 2.3. Nuclear Gauge Readings around Previously Cored Location.

Gauge Calibration-Data Collection

- Turn the gauge on, allow it to warm up, and take standard counts (see page 4-3 in the Users' Guide)
- Place gauge on standard block with the keypad side of the gauge on the side of the block with the metal plate
- Press "Standard"
- With source rod in standard position, press "Enter"
- Verify that standard counts pass. If any fail, see pages 4-5 and 4-6 in Users' Manual
- Set gauge to thin layer mode by pressing "Mode" then select "Thin Layer Mode"
- Record readings as described in *Gauge Placement* on at least three calibration test locations
    - Troxler recommends calibration cores close together with very little variation in density, preferably each location 2 to 5 ft. apart
- After deciding upon which locations to core, enter the thin layer special calibration menu by pressing the "Special" key
    - Select "Special Operation"
    - Select "Thin Lift Special"
    - Select "New"
- Select "Measure Density"
- Enter the number of measurements you will take then press "Enter." You should take at least four readings at each core location, but take the same number of readings at every location. The total number of readings should be at least 12. For example, if you will core four locations, you will need to enter "16" for the number of measurements if you are going to take four readings at each location.
- Troxler recommends taking the calibration readings with the gauge centered on the core location. Take two readings, then rotate the gauge 180^{o} and take the last two readings
    - Place source rod in backscatter position and press "Start"
    - Follow the gauge prompts and complete all the readings
- After collecting all the calibration counts, press "Enter" at the gauge prompt
- Select "Store Partial Calibration" so the gauge stores the readings for later use
- Collect cores and return them to the laboratory for bulk density measurements
- Average the core densities

Gauge Calibration

- After obtaining laboratory densities on the calibration cores, enter the thin layer special calibration functions by pressing "Special," then select "Special Operation"
- Select "Thin Lift Special" then "New"
- There should be a "P" to the right of the "Measure Density" option indicating a partial calibration is stored in memory. Select "Input True Density"
- Enter the average core density from the calibration cores and press "Enter"
- The gauge should prompt for a calibration name. Enter a name for the calibration
- Note the calibration name/number and what job it corresponds to

CHAPTER 3

RESULTS FROM US 281

SUMMARY

TTI researchers performed density profiles with the nuclear gauge, the Pavetracker, and the PQI, on US 281 north of Stephenville. Researchers collected data to calibrate the gauges on June 30, 2003, then performed the density profile with the calibrated gauges on July 1, 2003. With respect to accuracy, the nuclear gauge performed best, followed by the PQI, then the Pavetracker. With respect to TxDOT's density profile criteria, all the gauges indicated the mat passed the density uniformity requirement. Analysis of cores taken from the site verified the results from the gauges. Thus, despite some accuracy issues with the non-nuclear gauges, on this project both non-nuclear gauges tested resulted in the same pass/fail decision as the nuclear gauge in TxDOT's density profile test.

DESCRIPTION OF TEST SITE

The test site on US 281 was 25 miles north of Stephenville, Texas, and was a 2 inch layer of Type D mix with JMF as shown in Table 3.1. Researchers tested the northbound lane and performed calibrations with five cores on June 30, 2003. Although no visible segregation was present, on July 1, researches performed a density profile in the northbound lane 1000 ft north of the calibration site. There was no joint profile due to working conditions and time constraints. The profile was tested using default gauge settings and then retested with calibrated gauges. Figure 3.1 shows the site of the density profile testing.

Table 3.1. US 281 JMF.

Mix Type:	Type D
Binder Percent, (%):	5.1
Rice Sp. Gravity:	2.469

Sieve Sizes	Cum. % Passing
½”	100.0
3/8”	98.9
No. 4	84.2
No. 10	36.8
No. 40	18.7
No. 80	8.1
No. 200	3.0

Figure 3.1. US 281 Test Site.

GAUGE CALIBRATION DATA

Table 3.2 shows the data collected on US 281 to calibrate the density gauges to the mix. Nuclear gauge data are not presented, since the gauge calibration is performed internally with this gauge. On average, the PQI read 9.4 pcf too low, and the Pavetracker read 12.9 pcf too high. Thus, the appropriate linear offset was input into the gauges for calibration.

Table 3.2. Gauge Calibration Data for US 281.

Core #	Actual Core Density (pcf)	PQI Core Density (pcf)	PQI Error	PT Core Density (pcf)	PT Error
1	140.7	130.5	-10.2	147.5	6.8
2	142.1	133.3	-8.8	151.5	9.4
3	140.5	130.2	-10.3	157.6	17.1
4	140.8	131.1	-9.7	147.1	6.3
5	139.7	131.7	-8.0	164.7	25.0
Avg	**140.8**	**131.4**	**-9.4**	**153.7**	**12.9**

EVALUATION OF GAUGE PERFORMANCE

Density Profile

Upon calibration of the gauges, all gauges gave a passing decision in the density profile for the test site on US 281. The density range from highest to lowest of the mat was 1.6 pcf for the nuclear gauge, 2.4 pcf for the Pavetracker, and 0.9 pcf for the PQI. In comparison, the actual range from the cores was 1.9 pcf. Figure 3.2 illustrates the results from the density profile on this job. Table 3.3 contains all the data collected on this density profile.

Another important issue is whether the profile results of uncalibrated gauges match the results from the calibrated gauges. Thus, researchers also collected the density profile data with the gauges set at their factory defaults. Table 3.3 also includes these results, which show that the Pavetracker failed the density profile when operated uncalibrated, but passed the profile when operated calibrated. Both the nuclear gauge and the PQI passed the profile whether the gauge was calibrated to the mix or not.

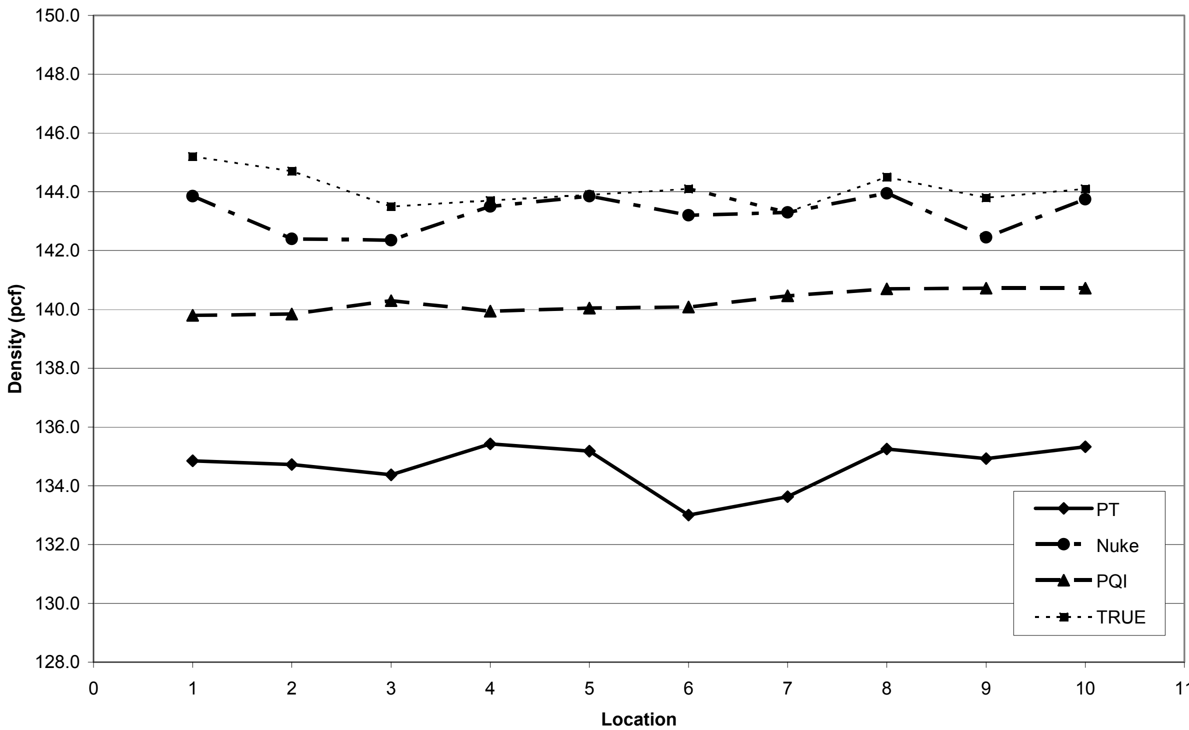


Figure 3.2. US 281 Density Profile with Calibrated Gauges versus True Densities.

Table 3.3. Density Profile Results on US 281.

	Calibrated Gauges			Uncalibrated Gauges			
Location	**Nuke**	**PT**	**PQI**	**Nuke**	**PT**	**PQI**	**Cores**
1	143.9	134.9	139.8	142.8	143.2	130.6	145.2
2	142.4	134.7	139.8	142.2	147.6	130.6	144.7
3	142.4	134.4	140.3	141.8	146.5	130.8	143.5
4	143.5	135.4	139.9	142.0	148.0	130.4	143.7
5	143.9	135.2	140.0	142.8	146.5	130.8	143.9
6	143.2	133.0	140.1	142.6	147.2	130.7	144.1
7	143.3	133.6	140.5	142.0	146.3	131.0	143.3
8	144.0	135.3	140.7	143.0	147.2	131.4	144.5
9	142.5	134.9	140.7	142.6	147.4	131.2	143.8
10	143.8	135.3	140.7	143.3	147.2	131.4	144.1
Highest	144.0	135.4	140.7	143.3	148.0	131.4	145.2
Lowest	142.4	133.0	139.8	141.8	143.2	130.4	143.3
Average	143.3	134.7	140.3	142.5	146.7	130.9	144.1
High-Low	1.6	2.4	0.9	1.5	4.8	1.0	1.9
Mat P/F	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Avg-Low	0.9	1.7	0.5	0.7	3.5	0.5	0.8
Mat P/F	Pass	Pass	Pass	Pass	Fail	Pass	Pass

Gauge Accuracy

On this project, researchers had the luxury of being able to core all 11 test locations. Tables 3.4 through 3.6 present the results from the calibrated gauges as compared to core results. Based upon the average error, the sum of squared errors, and the mean squared error the nuclear gauge performed the best, followed by the PQI, then the Pavetracker. After calibration, the nuclear gauge was the most accurate with an average error of -0.6 percent once calibrated. The PQI followed the nuclear gauge with an average error of -2.6 percent, and the Pavetracker was the worst with an average error of -6.5 percent. A concern with the non-nuclear gauges is the fact that, despite being previously calibrated, the data in Tables 3.5 and 3.6 indicate that on average these gauges are still reading either too high or too low. It is thought slight changes in the mix JMF from day to day may be responsible for the bias exhibited, as the section profiled was approximately 1000 ft. from the calibration site.

Another concern with gauge accuracy is the dispersion of errors. Ideally, the errors should be constant, meaning that the gauge can be calibrated by a simple linear adjustment. However, the calibration data in Table 3.2 shows the Pavetracker errors were widely dispersed, even though the range of true core densities was small. Core densities only varied by 2.4 pcf, but Pavetracker errors ranged from 6.3 to 25.0 pcf. It is possible the contact of the gauge was better with the HMA mat at the core locations with the higher errors; it is well known that slight gaps between the gauge and the mat can drastically affect the readings. However, the research team took special caution to test locations with good contact between the gauge and the mat. It appears the Pavetracker either had an internal glitch, is outright flawed, or out-of-the-ordinary testing procedures are needed to get reasonable results with this gauge.

Table 3.4. US 281 Calibrated Nuclear Density Readings.

Core #	Actual Core Density (pcf)	Nuke Gauge Density (pcf)	Error (gauge-core)	SSE $(Error)^2$	MSE (AVG of SSE)	% Error (Error/Core)
1	145.2	143.9	-1.3	1.8		-0.9%
2	144.7	142.4	-2.3	5.3		-1.6%
3	143.5	142.4	-1.2	1.3		-0.8%
4	143.7	143.5	-0.2	0.0		-0.1%
5	143.9	143.9	-0.1	0.0		0.0%
6	144.1	143.2	-0.9	0.8		-0.6%
7	143.3	143.3	0.0	0.0		0.0%
8	144.5	144.0	-0.6	0.3		-0.4%
9	143.8	142.5	-1.4	1.8		-0.9%
10	144.1	143.8	-0.3	0.1		-0.2%
Avg	**144.1**	**143.3**	**-0.8**	**11.5**	**1.2**	**-0.6%**

Table 3.5. US 281 Calibrated Pavetracker Density Readings.

