US Army Corps
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Waterways Experiment
Station

Technical Report GL-93-19
September 1993

Evaluation of Surface Density Nuclear Gauges for Acceptance Testing of Asphalt Concrete Overlays

by *Lee E. Tidwell, Randy C. Ahlrich, George L. Regan*
Geotechnical Laboratory

WES

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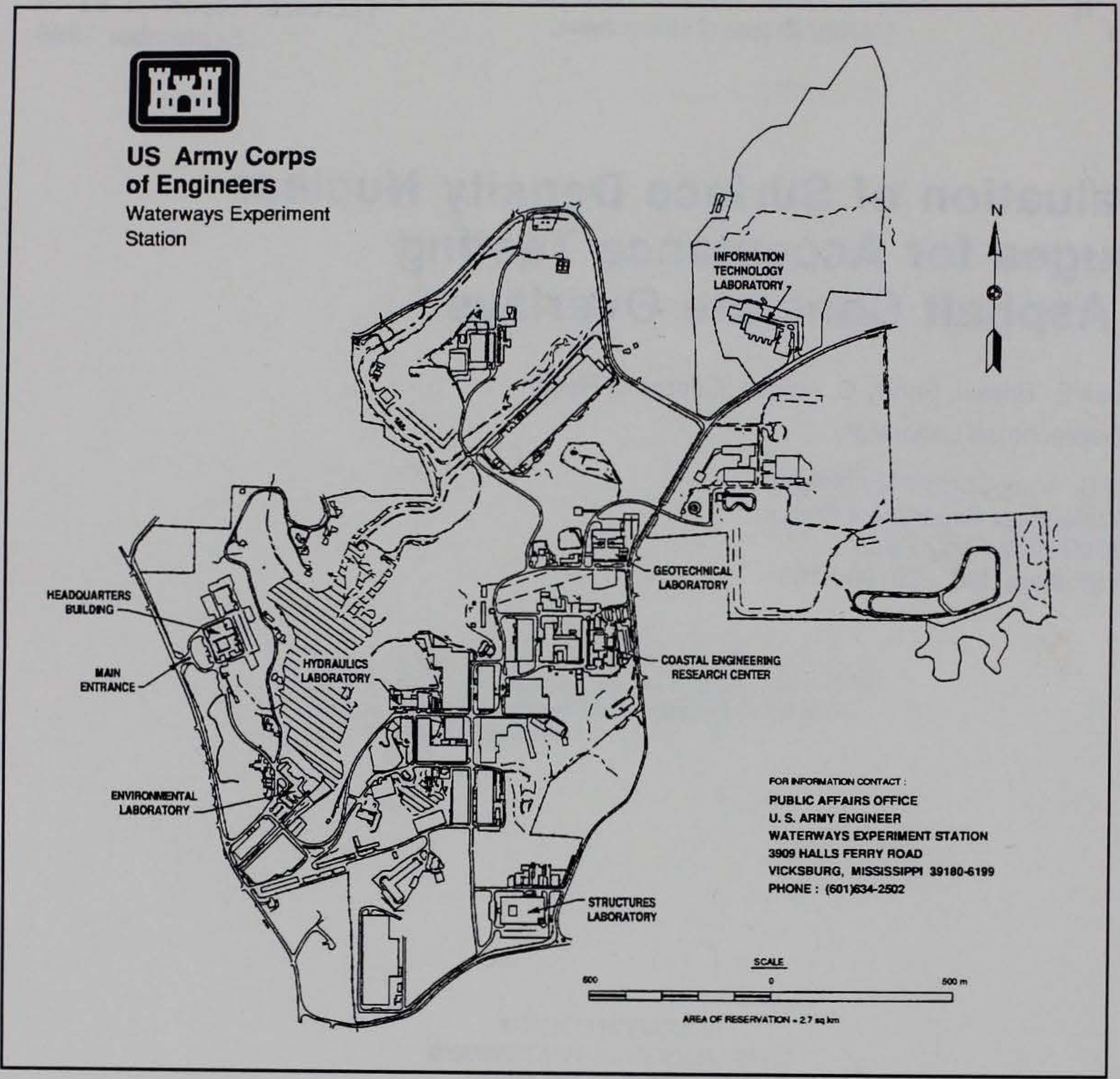

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Contents

List of Figures

List of Tables

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
inches	2.54	centimeters
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter

Preface

The information reported herein was sponsored by the U.S. Department of Transportation, Federal Highway Administration (FHWA) under the Federal Lands Highway Coordinated Technology Implementation Program (CTIP) study C-3, "Evaluation of Thin Layer Nuclear Gauges for Acceptance Testing." Technical Monitor for this study was Mr. Alfred Logie.

This study was conducted by personnel of the Pavement Systems Division (PSD), Geotechnical Laboratory (GL) at the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, from May 1989 through December 1992. Ms. Lee E. Tidwell, Mr. Randy C. Ahlrich, and Mr. George L. Regan were the Principal Investigators and authors of the report. Messrs. C. W. Dorman, J. P. Duncan, and R. T. Graham obtained the field cut cores and the nuclear density gauge readings. Messrs. H. McKnight and J. K. Simmons conducted the laboratory density tests on the field cut cores.

This study was conducted under the general supervision of Dr. W. F. Marcuson III, Director, GL. Direct supervision was provided by Dr. G. M. Hammitt II, Chief, PSD, and Mr. T. W. Vollor, Chief, Material Research and Construction Technology Branch.

The Director of WES during the preparation and publication of this report was Dr. Robert W. Whalin. The Commander was COL Bruce K. Howard, EN.

1 Introduction

Background

Nuclear density and moisture content gauges are examples of technical applications of radiological materials in the construction industry. Nuclear gauges use gamma radiation energy to interact with various geomaterials to allow quick approximations of density. Early applications to geotechnical engineering construction were made during the 1950's (NCHRP 125, 1977, and USDA 1955). Some of these applications included new ways of determining density and moisture content of soils during earth mass construction such as dams and levees. Other applications included density determinations of pavement materials to enhance compaction control during construction (Hughes 1962, Webster 1974). Since the mid 1980's, a newer generation of nuclear density measuring devices has been developed for the use on thin layer asphalt concrete. The ability of this type of device to provide quick indications of density in a nondestructive manner is appealing to both pavement owners and contractors. This appeal formed the basis of the study to evaluate nuclear density gauges for possible use on Federal Lands Highway Program (FLHP) projects.

Objective

The objective of this study is to compare the field densities obtained with a thin layer nuclear density gauge and a surface moisture-density nuclear gauge to the laboratory densities obtained from conventional field cut cores from asphalt construction jobs. The study findings are to provide guidance on use of nuclear density gauges on FLHP projects.

Scope

The scope of this study included a review of available literature and existing data, field density determinations and a statistical analysis of the data. Two nuclear gauges, Troxler Models 4640 and 3411-B, were used in six field studies to determine in-place densities of the asphalt concrete pavement. These nuclear density readings were compared to field cores cut at the same locations. These data were evaluated to determine the correlation between gauge densities and field cores and the effect of gauge placement. Recommendations were made concerning the use of these gauges for quality verification and for acceptance testing of asphalt concrete pavements.

2 Methods for Density Determination

Density by Conventional Methods

Density and bulk specific gravity of bituminous mixes have been conventionally determined on both laboratory manufactured specimens and field cut cores by weighing them and determining their volumes. There are two main methods of doing this: the "two mass" method and the "three mass" method. These methods involve procedures as given in ASTM Standard D 2726, AASHTO T 166, and MIL-STD-620A Method 101.

"Two Mass" Method

The "two mass" method carries an assumption of mix impermeability by water; the specimens are generally weighed dry in air and submerged in water. The following equations are used to calculate density and bulk specific gravity by the "two mass" method.

$$\gamma = \frac{A\ G_w\ \gamma_w}{A-B}$$

$$BSG = \frac{A\ G_w}{A-B}$$

where

γ = density of mix assuming impermeability

A = mass of dry mix weighed in air, grams

B = mass of mix weighed in water, grams

G_w = specific gravity of water at test temperature

γ_w = density of water at test temperature

BSG = bulk specific gravity of mix

"Three Mass" Method

The "three mass" method includes a basic assumption; if water enters a specimen during submerged weighing, the water and volume are accounted for during the third weighing after the specimen has been removed from the water and wiped with a damp cloth (saturated surface dry condition). In other words, it assumes that all water entering a specimen during submerged weighing remains in the air voids and/or aggregate cut surfaces after removal. The following equations are used to calculate density and bulk specific gravity by the "three mass" method.

$$\gamma = \frac{A\ G_w\ \gamma_w}{A-B+C-A} = \frac{A\ G_w\ \gamma_w}{C-B}$$

$$BSG = \frac{A\ G_w}{C-B}$$

where

γ = density of mix allowing for permeability

A = mass of dry mix weighed in air, grams

B = mass of mix weighed in water, grams

C = damp mass of mix after wiping with damp cloth, grams

G_w = specific gravity of water at test temperature

γ_w = density of water at test temperature

BSG = bulk specific gravity of mix

Density by Nuclear Methods

Direct transmission density measurement

The direct transmission method requires making an access hole in the test material and lowering the nuclear source into the hole to the desired measurement depth (Figure 1) This method is generally applicable for any type of material where an access hole can be punched or drilled with only negligible disturbance to the volume of material to be measured. This method has the advantage that the depth of measurement can be controlled (usually in 2-in. increments up to depths of 8 in.). A disadvantage of this method is that it is not a truly nondestructive test since an access hole must be made in the material tested. This method is normally used with cohesive and cohesionless materials in base, subbase, and subgrade layers but not with asphalt concrete layers.

