Correlation of Nuclear Density Results with Core Densities

JAMES L. BURATI, JR., AND GEORGE B. ELZOGHBI

The paper 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. Data were collected on two runway paving projects selected by the FAA Eastern Region using cores and three nuclear gauges (CPN M-2, Seaman C-75BP, and Troxler 3411-B). The data were analyzed statistically to identify possible correlations among the nuclear gauges and between the nuclear gauge readings and the core results. The results indicated that the level of correlation among the core and gauge results varied from gauge to gauge and from project to project. There was a higher degree of correlation among the gauges than there was between the core densities and the gauge results. It is recommended that nuclear gauges not simply be substituted for core densities if the acceptance limits have been developed for cores because the gauge results do not necessarily correlate well with the core results. If nuclear gauges are to be used for acceptance purposes, then appropriate acceptance limits should be developed for use with the gauges.

During 1978, the Federal Aviation Administration (FAA) Eastern Region incorporated a statistically based acceptance plan into its bituminous surface course specification (P-401). This specification provided for the determination of a price adjustment factor based on the relative acceptability of the pavement materials (*1*). The acceptance plan allowed the use of either cores or nuclear gauges for pavement density determination. However, the FAA discontinued use of nuclear gauges for acceptance decisions after preliminary research (*2*) at the National Aviation Facilities Experiment Center (NAFEC) resulted in a lack of confidence in the consistency and accuracy of nuclear gauges.

The limited data from the NAFEC project are not sufficient grounds on which to base a rejection of nuclear gauges. A thorough study of nuclear gauge readings obtained under field conditions was essential if the FAA was to consider using nuclear gauges in its acceptance approach for bituminous pavements. To this end, two construction sites were selected on which to gather nuclear gauge data. The findings of the research effort on these projects are presented in this paper.

The objective of the research was to determine whether nuclear density gauges should be introduced in the FAA acceptance procedure. The specific objectives of the research were

Department of Civil Engineering, Clemson University, Clemson, S.C. 29634-0911.

1. To determine whether correlation exists between the results of nuclear density gauges and the core densities obtained in the field, and
2. To determine whether to use nuclear density gauges in the acceptance plan based on the correlations identified.

To meet the outlined objectives, the research was conducted in two major phases. First, field data were gathered on construction projects using three nuclear density gauges (Troxler 3411-B, Seaman C-75BP, and CPN M-2). Next, these data were analyzed statistically to identify possible correlations between nuclear gauge readings and core densities.

DATA COLLECTION

Data for the research were gathered on two construction projects during 1984. The projects were selected by the FAA Eastern Region. Data were to have originally been collected on three projects, but the Eastern Region was only able to identify two suitable projects for which data could be obtained.

Type of Data

For research purposes on the projects studied, four cores were collected for determining joint density in addition to the four cores normally drilled for mat density determination. Nuclear gauge readings were taken at locations where cores were drilled to identify whether correlations between the nuclear gauges and the core density results exist. These correlations can be used to determine whether nuclear gauges can be used as an alternative to cores for acceptance decisions. Nuclear gauge readings were also taken at random locations on the joints and within the mat. The ease and speed of the nuclear gauges allowed a large number of locations (approximately 30) to be selected from each paving lot.

Data Collection Procedures

Two projects were selected by the FAA Eastern Region for the collection of field data. The projects studied were the Morristown, New Jersey, Municipal Airport and the Rochester-Monroe County Airport in Rochester, New York. Data were collected on the projects by the research staff using three different gauges (Troxler 3411-B, Seaman C-75BP, CPN M-2). The Troxler and CPN gauges have Cesium^{137} sources, whereas the Seaman gauge has a Radium^{226} source. While the Troxler and CPN gauges both operate in the backscatter mode, the CPN gauge has two backscatter modes, BS or AC. The AC mode is used on thin-lift asphaltic concrete and the BS mode is used on deeper lifts. The BS mode was used in the research because it provided density values closer to the core results. The Seaman gauge operates differently from the other gauges. It uses the air-gap ratio method. The air-gap ratio method is used by Seaman to reduce the effect of the chemical composition of the mixture on the gauge density readings.

Data for each project consisted of the densities of the compacted pavement materials. The compacted materials were tested on a lot basis, with a lot consisting of 1 day's production, not to exceed 2,000 tons. Eight cores were selected for each lot, four for the mat and four for the joints. The random sampling and testing procedures used on the projects are outlined in the *Eastern Region Laboratory Procedures Manual* (ERLPM) (*4*).

A standard count was taken each working day for each gauge. For the Seaman gauge, an air-gap reading was taken for each lot. Care was taken to ensure that gauges were firmly seated at each location where readings were taken. The pavement surface was very dense and smooth; therefore, no filler material was needed to prevent air gaps. Care was taken to ensure that all manufacturers' operating procedures were followed for all readings taken.

Readings were obtained with each of the three nuclear density gauges at the exact locations where cores were to be drilled. The nuclear readings were taken immediately before drilling to guarantee no change in pavement density between the time of the nuclear gauge readings and the drilling of the cores. Each individual gauge reading was the average of two readings, with the gauge rotated 180 degrees prior to taking the second reading. While one gauge was being used, the other gauges were at least 30 ft away to ensure that they would not affect the reading being taken.

While the joint density readings were taken, at Morristown the gauges were oriented so that the radiation source and the detector were aligned longitudinally along the joint between the pavement sections. On the Rochester project, two joint readings were obtained for each sample location, one with the gauge parallel to the joint as at Morristown and one with the gauge perpendicular to the joint. The individual perpendicular gauge readings were the average of two readings with the gauge rotated 180 degrees between readings. The radiation source of the gauge and detector were on opposite sides of the joint between the pavement sections for each of the two readings.

RESULTS OF DENSITY DATA ANALYSIS

After collection, the data were transferred to the computer in preparation for analysis. Separate analyses were conducted for each project. The Statistical Analysis System (SAS)(*3*) was used for both the data management and the analysis. The results of the data analysis procedures are presented and discussed in this section. The relationships among the nuclear gauge results are considered first. The correlations between the nuclear gauge results and the core density values are then discussed. In the discussions that follow, density readings (core or nuclear) taken at coring locations are referred to as acceptance tests. Nuclear gauge readings taken at locations where cores were not drilled are referred to as random tests.

Nuclear Gauge Comparisons

One of the objectives of the study was to investigate how well the three different types of nuclear density gauges correlated with each other. This correlation was desired to determine how each gauge performed in comparison with the other gauges. An analysis of the performance of each of the gauges with respect to the core density values is presented in a later section. This section presents the results of the correlation analysis of the three gauges with respect to one another.

Scatter Plots

Plots of the density values obtained by each of the gauges are presented in Figures 1-3 and 4-6 for the Morristown and Rochester projects, respectively. The mat and joint density results are distinguished in each of the plots by closed and open circles, respectively. The mat density values are generally higher than the joint results for all of the plots. Figures 1, 2, and 3 present plots of CPN versus Troxler, CPN versus Seaman, and Troxler versus Seaman density results, respectively, for the Morristown project.