Core #	Actual Core Density (pcf)	PT Gauge Density (pcf)	Error (gauge-core)	SSE $(Error)^2$	MSE (AVG of SSE)	% Error (Error/Core)
1	145.2	134.9	-10.4	107.1		-7.1%
2	144.7	134.7	-10.0	99.5		-6.9%
3	143.5	134.4	-9.1	83.3		-6.4%
4	143.7	135.4	-8.3	68.5		-5.8%
5	143.9	135.2	-8.7	76.1		-6.1%
6	144.1	133.0	-11.1	123.2		-7.7%
7	143.3	133.6	-9.7	93.6		-6.8%
8	144.5	135.3	-9.3	85.6		-6.4%
9	143.8	134.9	-8.9	78.8		-6.2%
10	144.1	135.3	-8.8	77.0		-6.1%
Avg	**144.1**	**134.7**	**-9.4**	**892.6**	**89.3**	**-6.5%**

Table 3.6. US 281 Calibrated PQI Density Readings.

Core #	Actual Core Density (pcf)	PQI Gauge Density (pcf)	Error (gauge-core)	SSE $(Error)^2$	MSE (AVG of SSE)	% Error (Error/Core)
1	145.2	139.8	-5.4	29.2		-3.7%
2	144.7	139.8	-4.9	23.6		-3.4%
3	143.5	140.3	-3.2	10.2		-2.2%
4	143.7	139.9	-3.8	14.1		-2.6%
5	143.9	140.0	-3.9	14.9		-2.7%
6	144.1	140.1	-4.0	16.2		-2.8%
7	143.3	140.5	-2.8	8.1		-2.0%
8	144.5	140.7	-3.8	14.4		-2.6%
9	143.8	140.7	-3.1	9.5		-2.1%
10	144.1	140.7	-3.4	11.4		-2.3%
Avg	**144.1**	**140.3**	**-3.8**	**151.6**	**15.2**	**-2.6%**

CONCLUSIONS FROM TEST SITE

Results from the US 281 test site revealed that after calibration both of the non-nuclear gauges used resulted in the same pass/fail decision in TxDOT's density profile specification as the nuclear gauge. When the profile was performed with the Pavetracker at factory calibration settings, the test outcome differed from the core results and the other two gauges. Thus, results from this site indicate both calibrated non-nuclear gauges would be acceptable alternatives to the nuclear gauge for Tex-207-F, and the PQI would be an acceptable alternative even if not calibrated to the mix.

The accuracy from the non-nuclear gauges was disappointing despite the fact that they were calibrated to the mix. The data seem to indicate that calibration of the non-nuclear gauges is valid only within the station limits from which calibration cores were taken. On this project, researchers performed the density profile approximately 1000 ft. north of the calibration site, and both non-nuclear gauges exhibited accuracy results that indicate a new calibration was needed. In addition, during calibration the Pavetracker errors were widely dispersed, even though true core densities did not vary much. It seems either this gauge had an operational glitch, or out-of-the-ordinary test procedures are needed to achieve reasonable results with this gauge.

CHAPTER 4

RESULTS FROM FM 158

SUMMARY

TTI researchers tested FM 158 just east of Bryan, TX, in May 2003. The research team collected data to calibrate the gauges to the mix then performed a density profile test. The results indicated that both non-nuclear gauges resulted in the same pass/fail decision for the profile as the nuclear gauge. However, the Pavetracker failed a joint density test, whereas cores and the nuclear gauge indicated that the joint density should pass. Testing at this site also indicated that despite being calibrated from the previous day's paving, the PQI needed a new linear offset to be determined at the location where the profile was performed.

DESCRIPTION OF TEST SITE

The FM 158 test site was on the east side of Bryan, Texas, between FM 60 and SH 30 and was located on the inside southbound lane. Testing was performed on the second lift of a three-lift job where the second layer was Type C mix, 2 inches thick, with a JMF as shown in Table 4.1. On May 14, 2003, researchers used ground penetrating radar to scan for desired coring locations for gauge calibration from that day's paving. Prior to calibration coring, the sites were measured with the density gauges set at factory settings. The cores were then used for calibration. On May 15, researchers performed a density profile with the calibrated gauges on a section of HMA placed that morning. The profile consisted of 11 locations in the center of the lane with one joint location corresponding to location 5. Figure 4.1 shows the profile location.

Table 4.1. FM 158 JMF.

Mix Type:	Type C
Binder Percent, (%):	4.8
Rice Sp. Gravity:	2.456

Sieve Sizes	**Cum. % Passing**
7/8”	100.0
5/8”	99.8
3/8”	84.8
No. 4	61.9
No. 10	37.4
No. 40	16.6
No. 80	8.0
No. 200	5.8

Figure 4.1. Density Profile Location on FM 158.

GAUGE CALIBRATION DATA

Table 4.2 shows the calibration data collected from FM 158. On average the PQI read 12.4 pcf high, the Pavetracker 1.1 pcf high, and the nuclear gauge 1.5 pcf low. Unfortunately, at the time this project was tested, the calibration function of the nuclear gauge was not well understood, so only the non-nuclear gauges were actually calibrated to the job.

Table 4.2. Gauge Calibration Data for FM 158.

Core #	Actual Core Density (pcf)	PQI Core Density (pcf)	PQI Error	PT Core Density (pcf)	PT Error	Nuke Core Density (pcf)	Nuke Error
1	136.9	152.0	15.1	136.0	-0.9	134.7	-2.2
2	142.1	154.6	12.5	140.9	-1.2	137.9	-4.2
4	137.3	153.2	15.9	147.0	9.7	142.6	5.3
5	142.7	149.6	6.9	139.6	-3.1	138.3	-4.4
7	137.0	148.4	11.4	137.9	0.9	134.8	-2.2
Avg	**139.2**	**151.6**	**12.4**	**140.3**	**1.1**	**137.7**	**-1.5**

EVALUATION OF GAUGE PERFORMANCE

Density Profile

All gauges resulted in a pass decision on the density profile. Coring results also indicated the section should pass. The nuclear gauge gave a range of 3.1 pcf, the PQI showed a range of 2.1 pcf, and the Pavetracker gave a density range of 5.6 pcf. However, with the joint density criteria, the Pavetracker failed the test location, and both the nuclear gauge and cores gave a passing decision. The PQI was not used to measure the joint location. Figure 4.2 illustrates the results from the density profile, and Table 4.3 presents the profile data with the calibrated gauges.

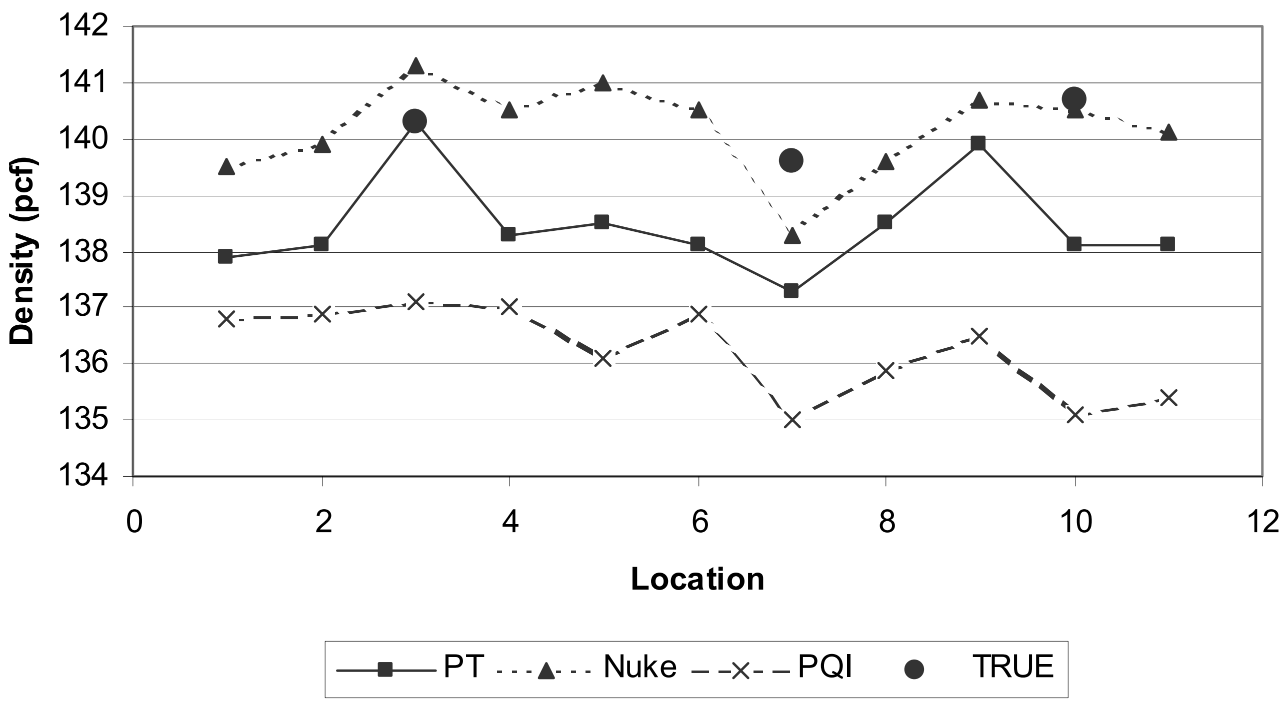


Figure 4.2. FM 158 Density Profile with Calibrated Gauges versus True Densities.

Table 4.3. Density Profile Results from FM 158.

Location	Center Nuke	Joint Nuke	Joint P/F	Center PT	Joint PT	Joint P/F	Center PQI	Center Cores	Joint Cores
1	139.5	-	-	137.9	-	-	136.8	-	-
2	139.9	-	-	138.1	-	-	136.9	-	-
3	141.3	-	-	140.3	-	-	137.1	140.3	-
4	140.5	-	-	138.3	-	-	137.0	-	-
5	141.0	139.4	Pass	138.5	134.4	Fail	136.1	-	138.3
6	140.5	-	-	138.1	-	-	136.9	-	-
7	138.3	-	-	137.3	-	-	135.0	139.6	-
8	139.6	-	-	138.5	-	-	135.9	-	-
9	140.7	-	-	139.9	-	-	136.5	-	-
10	140.5	-	-	138.1	-	-	135.1	140.7	-
11	140.1	-	-	138.1	-	-	135.4		-
Highest	141.3	-	-	140.3	-	-	137.1	140.7	-
Lowest	138.3	-	-	137.3	-	-	135.0	139.6	-
Average	140.1	-	-	138.5	-	-	136.2	140.2	-
High-Low	3.1	-	-	3.0	-	-	2.1	1.1	-
Mat P/F	Pass	-	-	Pass	-	-	Pass	Pass	-
Avg-Low	1.9	-	-	1.1	-	-	1.2	0.6	-
Mat P/F	Pass	-	-	Pass	-	-	Pass	Pass	-

Gauge Accuracy

Tables 4.4 through 4.6 show the gauge readings compared to the core densities for the FM 158 test site. With respect to accuracy, the nuclear gauge performed best, followed by the Pavetracker then the PQI.

The nuclear gauge, although not actually calibrated to the mix, had an average error of 0.1 percent. After calibration, the Pavetracker read low with an average error of -2.1 pcf, or -1.5 percent. Upon calibration with the linear offset, the PQI read too low with an error of -4.5 pcf, or -3.2 percent.

Table 4.4. FM 158 Calibrated Nuclear Density Readings.

Core #	Actual Core Density (pcf)	Nuke Gauge Density (pcf)	Error (gauge-core)	SSE $(Error)^2$	MSE (AVG of SSE)	% Error (Error/Core)
3	140.3	141.3	1.0	1.0		0.7%
7	139.6	138.3	-1.3	1.7		-0.9%
10	140.7	140.5	-0.2	0.0		-0.1%
J5	138.3	139.4	1.1	1.2		0.8%
Avg	**139.7**	**139.9**	**0.2**	**3.9**	**1.0**	**0.1%**

Table 4.5. FM 158 Calibrated Pavetracker Density Readings.