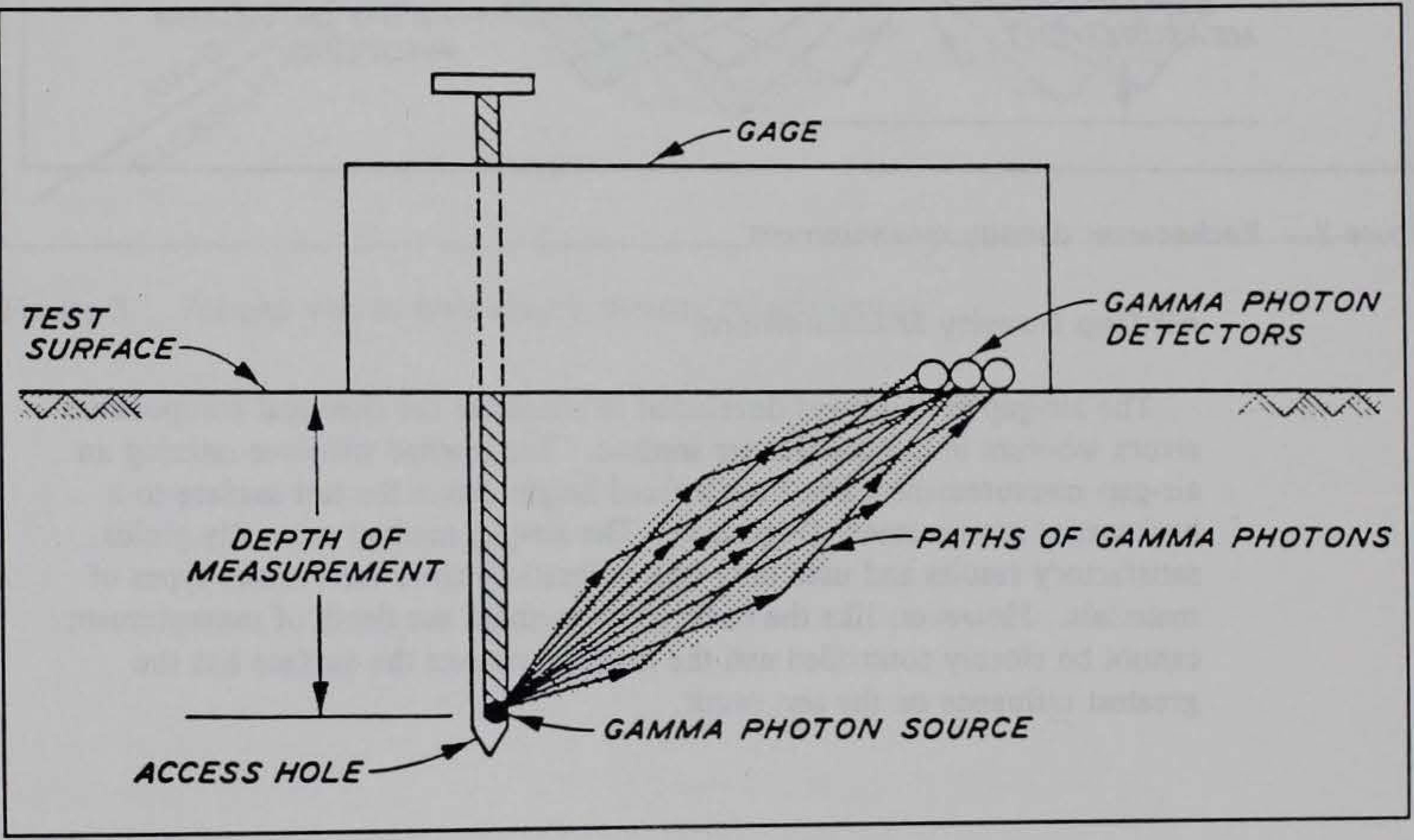

Figure 1. Direct transmission density measurement

Backscatter Density Measurement

Both the source and detectors remain in the gage near the test surface in the backscatter method (Figure 2). The depth of measurement usually ranges from 0.5 to 6 in. below the test surface. This method is applicable on materials for which a specific calibration curve has been developed. The main advantages of the backscatter method are: (a) it is simple to perform and (b) it is a nondestructive test. Disadvantages of this method are: (a) one calibration curve cannot be used for all materials, (b) the depth of measurement cannot be closely controlled, (c) the material nearest the test surface has the greatest influence on the test. This method is primarily used with asphalt concrete layers. NCHRP 125 (1971) contains two appendices with extensive literature reviews and discussions of factors affecting gamma sourced backscatter density gauges.

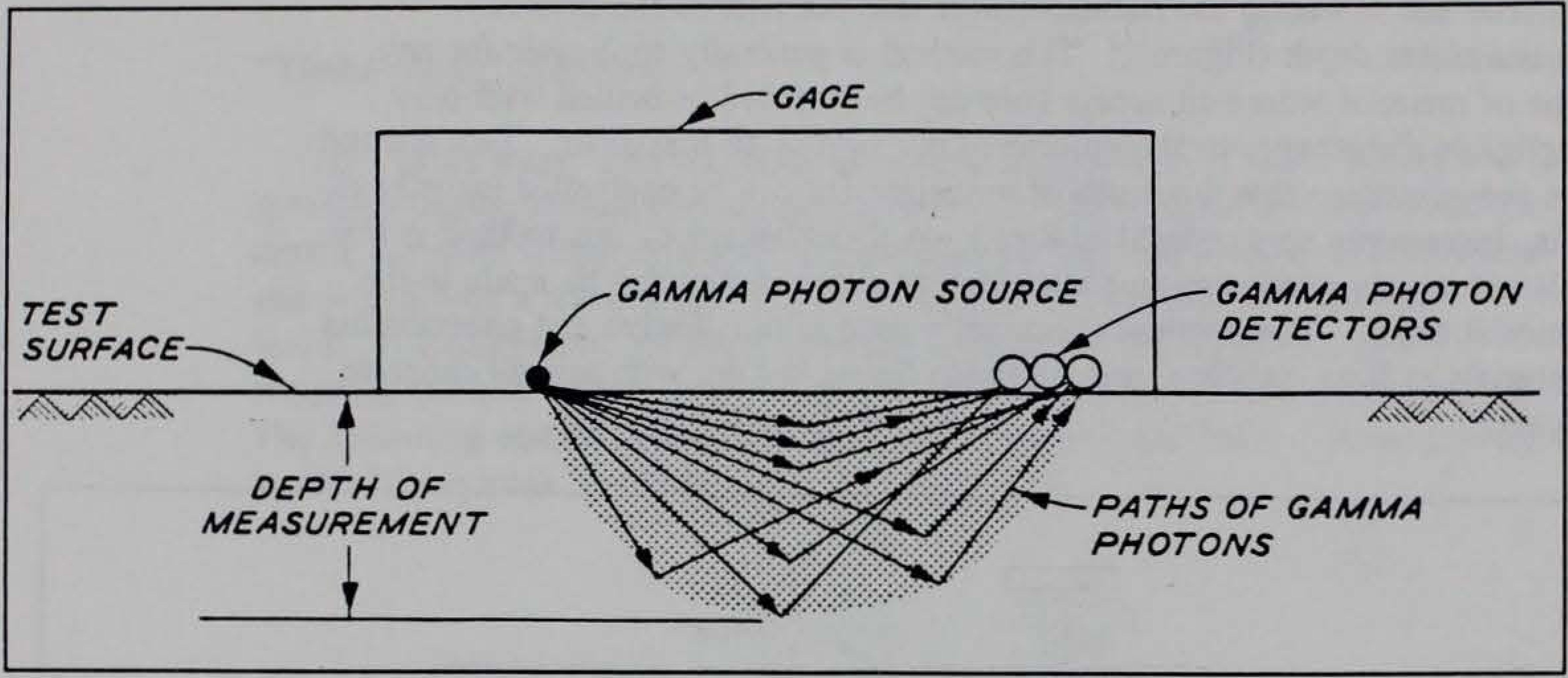

Figure 2. Backscatter density measurement

Air-Gap Density Measurement

The air-gap method was developed to eliminate the chemical composition errors inherent in the backscatter method. The method involves ratioing an air-gap measurement taken from a fixed height above the test surface to a backscatter measurement (Figure 3). The air-gap method generally yields satisfactory results and uses only one calibration curve for various types of materials. However, like the backscatter method, the depth of measurement cannot be closely controlled and the material nearest the surface has the greatest influence on the test result.

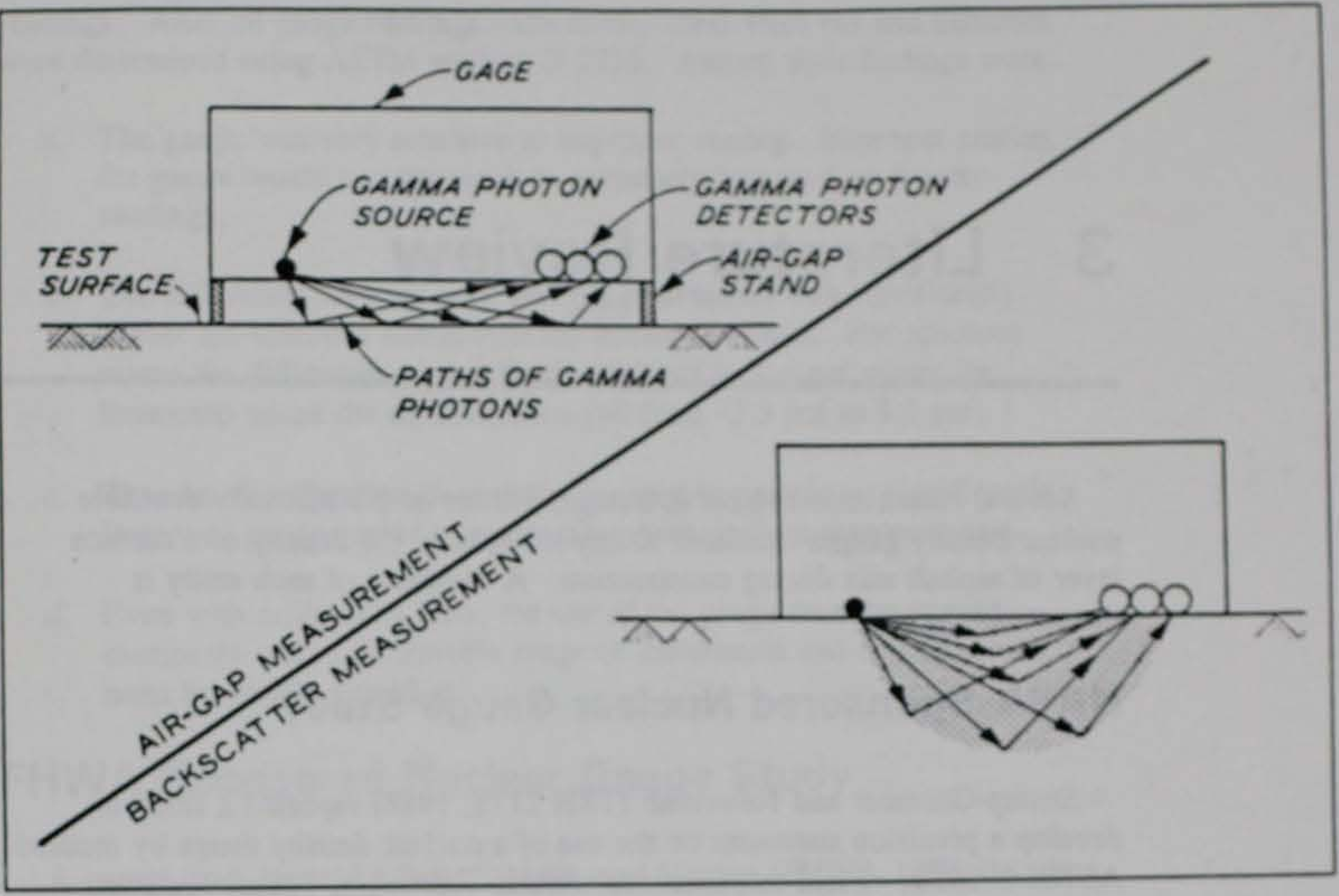

Figure 3. Air-gap versus backscatter density measurement

3 Literature Review

Several recent studies have investigated some of the currently available nuclear density gauges and their ability to estimate the density of a surface layer of asphalt mix during construction. A summary of each study is discussed below:

NAPA Sponsored Nuclear Gauge Study

Stroup-Gardiner and Newcomb (TRR 1178, 1988) reported a study to develop a precision statement on the use of a nuclear density gauge by method ASTM D 2950. Field test locations were in Galveston, Texas, McLean, Virginia, and Reno, Nevada. The field tests provided a database of more than 900 nuclear density readings generated by 31 laboratories using various models of gauges. Cores were cut after all gauge readings were made. Among their findings were the following:

a. Nuclear gauge reading times of 0.25, 1, and 4 minutes did not produce significantly different density readings at the selected mat locations.

b. The ranges of standard deviations between gauges for 1 minute gauge readings were 1.81 pcf to 3.86 pcf in Texas, 1.32 pcf to 3.79 pcf in Virginia, and 3.05 pcf to 5.75 pcf in Nevada.

c. Each gauge appeared to have its own individual regression relationship between core density and its approximation of that density.