As shown in the plots in Figures 1-3, there is generally a linear relationship between each of the pairwise combinations of gauges. The values fall close to a straight line with relatively little dispersion about the line. There appears to be more scatter in the joint density results than in the mat density values. This reflects a higher degree of variability in the joint density values.

Plots similar to those in Figures 1-3 are presented in Figures 4-6 for the Rochester project. There is more scatter in the data for Rochester than is found in the plots for Morristown. The data are more spread out and the linear relationship seen in Figures 1-3 is less pronounced in Figures 4-6. There appears to be much less correlation between the gauge results in Figures 4-6 than is present in Figures 1-3. The reason for this difference is not known, but may be related to differences in the paving mixes and materials for the projects.

Hypothesis Testing

To further investigate the data plotted in Figures 1-6, the TTEST procedure in SAS was used on a pairwise basis to test the assumptions of equal means and variances between the results of the gauges. The possible pairwise comparisons include (a) CPN with Troxler, (b) CPN with Seaman, and (c) Troxler with Seaman. These comparisons were made individually for each of the projects, and for both the joint and mat density results. The results of the hypothesis tests are presented in Tables 1-4. The Morristown results are in Tables 1 and 3, while the Rochester results appear in Tables 2 and 4.

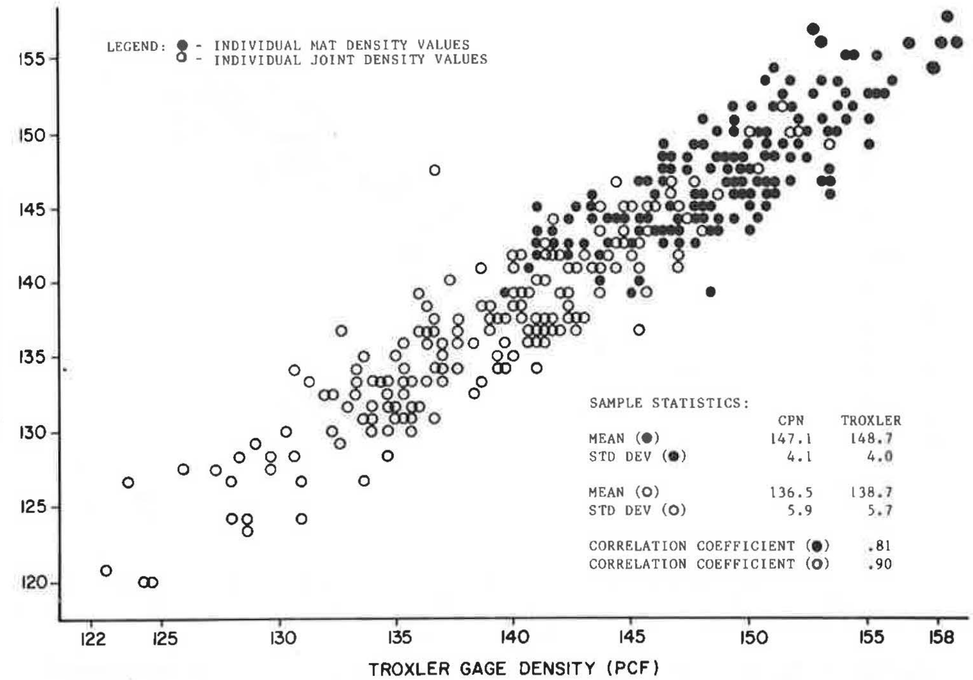

FIGURE 1 Plot of CPN versus Troxler gauge density results for the Morristown project.

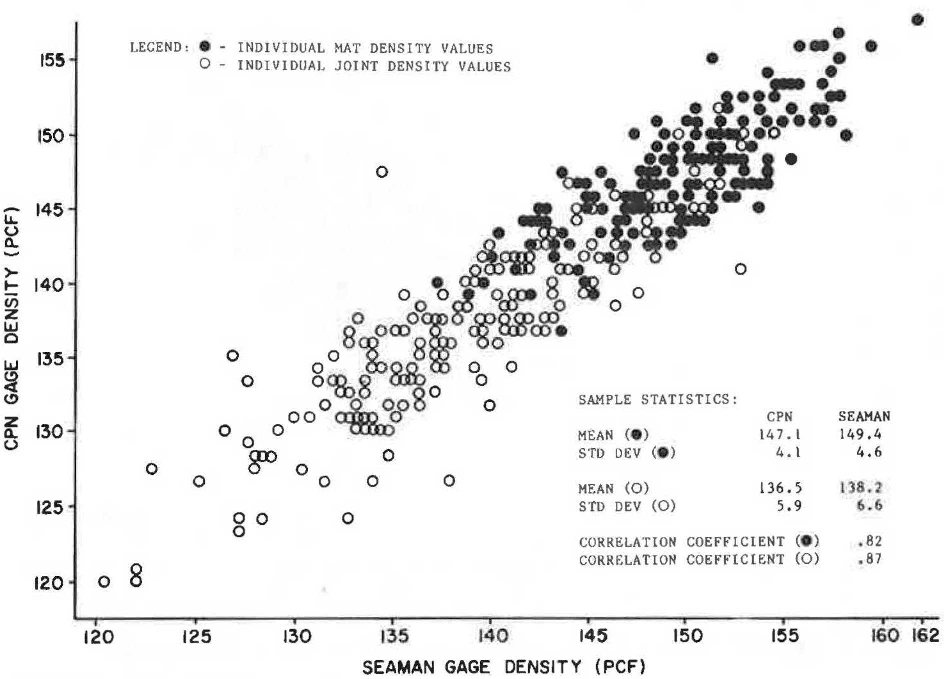

FIGURE 2 Plot of CPN versus Seaman gauge density results for the Morristown project.

Visual inspection of the statistics in Tables 1 and 2 identifies a trend in the relative magnitudes of the mat density means of the three gauges. On both projects, the Seaman gauge produced the largest mean value, followed by the Troxler and then the CPN gauges. If the t-statistics are considered, the Seaman mean at Morristown is not significantly different from the Troxler mean at the 0.11 level of significance. There is little consistency in the standard deviation values for the mat density results. The Seaman gauge had the largest (0.10 level of significance) standard deviation for Morristown, but had the smallest (0.16 level of significance) standard deviation for Rochester.