Core #	Actual Core Density (pcf)	PT Gauge Density (pcf)	Error (gauge-core)	SSE $(Error)^2$	MSE (AVG of SSE)	% Error (Error/Core)
3	140.3	140.3	0.0	0.0		0.0%
7	139.6	137.7	-1.9	3.6		-1.4%
10	140.7	138.1	-2.6	6.8		-1.8%
J5	138.3	134.4	-3.9	15.2		-2.8%
Avg	**139.7**	**137.6**	**-2.1**	**25.6**	**6.4**	**-1.5%**

Table 4.6. FM 158 Calibrated PQI with Linear Offset Density Readings.

Core #	Actual Core Density (pcf)	PQI Gauge Density (pcf)	Error (gauge-core)	SSE $(Error)^2$	MSE (AVG of SSE)	% Error (Error/Core)
3	140.3	137.1	-3.2	10.2		-2.3%
7	139.6	135.0	-4.6	21.2		-3.3%
10	140.7	135.1	-5.6	31.4		-4.0%
Avg	**140.2**	**135.7**	**-4.5**	**62.8**	**20.9**	**-3.2%**

CONCLUSIONS FROM TEST SITE

The testing on FM 158 indicated that, in general, the non-nuclear gauges yield the same pass/fail decisions for density uniformity as the nuclear gauge. Testing at this site also indicated that calibrations with the non-nuclear gauges performed at one part of a project might not be ideal for testing on other parts of the project. For example, despite being previously calibrated, the PQI read on average 4.5 pcf low on the density profile, even though it had been previously calibrated on the day's prior paving. The calibration cores were taken approximately 1000 ft. from where the profile was conducted.

CHAPTER 5

RESULTS FROM SH 6

SUMMARY

TTI researchers performed testing on SH 6 north of Riesel, Texas, in June 2003 with uncalibrated gauges. Due to time constraints, calibration was not possible. On this project, both a density profile and corresponding joint densities at all 11 locations were measured with the gauges. All of the gauges indicated that the density profile passed. Coring also showed that the density profile passed TxDOT's specifications. With respect to joint densities, cores indicated the joints should all pass, whereas the nuclear gauge failed one out of 11 joint tests, and the Pavetracker failed six test locations. The PQI passed all the joint densities.

DESCRIPTION OF TEST SITE

The test site was located just north of Riesel, Texas in the outside northbound lane and consisted of a 2 inch layer of Type C mix with a JMF as shown in Table 5.1. On June 3, researchers performed a density profile with the uncalibrated gauges. The density profile consisted of 11 locations spaced 5 ft. apart. At each location, readings were taken in the center of the lane and at the corresponding joint location. Figure 5.1 shows the location of the testing.

Table 5.1. SH 6 JMF.

Mix Type:	Type C
Binder Percent, (%):	4.3
Rice Sp. Gravity:	2.49

Sieve Sizes	Cum. % Passing
7/8”	100.0
5/8”	99.1
3/8”	79.3
No. 4	52.9
No. 10	32.1
No. 40	18.2
No. 80	10.5
No. 200	2.4

Figure 5.1. Location of Testing on SH 6.

EVALUATION OF GAUGE PERFORMANCE

Density Profile

Table 5.2 shows the data and results from the density profile testing. All the gauges resulted in a pass decision for the density profile on the main lane. For joint densities, the PQI gave passing readings for all the joint density tests. The nuclear gauge yielded one failing reading for the joint density criteria. With the Pavetracker, failing joint density decisions were made on locations 1, 4, 5, 7, 8, and 9 for the joint density criteria. Core data indicate all joint densities should have passed. Figure 5.2 illustrates the results from the density profile. Thus, the results from the nuclear gauge and the PQI matched up well with core results, but the Pavetracker joint density test results were contradicted by cores.

Table 5.2. Density Profile Results from SH 6.

	Center	Joint		Center	Joint		Center	Joint		Center	Joint	
Location	**Nuke**	**Nuke**	**Joint P/F**	**PT**	**PT**	**Joint P/F**	**PQI**	**PQI**	**Joint P/F**	**Cores**	**Cores**	**Joint P/F**
1	142.5	138.9	Fail	143.6	132.1	Fail	128.0	126.9	Pass	144.4	147.3	Pass
1a	-	139.9	-	-	137.6	-	-	128.1	-	-	145.6	-
2	142.0	139.8	Pass	143.4	141.0	Pass	128.4	127.5	Pass	-	-	-
3	141.7	142.2	Pass	142.8	141.6	Pass	128.2	127.9	Pass	-	-	-
4	141.4	138.8	Pass	141.4	137.3	Fail	128.3	127.1	Pass	143.9	147.3	Pass
5	143.1	141.7	Pass	146.7	140.2	Fail	128.1	128.5	Pass	-	-	-
6	142.1	139.1	Pass	144.2	142.0	Pass	128.7	128.3	Pass	-	-	-
7	140.4	139.1	Pass	142.6	138.4	Fail	127.8	127.9	Pass	-	-	-
8	144.2	142.2	Pass	146.2	138.9	Fail	129.0	128.1	Pass	145	-	-
9	141.8	139.5	Pass	143.8	138.6	Fail	128.0	127.6	Pass	-	-	-
10	142.5	140.7	Pass	141.1	139.5	Pass	128.5	128.4	Pass	-	-	-
11	141.8	142.1	Pass	142.7	143.5	Pass	128.8	128.4	Pass	-	147.8	-
Highest	144.2	142.2	-	146.7	143.5	-	129.0	128.5	-	145.0	147.8	-
Lowest	140.4	138.8	-	141.1	132.1	-	127.8	126.9	-	143.9	145.6	-
Average	142.1	140.3	-	143.5	139.2	-	128.4	127.9	-	144.4	147.0	-
High-Low	3.8	3.4	-	5.6	11.4	-	1.1	1.6	-	1.1	2.2	-
Mat P/F	Pass	Pass	-	Pass	Fail	-	Pass	Pass	-	Pass	Pass	-
Avg-Low	1.7	1.6	-	2.4	7.1	-	0.5	1.0	-	0.5	1.4	-
Mat P/F	Pass	Pass	-	Pass	Fail	-	Pass	Pass	-	Pass	Pass	-

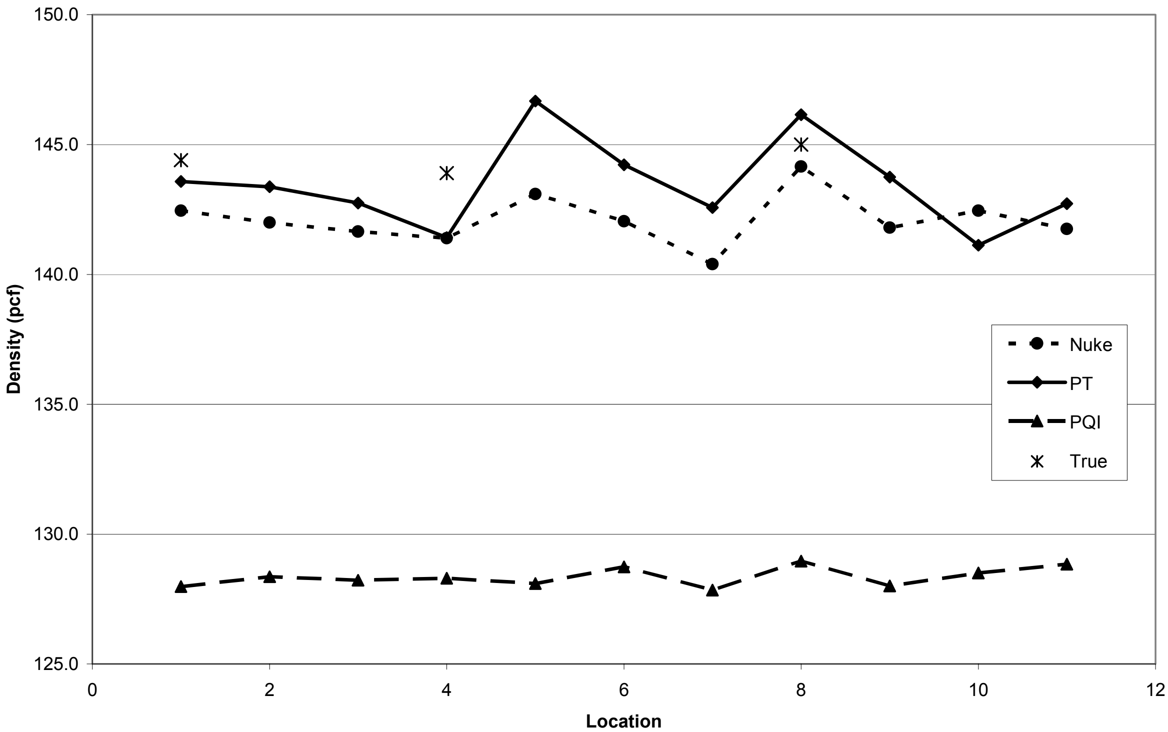


Figure 5.2. SH 6 Density Profile with Uncalibrated Gauges versus True Densities of the Centerline.

CONCLUSIONS FROM TEST SITE

Due to time constraints, calibration of the gauges was not possible on the SH 6 project; however, both non-nuclear gauges resulted in the same pass/fail decision as the nuclear gauge in the density profile. This observation is promising, as significant time advantages will be gained if the non-nuclear devices can be used in the field in place of the nuclear gauge, especially if they do not need to be calibrated prior to testing. Unfortunately the Pavetracker did not match up well with the nuclear gauge or the core readings with respect to joint densities. The Pavetracker failed many joint density tests, whereas the cores indicated the joint densities should have passed. Results from this site indicate the PQI could be used in place of the nuclear gauge for density profile and joint density criteria, whereas the Pavetracker should not be used for enforcing the joint density specification.

CHAPTER 6

RESULTS FROM IH 20

SUMMARY

The research team performed testing on SFA mix in Cisco, TX, on a 3 inch thick layer. All the gauges passed the density profile; cores taken likewise indicated the profile should pass. The density profile was also conducted with the gauges at their factory calibration settings, and all the gauges again passed the section. After calibration, the accuracy of the PQI was excellent. Unfortunately, both the nuclear gauge and the Pavetracker exhibited problems in accuracy, despite being calibrated to the mix. Analysis of the data revealed both of these gauges had a slope problem on this job.

DESCRIPTION OF TEST SITE

The test site was located west of Cisco in the westbound lane and consisted of a 3 inch thick layer of 3/4 inch stone-filled mix located on the shoulder. The layer being tested was placed the previous day. On August 12, 2003, researchers located calibration sites, measured densities of these sites, and cored the sites. Researchers then performed a density profile with the gauges and collected data. Table 6.1 shows the JMF for the IH 20 mix. Figure 6.1 shows the profile site.

Table 6.1. IH 20 JMF.

Mix Type:	3/4" Stone Fill
Binder Percent, (%):	4.5
Rice Sp. Gravity:	2.498

Sieve Sizes	Cum. % Passing
1"	100.0
3/4"	94.3
1/2"	80.2
No. 8	24.0
No. 16	16.4
No. 30	10.9
No. 50	7.5
No. 200	4.6

Figure 6.1. IH 20 Profile Site.

GAUGE CALIBRATION DATA

Table 6.2 presents the gauge calibration data for IH 20. The nuclear gauge calibration is performed within the gauge, so only results from the PQI and Pavetracker are shown. The PQI needed a linear offset of 16.8 pcf, and the required offset with the Pavetracker was 4.7 pcf.

Table 6.2. Gauge Calibration Data from IH 20.

Core #	Actual Core Density (pcf)	PQI Core Density (pcf)	PQI Error	PT Core Density (pcf)	PT Error
1	145.7	128.5	-17.2	143.7	-2.0
2	142.1	124.7	-17.4	132.8	-9.3
3	145.1	128.4	-16.7	143.1	-2.0
4	143.9	128.1	-15.8	138.3	-5.6
Avg	**144.2**	**127.4**	**-16.8**	**139.5**	**-4.7**

EVALUATION OF GAUGE PERFORMANCE

Density Profile

Figure 6.2 illustrates the results from the density profile on the IH 20 project. All the gauges and core results indicated the density profile passed. Table 6.3 presents all the density profile and joint density data collected on this project. For the joint density criteria, the nuclear gauge gave 10 failing decisions and one passing, the Pavetracker failed all joint locations, and the PQI gave six failing decisions and five passing. Given that the average main lane core density was 145.8 pcf, and the average joint core density was 142.5 pcf, it is likely some joint locations truly exceeded the allowable 3.0 pcf drop; however, given the variability in cores from both the main lane and the joint, a determination cannot be made as to how many joint locations truly should have failed. Only coring of all the locations would have made such a determination possible.