Texas DOT Sponsored Nuclear Gauge Study

Kennedy, Tahmoressi, and Solaimanian (TRB 1989) evaluated a Troxler 4640 thin layer density gauge to determine if it could be used to accurately determine in-place density of hot mix asphalt concrete surfaces. Gauge and corresponding core densities, at several test areas within seven different Texas paving projects, were studied. Four projects contained limestone aggregates and three contained siliceous aggregates. The gauge was placed at the test areas and rotated in 90 degree increments before recording four 1 minute readings. After all gauge readings were made, cores were cut and densities were determined using ASTM method D 2726. Among their findings were:

a. The gauge was very sensitive to improper seating. Improper seating of the gauge would usually result in extremely low nuclear density readings.

b. The difference between core and gauge densities was significantly higher for siliceous mixes than for limestone mixes. For siliceous mixes the difference ranged from -12.2 pcf to 2.4 pcf where for limestone mixes the difference ranged from -3.9 pcf to 3.2 pcf.

c. The use of calibration lines through regression analyses significantly improved prediction of core densities from nuclear measurements.

d. Even with calibration lines, the use of the gauge must be treated cautiously and an acceptable range of differences and risk of error must be clearly specified.

FHWA Sponsored Nuclear Gauge Study

A recent draft report by Belt, Santelli, and Hansen (FHWA 1990) details their evaluation of the state-of-the-art capabilities of nuclear density gauges to monitor the density of asphalt concrete. One of the objectives of this report was to establish the capability of commercially available, thin-lift and full-depth static nuclear gauges for monitoring the density of thin asphalt concrete layers. Five models of static gauges manufactured by Campbell Pacific Nuclear, Seaman Nuclear, Humboldt Scientific, and Troxler Electronics, and three dynamic models (including an FHWA prototype) were compared in the study. The Troxler 4640 thin layer density gauge was one of the static backscatter gauges that was evaluated.

The gauges were initially tested in the laboratory under controlled conditions and subsequently tested in the field. All manufacturers' instructions and recommendations were strictly followed. A minimum of four density readings were taken and averaged for each density measurement. The density measurement was then compared with the actual densities of the material. When very questionable readings were observed, they were discarded and repeated immediately. The study is summarized below:

a. When the Troxler 4640 gauge was used in the rough surface mode, the scatter in the data appeared to be greater than usual.

b. There was always scatter in the individual data points and occasionally, a gauge would give a very questionable reading. This was sometimes caused by improperly seating the gauge but on most occasions there was no apparent cause for the error.

c. Chemical composition error is one of the most significant sources of error in nuclear density measurements.

d. Nuclear gauges can significantly over- or underestimate density if the operator relies only on the standard factory calibration.

e. Proper offset correction for each project was found to be critical in maintaining the accuracy of nuclear density measurements.

f. Both static and dynamic nuclear gauges were recommended as useful tools in construction monitoring of density and density growth of thin lift asphalt mixes.

Australian Nuclear Gauge Study

The Materials Engineering Branch of the Main Roads Department in Western Australia investigated the suitability of a Troxler 4640-B thin layer nuclear density gauge to determine the density of asphalt (Asphalt Review 1992). Their objective was to determine the ability of the gauge to measure asphalt density with sufficient accuracy and reliability for use in deciding conformance with project specifications. The 4640-B gauge was used at 10 randomly selected sites in 13 lots of asphalt, and cores were subsequently taken from the same locations. Densities were computed using the factory calibration equation and special calibration equations. The asphalt lots included both dense and open graded asphalt. Among their findings were:

a. For dense graded asphaltic concrete, the gauge underestimated density in comparison with the core results, while for open graded mix, the gauge overestimated results.

b. For dense graded asphaltic concrete, the variability of measurement was higher with the gauge than with the core result while with the open graded mix the gauge gave a lower variability.

c. The gauge has the potential to provide a suitable measurement of asphalt density, but more appropriate calibration equations are needed.

TRB Sponsored Nuclear Gauge Survey

The Transportation Research Board (TRB) published a TR Circular entitled "Nuclear Density Gauge Monitoring of Asphalt Concrete Compaction" (TRB 1987). For this circular, TRB surveyed 49 State highway agencies and five Canadian provincial highway agencies on their use of nuclear moisture and density gauges.

The most common problem was the poor agreement between cores and gauge readings. Attempts to correlate the two methods by comparing measurements at exactly the same point in the field usually failed. Likely reasons for the poor correlations at specific sites included:

a. The different volumes of material examined by each method.

b. Surface roughness effects and chemical composition effects on the gauge readings.

c. Surface roughness effects on the core density determination.

d. Inherent variability of both test methods.

e. Inadequate calibration of the nuclear gauges.

f. Operator errors.

FAA Sponsored Nuclear Gauge Study

A FAA sponsored report by Burati and Elzoghbi (TRB 1987) summarizes the findings of a research effort (a) to determine whether correlation exists between the results of nuclear density gauges and core densities obtained in the field and (b) to determine whether the use of nuclear density gauges in lieu of cores is warranted. Field data were gathered on two construction projects (the Morristown, NJ Municipal Airport and the Rochester-Monroe County Airport in Rochester, NY) using three nuclear density gauges (Troxler 3411-B, Seaman C-75BP, and CPN M-2). The data was statistically analyzed to identify correlations between the gauge readings and the core densities. The following conclusions were found in this study:

a. There appeared to be a higher degree of correlation between the gauges than between the gauges and the core densities.

b. When taking gauge readings of a joint, perpendicular gauge orientation (i.e. the radiation source of the gauge and detector were on opposite sides of the joint) yielded results closer to the core density.

c. In all cases, the gauge results had lower mat mean density values than the core mean value.

d. Use of nuclear gauges should not simply be substituted into current acceptance plans in place of cores if the current acceptance limits and procedures were developed from historical core data. The development of acceptance procedures specifically for nuclear gauges would be advantageous because of the large sample sizes and the rapid results that are possible from such gauges.

Minnesota DOT Sponsored Nuclear Gauge Study

The Minnesota DOT published an interim report entitled "Accuracy and Precision of Thin Lift Nuclear Density Gauges" (Reinaas, 1989). The purpose of this study was to evaluate the accuracy and precision of the recently manufactured thin lift nuclear density gauges. The Seaman C-200 nuclear density gauge equipped with accudepth, a Troxler Model 4640 thin lift nuclear density gauge, and a Troxler Model 3411-B nuclear density gauge was used in this study. All of the projects involved in the study had an asphalt wearing course of 1.5 inches or less. The gauges were tested on various mix designs including modified mixes with steel slag, taconite tailings, and granite; as well as other conventional mix designs. The following trends were obtained from the data:

a. The Seaman C-200 nuclear density gauge reads significantly higher values than the Troxler Model 4640.

b. Material content of the mix appears to have a significant affect on the accuracy of the nuclear gauge readings.

c. On conventional mixes containing steel slag, granite and traprock, the Troxler Model 4640 consistently under estimated the core density. On mixtures with taconite tailings, the gauge consistently over estimated the core density.

d. The Seaman C-200 consistently over estimated the core density on all mix designs except the granite mixes with low AC content.

e. The predictive ability of the nuclear density gauges with respect to core results varied from project to project and from gauge to gauge.

The results of the research showed that the readings of the nuclear density gauges and the density of the cores had a strong correlation to one another but the relationship was not consistent. It was determined that since the nuclear density gauges can significantly over or under estimate the core density, the use of nuclear density measurements in lieu of core samples, with existing acceptance limits, is not appropriate.

4 Gauge Characteristics

Troxler's Model 4640 Thin Layer Density Gauge

The Troxler model 4640 Thin Layer Density Gauge is designed to measure the density of a thin layer of asphaltic concrete (1 to 2 1/2 inches). The 4640 gauge contains an 8 millicurie Cesium 137 source of gamma energy, microprocessor electronics, stored software, and Geiger Mueller detectors. According to manufacturer's literature (Troxler 1987), the 4640 gauge is capable of operating in the following user selectable modes:

a. *Normal or surface voids*. When a mix gradation has more than 40 percent by weight passing the No. 8 sieve (2.38 mm) use the normal (smooth) mode.

b. *Time of reading*. This is selectable from 1/2, 1, 2, or 4 minute periods.

c. *Surface layer thickness*. This is selectable from 1 to 2 1/2 inches as appropriate for the asphalt layer under construction.

d. *Regular or special calibration*. The user selects either the internal factory calibration or inputs a special calibration for a particular paving job/mix. Calibration range is from 100 to 170 pcf.

Gauge precision has been described by the manufacturer (Troxler 1987) for both the normal (smooth surface) mode and the surface voids mode for an average density of 140 pcf. The values given are one standard deviation. The following summarizes precision values given for a typical 2 inch (5 cm) thick reading.

Table 1
4640 Gauge Precision Values

		Precision	
Mode	**Time (minutes)**	**pcf**	**kg/m³**
Normal	0.5	1.13	18.12
	1	0.80	12.81
	2	0.57	9.13
	4	0.40	6.41
Surface Voids	0.5	3.54	56.64
	1	2.26	36.20
	2	1.60	25.63
	4	1.13	18.10

The electronic system is capable of storing 40 watt-hours of energy in rechargeable batteries and consuming 0.4 watts maximum. Its internal memory stores all user settings and up to 100 separate test data summaries with each summary capable of including station number, distance and direction from centerline, density and percent Marshall compaction, or density and percent voids. An RS 232C serial port allows downloading of the stored information from the gauge to a computer at a rate of 37.5 to 9600 baud.

Case dimensions are approximately 19 by 9 by 6 inches with a handle that extends 11 inches above the bottom of the gauge. The unit weighs about 36 pounds and can operate in ambient temperatures of 14-158° F (-10-70° C) on a surface temperature up to 350° F (175° C).