The hypothesis test results for joint density are presented in Tables 3 and 4. As with the mat density results, the CPN gauge had the lowest mean (0.0001 level of significance). The Seaman mean was larger than the Troxler mean at the 0.03 significance level. On the Rochester project there were no significant differences among the standard deviations for the

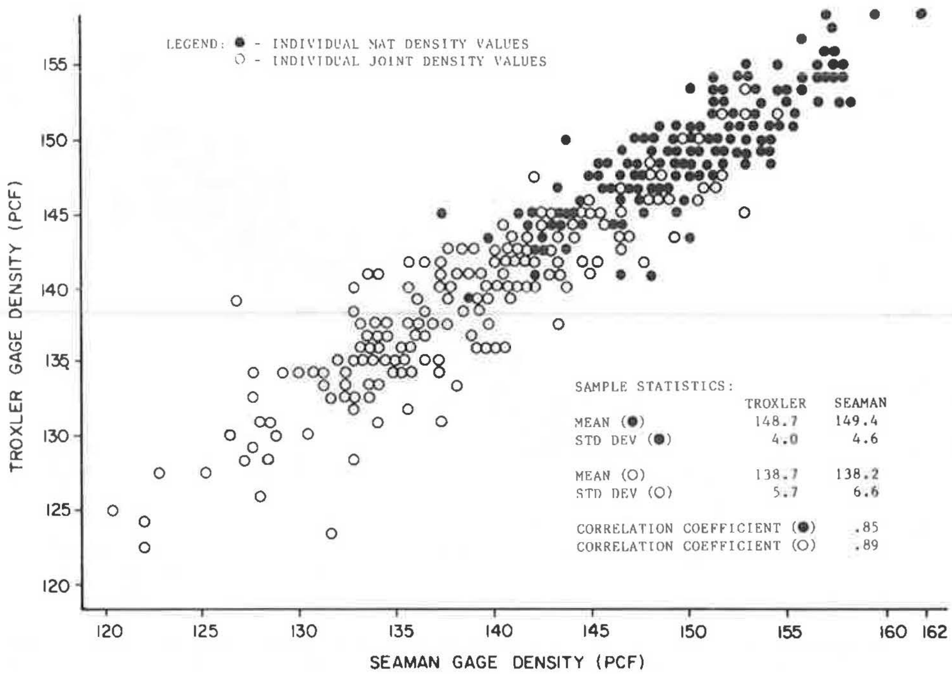

FIGURE 3 Plot of Troxler versus Seaman gauge density results for the Morristown project.

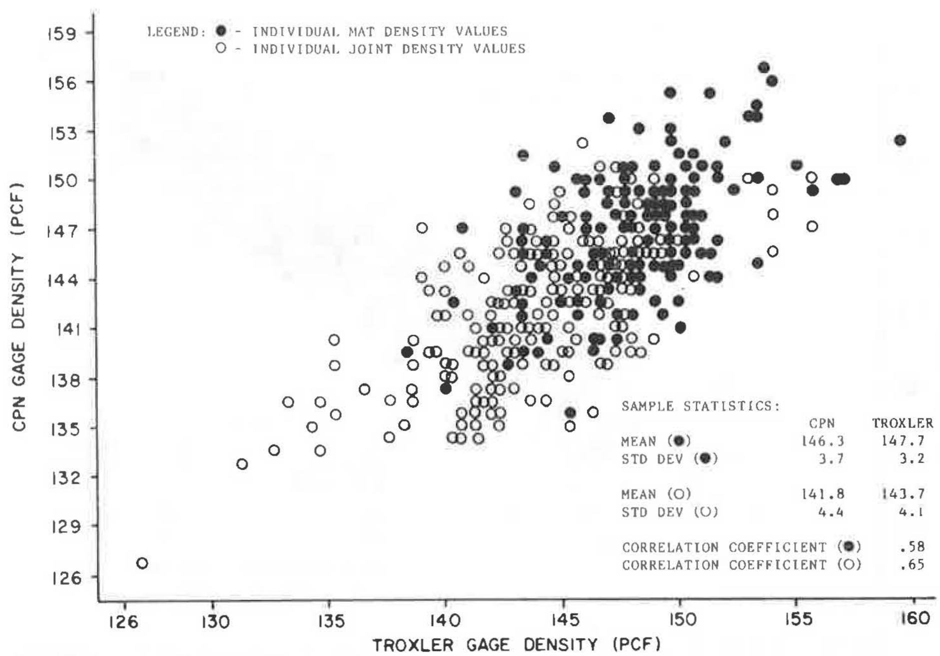

FIGURE 4 Plot of CPN versus Troxler gauge density results for the Rochester project.

gauges. For Morristown, the Seaman standard deviation was larger than the Troxler value at the 0.04 significance level, but was not significantly larger than the CPN value at the 0.11 significance level.

It is not possible to establish trends with only two projects. However, it can be concluded from Tables 1-4 that the three gauges will not always produce the same mean results, and that the variability may differ from gauge to gauge.

Correlation Analysis

Because all three gauges were used to obtain density values at each location, it is possible to correlate the individual values on a pairwise basis between the gauges. Tables 5 and 6 present the results of the correlation analysis. Table 5 presents the correlation coefficients for mat and joint density for each

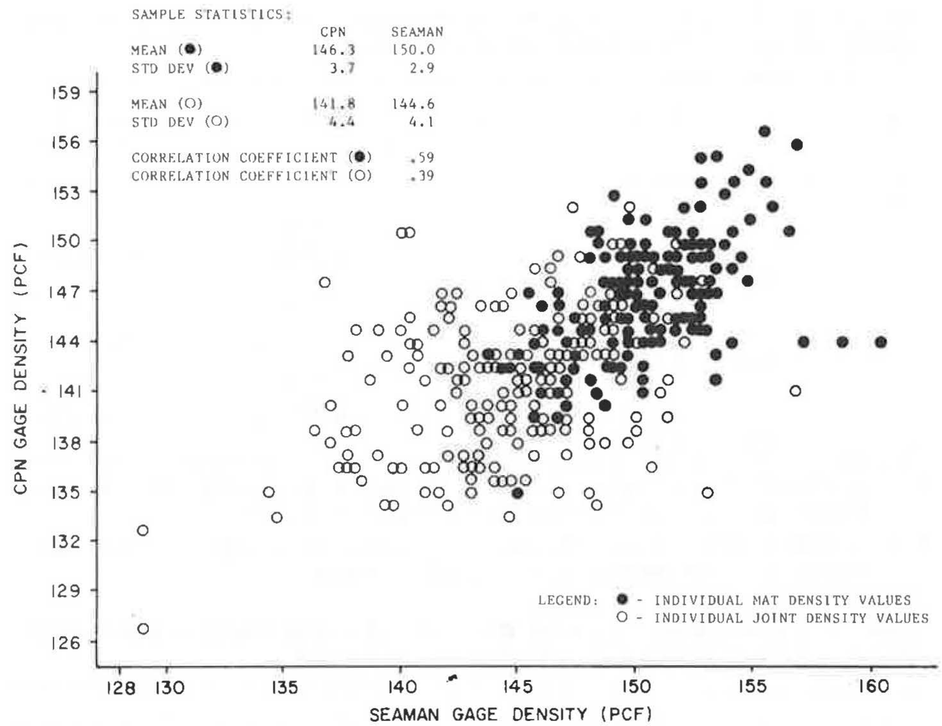

FIGURE 5 Plot of CPN versus Seaman gauge density results for the Rochester project.

