STATE OF FLORIDA

AN EVALUATION OF FIELD DENSITY MEASURING DEVICES

Research Report
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STATE MATERIALS OFFICE

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EXECUTIVE SUMMARY

The use of non-destructive devices for the measurement of in-place density of a compacted asphalt mat would be beneficial in that it would save time and money compared to cutting roadway cores for the determination of pay factors by Florida Department of Transportation (FDOT) Acceptance personnel. However, the use of non-destructive devices was discontinued by the FDOT in 1997 during the onset of Superpave construction because it was found that the gauges were not providing accurate readings when compared to the core densities. The recent development of non-nuclear density measuring devices has prompted the need for research studies that would again compare core density values to gauge density values for both coarse and fine graded Superpave mixes. This study compared core and gauge densities for two separate test sections (one coarse and one fine graded Superpave mix). Nuclear gauges from Troxler and CPN and non-nuclear gauges from Transtech were used in the study. The results indicate that when comparing standard deviations and means of the gauge densities to the core densities, the CPN MC3 gauge outperformed all of the other gauges used in this study. The Transtech gauges had comparably equivalent mean density values but had very high standard deviations. The Troxler gauges (three models were tested) had mixed results. In general, all of the gauges did not perform better on the fine graded mix as compared to the coarse graded mix.

Although the CPN MC3 gauge used in this study provided results very close to the core density values, use of the gauge for Acceptance is not recommended at this time since these results are based on one gauge and there are issues related to requiring a specific manufacturer's gauge to be used. It is recommended that the Transtech gauges be allowed for use as a Quality Control tool since their variability is not necessarily worse than an allowable nuclear gauge.

INTRODUCTION

The use of non-destructive devices for measuring the density of asphalt pavements in lieu of cutting cores is beneficial for several reasons: it is faster, it does not disturb the pavement, and does not require as much equipment. However, these benefits are more than offset if the non-destructive devices do not produce accurate density values. Two previous FDOT studies ***(1,2)*** have shown that both nuclear and electrical impedance devices have not proven to be reliable when measuring density on Superpave mixes. The variability of the density data was too high in comparison to the actual core densities. This would prevent such a device from being used for Acceptance where pay factors are determined based on the in-place density of the mix.

As part of FDOT's QC 2000 implementation, a study was conducted to determine the variability of density in terms of transverse and longitudinal location throughout a pavement test section. Thirty locations were laid out in a specific pattern at two different pavement test sections (**Figures 1 and 2**). Cores were then obtained at each of the thirty locations for laboratory density determination. It was also decided that this study would provide an opportunity to reevaluate a variety of non-destructive density measuring devices. This report focuses on the comparisons of the core densities to the gauge densities for the two different roadway test sections. The variability of density in terms of transverse and longitudinal location will not be addressed in this report.

EXPERIMENTAL PLAN

Test Section #1

The test section was located on southbound US 301 south of Starke in Bradford County. The asphalt mix was a 12.5 mm, coarse graded, Superpave mix placed approximately 50 mm thick, over a milled asphalt surface. The aggregate types used in the asphalt mix were: South Florida Limestone (30%), Nova Scotia granite (45%) and reclaimed asphalt pavement (25%). The pavement had been placed approximately one month prior to the density testing. The testing date was May 11, 1999.

There were four non-destructive gauges that were used to measure the density at each of the thirty test locations. Two of the four gauges were of the nuclear type operated in the backscatter mode: Troxler model 3450 (thin-lift gauge) and CPN model MC3. The other two gauges were of the electrical impedance type: Transtech PQI #100 and #200. All of the gauges were operated by a representative from each manufacturer. The manufacturers' representatives were allowed to take readings over the coring location in a manner that they believed would give the most accurate density reading. **Table 1** summarizes the number of readings taken and orientation of the gauge for each of the four gauges. FDOT representatives recorded all of the data values.

Test Section #2

The test section was located on SR 235, just south of US 441, in the town of Alachua in Alachua County. The asphalt mix was a 12.5 mm, fine graded, Superpave friction course mix placed approximately 40 mm thick, over a milled asphalt surface. The aggregate types used in the asphalt mix were: South Florida Limestone (90%) and local sand (10%). The asphalt binder was mixed with 12% ground tire rubber by weight of the binder. The pavement was placed immediately prior to the density testing. The testing date was September 16, 1999.