Troxler's Model 3411-B Surface Moisture-Density Gauge

The 3411-B gauge is specifically designed to measure the moisture content and density of soils, soil-stone aggregate bases, cement and asphalt treated bases, and asphalt paving. Density measurements are made utilizing an 8 mCi Cesium 137 radioactive source and 2 Geiger Mueller gamma ray detectors. Some of the gamma rays emitted by the Cesium source are transmitted through the test material to the detectors and are counted. Counts over a fixed time period, such as one minute, are related to density.

In the backscatter density mode, gauge density precision has been described by the manufacturer (Troxler 1984) for a material with an average density of 120 pcf as is shown in Table 2.

Table 2
3411-B Gauge Precision Values

	Precision					
	Backscatter Mode (pcf)			Backscatter Mode (kg/m^3)		
	Fast	Normal	Slow	Fast	Normal	Slow
Precision	± 1.04	± 0.52	± 0.26	±16.6	± 8.3	± 4.15
Composition Error	± 2.50	± 2.50	± 2.50	±40.0	±40.0	±40.0
Surface Error (0.05 in./1.25 mm, 100% void)	− 4.00	− 4.00	− 4.00	−64.0	−64.0	−64.0
Expected Total Error	± 3.90	± 3.40	± 3.30	±62.4	±54.4	±52.8
Depth of Measurement (95%)		3 in.			75 mm	

The 3411-B gauge contains a microcomputer which holds all calibration constants and algorithms necessary to compute and display directly wet density, moisture, dry density, percent moisture, and percent compaction in either kilograms per cubic meter or pounds per cubic foot. For obtaining the density of asphaltic concrete overlays, only the wet density measurements are required.

The 3411-B gauge is 14.5 by 9 by 7.2 inches in size and weighs 36 pounds. The shipping weight of the gauge with case is 75 pounds (Troxler 3400 Series Operators Manual, 1984).

Gauge Calibration

Nuclear gauges are calibrated in order to establish the relationship between gauge output and sample density. Nuclear gauge manufacturers typically supply calibration curves that have been established by taking counts on a series of large natural or manufactured blocks and then statistically fitting a calibration curve through the data points (TR Circular, 1987).

The most widely used calibration procedure is to adjust the calibration curve on a project by project basis by applying a correction factor established from cores. Nuclear gauge readings and cores are both taken initially on a project. The average difference between the densities by the two methods is established. That difference becomes an adjustment factor which is applied to all subsequent nuclear gauge readings.

5 Experimental Plan

This study was conducted to compare the densities obtained from a Troxler model 4640 gauge and a Troxler model 3411-B gauge to the densities obtained from cored specimens at selected test sites. These test sites were pavements from various geographical locations; some of the pavements were relatively old (1 year or more past construction) while others were under construction. The following experimental procedure was used:

a. Nuclear gauge readings were taken at random locations at each test site.

b. At each location, four consecutive readings were obtained. Each gauge was rotated 90 degrees between each reading (Figure 4) such that two readings were taken parallel to the paving direction and two readings were taken transverse to the paving direction.

c. For the 4640 gauge, the gauge was set for a two inch asphalt layer thickness with one minute readings. The gauge orientation and the corresponding gauge calculated density were recorded for each measurement.

d. For the 3411-B gauge, the gauge was set on backscatter mode with one minute readings. The gauge orientation and the corresponding gauge calculated wet density were recorded for each measurement.

e. A 4 inch diameter core was cut from each location where gauge readings were taken. The cores were labelled and returned to the laboratory. The density of the portion of the core that corresponds to the gauge layer thickness (i.e. top 2 inches of core) was obtained by ASTM D 2726.

f. The gauge densities obtained in steps c and d were compared to the cut core densities obtained in step e.

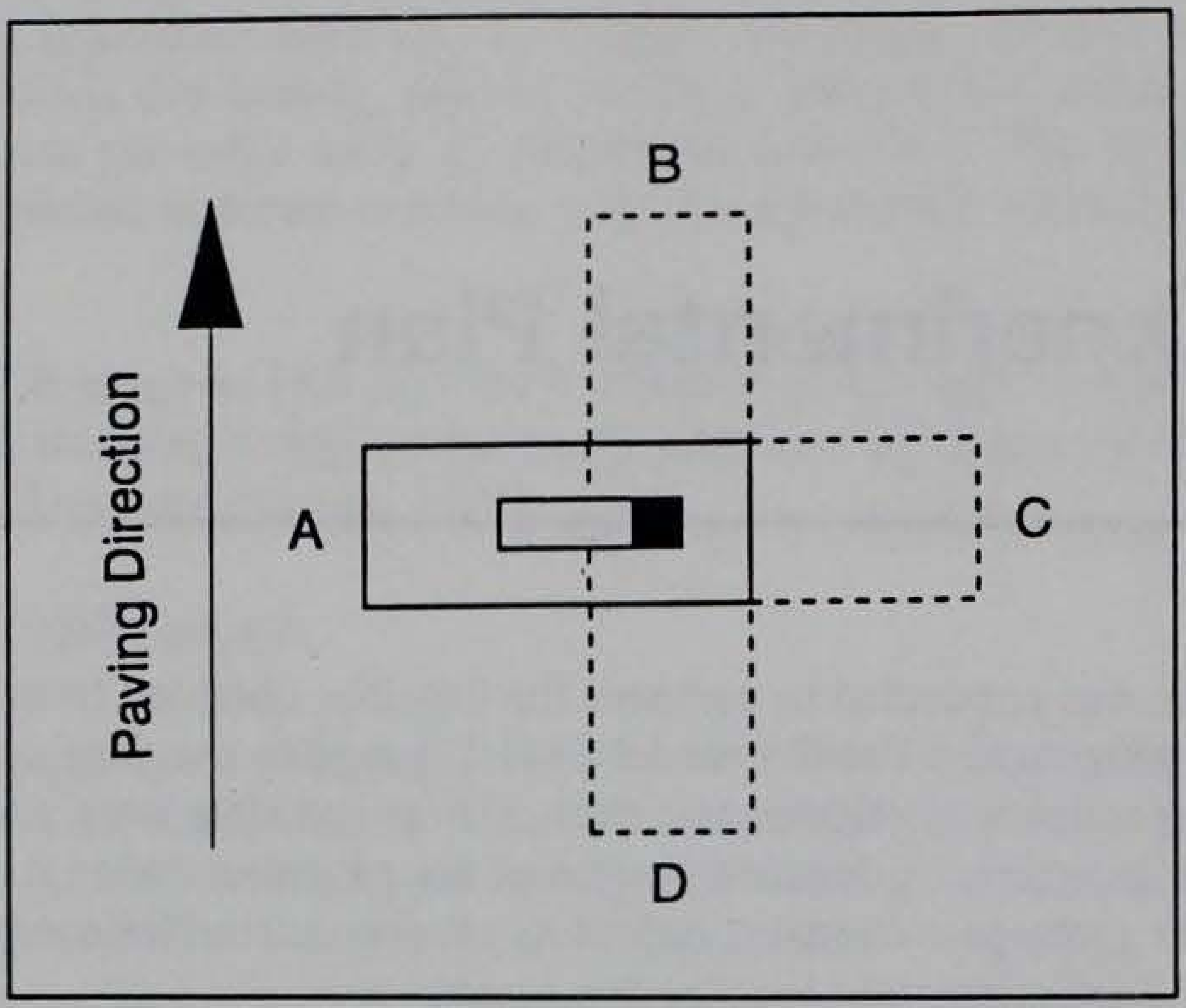

Figure 4. Placement of Gauges

6 Description of Test Locations and Density Data

Albany County Airport, New York

On July 8, 1992, WES personnel used the 4640 gauge and the 3411-B gauge to obtain density measurements on a small parking apron at the Albany County Airport in New York. The parking apron had been overlaid in September 1991. The asphalt concrete overlay was approximately 2 inches thick. The asphalt concrete material was produced and placed according to New York Department of Transportation specifications. The asphalt concrete mix properties are listed in Table 3. Gauge and core densities were obtained as described in Part 5.

The results of the core density values and nuclear gauge readings are listed in Tables 4-5. The core density values ranged from 134.5 pcf to 147.9 pcf with a mean of 143.2 pcf and a standard deviation of 4.9 pcf. The 4640 gauge density readings in the parallel direction ranged from 138.0 pcf to 163.8 pcf with a mean of 146.5 pcf and a standard deviation of 9.3 pcf. The 4640 gauge density readings in the transverse direction ranged from 141.4 pcf to 155.9 pcf with a mean of 145.3 pcf and a standard deviation of 5.0 pcf. The 3411-B gauge density readings in the parallel direction ranged from 120.1 pcf to 142.9 pcf with a mean of 137.4 pcf and a standard deviation of 7.9 pcf. The 3411-B gauge density readings in the transverse direction ranged from 116.9 pcf to 145.8 pcf with a mean of 137.3 pcf and a standard deviation of 9.6 pcf.

The difference between the core density values and the nuclear gauge readings were also determined. The percent difference between the core density and the 4640 gauge density readings in the parallel direction ranged from -5.5 to 11.7 with a mean of 2.4 and a standard deviation of 5.6. The percent difference between the core density and the 4640 gauge density readings in the transverse direction ranged from -4.3 to 7.7 with a mean of 1.6 and a standard deviation of 4.7. The percent difference between the core density and the 3411-B gauge density readings in the parallel direction ranged from -16.6 to 2.1 with a mean of -3.9 and a standard deviation of 6.3. The percent difference between the core density and the 3411-B gauge density readings in the transverse direction ranged from -18.8 to 5.7 with a mean of -3.9 and a standard deviation of 8.1.

Coffeeville, Mississippi

The Corps of Engineers (COE) was responsible for overlaying a city road in Coffeeville, MS. The COE damaged the road by hauling sand bags and heavy equipment on it to protect a levee from flooding. On October 21, 1992, the 4640 gauge and the 3411-B gauge were evaluated on this newly overlaid road. The asphalt concrete overlay was approximately 2 inches thick. The asphalt concrete mix properties are listed in Table 3. Gauge and core densities were obtained as described in Part 5.