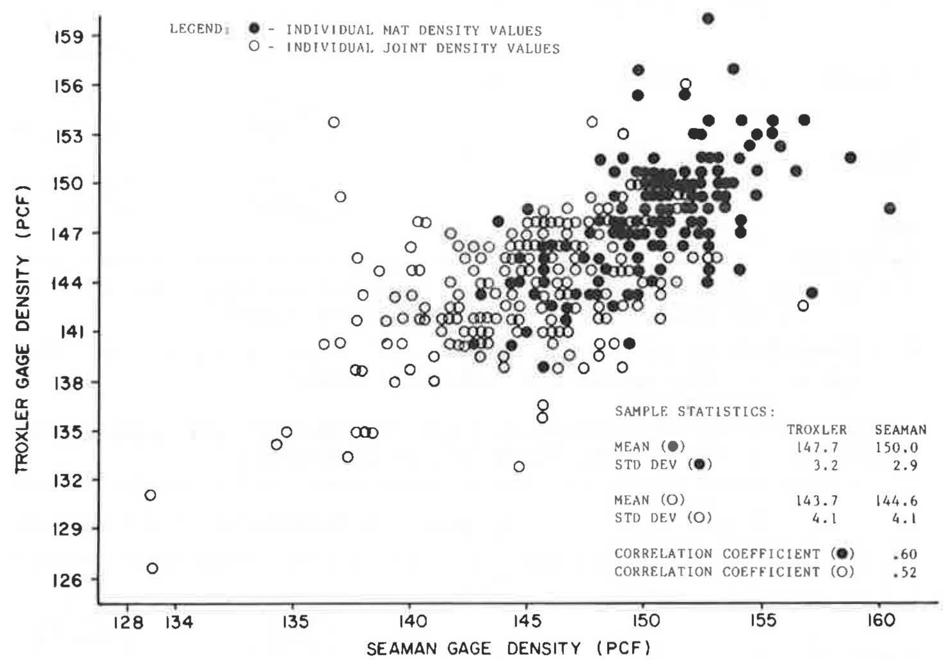

FIGURE 6 Plot of Troxler versus Seaman gauge density results for the Rochester project.

gauge combination for the Morristown project. Table 6 presents similar results for Rochester.

The correlation coefficients among the gauge combinations are similar for each project when considered individually. However, the coefficients for Morristown are consistently larger than the ones at Rochester. For Morristown, the mat density coefficients are 0.81, 0.82, and 0.85 for the CPN-Troxler, CPN-Seaman, and Troxler-Seaman comparisons, respectively. For Rochester, the coefficients are 0.58, 0.59, and 0.60 for the same comparisons. Similar results are exhibited for the joint density correlations. The joint density correlations for Rochester are not as uniform as the joint density results for Morristown. They are, however, still consistently lower than the Morristown joint density results.

TABLE 1 RESULTS OF PAIRWISE HYPOTHESIS TESTS ON NUCLEAR GAUGE MAT DENSITY RESULTS FOR THE MORRISTOWN PROJECT

Gage	No.	Mean	Std. Dev.	F-Statistic (Prob > F)*	t-Statistic (Prob>|t|)#
CPN	192	147.1	4.1		
				1.06 (.711)	-3.96 (.0001)
Troxler	191	148.7	4.0		
				1.34 (.042)	1.58 (.115)
Seaman	192	149.4	4.6		
				1.27 (.095)	-5.24 (.0001)
CPN	192	147.1	4.1		

* - probability of obtaining an F value as large as the one shown if the variances are actually equal

\# - probability of obtaining a t value as large as the one shown if the means are actually equal

TABLE 2 RESULTS OF PAIRWISE HYPOTHESIS TESTS ON NUCLEAR GAUGE MAT DENSITY RESULTS FOR THE ROCHESTER PROJECT

Gage	No.	Mean	Std. Dev.	F-Statistic (Prob > F)*	t-Statistic (Prob>|t|)#
CPN	207	146.3	3.7		
				1.31 (.053)	-4.23 (.0001)
Troxler	207	147.7	3.2		
				1.21 (.169)	7.38 (.0001)
Seaman	207	150.0	2.9		
				1.59 (.001)	-11.22 (.0001)
CPN	207	146.3	3.7		

* - probability of obtaining an F value as large as the one shown if the variances are actually equal

\# - probability of obtaining a t value as large as the one shown if the means are actually equal

TABLE 3 RESULTS OF PAIRWISE HYPOTHESIS TESTS ON NUCLEAR GAUGE JOINT DENSITY RESULTS FOR THE MORRISTOWN PROJECT

	No.	Mean	Std. Dev.	F-Statistic	t-Statistic
CPN	192	136.5	5.9		
				1.07 (.621)	-3.72 (.0002)
Troxler	192	138.7	5.7		
				1.35 (.040)	-0.78 (.437)
Seaman	192	138.2	6.6		
				1.25 (.118)	-2.68 (.008)
CPN	192	136.5	5.9		

* - probability of obtaining an F value as large as the one shown if the variances are actually equal

\# - probability of obtaining a t value as large as the one shown if the means are actualy equal

TABLE 4 RESULTS OF PAIRWISE HYPOTHESIS TESTS ON NUCLEAR GAUGE JOINT DENSITY RESULTS FOR THE ROCHESTER PROJECT

Gage	No.	Mean	Std. Dev.	F-Statistic	t-Statistic
CPN	207	141.8	4.4		
				1.12 (.418)	-4.61 (.0001)
Troxler	207	143.7	4.1		
				1.00 (.994)	2.17 (.031)
Seaman	207	144.6	4.1		
				1.12 (.422)	-6.71 (.0001)
CPN	207	141.8	4.4		

* - probability of obtaining an F value as large as the one shown if the variances are actually equal

\# - probability of obtaining a t value as large as the one shown if the means are actually equal

TABLE 5 CORRELATION COEFFICIENTS BETWEEN NUCLEAR GAUGES FOR MAT AND JOINT DENSITIES ON THE MORRISTOWN PROJECT (192 OBSERVATIONS)

	Type	CPN	Troxler	Seaman
CPN	Mat	---	.81	.82
	Joint	---	.90	.87
Troxler	Mat	.81	---	.85
	Joint	.90	---	.89
Seaman	Mat	.82	.85	---
	Joint	.87	.89	---

NOTE - the probability that any individual coefficient in the table would be obtained if the true correlation is zero is .0001

It appears that the gauges correlate equally well with one another, but that the level of correlation may vary from one project to the next.

Gauge Versus Core Comparisons

If nuclear density gauges are to be considered for use in acceptance decisions, it is desirable to investigate how well their results compare with the method that is currently used for this purpose, that is, the use of core densities. The core and nuclear density results on each of the projects were analyzed to determine how well the gauge results correlated with the core densities.

Scatter Plots

Plots of the density results for each gauge versus the core density results are presented in Figures 7-9 for Morristown and Figures 10-12 for Rochester. The mat and joint density results are distinguished in each of the plots by closed and open circles, respectively. Figures 7, 8, and 9 present plots of the CPN, Troxler, and Seaman results, respectively, against the corresponding core densities.