Researchers also collected the density profile with the gauge calibrations at their factory defaults on this job to investigate if the same pass/fail decision would be reached. Table 6.4 presents this data. The results were similar, with all gauges still passing the density profile. Both the nuclear and Pavetracker failed most of the joint densities, and the PQI failed a majority of joint density tests.

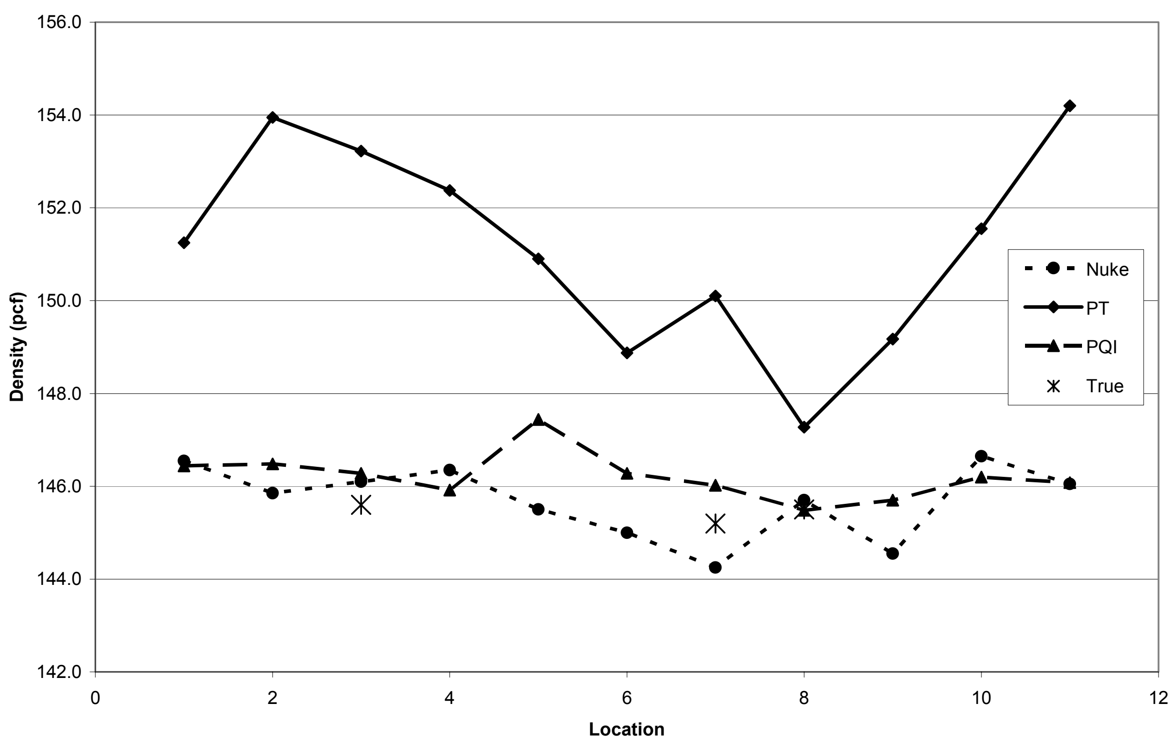


Figure 6.2. IH 20 Density Profile with Calibrated Gauges versus True Densities of the Centerline.

Table 6.3. IH 20 Profile Results after Calibration.

	Center	Joint		Center	Joint		Center	Joint		Center	Joint	
Location	**Nuke**	**Nuke**	**Joint P/F**	**PT**	**PT**	**Joint P/F**	**PQI**	**PQI**	**Joint P/F**	**Cores**	**Cores**	**Joint P/F**
1	146.6	140.3	Fail	151.3	143.9	Fail	146.4	144.2	Pass	-	-	-
2	145.9	140.6	Fail	154.0	141.2	Fail	146.5	143.5	Pass	-	-	-
3	146.1	140.1	Fail	153.2	141.4	Fail	146.3	143.0	Fail	146.6	-	-
4	146.4	141.2	Fail	152.4	144.8	Fail	145.9	143.2	Pass	-	-	-
5	145.5	140.5	Fail	150.9	145.5	Fail	147.4	143.1	Fail	-	142.6	-
6	145.0	137.8	Fail	148.9	142.5	Fail	146.3	142.4	Fail	-	143.1	-
7	144.3	140.4	Fail	150.1	142.5	Fail	146.0	142.7	Fail	145.2	-	-
8	145.7	141.6	Fail	147.3	142.2	Fail	145.5	142.1	Fail	145.5	-	-
9	144.6	141.9	Pass	149.2	145.0	Fail	145.7	143.4	Pass	-	-	-
10	146.7	139.9	Fail	151.6	141.9	Fail	146.2	143.3	Pass	-	-	-
11	146.1	138.5	Fail	154.2	141.4	Fail	146.1	142.0	Fail	-	141.9	-
Highest	146.7	141.9	-	154.2	145.5	-	147.4	144.2	-	146.6	143.1	-
Lowest	144.3	137.8	-	147.3	141.2	-	145.5	142.0	-	145.2	141.9	-
Average	145.7	140.2	-	151.2	142.9	-	146.2	143.0	-	145.8	142.5	-
High-Low	2.4	4.2	-	6.9	4.3	-	2.0	2.2	-	1.4	1.2	-
Mat P/F	Pass	Pass	-	Pass	Pass	-	Pass	Pass	-	Pass	Pass	-
Avg-Low	1.4	2.5	-	3.9	1.8	-	0.7	1.0	-	0.6	0.6	-
Mat P/F	Pass	Pass	-	Pass	Pass	-	Pass	Pass	-	Pass	Pass	-

Table 6.4. IH 20 Profile Results Prior to Calibration.

Location	Center Nuke	Joint Nuke	Joint P/F	Center PT	Joint PT	Joint P/F	Center PQI	Joint PQI	Joint P/F	Center Cores	Joint Cores	Joint P/F
1	143.0	137.2	Fail	146.0	136.6	Fail	130.4	127.3	Fail	-	-	-
2	142.2	136.7	Fail	146.6	137.4	Fail	129.8	126.9	Pass	-	-	-
3	142.5	136.4	Fail	150.4	138.9	Fail	129.9	126.7	Fail	146.6	-	-
4	141.8	137.4	Fail	146.1	140.7	Fail	129.2	126.7	Pass	-	-	-
5	141.1	134.8	Fail	148.7	139.1	Fail	129.1	126.1	Fail	-	142.6	-
6	140.4	133.4	Fail	145.8	136.5	Fail	129.4	125.3	Fail	-	143.1	-
7	139.8	136.2	Fail	145.5	137.6	Fail	128.9	126.1	Pass	145.2	-	-
8	142.3	137.4	Fail	146.3	135.6	Fail	129.5	125.3	Fail	145.5	-	-
9	140.5	137.2	Fail	144.6	144.4	Pass	129.0	126.2	Pass	-	-	-
10	142.7	136.5	Fail	147.9	137.5	Fail	129.5	126.4	Fail	-	-	-
11	142.0	135.0	Fail	148.6	136.9	Fail	129.3	125.1	Fail	-	141.9	-
Highest	143.0	137.4	-	150.4	144.4	-	130.4	127.3	-	146.6	143.1	-
Lowest	139.8	133.4	-	144.6	135.6	-	128.9	125.1	-	145.2	141.9	-
Average	141.6	136.2	-	146.9	138.3	-	129.5	126.2	-	145.8	142.5	-
High-Low	3.1	4.1	-	5.9	8.9	-	1.5	2.2	-	1.4	1.2	-
Mat P/F	Pass	Pass	-	Pass	Fail	-	Pass	Pass	-	Pass	Pass	-
Avg-Low	1.8	2.8	-	2.4	2.7	-	0.6	1.1	-	0.6	0.6	-
Mat P/F	Pass	Pass	-	Pass	Pass	-	Pass	Pass	-	Pass	Pass	-

Gauge Accuracy

Tables 6.5 through 6.7 present the results from the calibrated gauges. Based upon the measures of gauge accuracy, the PQI performed best, followed by the nuclear gauge, then the Pavetracker. The PQI results were excellent on this project; the results from the nuclear gauge and the Pavetracker were less than desirable. The nuclear gauge was off by as much as 5.3 pcf, and the Pavetracker was off by as much as 7.6 pcf. Furthermore, neither gauge consistently was off by a constant amount. For example, examining the errors of the Pavetracker in Table 6.6 reveals that although the average error was 2.7 pcf, the errors ranged from –0.6 pcf up to 7.6 pcf. When performing density profiles, it is acceptable for the gauge accuracy to be off, as long as the error is relatively constant. However, if the errors are widely scattered, then it is likely the gauge may be exaggerating the extremes of the density values (i.e., slope problems in the calibration). For example, Figure 6.3 shows the slopes of the nuclear and Pavetracker gauges were more than double that of the perfect-fit line on this job.

Table 6.5. IH 20 Calibrated Nuclear Density Readings.

Core #	Actual Core Density (pcf)	Nuke Core Density (pcf)	Error (gauge-core)	SSE sum(Error)^2	MSE (AVG of SSE)	% Error (Error/Core)
3	145.6	146.1	0.5	0.3		0.3%
7	145.2	144.3	-0.9	0.8		-0.6%
8	145.5	145.7	0.2	0.0		0.1%
J-5	142.6	140.5	-2.1	4.4		-1.5%
J-6	143.1	137.8	-5.3	28.1		-3.7%
J-11	141.9	138.5	-3.4	11.6		-2.4%
Avg	144.0	142.2	-1.8	45.2	7.5	-1.3%

Table 6.6. IH 20 Calibrated Pavetracker Density Readings.

Core #	Actual Core Density (pcf)	PT Core Density (pcf)	Error (gauge-core)	SSE sum(Error)^2	MSE (AVG of SSE)	% Error (Error/Core)
1	145.6	153.2	7.6	57.8		5.2%
7	145.2	150.1	4.9	24.0		3.4%
8	145.5	147.3	1.8	3.2		1.2%
J-5	142.6	145.5	2.9	8.4		2.0%
J-6	143.1	142.5	-0.6	0.4		-0.4%
J-11	141.9	141.4	-0.5	0.3		-0.4%
Avg	144.0	146.7	2.7	94.0	15.7	1.8%

Table 6.7. IH 20 Calibrated PQI Density Readings.

Core #	Actual Core Density (pcf)	PQI Core Density (pcf)	Error (gauge-core)	SSE sum(Error)^2	MSE (AVG of SSE)	% Error (Error/Core)
3	145.6	146.3	0.7	0.5		0.5%
7	145.2	146.0	0.8	0.6		0.6%
8	145.5	145.5	0.0	0.0		0.0%
J-5	142.6	143.1	0.5	0.3		0.4%
J-6	143.1	142.4	-0.7	0.5		-0.5%
J-11	141.9	142.0	0.1	0.0		0.1%
Avg	144.0	144.2	0.2	1.9	0.3	0.2%