Table 3
Summary of Asphalt Concrete Properties

Sieve Size	Albany	Coffee-ville	Enid	PA Turnpike	Saratoga	WES
3/4	100	100	100	100	100	100
1/2	100	100	100	96.7	99	95.3
3/8	98	95	95	90.5	90	88.9
No. 4	64	59	59	61.4	62	71.3
No. 8	49	43	43	44.9	50	49.8
No. 16	30	33	33	32.4	38	38.3
No. 30	20	23	23	24.0	26	31.6
No. 50	12	10	10	16.1	16	18.5
No. 100	8	7	7	10.2	9	8.9
No. 200	5	4.7	4.7	7.1	6	6.7
Asphalt Content (%)	5.5	6.0	6.0	5.1	5.65	4.9
Stability (lbs)	3010	1985	1985	4500	2529	2232
Flow (in.)	11.1	11	11	14.5	11.8	12
VTM	4.5	4.0	4.0	3.0	3.5	3.6
VFA	74.6	76.3	76.3	79.6	78.5	76.2
Density	150.4	144.4	144.4	151.2	146.6	150.4
Theoretical Density	157.5	150.1	150.1	158.2	152.0	155.9
Aggregate Type	lime-stone	gravel	gravel	granite	lime-stone	gravel

Table 4
Gauge Densities Parallel to Paving Direction versus Core Densities - Albany County Airport, New York

Location	Core Density (pcf)	4640 Gauge Density (pcf)	3411-B Gauge Density (pcf)	4640/Core Density Difference (%)	3411-B/ Core Density Difference (%)
A-1	138.2	139.1	141.1	+ 0.7	+ 2.1
A-2	146.6	163.8	140.1	+ 11.7	- 4.4
A-3	144.0	144.2	120.1	+ 0.1	- 16.6
A-4	134.5	142.8	136.9	+ 6.2	+ 1.8
A-5	147.9	154.4	138.8	+ 4.4	- 6.2
A-6	144.8	143.3	141.9	- 1.0	- 2.0
A-7	146.1	138.0	142.9	- 5.5	- 2.2
Mean	143.2	146.5	137.4	+ 2.4	- 3.9
Standard Deviation	4.9	9.3	7.9	5.6	6.3

Table 5
Gauge Densities Transverse to Paving Direction versus Core Densities - Albany County Airport, New York

Location	Core Density (pcf)	4640 Gauge Density (pcf)	3411-B Gauge Density (pcf)	4640/Core Density Difference (%)	3411-B/ Core Density Difference (%)
A-1	138.2	142.6	142.6	+ 3.2	+ 3.2
A-2	146.6	145.9	139.3	- 0.5	- 5.0
A-3	144.0	141.4	116.9	- 1.8	- 18.8
A-4	134.5	144.9	142.1	+ 7.7	+ 5.7
A-5	147.9	141.6	138.9	- 4.3	- 6.1
A-6	144.8	155.9	135.8	+ 7.7	- 6.2
A-7	146.1	144.7	145.8	- 1.0	- 0.2
Mean	143.2	145.3	137.3	+ 1.6	- 3.9
Standard Deviation	4.9	5.0	9.6	4.7	8.1

The results of the core density values and nuclear gauge readings are listed in Tables 6 and 7. The core density values ranged from 126.7 pcf to 139.9 pcf with a mean of 134.4 pcf and a standard deviation of 5.4 pcf. The 4640 gauge density readings in the parallel direction ranged from 123.6 pcf to 138.0 pcf with a mean of 130.7 pcf and a standard deviation of 5.0 pcf. The 4640 gauge density readings in the transverse direction ranged from 125.6 pcf to 134.4 pcf with a mean of 131.1 pcf and a standard deviation of 3.5 pcf. The 3411-B gauge density readings in the parallel direction ranged from 121.6 pcf to 135.5 pcf with a mean of 129.2 pcf and a standard deviation of 4.7 pcf. The 3411-B gauge density readings in the transverse direction ranged from 121.0 pcf to 133.5 pcf with a mean of 128.2 pcf and a standard deviation of 4.5 pcf.

The difference between the core density values and the nuclear gauge readings were also determined. The percent difference between the core density and the 4640 gauge density readings in the parallel direction ranged from -6.4 to -1.0 with a mean of -2.8 and a standard deviation of 2.2. The percent difference between the core density and the 4640 gauge density readings in the transverse direction ranged from -5.2 to -0.9 with a mean of -2.4 and a standard deviation of 1.8. The percent difference between the core density and the 3411-B gauge density readings in the parallel direction ranged from -6.2 to -2.2 with a mean of -3.9 and a standard deviation of 1.3. The percent difference between the core density and the 3411-B gauge density readings in the transverse direction ranged from -7.5 to -3.4 with a mean of -4.6 and a standard deviation of 1.5.

Enid, Mississippi

On October 22, 1992, WES personnel used the 4640 gauge and the 3411-B gauge on a small parking lot in Enid, MS to determine in-place densities. This parking lot had been recently overlaid by the Corps of Engineers. The asphalt concrete overlay was approximately 2 inches thick. The asphalt concrete mix properties are listed in Table 3. Gauge and core densities were obtained in the same manner as previously described in Part 5.

The results of the core density values and nuclear gauge readings are listed in Tables 8 and 9. The core density values ranged from 130.7 pcf to 140.0 pcf with a mean of 136.1 pcf and a standard deviation of 3.6 pcf. The 4640 gauge density readings in the parallel direction ranged from 112.4 pcf to 132.0 pcf with a mean of 127.4 pcf and a standard deviation of 8.4 pcf. The 4640 gauge density readings in the transverse direction ranged from 118.3 pcf to 132.1 pcf with a mean of 127.8 pcf and a standard deviation of 5.4 pcf. The 3411-B gauge density readings in the parallel direction ranged from 126.2 pcf to 133.9 pcf with a mean of 130.9 pcf and a standard deviation of 2.9 pcf. The 3411-B gauge density readings in the transverse direction ranged from 123.5 pcf to 134.3 pcf with a mean of 129.8 pcf and a standard deviation of 4.3 pcf.

Table 6
Gauge Densities Parallel to Paving Direction versus Core Densities - Coffeeville, Mississippi

Location	Core Density (pcf)	4640 Gauge Density (pcf)	3411-B Gauge Density (pcf)	4640/Core Density Difference (%)	3411-B/ Core Density Difference (%)
C-1	135.4	129.4	129.8	- 4.4	- 4.1
C-2	135.4	133.9	130.3	- 1.1	- 3.8
C-3	126.7	123.6	121.6	- 2.5	- 4.0
C-4	139.8	138.0	135.5	- 1.3	- 3.1
C-5	129.3	128.0	126.5	- 1.0	- 2.2
C-6	139.9	131.0	131.2	- 6.4	- 6.2
Mean	134.4	130.7	129.2	- 2.8	- 3.9
Standard Deviation	5.4	5.0	4.7	2.2	1.3

Table 7
Gauge Densities Transverse to Paving Direction versus Core Densities - Coffeeville, Mississippi

Location	Core Density (pcf)	4640 Gauge Density (pcf)	3411-B Gauge Density (pcf)	4640/Core Density Difference (%)	3411-B/ Core Density Difference (%)
C-1	135.4	132.4	129.8	- 2.2	- 4.1
C-2	135.4	133.6	130.3	- 1.3	- 3.8
C-3	126.7	125.6	121.0	- 0.9	- 4.5
C-4	139.8	134.4	133.5	- 3.9	- 4.5
C-5	129.3	128.2	124.9	- 0.9	- 3.4
C-6	139.9	132.6	129.4	- 5.2	- 7.5
Mean	134.4	131.1	128.2	- 2.4	- 4.6
Standard Deviation	5.4	3.5	4.5	1.8	1.5

Table 8
Gauge Densities Parallel to Paving Direction versus Core Densities - Enid Lake, Mississippi

Location	Core Density (pcf)	4640 Gauge Density (pcf)	3411-B Gauge Density (pcf)	4640/Core Density Difference (%)	3411-B/ Core Density Difference (%)
E-1	138.3	130.9	132.5	- 5.4	- 4.2
E-2	130.7	112.4	126.2	- 14.0	- 3.4
E-3	136.8	130.9	130.6	- 4.3	- 4.5
E-4	140.0	132.0	133.9	- 5.7	- 4.4
E-5	134.6	130.8	131.3	- 2.8	- 2.5
Mean	136.1	127.4	130.9	- 6.4	- 3.8
Standard Deviation	3.6	8.4	2.9	4.4	0.9

Table 9
Gauge Densities Transverse to Paving Direction versus Core Densities - Enid Lake, Mississippi

Location	Core Density (pcf)	4640 Gauge Density (pcf)	3411-B Gauge Density (pcf)	4640/Core Density Difference (%)	3411-B/ Core Density Difference (%)
E-1	138.3	129.5	130.3	- 6.4	- 5.8
E-2	130.7	118.3	123.5	- 9.5	- 5.5
E-3	136.8	129.6	134.3	- 5.3	- 1.8
E-4	140.0	132.1	133.0	- 5.6	- 5.0
E-5	134.6	129.6	127.9	- 3.7	- 5.0
Mean	136.1	127.8	129.8	- 6.1	- 4.6
Standard Deviation	3.6	5.4	4.3	2.1	1.6

The difference between the core density values and the nuclear gauge readings were also determined. The percent difference between the core density and the 4640 gauge density readings in the parallel direction ranged from -14.0 to -2.8 with a mean of -6.4 and a standard deviation of 4.4. The percent difference between the core density and the 4640 gauge density readings in the transverse direction ranged from -9.5 to -3.7 with a mean of -6.1 and a standard deviation of 2.1. The percent difference between the core density and the 3411-B gauge density readings in the parallel direction ranged from -4.5 to -2.5 with a mean of -3.8 and a standard deviation of 0.9. The percent difference between the core density and the 3411-B gauge density readings in the transverse direction ranged from -5.8 to -1.8 with a mean of -4.6 and a standard deviation of 1.6.

Pennsylvania Turnpike

On September 30, 1992, the 4640 gauge was evaluated by WES personnel on a microwave recycling job on the Pennsylvania turnpike near Lebanon, PA. One and a half inches of pavement was milled up, stockpiled, and recycled using Cyclean Incorporated microwave recycling process, and replaced back at 1 1/2 inch depth. The recycled asphalt concrete mix properties are listed in Table 3. The 4640 gauge testing was conducted and the core densities were obtained in the same manner as described in Part 5, with the exception that the readings were taken at 1.5 inch depth instead of the 2 inch depth.

The results of the core density values and nuclear gauge readings are listed in Tables 10 and 11. The core density values ranged from 146.8 pcf to 148.6 pcf with a mean of 148.0 pcf and a standard deviation of 0.7 pcf. The 4640 gauge density readings in the parallel direction ranged from 132.1 pcf to 147.4 pcf with a mean of 142.5 pcf and a standard deviation of 5.4 pcf. The 4640 gauge density readings in the transverse direction ranged from 134.7 pcf to 147.1 pcf with a mean of 144.2 pcf and a standard deviation of 4.7 pcf.

The difference between the core density values and the nuclear gauge readings were also determined. The percent difference between the core density and the 4640 gauge density readings in the parallel direction ranged from -11.1 to -0.7 with a mean of -3.7 and a standard deviation of 3.7. The percent difference between the core density and the 4640 gauge density readings in the transverse direction ranged from -9.4 to -0.6 with a mean of -2.9 and a standard deviation of 3.7.

Saratoga County Airport, New York

On July 9, 1992, WES personnel evaluated the 4640 gauge and the 3411-B gauge at the Saratoga County Airport. The section of pavement that the gauges were used on was a newly constructed runway extension. The asphalt concrete material was produced and placed according the NYDOT specifications. The asphalt concrete mix properties are listed in Table 3.