The data in Figures 7-9 are more scattered than the corresponding plots for each of the nuclear gauge results against each other gauge that are presented in Figures 1-3. The linear relationships between the gauges in Figure 1-3 are not apparent in the gauge versus core plots (Figures 7-9) because of the increased spread among the data values. It

TABLE 6 CORRELATION COEFFICIENTS BETWEEN NUCLEAR GAUGES FOR MAT AND JOINT DENSITIES ON THE ROCHESTER PROJECT (207 OBSERVATIONS)

	Type	CPN	Troxler	Seaman
CPN	Mat	---	.58	.59
	Joint	---	.65	.39
Troxler	Mat	.58	---	.60
	Joint	.65	---	.52
Seaman	Mat	.59	.60	---
	Joint	.39	.52	---

NOTE - the probability that any individual coefficient in the table would be obtained if the true correlation is zero is .0001

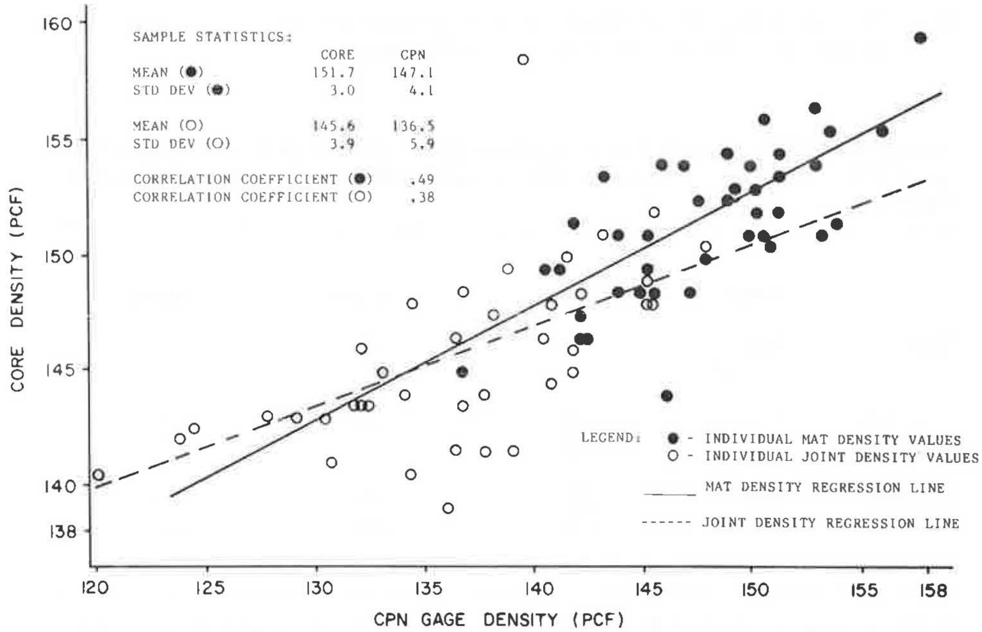

FIGURE 7 Plot of joint and mat density regression lines for core density versus CPN gauge density for the Morristown project.

appears that there is a much higher degree of correlation between the gauges than there is between the gauges and the core densities. Plots similar to those in Figures 7-9 are presented for the Rochester project in Figures 10-12. The plots for the Rochester data appear to be even more scattered than those for Morristown.

Hypothesis Testing

To further investigate the relationships between the gauge densities and the core results, the TTEST procedure was used to test the hypotheses that the means and variances of each of the gauges were equal to the core values. F-statistics and t-statistics were determined individually for the mat and joint density results for each gauge for each project. The results of the hypothesis tests are presented in Tables 7-10. The Morristown results appear in Tables 7 and 9. The Rochester results are in Tables 8 and 10.

The mat density results for the projects are presented in Tables 7 and 8 for Morristown and Rochester, respectively. For both Morristown and Rochester, for each of the three gauges both the means and variances are statistically significantly different from the core results at the 0.03 level of significance. These results, along with visual inspection of the plots, indicate that the nuclear gauges provide lower mat density values than are obtained from cores. It also appears that for mat density the nuclear gauge results are slightly more variable than the core results.

The hypothesis test results for joint density are presented in Tables 9 and 10 for the Morristown and Rochester projects, respectively. For Morristown (Table 9), all of the gauges

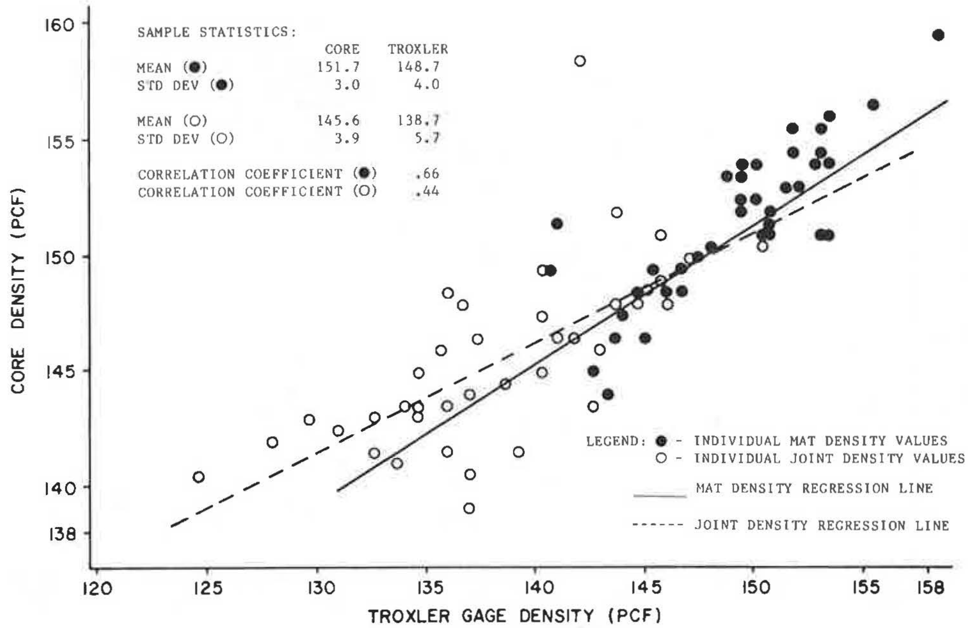

FIGURE 8 Plot of joint and mat density regression lines for core density versus Troxler gauge density for the Morristown project.