There were four non-destructive gauges that were used to measure the density at each of the thirty test locations. Three of the four gauges were of the nuclear type operated in backscatter mode: Troxler model 3440, Troxler model 4640B (thin-lift gauge) and CPN model MC3. The other gauge was of the electrical impedance type: Transtech PQI #200. The CPN and Transtech gauges were operated by a representative from each respective manufacturer. The Troxler gauges were operated by a certified FDOT nuclear gauge operator because a Troxler representative was not able to attend the field testing. The CPN and Transtech manufacturers' representatives obtained readings at each coring location in the same pattern and frequency as described for test section #1. Since a Troxler representative was not present, readings taken with the two Troxler gauges were obtained with the same pattern and frequency as occurred at test section #1. FDOT representatives recorded all of the data values.

For both test sections, cores were then cut and brought to the State Materials Office. The desired Superpave layers were then cut from the cores using a wet saw equipped with a diamond tipped blade. The density of each core slice was then determined using Florida Test Method FM 1-T 166, Method B. The core densities would serve as the reference to which each of the non-destructive gauges would be compared.

DATA ANALYSIS

Test Section #1

As described in **Table 1**, multiple readings were taken with each gauge at each core location (either four or five readings depending on the gauge type). The multiple readings for each gauge were then averaged to determine one density value per gauge per core location (see **Table 2** for the average gauge readings and the core density values). The core density values and the uncorrected average gauge readings are plotted in **Figure 3**. A correction factor was then calculated for each gauge and applied to each average gauge density reading. To determine the correction factor, five cores were randomly selected in a stratified manner, where one core was randomly picked from each consecutive subset of six cores, see **Table 3**. The corresponding average gauge density reading for each of the six cores was subtracted from each core density value and the differences averaged to determine a correction factor for each gauge, see **Table 4**. The respective correction factors were then added to each average gauge density reading to arrive at corrected density values for the gauges. It should be noted that this method of calculating the correction factor was discussed and agreed upon by all of the gauge representatives. The core and corrected gauge density values were then plotted in **Figure 4**. The corrected gauge density values were then subtracted from the core density values. The core and corrected gauge density values as well as the differences between the two are shown in **Table 5**. The core and corrected gauge density values expressed in terms of air voids are shown in **Table 6**.

Several statistics (average difference, standard deviation, t-test and correlation coefficient) were calculated based on the differences between the core density values and the corrected gauge density values. These results will be discussed separately below. The values are summarized in **Table 7**.

Average Difference

All of the gauges had an average difference of less than one pcf. The highest average difference was with the Toxler 3450 gauge (0.69 pcf). This is equal to 0.48 % when expressed as a percentage of the average core density (144.5 pcf). The lowest average difference was with the CPN MC3 gauge (-0.05 pcf) which is equal to 0.03% of the average core density. The PQI 100 and 200 gauges had average differences of 0.20 pcf (0.14%) and -0.29 pcf (0.20%) respectively.

In terms of air voids, the highest average difference was with the Toxler 3450 gauge (-0.47 % air voids). The lowest average difference was with the CPN MC3 gauge (0.03 % air voids). The PQI 100 and 200 gauges had average differences of -0.13 % and 0.20 % air voids respectively.

Standard Deviation

A more meaningful statistic for this application is the standard deviation of the differences between the core densities and the corrected average gauge values. In practical application, the operator will not be taking an adequate number of readings that would result in an accurate average. Typically, only a few readings would be taken, therefore it is desirable for those readings to be as close to the actual core values as possible. Therefore, a smaller standard deviation would be beneficial. Both of the nuclear gauges had much smaller standard deviations (Troxler 3450, 1.12 pcf and CPN MC3, 0.78 pcf) than the two PQI gauges (PQI 100, 2.67 pcf and PQI 200, 2.98 pcf).

In terms of air voids, both of the nuclear gauges had much smaller standard deviations (Troxler 3450, 0.75 % air voids and CPN MC3, 0.53 % air voids) than the two PQI gauges (PQI 100, 1.80 % air voids and PQI 200, 2.00 % air voids).