Table 10
Gauge Densities Parallel to Paving Direction versus Core Densities - Pennsylvania Turnpike

Location	Core Density (pcf)	4640 Gauge Density (pcf)	4640/Core Density Difference (%)
P-1	148.6	132.1	- 11.1
P-2	146.8	142.8	- 2.7
P-3	148.0	144.8	- 2.2
P-4	148.6	144.8	- 2.6
P-5	148.5	147.4	- 0.7
P-6	147.7	143.2	- 3.0
Mean	148.0	142.5	- 3.7
Standard Deviation	0.7	5.4	3.7

Table 11
Gauge Densities Transverse to Paving Direction versus Core Densities - Pennsylvania Turnpike

Location	Core Density (pcf)	4640 Gauge Density (pcf)	4640/Core Density Difference (%)
P-1	148.6	134.7	- 9.4
P-2	146.8	144.6	- 1.5
P-3	148.0	147.1	- 0.6
P-4	148.6	147.1	- 1.0
P-5	148.5	145.8	- 1.8
P-6	147.7	145.7	- 1.4
Mean	148.0	144.2	- 2.9
Standard Deviation	0.7	4.7	3.7

Gauge and core densities were obtained in the same manner as previously described in Part 5.

The results of the core density values and nuclear gauge readings are listed in Tables 12 and 13. The core density values ranged from 144.0 pcf to 150.7 pcf with a mean of 147.9 pcf and a standard deviation of 3.0 pcf. The 4640 gauge density readings in the parallel direction ranged from 143.0 pcf to 160.6 pcf with a mean of 148.8 pcf and a standard deviation of 7.0 pcf. The 4640 gauge density readings in the transverse direction ranged from 143.2 pcf to 166.5 pcf with a mean of 153.4 pcf and a standard deviation of 9.2 pcf. The 3411-B gauge density readings in the parallel direction ranged from 138.8 pcf to 150.2 pcf with a mean of 144.9 pcf and a standard deviation of 4.1 pcf. The 3411-B gauge density readings in the transverse direction ranged from 135.0 pcf to 148.9 pcf with a mean of 143.5 pcf and a standard deviation of 5.2 pcf.

The difference between the core density values and the nuclear gauge readings were also determined. The percent difference between the core density and the 4640 gauge density readings in the parallel direction ranged from -3.5 to 11.5 with a mean of 0.8 and a standard deviation of 6.0. The percent difference between the core density and the 4640 gauge density readings in the transverse direction ranged from -3.4 to 14.8 with a mean of 4.0 and a standard deviation of 8.0. The percent difference between the core density and the 3411-B gauge density readings in the parallel direction ranged from -3.6 to -0.3 with a mean of -1.9 and a standard deviation of 1.4. The percent difference between the core density and the 3411-B gauge density readings in the transverse direction ranged from -6.3 to -1.2 with a mean of -2.9 and a standard deviation of 2.1.

WES Test Section

On September 1, 1992, WES personnel evaluated the 4640 gauge and the 3411-B gauge on an asphalt concrete overlay test section that was constructed for an Army Corps of Engineers (USACE) sponsored project during the summer of 1989. The asphalt concrete overlay was approximately 2 inches thick and was placed and produced according to COE specifications. The asphalt concrete mix properties are listed in Table 3. Gauge and core densities were obtained in the same manner as previously described in Part 5.

The results of the core density values and nuclear gauge readings are listed in Tables 14 and 15. The core density values ranged from 145.5 pcf to 151.1 pcf with a mean of 149.1 pcf and a standard deviation of 3.1 pcf. The 4640 gauge density readings in the parallel direction ranged from 142.2 pcf to 147.9 pcf with a mean of 145.1 pcf and a standard deviation of 2.9 pcf. The 4640 gauge density readings in the transverse direction ranged from 141.6 pcf to 147.1 pcf with a mean of 145.0 pcf and a standard deviation of 3.0 pcf. The 3411-B gauge density readings in the parallel direction ranged from 141.7 pcf to 149.1 pcf with a mean of 146.3 pcf and a standard deviation of 4.0 pcf. The 3411-B gauge density readings in the transverse direction ranged from 143.1 pcf to 150.6 pcf with a mean of 147.4 pcf and a standard deviation of 3.9 pcf.

Table 12
Gauge Densities Parallel to Paving Direction versus Core Densities - Saratoga County Airport, New York

Location	Core Density (pcf)	4640 Gauge Density (pcf)	3411-B Gauge Density (pcf)	4640/Core Density Difference (%)	3411-B/ Core Density Difference (%)
S-1	144.0	160.6	138.8	+ 11.5	- 3.6
S-2	145.0	143.0	144.2	- 1.4	- 0.6
S-3	150.1	144.9	146.3	- 3.5	- 2.5
S-4	148.2	145.8	144.8	- 1.6	- 2.3
S-5	150.7	149.5	150.2	- 0.8	- 0.3
Mean	147.9	148.8	144.9	0.8	- 1.9
Standard Deviation	3.0	7.0	4.1	6.0	1.4

Table 13
Gauge Densities Transverse to Paving Direction versus Core Densities - Saratoga County Airport, New York

Location	Core Density (pcf)	4640 Gauge Density (pcf)	3411-B Gauge Density (pcf)	4640/Core Density Difference (%)	3411-B/ Core Density Difference (%)
S-1	144.0	158.5	135.0	+ 10.1	- 6.3
S-2	145.0	166.5	142.9	+ 14.8	- 1.5
S-3	150.1	148.0	144.9	- 1.4	- 3.5
S-4	148.2	143.2	145.6	- 3.4	- 1.8
S-5	150.7	150.9	148.9	+ 0.1	- 1.2
Mean	147.9	153.4	143.5	+ 4.0	- 2.9
Standard Deviation	3.0	9.2	5.2	8.0	2.1

Table 14
Gauge Densities Parallel to Paving Direction versus Core Densities - WES Test Sections

Location	Core Density (pcf)	4640 Gauge Density (pcf)	3411-B Gauge Density (pcf)	4640/Core Density Difference (%)	3411-B/ Core Density Difference (%)
W-1	145.5	142.2	141.7	- 2.3	- 2.6
W-2	151.1	147.9	148.2	- 2.1	- 1.9
W-3	150.6	145.2	149.1	- 3.6	- 1.0
Mean	149.1	145.1	146.3	- 2.7	- 1.8
Standard Deviation	3.1	2.9	4.0	0.8	0.8

Table 15
Gauge Densities Transverse to Paving Direction versus Core Densities - WES Test Sections

Location	Core Density (pcf)	4640 Gauge Density (pcf)	3411-B Gauge Density (pcf)	4640/Core Density Difference (%)	3411-B/ Core Density Difference (%)
W-1	145.5	141.6	143.1	- 2.7	- 1.7
W-2	151.1	147.1	148.5	- 2.7	- 1.7
W-3	150.6	146.3	150.6	- 2.9	0.0
Mean	149.1	145.0	147.4	- 2.8	- 1.1
Standard Deviation	3.1	3.0	3.9	0.1	1.0

The difference between the core density values and the nuclear gauge readings were also determined. The percent difference between the core density and the 4640 gauge density readings in the parallel direction ranged from -3.6 to -2.1 with a mean of -2.7 and a standard deviation of 0.8. The percent difference between the core density and the 4640 gauge density readings in the transverse direction ranged from -2.9 to -2.7 with a mean of -2.8 and a standard deviation of 0.1. The percent difference between the core density and the 3411-B gauge density readings in the parallel direction ranged from -2.6 to -1.0 with a mean of -1.8 and a standard deviation of 0.8. The percent difference between the core density and the 3411-B gauge density readings in the transverse direction ranged from -1.7 to 0.0 with a mean of -1.1 and a standard deviation of 1.0.

7 Discussion of Results

This study was conducted to compare field core density values with nuclear density gauge readings and to determine the effects of gauge placement. This analysis involved comparing the results of field core data to nuclear gauge readings for each gauge individually. The effects of gauge placement was determined by comparing parallel readings to transverse readings at each location. This part of the report summarizes the findings of the nuclear density gauge evaluation.

Field Cores to 4640 Gauge

A summary of the means and standard deviations of the test results for the evaluation of the Troxler model 4640 nuclear density gauge are listed in Table 16 and are shown graphically in Figures 5 and 6. For the two projects located in New York State, the 4640 gauge overestimated the density when compared to standard field cores. At Albany and Saratoga, the nuclear gauge overestimated the field density by 2.7 pcf and 3.2 pcf, respectively. These asphalt concrete mixtures were primarily composed of limestone materials. The 4640 gauge underestimated the field core density at the remaining sites, where the asphalt concrete mixtures were primarily composed of siliceous (sand and gravel) materials.

The standard deviations of the field cores ranged from 0.7 pcf to 5.4 pcf. The Pennsylvania Turnpike site, a demonstration test site for microwave recycling, had the lowest standard deviation between cores. The highest standard deviation between cores was on the city road in Coffeeville, MS. The standard deviation of the 4640 nuclear gauge readings ranged from 2.9 pcf to 6.9 pcf. The lowest standard deviation between 4640 nuclear gauge readings was at the test site at WES. The highest standard deviation between 4640 nuclear gauge readings was at the parking lot in Enid, MS.

Table 16
Summary of Results - Core and 4640 Gauge

Location	Core Mean Density (pcf)	Standard Deviation of Core Density (pcf)	4640 Gauge Mean Density (pcf)	Standard Deviation of 4640 Gauge Density (pcf)	Difference Between 4640 Gauge Density and Core Density (pcf)
Albany	143.2	4.9	145.9	5.1	2.7
Coffeeville	134.4	5.4	130.9	4.1	- 3.5
Enid	136.1	3.6	127.6	6.9	- 8.5
PA Turnpike	148.0	0.7	143.4	5.0	- 4.6
Saratoga	147.9	3.0	151.1	6.2	3.2
WES	149.1	3.1	145.1	2.9	- 4.0