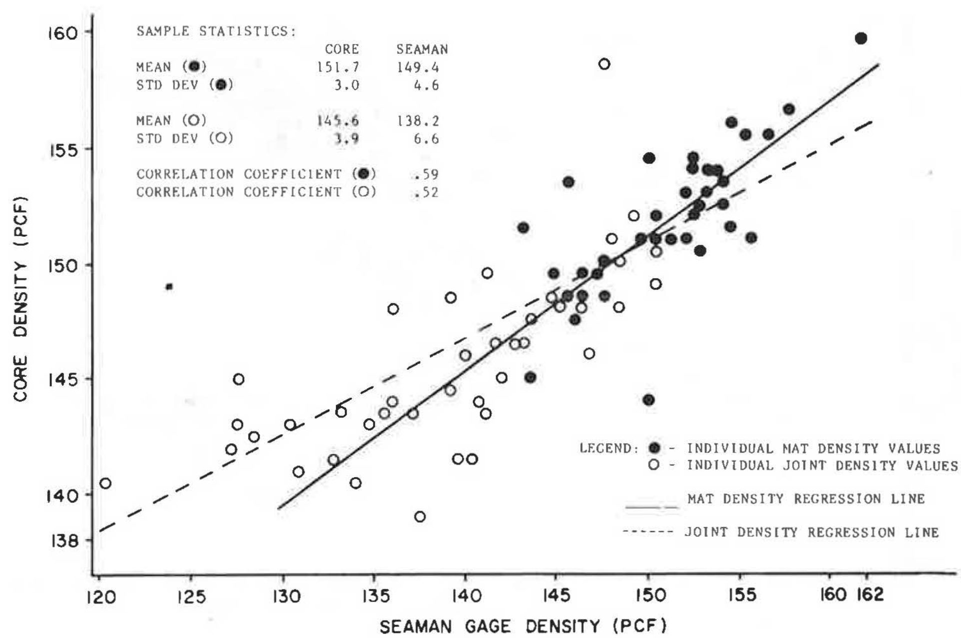

FIGURE 9 Plot of joint and mat density regression lines for core density versus Seaman gauge density for the Morristown project.

provided statistically significantly lower mean values (0.0001 level) and higher variance values (0.01 level) than the core joint density results. This trend was not found in the Rochester data. For Rochester, the CPN and Seaman mean joint density values were significantly different at the 0.022 level than the core mean. The CPN mean was smaller than the core mean, whereas the Seaman mean value was larger than the core mean value. The Troxler mean value was not significantly different from the core mean value at the 0.44 level.

On the Morristown project, the nuclear gauge joint density readings were obtained with the gauges oriented parallel to the joints. On the Rochester project, two nuclear gauge joint density readings were taken at each location with each gauge, one with the gauge parallel to the joints and one with the gauge perpendicular to the joints. Table 10 presents the results for the readings taken with the gauges perpendicular to the joints.

To investigate whether the Rochester joint nuclear gauge results were closer to the core results because of the different

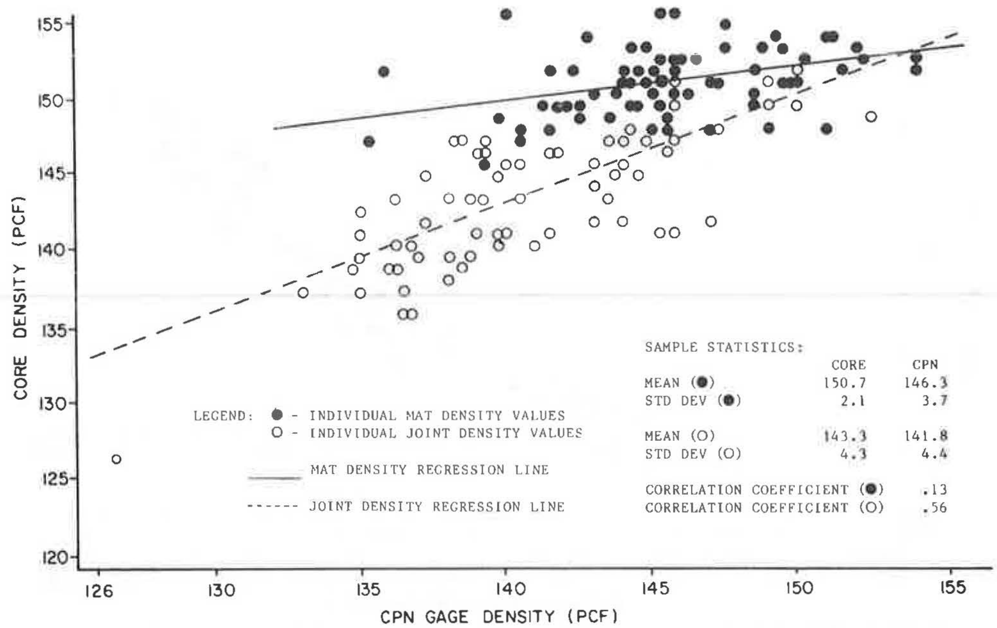

FIGURE 10 Plot of joint and mat density regression lines for core density versus CPN gauge density for the Rochester project.

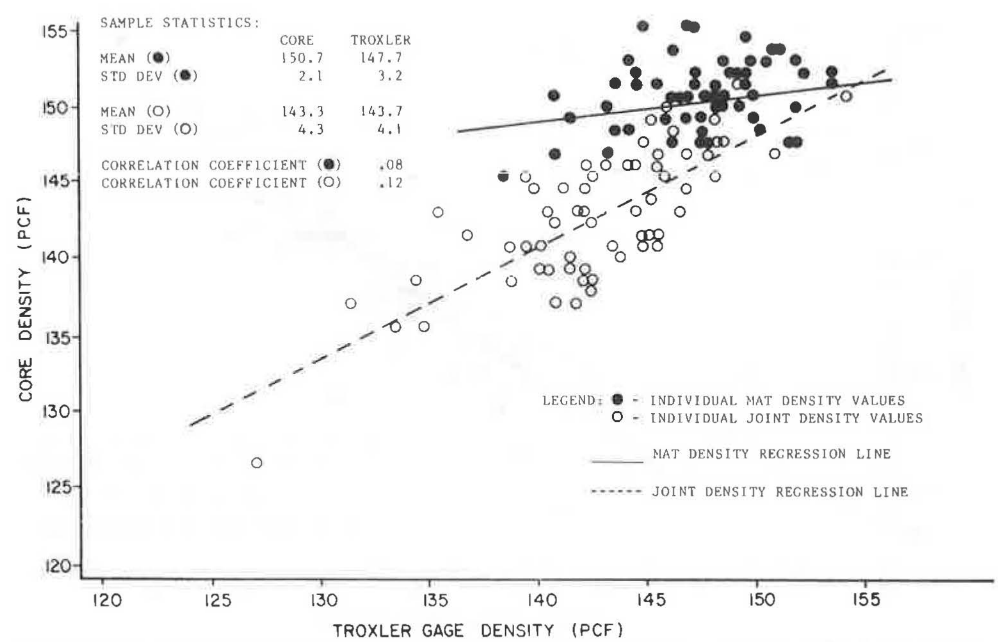

FIGURE 11 Plot of joint and mat density regression lines for core density versus Troxler gauge density for the Rochester project.

orientation of the gauges while readings were taken, an analysis of gauge readings taken parallel to the joints on the Rochester project was also conducted. The results of this analysis are presented in Table 11. As can be seen in this table, for each of the gauges the readings taken perpendicular to the joints were higher than those taken parallel to the joints. Because the core values were higher than the gauge results, it would appear that the perpendicular gauge orientation provides results that are closer to the core densities.