<u>t-test</u>

A paired difference analysis was performed on the differences between the core densities and the corrected average gauge densities for each gauge type. This analysis is used to compare the mean values for the cores and each gauge type. A confidence level of $\alpha = 0.05$ was used with $n = 30 - 1 = 29$ degrees of freedom. The critical t-value is 2.045. Examination of the results shows that only the Troxler 3450 model had a calculated t-value exceeding the critical t-value (3.387 vs. 2.045). In can be inferred that the Troxler gauge was not reading on the same mean level as the core densities for this confidence level. The calculated t-values for the CPN MC3, PQI 100 and PQI 200 were -0.333, 0.409 and -0.537 respectively.

<u>Correlation Coefficient</u>

The correlation coefficient, r, is used to determine the goodness of fit of a linear regression line to the data. The more familiar term, R^2, is the square of the r value. R^2

values closer to 1.0 indicate a better relationship between the dependent and independent variables (gauge density and core density). In this study, the relationship between the core densities and the average gauge densities should be linear regardless of whether a correction factor was applied to the gauge values or not. Therefore, the R^2 value should be a useful statistic in seeing how well the average gauge density values correlate to the core densities. The R^2 values for the gauges are as follows: Troxler 3450 (0.61), CPN MC3 (0.68), PQI 100 (0.003) and PQI 200 (0.03). This indicates that the CPN MC3 gauge had moderate correlation to the cores, the Troxler 3450 was slightly worse than the CPN MC3 and the two PQI gauges did not correlate at all with the core densities.

The data in **Table 2** indicate that density values measured by both PQI gauges tended to slightly increase as testing progressed along the test section. This was not observed with the core densities or either of the nuclear gauges. This effect can better be seen in **Figure 5**, which is a plot of the core density values and uncorrected gauge values. Trendlines have been added to each data series in the plot. The slopes of the trendlines for both of the PQI gauges indicate the density values were increasing while the slopes of the trendlines for the core densities and both nuclear gauges are nearly horizontal. The cause of this effect for the PQI gauges is not known but may account for some of the high variability.

<u>Test Section #2</u>

As described in **Table 1**, multiple readings were taken with each gauge at each core location (either four or five readings depending on the gauge type). The multiple readings for each gauge were averaged to determine one density value per gauge per core location (see **Table 8** for the average gauge readings and the core density readings). The core density readings and the uncorrected average gauge readings are plotted in **Figure 6**. A correction value was then calculated for each gauge and applied to each average gauge density reading. To calculate the correction factor, five cores were randomly picked in a stratified manner, where one core was randomly picked from each consecutive subset of six cores, see **Table 9**. The corresponding average gauge density reading for each of the six cores was subtracted from each core density reading and the differences averaged to determine a correction factor for each gauge, see **Table 10**. The respective correction factors were then added to each average gauge density reading to arrive at corrected gauge density values. The core and corrected average gauge density values were then plotted in **Figure 7**. The corrected average gauge density values were then subtracted from the core density values. The core and corrected average gauge density values as well as the differences between the two are shown in **Table 11**. The core and corrected average gauge density values expressed in terms of air voids is shown in **Table 12**.

Several statistics (average difference, standard deviation, t-test and correlation coefficient) were calculated based on the differences between the core density values and the corrected gauge density values. The values are summarized in **Table 13**.

<u>Average Difference</u>

All of the gauges had an average difference of less than one pcf. The highest average difference was with the Toxler 3440 gauge (0.92 pcf). This is equal to 0.69 % when expressed as a percentage of the average core density (134.3 pcf). The average difference for the remaining gauges was: Troxler 4640B, 0.14 pcf (0.10%), PQI 200, 0.12 pcf (0.09%) and the CPN MC3, 0.55 pcf (0.41%).

In terms of air voids, the highest average difference was with the Toxler 3440 gauge (-0.65 % air voids). The average air void difference for the other three gauges are: Troxler 4640B (-0.10 %), PQI 200 (-0.08 %) and CPN MC3 (-0.39 %).

Standard Deviation

As mentioned previously, a more meaningful statistic for this application is the standard deviation of the differences between the core densities and the corrected average gauge values. The standard deviations are as follows: Troxler 3440 (1.43 pcf), Troxler 4640B (1.88 pcf), PQI 200 (1.88 pcf) and CPN MC3 (1.17 pcf).