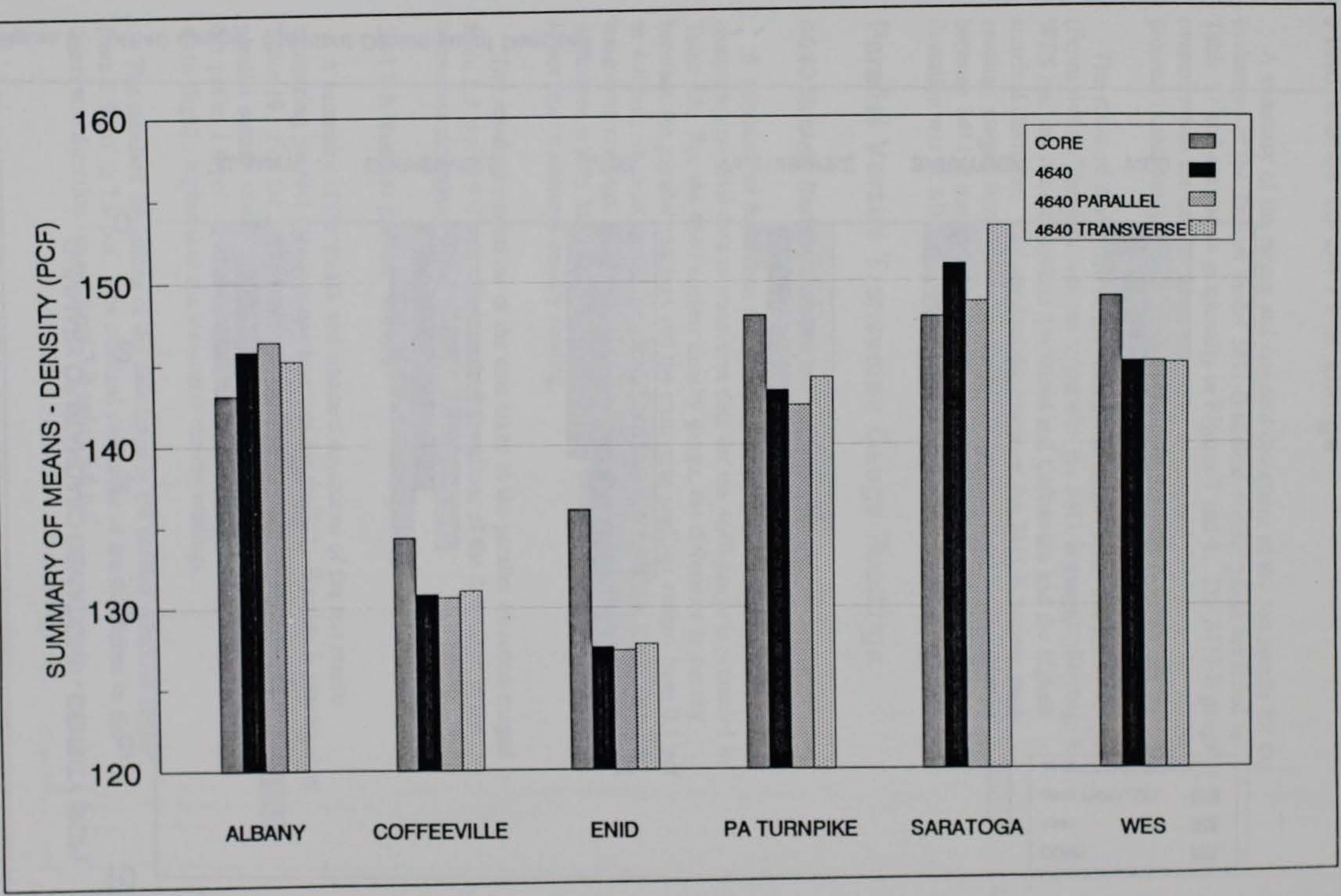

Figure 5. 4640 Gauge - Mean of Densities

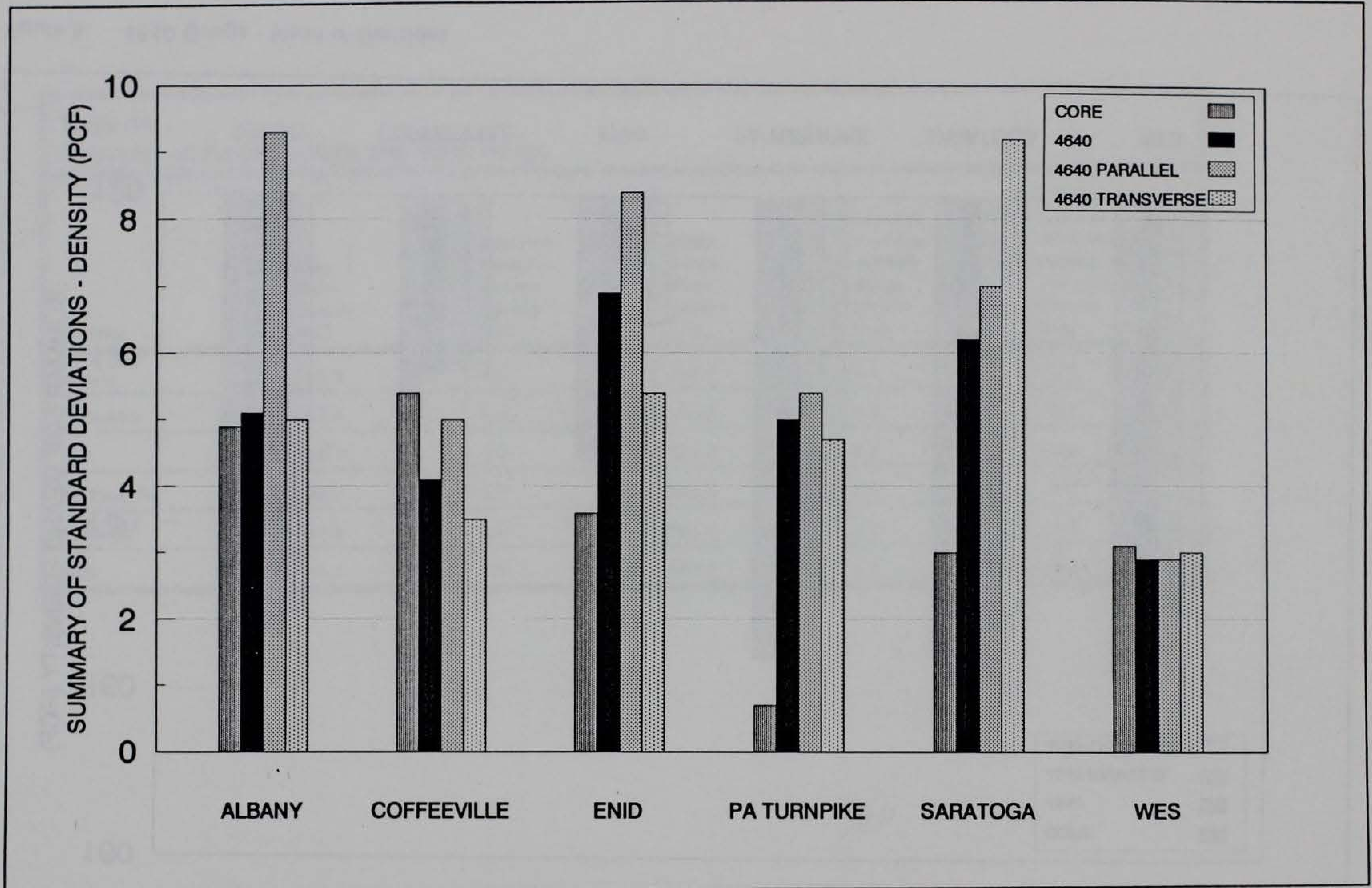

Figure 6. 4640 Gauge - Standard Deviations of Densities

Field Cores to 3411-B Gauge

A summary of the means and standard deviations of the test results for the evaluation of the Troxler model 3411-B nuclear density gauge are listed in Table 17 and are shown graphically in Figures 7 and 8. The 3411-B gauge overestimated the density when compared to standard field cores for all the projects in this study (ranging from 2.2 pcf to 5.8 pcf).

The standard deviations of the field cores ranged from 3.0 pcf to 5.4 pcf (Pennsylvania Turnpike was not tested with the 3411-B gauge). Saratoga and WES had the lowest standard deviations and Coffeeville had the highest standard deviation. The standard deviations of the 3411-B nuclear gauge readings ranged from 3.4 pcf to 8.6 pcf. The lowest standard deviation between 3411-B nuclear gauge readings was at Enid and the highest standard deviation was at Albany.

Parallel Versus Transverse Gauge Readings

4640 Nuclear Density Gauge

A summary of the means and standard deviations of the test results comparing parallel data to transverse data for the 4640 gauge is presented in Table 18. For the 4640 nuclear density gauge, the difference in density between the parallel readings and the transverse readings ranged from 0.1 pcf to 4.6 pcf. In most cases, the parallel readings were slightly lower than the transverse readings. The only location where the data showed significant difference was at Saratoga where the parallel density reading was 4.6 pcf lower than transverse density reading.

The standard deviations of the data taken in the parallel direction ranged from 2.9 pcf to 9.3 pcf. The standard deviations of the data taken in the transverse direction ranged from 3.0 pcf to 9.2 pcf.

3411-B Nuclear Density Gauge

A summary of the means and standard deviations of the test results comparing parallel data to transverse data for the 3411-B gauge is presented in Table 19. For the 3411-B nuclear density gauge, the difference between the parallel density readings and the transverse density readings ranged from 0.1 pcf to 1.4 pcf. In all cases but one (WES), the parallel density readings were slightly higher than the transverse density readings.

The standard deviations of the data taken in the parallel direction ranged from 2.9 pcf to 7.9 pcf. The standard deviations of the data taken in the transverse direction ranged from 3.9 pcf to 9.6 pcf.

Table 17
Summary of Results - Core and 3411-B Gauge

Location	Core Mean Density (pcf)	Standard Deviation of Core Density (pcf)	3411-B Gauge Mean Density (pcf)	Standard Deviation of 3411-B Gauge Density (pcf)	Difference Between 3411-B Gauge Density and Core Density (pcf)
Albany	143.2	4.9	137.4	8.6	- 5.8
Coffeeville	134.4	5.4	128.7	4.6	- 5.7
Enid	136.1	3.6	130.4	3.4	- 5.7
Saratoga	147.9	3.0	144.2	4.6	- 3.7
WES	149.1	3.1	146.9	4.0	- 2.2