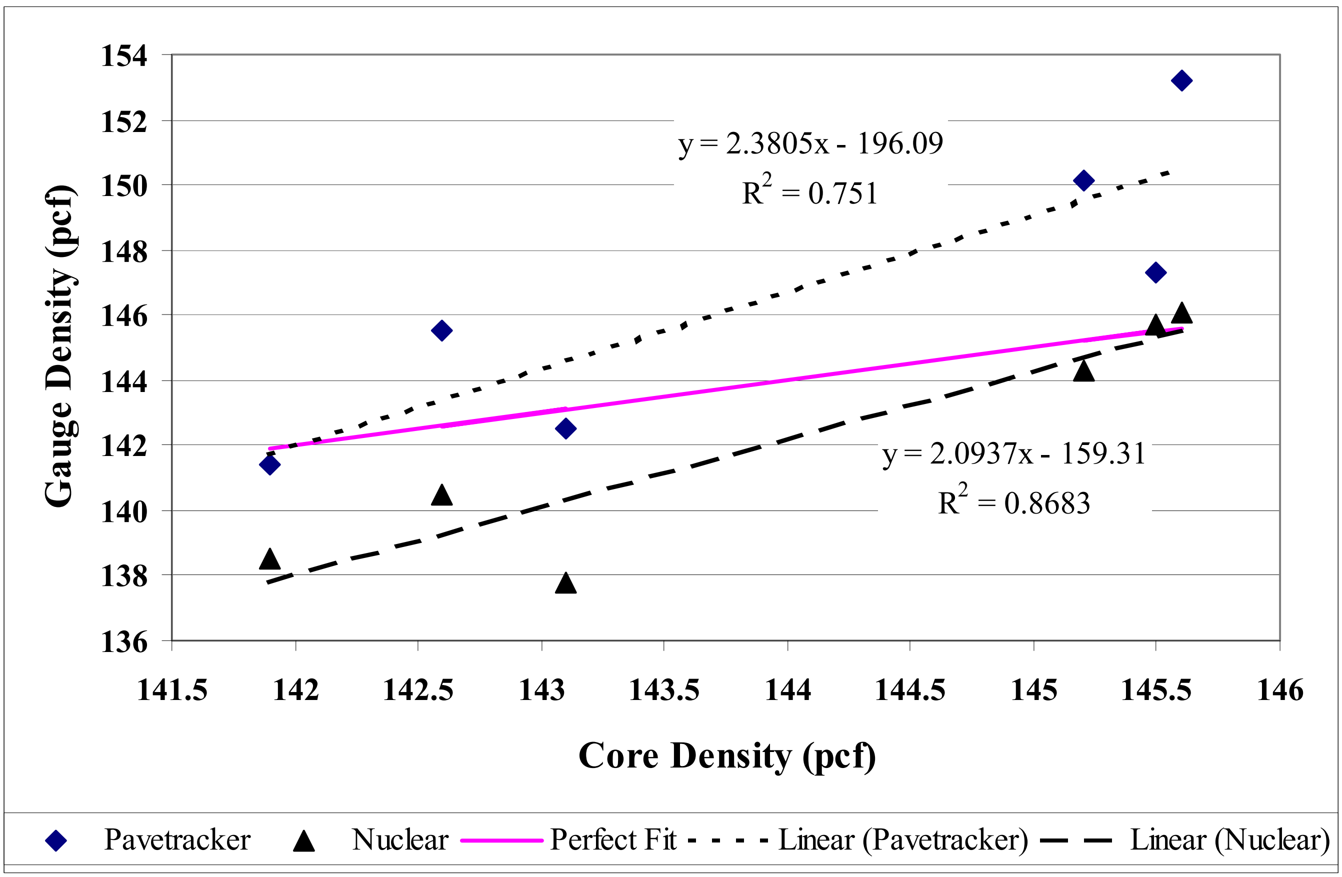


Figure 6.3. Slope Problems with Pavetracker and Nuclear Gauges on IH 20.

CONCLUSIONS FROM TEST SITE

The density profiling results from the non-nuclear gauges matched well with the results from the nuclear gauge on this project. Furthermore, the pass/fail decision for the density profile was the same whether the gauges were calibrated or not. Most of the gauges indicated the joints would not pass TxDOT's joint density criteria; however, sufficient cores were not available to make a definitive assessment. To improve the reliability of enforcing the joint density specification, TxDOT should consider testing multiple locations. Rather than compare one joint reading to one main lane reading, multiple readings both in the main lane and along the joint could be averaged, then the difference in the averages compared to the 3.0 pcf criteria. Alternatively, multiple readings at distinct locations both in the main lane and along the joint could be statistically compared to test if the true mean joint density indeed exceeds the allowable density drop.

With respect to gauge accuracy, neither the nuclear gauge nor the Pavetracker performed very well on this job. However, the accuracy of the PQI was excellent on this job. This gauge was within 0.8 pcf of the core values. It is not known why the accuracy of the nuclear and Pavetracker gauges was less than desirable. Both of these gauges exhibited slopes more than twice that of a perfect-fit line as compared to cores. Data from this project illustrate the importance of manufacturers including slope calibration functions in their gauges.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The work conducted in the first year of this research project focused on evaluating the ruggedness, repeatability, and accuracy of the Troxler 3450 nuclear gauge and the Pavetracker and PQI gauges. Through a laboratory setting, researchers evaluated how mix temperature, the presence of moisture on the HMA, and gauge battery voltage may affect the readings from the PQI, Pavetracker, and nuclear gauge. In addition, researchers investigated the lift thickness function on the PQI, and the precision of the devices. The laboratory slabs were found unsuitable for evaluation of gauge accuracy. In the field, researchers used all three gauges and first calibrated the gauges to the job. Then, they performed density profiles and collected field cores. This work served two purposes: first, the research team evaluated if the non-nuclear gauges could be used in place of the nuclear gauge for density profiles and joint density measurements; second, the accuracy of the gauges was evaluated in a field setting.

FINDINGS FROM LABORATORY WORK

The laboratory testing indicated all devices could be affected by mix temperature, where gauge readings typically decrease with decreasing mix temperature. All gauges' readings were also impacted by moisture. In general, the presence of moisture on the HMA resulted in an increase in the density readings for all the gauges. The nuclear gauge was impacted least by moisture. However, unless the test location is excessively wet, both non-nuclear gauges provided stable readings. Regarding the effects of battery voltage on gauge readings, users should be safe operating the Pavetracker at battery levels down to 8.2 V. Due to its auto-shutdown feature, testing the impact of battery level on the PQI was not practical. The manufacturer states the PQI provides at least 13 hours of run time on a charge.

The precision of all gauges in the lab was good, with single-operator standard deviations of repeat readings below 0.5 pcf with the non-nuclear gauges and less than 1.0 pcf with the nuclear gauge. Taking multiple readings with the gauge orientation changed between readings and then averaging the test results as one measurement resulted in the best repeatability. Conducted in this manner, the observed repeatability standard deviation was 0.14, 0.16, and 0.40 pcf for the PQI, Pavetracker, and nuclear gauge, respectively. The non-nuclear gauges were rotated 90° between readings, for a total of four readings per measurement, whereas the nuclear gauge was rotated 180° between readings, for a total of two readings per measurement.

FINDINGS FROM FIELD WORK

The field-testing phase of the work described in this report placed all three gauges on actual HMA-paving projects. When possible, researchers calibrated the gauges to the mix, then performed density profiles and joint density tests on the projects. Cores taken served as referee for evaluating if the gauge results were reliable. Of special interest on this project was if the non-nuclear gauges could be used in place of the nuclear gauge for performing TxDOT's density profile and joint density procedures. Researchers also investigated the accuracy of the gauges through the field work.

Results from Density Profile and Joint Density Testing

Tables 7.1 and 7.2 present a summary of the gauge and core results for the density profiles and joint densities, respectively. The nuclear gauge and PQI density profile results matched the cores for all the projects, regardless of whether the gauges were calibrated or uncalibrated. Users should verify if the slope of their particular gauge is appropriate for the HMA mixture being tested. The Pavetracker density profile results matched the cores every time the gauge was operated with the calibration, but failed a profile that should have passed when operated without the calibration input into the gauge. Thus, the PQI appears to be an acceptable alternative to the nuclear gauge for density profiling, even if not calibrated, whereas the Pavetracker should always be calibrated to the mix before performing density profiling.

Table 7.2 shows the joint density results. On most projects, multiple joint and main lane readings were made. Thus, the summary results are based on the difference between the average main lane density and the average joint density. The data indicate both the nuclear and PQI results consistently match that of the cores, whereas the Pavetracker resulted in the wrong test outcome 67 percent of the time. Thus, the PQI should be an acceptable alternative to the nuclear gauge for testing joint densities, but the Pavetracker should not be used to enforce the joint density specification until improvements to the gauge and subsequent verification with the improved gauge is performed.

Table 7.1. Summary of Density Profile Results from Projects Tested.

Project	**Density Profile Pass/Fail with Calibrated Gauges**			**Density Profile Pass/Fail with Uncalibrated Gauges**			**Cores**
	Nuclear	Pavetracker	PQI	Nuclear	Pavetracker	PQI	
US 281	Pass	Pass	Pass	Pass	Fail	Pass	Pass
FM 158	Pass	Pass	Pass	*	*	*	Pass
SH 6	**	**	**	Pass	Pass	Pass	Pass
IH 20	Pass	Pass	Pass	Pass	Pass	Pass	Pass

**Gauges not tested uncalibrated*
***Gauge calibration not feasible due to time constraints*

Table 7.2. Summary of Joint Density Results from Projects Tested.

Project	**Density Profile Pass/Fail with Calibrated Gauges**			**Density Profile Pass/Fail with Uncalibrated Gauges**			**Cores**
	Nuclear	Pavetracker	PQI	Nuclear	Pavetracker	PQI	
FM 158	Pass	Fail	*	**	**	**	Pass
SH 6	***	***	***	Pass	Fail	Pass	Pass
IH 20	Fail	Fail	Fail	Fail	Fail	Fail	Fail

**Joint not tested with PQI*
***Gauges not tested uncalibrated*
****Gauge calibration not feasible due to time constraints*

Gauge Accuracy Results

Analyzing the data collected with calibrated gauges, as compared to the true core values, yields the best indication of how accurately the gauges perform. The gauges were calibrated to the mix on US 281, FM 158, and IH 20. Table 7.3 summarizes how well each gauge performed on each project. The gauges are ranked from best to worst performing as based on statistical measures of accuracy including the sum of squared errors, the mean squared error, and the mean percent error. The results show that no gauge consistently performed best regarding accuracy of true density values. There is room for improvement with all the gauges.

The research team also sought to get a feel for the bias and reliability of each gauge. Table 7.4 shows the average error and the standard deviation of the error for each calibrated gauge on the projects tested. It is apparent that gauge performance varied between projects. Ideally, the average error would be zero (indicating no bias), and the standard deviation of the errors would be small. Statistical tests for the mean average error show all gauges were biased on the US 281 project; both the PQI and the Pavetracker were biased on FM 158, and the Pavetracker was biased on IH 20. Bias was exhibited in these instances despite the fact that all gauges were previously calibrated to the mix. Unfortunately, as shown by the data, the level of bias may vary significantly. Furthermore, the data also show that on some projects the gauges may not exhibit any bias; thus, a valid estimate of bias cannot be made.

Assuming that gauge calibration could be performed to where the non-nuclear gauges are consistently unbiased, using the standard deviation of observed errors provides a means of estimating gauge accuracy. This sample standard deviation serves as a point estimate for the population standard deviation. Assuming the distribution of the entire population of errors is normal, virtually all errors should be within ±3 standard deviations. Thus, *if the gauges were unbiased*, the levels of accuracy shown in Table 7.5 should be obtained from the respective projects. The data collected indicate the PQI would be the most reliable gauge if the gauge exhibited no bias. This means that, in general, the PQI provides the most accurate estimate of density differentials. The next section discusses issues that need to be resolved with the density gauges for improved reliability of readings.

Table 7.3. Ranking of Gauge Accuracy.

Project	**Gauge Ranking**		
	1	2	3
US 281	Nuclear	PQI	Pavetracker
FM 158	Nuclear	Pavetracker	PQI
IH 20	PQI	Nuclear	Pavetracker

Table 7.4. Average Error and Standard Deviation of Errors for Calibrated Gauge Densities.

Project	Nuclear		Pavetracker		PQI	
	Average Error (pcf)	Standard Deviation of Errors (pcf)	Average Error (pcf)	Standard Deviation of Errors (pcf)	Average Error (pcf)	Standard Deviation of Errors (pcf)
US 281	-0.8	0.73	-9.4	0.86	-3.83	0.80
FM 158	0.2	1.13	-2.1	1.63	-4.5	1.20
IH 20	-1.8	2.24	2.7	3.19	0.2	0.56

Table 7.5. Expected Levels of Accuracy Assuming Gauge Bias of Zero.

Project	Nuclear	Pavetracker	PQI
US 281	±2.2	±2.6	±2.4
FM 158	±3.4	±4.9	±3.6
IH 20	±6.7	±9.6	±1.7
AVERAGE	**±4.1**	**±5.7**	**±2.6**

RECOMMENDATION FOR IMPROVEMENT OF DENSITY GAUGES

There are three key issues that need to be resolved with respect to gauge accuracy. First, the field data collected show that a calibration performed with the non-nuclear gauges on one section of the project may not work on a different section of the same project with the same mix type. For example, on US 281, the PQI read on average 3.8 pcf too low, and the Pavetracker read on average 9.4 pcf too low, despite the fact that both gauges were calibrated one day prior to testing with five calibration cores at a location approximately 1000 ft. from where researchers conducted density profiling. Similarly, on FM 158, the PQI read 4.5 pcf too low, on average, even though it was calibrated one day prior to conducting density profiles. What these observations imply is a calibration performed on yesterday's paving may not work on the mix placed today with the non-nuclear gauges. If field results are ever going to be consistently reliable with respect to accuracy of the non-nuclear gauges, this aspect of calibration needs to be addressed.