Regression Analysis

To investigate the relationships between each of the gauges and the core densities, regression analyses were conducted on the data. Linear regression analyses were conducted on the data from each project and for each gauge individually. The analyses were performed to determine how well each gauge predicted the core density results. The results of the regression analyses are presented in Tables 12-15. Tables 12 and 13

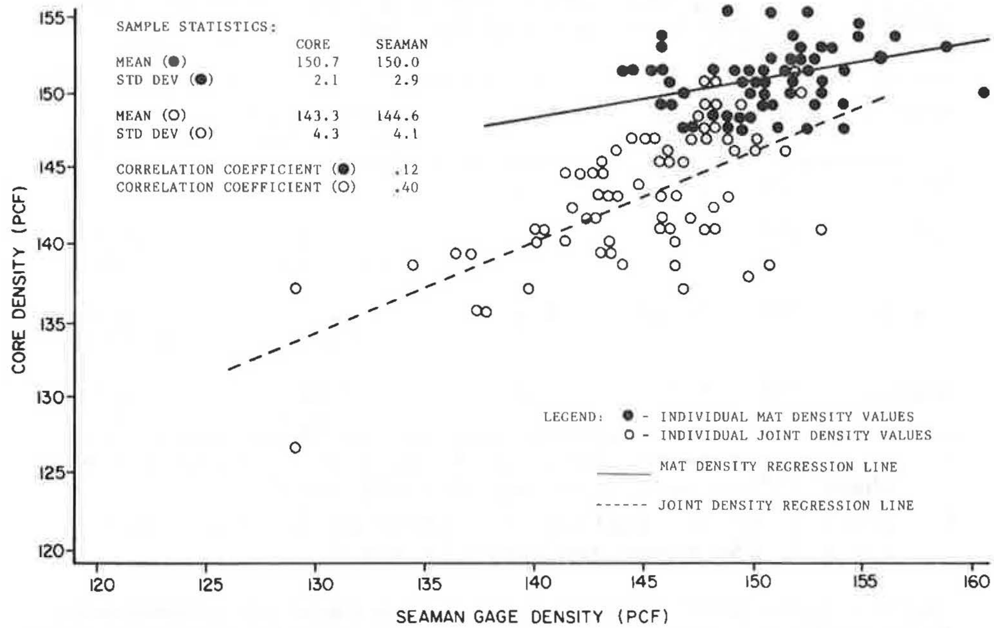

FIGURE 12 Plot of joint and mat density regression lines for core density versus Seaman gauge density for the Rochester project.

TABLE 7 RESULTS OF HYPOTHESIS TESTS FOR PAIRWISE COMPARISONS BETWEEN CORE AND NUCLEAR GAUGE MAT DENSITY RESULTS FOR THE MORRISTOWN PROJECT

Source	No.	Mean	Std. Dev.	F-Statistic (Prob > F)*	t-statistic (Prob>|t|)#
Core	40	151.7	3.0	---	---
CPN	192	147.1	4.1	1.81 (.030)	8.13 (.0001)
Troxler	191	148.7	4.0	1.72 (.047)	5.27 (.0001)
Seaman	192	149.4	4.6	2.31 (.003)	3.86 (.0002)

* - probability of obtaining an F value as large as the one shown if the variances are actually equal

\# - Probability of obtaining a t value as large as the one shown if the means are actually equal

present the mat density results for the Morristown and Rochester projects, respectively. The joint density results appear in Tables 14 and 15.

The tables present the regression equations using each of the gauge results as the independent variable and the core density results as the dependent variable. The slopes and intercepts for the regression lines are presented along with the t-statistic for testing the hypothesis that the values (slope and intercept) are equal to zero. The R^2 values presented in the tables are measures of how well the variation of the dependent variable is described by the variation in the independent variable. As can be seen in Table 13, the R^2 values for mat density for Rochester are much smaller than the values in Tables 12, 14, and 15. The small R^2 values presented in Table 13 are the result of the greater variability for the mat density data at Rochester. To illustrate the spread in the data and the relationships of the regression equations to the data, Figures 7-12 show plots of the regression equations for each gauge for each project with the mat and joint density values also shown. Figures 7-9 show the Morristown results, and Figures 10-12 show the results from Rochester.

There is no consistency between the projects with respect to the plots. For Morristown, the mat density regression lines have steeper slopes than the corresponding joint density lines.

TABLE 8 RESULTS OF HYPOTHESIS TESTS FOR PAIRWISE COMPARISONS BETWEEN CORE AND NUCLEAR GAUGE MAT DENSITY RESULTS FOR THE ROCHESTER PROJECT

Source	No.	Mean	Std. Dev.	F-Statistic (Prob > F)*	t-Statistic (Prob>|t|)#
Core	72	150.7	2.1	---	---
CPN	207	146.3	3.7	3.03 (.0001)	12.23 (.0001)
Troxler	207	147.7	3.2	2.31 (.0001)	8.76 (.0001)
Seaman	207	150.0	2.9	1.91 (.002)	2.19 (.030)

* - probability of obtaining an F value as large as the one shown if the variances are actually equal

\# - probability of obtaining a t value as large as the one shown if the means are actually equal

TABLE 9 RESULTS OF HYPOTHESIS TESTS FOR PAIRWISE COMPARISONS BETWEEN CORE AND NUCLEAR GAUGE JOINT DENSITY RESULTS FOR THE MORRISTOWN PROJECT (PARALLEL)

Source	No.	Mean	Std. Dev.	F-Statistic (Prob > F)*	t-statistic (Prob>|t|)#
Core	40	145.6	3.9	---	---
CPN	192	136.5	5.9	2.29 (.003)	12.16 (.0001)
Troxler	192	138.7	5.7	2.13 (.006)	9.33 (.0001)
Seaman	192	138.2	6.6	2.87 (.0002)	9.49 (.0001)

* - probability of obtaining an F value as large as the one shown if the variances are actually equal

\# - Probability of obtaining a t value as large as the one shown if the means are actually equal

TABLE 10 RESULTS OF HYPOTHESIS TESTS FOR PAIRWISE COMPARISONS BETWEEN CORE AND NUCLEAR GAUGE JOINT DENSITY RESULTS FOR THE ROCHESTER PROJECT (PERPENDICULAR)

Source	No.	Mean	Std. Dev.	F-Statistic (Prob > F)*	t-Statistic (Prob>|t|)#
Core	72	143.3	4.3	---	---
CPN	207	141.8	4.4	1.03 (.411)	2.51 (.013)
Troxler	207	143.7	4.1	1.09 (.638)	-0.76 (.448)
Seaman	207	144.6	4.1	1.09 (.642)	-2.30 (.022)

* - probability of obtaining an F value as large as the one shown if the variances are actually equal

\# - probability of obtaining a t value as large as the one shown if the means are actually equal