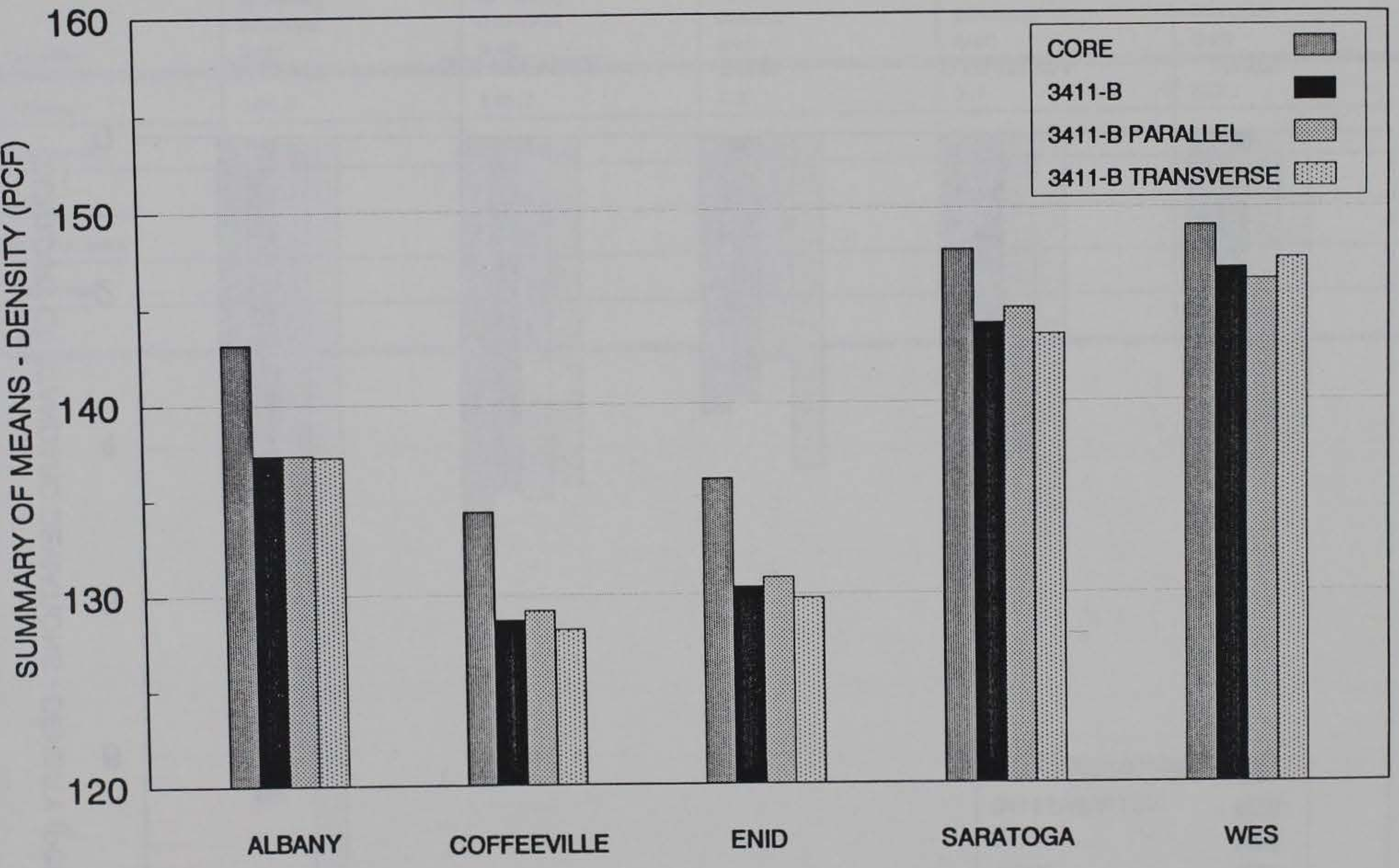

Figure 7. 3411-B Gauge - Mean of Densities

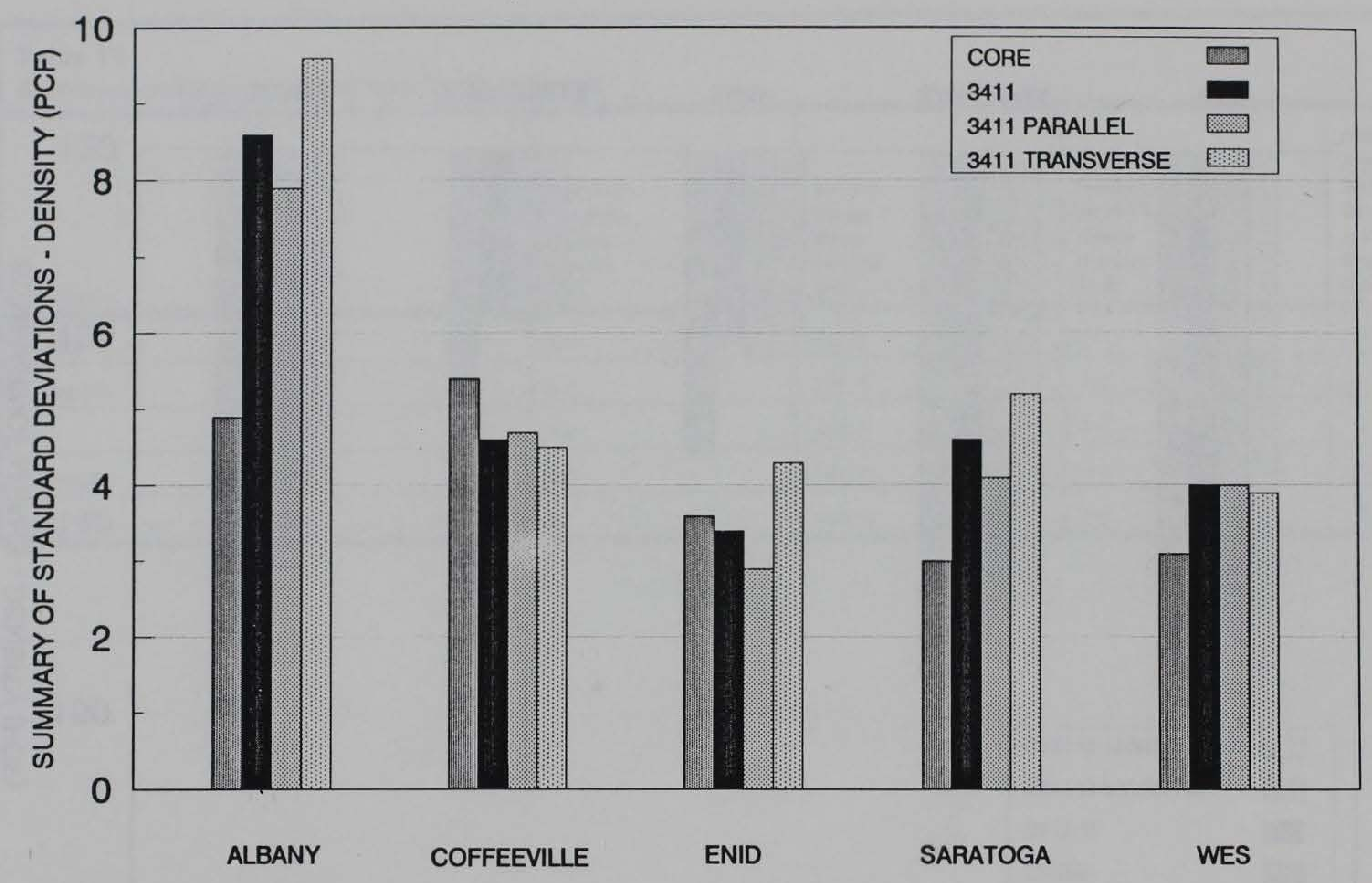

Figure 8. 3411-B Gauge - Standard Deviations of Densities

Table 18
Parallel Gauge Readings to Transverse Gauge Readings - 4640 Gauge

Location	Mean of Density Parallel to Paving Direction (pcf)	Mean of Density Transverse to Paving Direction (pcf)	Difference Between Parallel Density & Transverse Density (pcf)	Standard Deviation of Density Parallel to Paving Direction (pcf)	Standard Deviation of Density Transverse to Paving Direction (pcf)
Albany	146.5	145.3	1.2	9.3	5.0
Coffeeville	130.7	131.1	0.4	5.0	3.5
Enid	127.4	127.8	0.4	8.4	5.4
PA Turnpike	142.5	144.2	1.7	5.4	4.7
Saratoga	148.8	153.4	4.6	7.0	9.2
WES	145.1	145.0	0.1	2.9	3.0

Table 19
Parallel Gauge Readings to Transverse Gauge Readings - 3411-B Gauge

Location	Mean of Density Parallel to Paving Direction (pcf)	Mean of Density Transverse to Paving Direction (pcf)	Difference Between Parallel Density & Transverse Density (pcf)	Standard Deviation of Density Parallel to Paving Direction (pcf)	Standard Deviation of Density Transverse to Paving Direction (pcf)
Albany	137.4	137.3	0.1	7.9	9.6
Coffeeville	129.2	128.2	1.0	4.7	4.5
Enid	130.9	129.8	1.1	2.9	4.3
Saratoga	144.9	143.5	1.4	4.1	5.2
WES	146.3	147.4	1.1	4.0	3.9

8 Conclusions and Recommendations

Conclusions

Based on the results of this investigation, which included a literature review, field study, and laboratory study, the following conclusions were made on the use of surface density nuclear gauges for measuring the in-place density of thin layers of asphalt concrete:

a. The Troxler Model 4640 Thin Layer Density Gauge is very sensitive to improper seating. Improper seating can result in erratic gauge readings.

b. Significant scatter in the individual data points existed for both gauges.

c. The 4640 gauge mean densities were higher than the field core mean densities for asphalt concrete mixes where the predominant aggregate was carbonate (limestone).

d. The 4640 gauge mean densities were lower than the field core mean densities for asphalt concrete mixes where the predominant aggregate was siliceous (gravel and granite).

e. In most cases, the standard deviations of the 4640 gauge readings were significantly higher than the standard deviations of the field core densities.

f. There were only small differences between average parallel and transverse density readings for the 4640 gauge.

g. The Troxler Model 3411-B Surface Moisture-Density Gauge mean densities were always lower than the field core mean densities.

h. The standard deviations of the 3411-B gauge were significantly higher than the standard deviations of the field core densities for Albany, NY and Saratoga, NY.

i. There were only small differences between average parallel and transverse density readings for the 3411-B gauge.

Recommendations

Based on the conclusions derived from the results of the field/laboratory study, the following recommendations were made:

a. Due to the excessive variability and high standard deviations between the gauges and the laboratory densities, surface density nuclear gauges should not be used as the sole method for acceptance testing of asphalt concrete pavements.

b. Surface density nuclear gauges can be used as quality control tools for asphalt concrete pavements (e.g., establishing roller patterns).

c. More research is needed to determine the effect of gauge calibration on the density readings of surface density nuclear gauges.

d. The chemical composition of the asphalt mixture should be determined to know whether or not the gauge readings will be higher or lower than the field cores.

e. Extreme care should be taken by the operator in setting up gauges to eliminate the possibility of set-up error.

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13. ABSTRACT *(Maximum 200 words)*

This report documents field evaluations of a thin lift nuclear gauge and a surface moisture/density nuclear gauge for asphalt concrete mixtures. The study includes density determinations by conventional methods, density by nuclear methods and a review of literature. A field evaluation of two commercially available nuclear gauges was performed on an airport apron in New Albany, NY, a city road in Coffeeville, MS, a parking lot in Enid, MS, the east-west extension of the Pennsylvania Turnpike near Lebanon, PA, an airport runway extension in Saratoga, NY, and a test section at the U.S. Army Engineer Waterways Experiment Station (WES), in Vicksburg, MS.

The basis of this study was to determine if densities obtained from surface density nuclear gauges correlate with corresponding densities measured in the laboratory from cored samples. The effects of gauge placement was also examined. Data from each project are included in the report. An analysis was performed on the data. Graphs were created for optimum visualization.

Nuclear gauges of this type are recommeded as quality control tools but not for quality assurance and acceptance. Due to excessive variability and high standard deviations between the nuclear gauges and laboratory densities, gauges are not recommended as the sole means of acceptance testing asphalt concretes.

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