The second issue that needs to be addressed with all the gauges is calibrating the response of the device to changes in mix density, (i.e., the slope of the gauge). At this time only the PQI includes a slope function, and this function only allows two points to be input into the gauge. Neither the nuclear gauge nor the Pavetracker have any kind of user-accessible slope calibration. Both laboratory and field data show that all the gauges can have slope problems. For the best accuracy, gauges should have a function that allows calibration by inputting several core and gauge values into the gauge throughout a range of densities. The gauge could then internally adjust the slope to match the data.

The final area that needs to be addressed with the gauges is contact with the HMA. In the field researchers sometimes observed strange results where core densities barely changed but gauge readings changed dramatically. One contributing factor to this unreliable performance could be gauge contact with the HMA. Although the research team took special care to only test locations where gauge contact with the HMA seemed good, problems were still experienced. These kinds of problems were especially observed with the Pavetracker. It is believed the Pavetracker, with its small size and rigid measurement surface, is especially prone to contact-area problems. Sometimes the Pavetracker numbers bounced around so drastically that the research team believes there may be an electronic glitch occurring in the gauge. The PQI is larger in size and has a thin pad over the measurement surface; this pad should help provide more uniform contact between the gauge and the HMA mat. Ideally, a density gauge should be developed that is non-contact.

RECOMMENDATIONS FOR TXDOT FROM RESEARCH FINDINGS

Recommendations for Density Profile

Work conducted in this research project has shown the PQI can be used as an alternative for the nuclear density gauge for density profiles. Although the PQI often exhibited calibration drift, this gauge should be a satisfactory substitute for the nuclear gauge since density differentials are the primary concern with this test procedure and not true accuracy of the density values. Results were obtained with both the nuclear gauge and a PQI gauge that consistently matched core results. The Pavetracker, even if unbiased, on average would have poorer accuracy than the other gauges used. In this project, researchers collected nuclear readings during the density profile by rotating the gauge 180° between readings, and then averaging the two readings for one measurement. Since the results matched core results, TxDOT should consider revising the procedure for the nuclear gauge to match the procedure used in this project. Performing the testing with the nuclear gauge in this manner would eliminate one reading per location and could save substantial time in the testing process without sacrificing the reliability of the test outcome. Since the PQI also worked well, Appendix B of this report details recommended test procedures for performing density profiles with either the nuclear gauge or the PQI. A word of caution is that, depending on mix type, the slope of the PQI gauge may or may not adequately reflect changes in true mat density. Districts that choose to use a non-nuclear gauge should perform some validation testing with their gauge on their HMA mixtures and determine if a new slope is needed before openly allowing the gauge for profiling on projects.

The Pavetracker used in this project should only be used for density profiles if the gauge is calibrated to the mix. At one project the Pavetracker results did not match the cores when test data were collected with the gauge at factory calibration settings. However, Troxler now produces the Pavetracker and they reportedly changed some of the internals of the device; before any final recommendations can be made regarding this device, more testing should be conducted with the new gauge from Troxler.

Recommendation for Joint Density

Data collected in this project indicate the PQI can be used as an alternative for the nuclear density gauge for joint density quality assurance. Just as with density profiling, TxDOT districts choosing to use a non-nuclear gauge should perform some validation testing on their HMA mixtures with the gauge to determine if the slope of the gauge is appropriate before openly allowing the gauge for density profiling on projects. Data indicate the Pavetracker used in this project should not be used for enforcement of the joint density specification; however the research team has not yet tested Troxler's new Pavetracker for joint density testing. It is unknown at this time if the new Pavetracker will perform better.

One issue that arose from this project was the reliability of the joint density test. As currently written, only one measurement is required in the main mat and one at the joint. If conducted in this manner, the test may pass a joint that truly should fail, or fail a joint that should pass. More complete coverage would improve the reliability of the test. TxDOT may want to consider collecting multiple readings in both the main lane and along the joint, then differencing the average density from each area of the mat, rather than comparing a single joint reading to a single main mat reading. Alternatively, multiple readings at distinct locations both in the main lane and along the joint could be statistically compared to test if the true mean joint density indeed exceeds the allowable density drop.

Recommendation for Ongoing Efforts

Based upon the findings presented in this report, ongoing efforts should focus on:

- adding the PQI as an approved device for density profile and joint density tests. The PQI and nuclear gauge should be used side by side on several additional projects to validate the observations from the work described in this report. Appendix B and Appendix C contain density profile and joint density procedures incorporating the use of the PQI.
- monitoring advancements in the Pavetracker gauge. Troxler has purchased the rights to the Pavetracker device and is in the process of trying to improve this gauge. TTI now has a Troxler Pavetracker which should be tested on additional projects of varying mixture designs.
- establishing a database of gauge calibration parameters for various projects with the non-nuclear gauges to investigate if there is any general trend in calibration constants for specific mix types, and
- developing a non-contact density measurement system.

APPENDIX A

LABORATORY DATA ON TEST SLABS

SFA 2.5 Inch Thick in Dry Condition.

Sample ID	Measured Bulk Density slab	Measured Air Void Slab	Measured Bulk Den Core	Measured Air Void Core	Temp °F	Density Reading															
						PQI (Transtech)						PaveTracker						Nuclear			
						1	2	3	4	Avg	STDEV	1	2	3	4	Avg	STDEV	1	2	Avg	STDEV
SF_2.5_1	152.006	2.6	153.52	1.7	210	133.3	132.9	134.5	133.6	133.58	0.68	149.9	153.1	156.0	150.4	152.35	2.81	142.9	147.0	144.95	2.90
					155	133.5	132.9	133.8	133.0	133.30	0.42	156.1	154.6	149.4	145.7	151.45	4.79	144.5	146.8	145.65	1.63
					127	133.4	132.8	133.0	133.0	133.05	0.25	153.9	146.0	148.0	142.3	147.55	4.85	141.8	144.9	143.35	2.19
					71	132.0	132.2	132.0	132.2	132.10	0.12	154.9	153.5	154.1	152.6	153.78	0.97	143.8	141.1	142.45	1.91
										133.0						151.3				144.1	
										0.6						2.7				1.5	
										0.5						1.8				1.0	
SF_2.5_2	150.384	3.7	151.619	2.9	240	131.4	134.3	133.6	134.1	133.35	1.33	144.1	146.9	146.5	143.8	145.33	1.60	142.5	140.5	141.50	1.41
					210	130.6	133.1	132.7	133.7	132.53	1.35	144.9	144.0	148.6	146.0	145.88	1.99	142.5	141.4	141.95	0.78
					180	124.7	125.7	125.7	125.5	125.40	0.48	140.3	145.3	142.0	137.4	141.25	3.30	142.7	139.1	140.90	2.55
					150	131.2	132.4	133.2	132.2	132.25	0.82	149.3	150.1	147.4	148.8	148.90	1.13	141.5	138.8	140.15	1.91
					120	131.7	132.0	132.0	131.9	131.90	0.14	142.7	147.1	143.8	147.2	145.20	2.30	141.5	140.2	140.85	0.92
					73	129.7	129.6	130.6	130.8	130.18	0.61	147.4	147.7	142.5	149.1	146.68	2.88	142.5	138.6	140.55	2.76
										130.9						145.5				141.0	
										2.9						2.5				0.6	
										2.2						1.7				0.5	
SF_2.5_3	148.64	4.8	149.904	4	250	129.7	130.9	130.3	131.4	130.58	0.74	154.3	153.1	147.4	149.1	150.98	3.26	139.8	127.2	133.50	8.91
					220	131.0	132.2	130.9	132.2	131.58	0.72	153.9	150.3	147.1	152.1	150.85	2.90	140.8	127.2	134.00	9.62
					190	130.0	132.1	131.0	131.0	131.03	0.86	156.4	150.5	153.1	147.8	151.95	3.67	141.3	128.5	134.90	9.05
					160	126.7	130.3	129.0	131.4	129.35	2.02	139.0	135.9	142.9	136.8	138.65	3.12	140.4	128.5	134.45	8.41
					130	126.9	129.5	129.1	131.4	129.23	1.85	139.9	139.8	143.3	148.1	142.78	3.91	139.1	128.2	133.65	7.71
					73	125.8	128.5	129.9	129.9	128.53	1.93	143.7	142.2	136.5	140.7	140.78	3.10	127.3	139.0	133.15	8.27
										130.0						146.0				133.9	
										1.2						5.9				0.6	
										0.9						4.1				0.5	
SF_2.5_4	145.39	8.9	145.797	6.6	250	127.5	129.4	128.2	130.2	128.83	1.21	139.4	142.8	144.7	145.8	143.18	2.81	125.6	124.4	125.00	0.85
					220	126.6	131.0	130.8	130.5	129.73	2.09	140.3	147.3	144.0	143.0	143.65	2.89	130.3	124.4	127.35	4.17
					190	126.8	130.8	131.0	131.3	129.98	2.13	145.9	133.9	144.2	143.2	141.80	5.38	131.1	124.5	127.80	4.67
					160	126.0	128.4	129.3	128.7	128.10	1.45	136.8	124.8	141.2	130.8	133.40	7.14	132.0	123.7	127.85	5.87
					130	124.9	126.7	129.3	128.8	127.43	2.03	136.5	139.0	136.8	141.3	138.40	2.23	128.7	124.7	126.70	2.83
					69	125.4	123.7	125.4	125.2	124.93	0.82	127.3	126.9	127.6	126.7	127.13	0.40	130.3	124.4	127.35	4.17
										128.2						137.9				127.0	
										1.1						4.3				1.2	
										0.8						3.1				0.9	

SFA 3.0 Inch Thick in Dry Condition.

Sample ID	Measured Bulk Density slab	Measured Air Void Slab	Measured Bulk Den Core	Measured Air Void Core	Temp °F	Density Reading															
						PQI (Transtech)						PaveTracker						Nuclear			
						1	2	3	4	Avg	STDEV	1	2	3	4	Avg	STDEV	1	2	Avg	STDEV
SF_3_1	148.64	4.8	150.911	3.3	230	133.0	133.1	133.0	133.9	133.25	0.44	138.7	142.7	141.6	144.9	141.98	2.58	132.2	140.4	136.30	5.80
					200	133.7	131.3	132.8	136.2	133.50	2.05	143.0	148.2	139.7	146.2	144.28	3.73	133.4	140.9	137.15	5.30
					170	134.9	134.4	132.7	133.7	133.93	0.95	150.8	155.6	156.0	152.5	153.73	2.50	133.9	141.0	137.45	5.02
					140	134.7	133.3	132.3	132.2	133.13	1.16	149.3	153.1	155.5	152.8	152.68	2.55	131.3	138.7	135.00	5.23
					73	132.8	130.5	130.1	130.2	130.90	1.28	142.6	147.2	149.7	143.8	145.83	3.24	132.6	140.3	136.45	5.44
										132.94						147.70				136.47	
										1.18						5.22				0.95	
										0.89						3.54				0.70	
SF_3_2	144.39	7.5	144.826	7.2	230	128.5	128.4	128.8	130.2	128.98	0.83	137.1	137.0	139.6	143.2	139.23	2.91	129.0	125.6	127.30	2.40
					200	128.5	130.4	128.6	129.4	129.23	0.88	146.7	142.0	143.0	139.3	142.75	3.06	131.1	125.0	128.05	4.31
					170	128.9	129.4	128.8	128.2	128.83	0.49	140.9	136.3	137.9	141.0	139.03	2.32	131.3	128.1	129.70	2.26
					140	128.1	128.1	128.3	128.4	128.23	0.15	141.7	142.7	142.2	139.9	141.63	1.22	131.5	126.6	129.05	3.46
					73	126.9	126.9	126.1	126.7	126.65	0.38	131.5	133.7	134.1	137.6	134.23	2.52	130.0	123.7	126.85	4.45
										128.38						139.4				128.2	
										1.03477						3.283				1.186	
										0.80602						2.356				0.925	

SFA 2.5 Inch Thick Slabs in Moist Condition.