TABLE 11 RESULTS OF HYPOTHESIS TESTS ON PERPENDICULAR AND PARALLEL GAUGE ORIENTATIONS FOR JOINT DENSITY READINGS FOR ROCHESTER PROJECT (72 OBSERVATIONS FOR EACH ORIENTATION)

Gage	Perpendicular Mean (Std Dev)	Parallel Mean (Std Dev)	F-Statistic (Prob > F)*	t-Statistic (Prob>|t|)#
CPN	140.7 (4.6)	138.0 (5.0)	1.18 (.489)	-3.31 (.001)
Troxler	142.9 (4.5)	139.8 (5.0)	1.24 (.367)	-3.91 (.0001)
Seaman	144.7 (4.6)	142.5 (5.4)	1.38 (.174)	-2.65 (.009)

* - probability of obtaining an F value as large as the one shown if the variances are actually equal

\# - probability of obtaining a t value as large as the one shown if the means are actually equal

TABLE 12 RESULTS OF REGRESSION ANALYSIS ON GAUGE AND CORE MAT DENSITY RESULTS FOR THE MORRISTOWN PROJECT (40 OBSERVATIONS)

Gage	Slope	t-Statistic (Prob>|t|)*	Intercept	t-Statistic (Prob>|t|)*	R-Square
CPN	0.505	6.2 (.0001)	76.96	6.4 (.0001)	0.493
Troxler	0.660	8.7 (.0001)	53.20	4.7 (.0001)	0.655
Seaman	0.574	7.6 (.0001)	65.09	5.7 (.0001)	0.594

* - probability of obtaining a t value as large as the one shown if the true slope or interest is actually zero

TABLE 13 RESULTS OF REGRESSION ANALYSIS ON GAUGE AND CORE MAT DENSITY RESULTS FOR THE ROCHESTER PROJECT (72 OBSERVATIONS)

Gage	Slope	t-Statistic (Prob>|t|)*	Intercept	t-Statistic (Prob>|t|)*	R-Square
CPN	0.211	3.4 (.0011)	119.96	13.3 (.0001)	0.139
Troxler	0.208	2.7 (.0087)	120.01	10.5 (.0001)	0.081
Seaman	0.233	3.3 (.0017)	115.70	10.8 (.0001)	0.120

* - probability of obtaining a t value as large as the one shown if the true slope or intercept is actually zero

TABLE 14 RESULTS OF REGRESSION ANALYSIS ON GAUGE AND CORE JOINT DENSITY RESULTS FOR THE MORRISTOWN PROJECT (40 OBSERVATIONS)

Gage	Slope	t-Statistic (Prob>|t|)*	Intercept	t-Statistic (Prob>|t|)*	R-Square
CPN	0.389	5.0 (.0001)	92.49	8.7 (.0001)	0.378
Troxler	0.466	5.6 (.0001)	80.93	7.0 (.0001)	0.436
Seaman	0.384	6.5 (.0001)	92.12	11.2 (.0001)	0.515

* - probability of obtaining a t value as large as the one shown if the true slope or interest is actually zero

TABLE 15 RESULTS OF REGRESSION ANALYSIS ON GAUGE AND CORE JOINT DENSITY RESULTS FOR THE ROCHESTER PROJECT (72 OBSERVATIONS)

Gage	Slope	t-Statistic (Prob>|t|)*	Intercept	t-Statistic (Prob>|t|)*	R-Square
CPN	0.702	9.6 (.0001)	44.52	4.3 (.0001)	0.562
Troxler	0.743	10.1 (.0001)	37.13	3.5 (.0008)	0.585
Seaman	0.591	6.9 (.0001)	57.80	4.7 (.069)	0.398

* - probability of obtaining a t value as large as the one shown if the true slope or intercept is actually zero

The opposite is true for Rochester where the mat density regression lines have shallow slopes. These shallow slopes are indicative of little relationship between the gauge densities and the core densities.

Use of Nuclear Gauges for Acceptance

Before the use of nuclear gauges is considered for acceptance decisions, it should be noted that any conclusions and discussions presented in this paper can apply only to the gauges used in this study. They can not necessarily be applied to a particular manufacturer's gauges in general because there is bound to be some degree of variability among the gauges produced even by a single gauge manufacturer.

The results of this research have shown that the readings of the three gauges can be significantly different statistically from one another and also from the core results. Furthermore, it was found that there is no consistency with respect to how the gauges will perform with respect to one another from one project to the next. If the intent of using nuclear gauges is to provide an estimate for, or to correlate with, the core results, then the findings of this research do not support the use of nuclear gauges for acceptance decisions. The use of nuclear gauges in lieu of coring, but with the same acceptance limits that were developed based on core results, is not appropriate.

The use of nuclear gauges, however, has some distinct advantages over the use of cores. These advantages are related to the number of tests that can be conducted nondestructively with the nuclear gauges in a short period of time. Such advantages allow for a large number of acceptance tests at random locations that can more thoroughly sample the total area of the paving lot. The nuclear gauges allow the acceptability of the lot to be determined without having to wait for the cores to be transported to the laboratory and tested. This continuous feedback aspect of nuclear gauges has led to their popularity as quality control devices by paving contractors.

Because it was found by this research that the nuclear gauges did not consistently correlate with the core results from project to project and for mat and joint densities, it is important that a test strip be used if nuclear gauges are to be considered for acceptance. The particular gauge that will be used on the project can be used on the test strip to determine the maximum density that is attained on the test strip. This approach of using the same gauge that will be used on the project on a test strip that is constructed with the same mix and materials that will be used on the project should eliminate some of the variability that was found among the projects studied in the current research.

RESEARCH FINDINGS

The major findings of the research effort to investigate the use of nuclear density gauges for acceptance purposes are as follows:

1. Statistically significant differences were found in the nuclear gauge results for both projects studied. Both the means and variances were found to differ significantly among the gauges on both projects, but the differences in the means were more pronounced.
2. In all cases for both projects the gauge results had statistically significantly lower mat mean density values than the core mean value. The same general trend was also found in the joint results with the exception of the Seaman gauge at Rochester that was significantly larger than the core joint values.
3. When nuclear gauges were used for determining joint density, it was found that orienting the gauge perpendicular rather than parallel to the joint provided results that were closer to the joint core density values.
4. Regression analyses indicated that the predictive ability of the nuclear gauges with respect to the core results varied from project to project. For Morristown, mat density regression equations yielded R^2 values of 0.493, 0.655, and 0.594 for the CPN, Troxler, and Seaman gauges, respectively. The corresponding R^2 values for mat density on the Rochester project were 0.130, 0.081, and 0.120.
5. 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. This should not rule out the development of acceptance procedures specifically for nuclear gauges to take advantage of the large sample sizes and rapid results that are possible with nuclear gauges.

ACKNOWLEDGMENT

The research and field work reported herein were supported by the FAA.

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Publication of this paper sponsored by Committee on Flexible Pavement Construction and Rehabilitation.