Temp °F	Density Reading with Moist Condition																	
	PQI (Transtech)							PaveTracker							Nuclear			
	1	2	3	4	Avg	STDEV	CV	1	2	3	4	Avg	STDEV	CV	1	2	Avg	STDEV
230	140.3	139.9	140.5	139.6	140.08	0.40	0.3	159.1	152.8	150.0	147.7	152.40	4.93	3.2	141.9	141.2	141.55	0.49
220	138.6	139.1	138.2	137.6	138.38	0.63	0.5	151.5	149.3	148.8	148.9	149.63	1.27	0.8	141.0	140.9	140.95	0.07
200	138.9	137.8	136.8	137.9	137.85	0.86	0.6	151.5	148.3	153.4	145.7	149.73	3.41	2.3	141.2	143.7	142.45	1.77
180	135.4	135.8	135.9	136.0	135.78	0.26	0.2	151.6	148.1	152.3	154.7	151.68	2.73	1.8	142.2	142.5	142.35	0.21
160	135.9	136.2	135.7	135.6	135.85	0.26	0.2	151.8	148.3	152.5	154.3	151.73	2.51	1.7	142.1	142.8	142.45	0.49
					0.00	#DIV/0!	#DIV/0!	147.4	147.7	142.5	149.1	146.68	2.88	2.0			0.00	#DIV/0!
					114.7							150.3					118.3	
for SF_2.5_2					56.2							2.1					58.0	
					49.0							1.4					49.0	
230	144.6	145.1	142.1	131.0	140.70	6.60	4.7	138.5	140.5	141.8	131.5	138.08	4.59	3.3	122.5	132.3	127.40	6.93
220	141.4	138.5	139.1	139.0	139.50	1.29	0.9	137.0	134.5	142.0	134.8	137.08	3.47	2.5	122.4	130.2	126.30	5.52
200	140.6	142.0	140.3	139.9	140.70	0.91	0.6	140.4	137.8	142.3	133.9	138.60	3.64	2.6	121.6	130.1	125.85	6.01
180	139.3	138.3	138.1	138.0	138.43	0.60	0.4	140.5	138.2	142.0	133.6	138.58	3.67	2.6	121.8	131.1	126.45	6.58
160	139.2	138.2	139.3	138.4	138.78	0.56	0.4	140.8	138.6	141.8	133.3	138.63	3.79	2.7	121.4	129.9	125.65	6.01
					#DIV/0!	#DIV/0!	#DIV/0!					#DIV/0!	#DIV/0!	#DIV/0!			#DIV/0!	#DIV/0!
for SF_2.5_4					#DIV/0!							#DIV/0!					#DIV/0!	
					1.1							0.7					0.7	
					#DIV/0!							#DIV/0!					#DIV/0!	

Type C 2.0 Inch Thick Slabs in Dry Condition.

Sample ID	Measured Bulk Density slab	Measured Air Void slab	Measured Bulk Den Core	Measured Air Void Core	Temp °F	Density Reading															
						PQI						PaveTracker						Nuclear			
						1	2	3	4	Avg	SDEV	1	2	3	4	Avg	SDEV	1	2	Avg	SDEV
					210	152.3	152.9	151.1	149.9	151.55	1.33	148.5	147.5	146.7	147	147.43	0.79				
					185	149.7	151.6	148.9	152	150.55	1.49	147.8	148.4	147.3	146.7	147.55	0.72				
C_2_1	147.576	2.9	148.26	2.5	153	146.7	146.3	146.8	146.5	146.58	0.22	139.8	142.8	139.6	139.5	140.43	1.59				
					125	145.6	147	145.7	146.5	146.20	0.67	146.1	141.2	138.5	143	142.20	3.19				
					70	149.3	146.9	147.9	146.3	147.60	1.31	147.2	144.8	146.2	145.9	146.03	0.99	142.7	142	142.35	0.49
										148.50						144.73					
										2.41						3.23					
										1.63						2.23					
					245	142.3	143.7	143.3	141.7	142.75	0.91	147.1	143.4	146.8	146.7	146.00	1.74				
					215	149.6	149.3	149.8	148.2	149.23	0.71	146	146.9	143.8	145.4	145.53	1.30				
					185	142.7	143.1	143.7	141.6	142.78	0.88	148.6	148.2	146.7	146.1	147.40	1.19				
C_2_2	144.706	4.8	145.86	4	156	143	144	144.3	143	143.58	0.68	148.9	147.8	148.4	145.6	147.68	1.45				
					124	144.9	146.6	147.1	145	145.90	1.12	147.6	146.4	146.8	144	146.20	1.55				
					70	142.3	143.6	141.2	144	142.78	1.28	145	144.2	142.7	144.4	144.08	0.98	134.9	134.1	134.5	0.57
										144.50						146.15					
										2.61						1.31					
										1.81						0.90					
					245	141.6	140.5	142	139.7	140.95	1.05	138.3	141.4	138.6	137.4	138.93	1.73				
					215	139.7	139.4	140.2	138.3	139.40	0.80	138.8	139.4	140	137.7	138.98	0.98				
					185	140.1	139.4	139.7	137.9	139.28	0.96	137.2	138.1	140.4	138.6	138.58	1.35				
C_2_3	141.461	6.9	142.07	6.5	150	140.8	141.3	140.2	141.4	140.93	0.55	139.3	141.5	137.8	138.9	139.38	1.55				
					125	141.9	141.2	141.9	140.9	141.48	0.51	139.7	140.8	139.4	139.3	139.80	0.69				
					70	140.7	140.9	141	141.1	140.93	0.17	136.4	137.9	139.2	137.1	137.65	1.20	133.4	132.1	132.75	0.92
										140.49						138.88					
										0.92						0.74					
										0.65						0.53					
					240	134.7	136.3	136.0	136.8	135.95	0.90	142.7	141.6	144.0	140.1	142.10	1.66	128.0	131.5	129.75	2.47
					210	135.5	135.8	135.6	136.6	135.88	0.50	142.8	142.0	144.1	142.5	142.85	0.90	128.4	131.8	130.1	2.40
					180	136.0	137.0	137.0	136.7	136.68	0.47	142.0	142.2	146.2	144.5	143.73	2.00	129.6	130.1	129.85	0.35
C_2_4	137.84	9.3	141.75	6.7	150	138.0	138.6	137.2	138.5	138.08	0.64	146.4	145.3	142.0	143.0	144.18	2.03	129.8	130.8	130.3	0.71
					120	138.8	139.0	138.8	139.0	138.90	0.12	140.7	142.1	143.1	141.8	141.93	0.99	128.3	130.8	129.55	1.77
					71	137.5	137.2	137.4	137.1	137.30	0.18	141.4	141.0	141.5	145.0	142.23	1.86	127.1	129.6	128.35	1.77
										137.13						142.83				129.65	
										1.20						0.93				0.6892	
										0.88						0.65				0.53	

Type C 2.5 Inch Thick Slabs in Dry Condition.

Sample ID	Measured Bulk Density slab	Measured Air Void Slab	Measured Bulk Den Core	Measured Air Void Core	Temp °F	Density Reading															
						PQI						PaveTracker						Nuclear			
						1	2	3	4	Avg	STDV	1	2	3	4	Avg	STDV	1	2	Avg	STDV
C_2.5_1	146.02	3.9	148.37	2.4	230	147.7	148.4	147.1	149.1	148.08	0.87	150.7	155.1	150.6	155.0	152.85	2.54	136.1	133.9	135.0	1.56
					200	137.8	138.1	138.2	138.6	138.18	0.33	153.2	155.3	153.1	154.0	153.90	1.02	133.3	132.1	132.7	0.85
					170	138.8	138.7	138.3	140.4	139.05	0.93	152.0	154.8	154.0	154.3	153.78	1.23	129.9	129.2	129.6	0.49
					140	139.8	138.8	138.5	138.7	138.95	0.58	151.2	155.9	151.4	154.7	153.30	2.36	131.9	129.1	130.5	1.98
					110	139.5	139.1	139.1	139.8	139.38	0.34	152.0	155.9	152.3	154.4	153.65	1.84	132.7	130.6	131.7	1.48
					70	138.9	139.0	139.8	139.1	139.20	0.41	148.7	152.0	148.1	153.5	150.58	2.60	130.8	129.7	130.3	0.78
										138.95						153.01				131.61	
										0.46						1.25				2.00	
										0.33						0.82				1.5	
C_2.5_2	138.15	9	135.79751	8.3	240	137.9	137.8	137.2	138.4	137.83	0.49	145.5	143.9	144.7	142.3	144.10	1.37	131.4	133.3	132.4	1.34
					210	137.3	138.0	137.3	137.3	137.48	0.35	142.3	145.1	143.4	142.0	143.20	1.40	130.9	132.7	131.8	1.27
					180	138.1	138.6	137.6	138.5	138.20	0.45	144.1	146.0	145.1	146.3	145.38	0.99	132.1	132.5	132.3	0.28
					150	138.6	139.0	138.1	138.6	138.58	0.37	145.8	145.9	145.4	144.7	145.45	0.54	129.8	131.8	130.8	1.41
					120	139.5	139.6	139.3	139.6	139.50	0.14	144.3	145.1	144.5	143.8	144.43	0.54	132.4	131.0	131.7	0.99
					71	137.1	137.2	137.6	137.4	137.33	0.22	142.8	140.4	142.8	143.0	142.25	1.24	130.3	129.4	129.9	0.64
										138.15						144.13				131.47	
										0.81						1.25				0.97	
										0.58						0.87				0.7	
C_2.5_3	137.72	9.4	139.38	10.7	220	136.9	137.9	136.1	137.7	137.15	0.82	142.6	146.3	143.8	144.1	144.20	1.54	129.0	129.6	129.3	0.42
					190	137.0	137.8	136.6	137.9	137.33	0.63	145.1	146.4	145.2	145.3	145.50	0.61	131.2	129.7	130.5	1.06
					160	137.3	137.2	137.7	138.4	137.65	0.54	144.8	147.4	144.5	143.6	145.08	1.63	130.6	129.4	130.0	0.85
					130	137.3	138.1	138.0	138.3	137.93	0.43	143.5	146.2	144.4	145.0	144.78	1.13	127.6	124.8	126.2	1.98
					70	136.7	137.0	137.5	137.6	137.20	0.42	141.2	142.3	141.8	141.6	141.73	0.46	126.0	126.5	126.3	0.35
										137.45						144.26				128.44	
										0.33						1.49				2.06	
										0.24						1.03				1.6	

Type C 3.0 Inch Thick Slabs in Dry Condition.

Sample ID	Measured Bulk Density slab	Measured Air Void Slab	Measured Bulk Den Core	Measured Air Void Core	Temp °F	Density Reading															
						PQI						PaveTracker						Nuclear			
						1	2	3	4	Avg	STDV	1	2	3	4	Avg	STDV	1	2	Avg	STDV
C_3_1	145.7	4.1	147.00194	3.3	245	131.4	131.9	131.6	132.9	131.95	0.67	154	149.2	152.7	147.7	150.90	2.94	142.4	143.1	142.75	0.49
					215	132.7	131.6	132.6	131.3	132.05	0.70	154	154.6	154.1	150.9	153.40	1.69	142.9	143.3	143.1	0.28
					185	131.8	132.5	131.7	132.2	132.05	0.37	154.7	157.1	153.4	153.4	154.65	1.74	142.6	142.1	142.35	0.35
					155	151.5	151	151.1	151	151.15	0.24	155.4	153	155.4	155.3	154.78	1.18	143	142.4	142.7	0.42
					125	152.1	151.8	150.8	151	151.43	0.62	155	155.1	155.3	155.2	155.15	0.13	142.8	143	142.9	0.14
					72	150.8	151.5	151.9	150.8	151.25	0.54	154.3	154.1	155.5	154.1	154.50	0.67	142.4	142.5	142.45	0.07
						First three reading excluded for avg calcula				151.28						153.90				142.71	
										10.55						1.58				0.28	
										6.97						1.03				0.2	
C-3_2	138.72	8.7	140.47662	7.6	240	126.9	127.3	127.3	128.5	127.50	0.69							136.5	135	135.75	1.06
					210	128.9	128.2	127.9	127.9	128.23	0.47							138.1	136.3	137.2	1.27
					180	130.5	129.2	129.4	130.1	129.80	0.61							137.1	135.9	136.5	0.85
					150	146.4	145.9	144.8	146.1	145.80	0.70	145.1	145.7	147.8	145.7	146.08	1.18	136.9	135.4	136.15	1.06
					120	143.7	143.1	143.3	143.6	143.43	0.28	150.8	149.4	149.6	149	149.70	0.77	137.3	135.8	136.55	1.06
					72	142.6	142.8	143.2	142.6	142.80	0.28	144.1	146.2	143.8	148.8	145.73	2.31	136.6	135.3	135.95	0.92
						First three reading excluded for avg calcula				144.01						147.17				136.35	
										8.58						2.20				0.52	
										5.96						1.50				0.4	

Type C 2.0 Inch Thick Slab in Moist Condition

Temp	**Density Reading (Moist) for C_2_3**																		
	PQI							PaveTracker							Nuclear				
	1	2	3	4	Avg	SDEV	CV	1	2	3	4	Avg	SDEV	CV	1	2	Avg	SDEV	CV
230	124.5	125.4	124.6	125.9	125.10	0.67	0.53	145.3	146.4	148.9	146.3	146.73	1.53	1.04	134.9	137	135.95	1.48	1.09
200	123.1	122.6	121.6	123	122.58	0.68	0.56	144.8	145.8	148.3	145.7	146.15	1.50	1.03	134.5	138.5	136.5	2.83	2.07
170	122.6	123	122	121.7	122.33	0.59	0.48	145.5	144.8	145.7	143.4	144.85	1.04	0.72	134.2	136.7	135.45	1.77	1.31
					123.33							145.91							
					1.54							0.96							
					1.24							0.66							

APPENDIX B

DENSITY PROFILE PROCEDURE INCORPORATING PQI

Part V, Determination of Mat Segregation Using a Density Testing Gauge
Use this procedure to identify segregation in bituminous pavement after placement on the roadway.

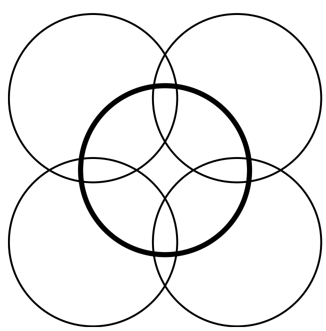
Apparatus
Use the following apparatus:

- nuclear density gauge
- thin lift density gauge (optional)
- electrical impedance measurement gauge, equipped with suitable equipment to compensate for moisture and temperature variances during compaction (optional)
- measuring tape (optional)
- 'Density Profile Form'.

Procedure
Follow these steps to determine mat segregation using an approved density gauge.

Determining Mat Segregation Using a Density Testing Gauge	
Step	**Action**
1	Refer to gauge manufacturer's recommendations for operating the gauge. NOTE: It is not necessary to calibrate the gauge to the mix.
2	A profile section is defined as a 15.2 m (50 ft.) length of mat with readings taken approximately every five feet. Additional longitudinal readings may be taken along the transverse offset where visible segregation is noticed.
3	Perform this step when profiling a location where it is known that the paver stopped. ♦ Identify the location where the lay-down machine stopped paving for some reason, such as sporadic mix delivery. ♦ Mark and record this location as the beginning of the profiled section, also called the zero point. ♦ The first reading location should be approximately ten feet behind the zero point. ♦ Proceed to Step 5.
4	Perform this step when profiling a location where it is not known if the paver stopped. ♦ Randomly select an area. ♦ If possible, choose an area with visible segregation. ♦ Proceed to Step 5.
5	Determine the transverse offset two feet or more from the pavement edge. ♦ Do not vary from this line. ♦ Visually observe the mat and note surface texture in the section to be profiled. ♦ Make note of areas that appear to be segregated. ♦ Visually segregated areas, if any, must be included in the section to be profiled.
6	After completion of the final rolling patterns, position the gauge at the identified location.

	Use of a nuclear density gauge ♦ Take 2 one-minute readings (minimum time length, longer readings can be used) in backscatter mode when using a nuclear density gauge at each random sample location. Rotate the gauge 180° between readings ♦ It is optional to use fine sand passing the No.40 sieve size to fill any voids without elevating the gauge above the rest of the mat. **Use of an electrical impedance gauge** ♦ As shown in the illustration, take 5 three-second readings beginning with a reading at the center and moving clockwise around the center moving the instrument at least 50 mm (2 inches) between readings when using an electrical impedance gauge at each random sample location. Record the in-place density gauge readings.
7	Before moving the gauge, average the readings. ♦ Compare each individual reading to the average.
8	Move the gauge approximately 5 feet forward in the direction of the paving operation. ♦ If a segregated area is visible in between the 5-ft. distance, take an additional set of readings at that location.
9	Repeat steps 6, 7 and 8. ♦ Continue to take readings until a minimum of ten sets of two readings has been completed (if using the nuclear gauge) or ten sets of five reading (if using the electrical impedance gauge).
10	Determine the average density from all locations.
11	Determine the difference between the highest and lowest average density.
12	Determine the difference between the average and lowest average density.
13	Record and plot the data using the 'Segregation Density Profile Form' as shown in the worksheet



Bold line is gauge position 1

Illustration of Data Collection Pattern for Electrical Impedance Gauge

Segregation Density Profile Form

Asphaltic Concrete Pavement

District:	?	CSJ:	?	Location Information for 1st Reading	
County:	?	Profile No:	?	Station:	?
Highway:	?	Test Date:	?	Lane Direction:*	?
Tester:	?	Contractor:	?	Lane:* ML FR - 1 2 3 4	?
Inspector:	?	Mix Type:	?	Distance From Outside Edge of Lane (ft):	?
		Spec. Item:	?		
Brand and Model of Paver: ?		Visible Segregation:	Yes / No	Lift: 1st 2nd 3rd	?
				Lift Thickness:	?

Describe Type of Remix Equipment Used In or Ahead of Paver: ?

Reading No.	Readings (lbs/cf) 1	2	3	Avg.
Before Screed @ 0'	?	?	?	
Before Screed @ 5'	?	?	?	
At Screed @ 10'	?	?	?	
1 @ 15'	?	?	?	
2 @ 20'	?	?	?	
3 @ 25'	?	?	?	
4 @ 30'	?	?	?	
5 @ 35'	?	?	?	
6 @ 40'	?	?	?	
7 @ 45'	?	?	?	
8 @ 50'	?	?	?	
9	?	?	?	
10	?	?	?	
11	?	?	?	
12	?	?	?	
13	?	?	?	
14	?	?	?	
15	?	?	?	
16	?	?	?	
17	?	?	?	

Average Reading:	
High Reading:	
Low Reading:	

Max Density Ranges	
High - Low	
Average - Low	

NOTES:

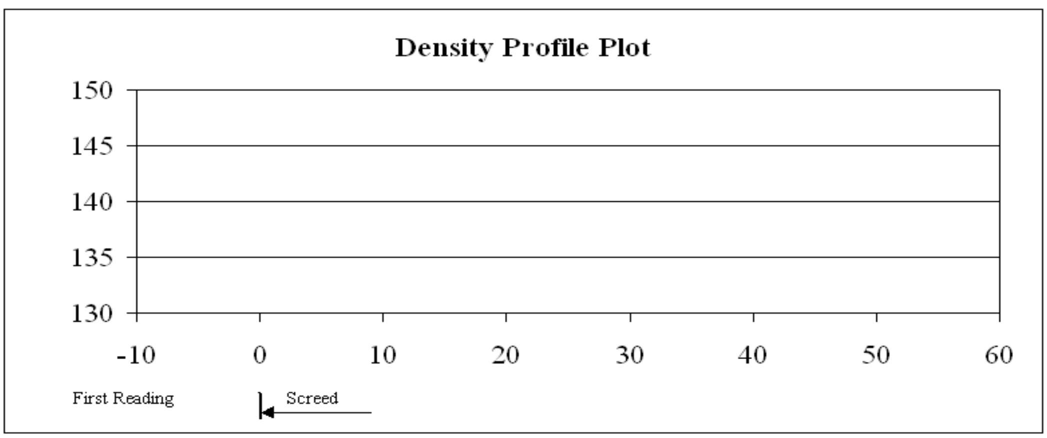
1 - * NB = North Bound, ML = Main Lane, FR = Frontage Road
Lanes numbered from centerline of facility (e.g. 1 = inside lane)

2 - Use a separate form for each density profile.

3 - Profile one 50' section from the first 1000 feet of project placement (Select the 50' section by method discussed in the specification).

4 - Profile a section each time the screed stops, including end of day.

CONSTRUCTION DIVISION
Flexible Pavements Branch
Segregation Profile 10-02.xls
October 25, 2002



APPENDIX C

JOINT DENSITY PROCEDURE INCORPORATING PQI

Part VII, Determination of Longitudinal Joint Density Using a Field Density Testing Gauge
Use this procedure to perform a longitudinal joint density evaluation on hot-mix asphalt pavement.

Apparatus

Use the following apparatus:

- nuclear density gauge
- electrical impedance measurement gauge, equipped with suitable equipment to compensate for moisture and temperature variances during compaction (optional)
- thin lift density gauge (optional)
- measuring tape (optional)
- forms

Procedure

Performing a Longitudinal Joint Density Using a Density Testing Gauge	
Step	**Action**
1	Refer to gauge manufacturer's recommendations for operating the gauge. NOTE: It is not necessary to calibrate the gauge to the mix.
2	Identify the random sample location selected for in-place air void testing. Mark and record this location as the reference point where the joint evaluation is to be performed. ♦ This point must be more than 2 feet from the pavement edge.
3	After completion of the final rolling pattern, position the gauge at the random sample location selected for in-place air void testing.
4	Use of a nuclear density gauge: ♦ Take 2 one-minute readings (minimum time length, longer readings can be used) in backscatter mode when using a nuclear density gauge. Rotate the gauge 180° between readings ♦ It is optional to use fine sand passing the No.40 sieve size to fill any voids without elevating the gauge above the rest of the mat. Use of an electrical impedance gauge: ♦ Take 5 readings beginning with a reading at the center and moving clockwise around the center moving the instrument at least 50 mm (2 inches) between readings when using an electrical impedance gauge, as shown in the illustration in Part V.
5	Determine the average density from the density gauge at each random sample location selected for in-place air void testing.
6	Perform a longitudinal joint density evaluation at the right and left edge of the mat which is or will become a longitudinal joint. The location should be perpendicular to the random sample location selected for in-place air void testing. ♦ Identify the joint type as 'Confined' or 'Unconfined'. ♦ Additional readings may be taken along the longitudinal joint where visible irregularities or segregation is noticed.

7	Position the gauge with the center of the gauge placed at 8 inches from the pavement edge that is or will become a longitudinal joint. Orient the gauge such that the longer dimension of the gauge is parallel to the longitudinal joint.
8	Use of a nuclear density gauge: ♦ Take 2 one-minute readings (minimum time length, longer readings can be used) in backscatter mode when using a nuclear density gauge. Rotate the gauge 180° between readings ♦ It is optional to use fine sand passing the No.40 sieve size to fill any voids without elevating the gauge above the rest of the mat. Use of an electrical impedance gauge: ♦ Take 5 readings beginning with a reading at the center and moving clockwise around the center moving the instrument at least 50 mm (2 inches) between readings when using an electrical impedance gauge.
9	Determine the average density from the location evaluated.
10	Determine the difference in density between the readings taken at the random sample location selected for in-place air void testing and the readings taken along the longitudinal joint.
11	Record and report the data using the 'Longitudinal Joint Density Worksheet' as shown in the example worksheet below.

Example Worksheet

LONGITUDINAL JOINT DENSITY WORKSHEET

Asphaltic Concrete Pavement

District:	?	CSJ:	?	County:	?	Contractor:	?
Highway:	?	Mix Type:	?	Lot Number:	?	Date Tested:	?

Correlation Factor: ?

Sublot Number	Station Number	Travel Lane
1	?	?
2	?	?
3	?	?
4	?	?

Sublot Number	Left Mat Edge Density					Density Difference Between Interior Mat & Left Mat Edge (lbs/cf)	Interior Mat Density @ In-Place Air Void Location				Right Mat Edge Density					Density Difference Between Interior Mat & Right Mat Edge (lbs/cf)
	Type of Joint	Readings (lbs/cf)			Avg.		Readings (lbs/cf)			Avg.	Type of Joint	Readings (lbs/cf)			Avg.	
		1	2	3			1	2	3			1	2	3		
1	?	?	?	?			?	?	?		?	?	?	?		
2	?	?	?	?			?	?	?		?	?	?	?		
3	?	?	?	?			?	?	?		?	?	?	?		
4	?	?	?	?			?	?	?		?	?	?	?		

In-Place Air Void Location - Core location as determined by TxDOT from random numbers

Type of Joint - Confined (C) or Unconfined (U)

Tolerance - Longitudinal Joint Density is passing if Mat Edge density is 3.0 lbs/cf or less than Interior Mat density

CONSTRUCTION DIVISION

Flexible Pavements

Joint Density 2-03.xls