In terms of air voids, the standard deviations are as follows: Troxler 3440 (1.02 %), Troxler 4640B (1.34 %), PQI 200 (1.34 %) and CPN MC3 (0.83 %).

t-test

A paired difference analysis was performed on the differences between the core densities and the corrected average gauge densities for each gauge type. This analysis is used to compare the mean values for the cores and each gauge type. A confidence level of $\alpha = 0.05$ was used with $n = 30 - 1 = 29$ degrees of freedom. The critical t-value is 2.045.

There were only 27 data points for the Troxler 4640B due to operator error therefore, n = 27 - 1 = 26 degrees of freedom. The critical t-value is 2.056. Examination of the results show that only the Troxler 4640B and the PQI 200 models have calculated t-values less than the critical t-value (0.382 vs. 2.056 and 0.343 vs. 2.045 respectively). The Troxler 3440 and CPN MC3 gauges have calculated t-values that exceed the critical t-value (3.504 vs. 2.045 and 2.566 vs. 2.045 respectively). In can be inferred that the Troxler 3440 and CPN MC3 gauges were not reading on the same mean level as the core densities for this confidence level.

Since the CPN MC3 gauge passed the t-test for Test Section #1 but did not pass it for Test Section #2, another stratified set of five random cores were selected for the calculation of the correction factor to see how this would affect the outcome of the t-test. The random cores used for correction factor were A1, C2, E3, E5 and H3. The results of the subsequent t-test show that the CPN MC3, Troxler 4640B and PQI 200 pass the t-test, but the Troxler 3440 still does not pass (**Table 14**). It should be noted that the correction factor applied to the average gauge values does not affect the variability of the results. It only affects the mean value for the difference between the core and average gauge values. The mean value is used in the numerator of the t-test calculation and therefore can significantly affect the outcome of the t-test. Therefore, it can be concluded that the selection of the cores used for the correction factor (even though randomly selected) can have significant effects on the outcome of the t-test.

Correlation Coefficient

As mentioned previously, the correlation coefficient, r, is used to determine the goodness of fit of a linear regression line to the data. The more familiar term, R^2, is the square of the r value. The R^2 values for the gauges are as follows: Troxler 3440 (0.46), Troxler 4640B (0.27), PQI 200 (0.26) and CPN MC3 (0.59). This indicates that the CPN MC3 gauge had moderate correlation to the core densities, the Troxler 3440 had poor correlation to the core densities and the Troxler 4640B and PQI 200 gauges had very little correlation with the core densities.

CONCLUSIONS

1. With respect to variability as measured by standard deviation and R^2 values, the CPN MC3 nuclear gauge outperformed the other gauges analyzed in this study. Troxler 3440 and 3450 gauges were the next best performers. The Troxler 4640B and PQI 100 and 200 gauges performed the worst with respect to standard deviation and R^2 values.

2. When comparing the mean density value for the 30 cores to the mean density value for the 30 gauge readings for each gauge type, both PQI gauges and the Troxler 4640B gauge performed very well. The CPN MC3 gauge performed very well for test section #1 but slightly worse for test section #2. The Troxler 3440 and 3450 models performed worse than the other gauges. As mentioned previously, the five random cores selected for determination of the correction factor can have a significant effect when comparing mean densities.

3. The use of gauges to measure field density did not appear to be more accurate or less variable for the fine graded Superpave mix (Test Section #2) compared to the coarse graded Superpave mix (Test Section #1) examined in this study.

RECOMMENDATIONS

1. Although the CPN MC3 gauge outperformed the other gauges with respect to variability and performed nearly as well with respect to the mean density difference, one recommendation could be to use the CPN MC3 gauge as an Acceptance tool on a trial basis. However, it would be difficult for an agency to require a specific manufacturer (and model) of a test device to be used. It is also unknown if all gauges of this manufacturer and model will perform equally. Therefore, it is recommended not to pursue the use of this device for Acceptance at this time

2. Although the variability of the PQI gauges is high compared to the CPN MC3, it is recommended that the PQI gauges be allowed by the FDOT for use as a Quality Control tool. Currently, the FDOT requires nuclear gauges to be used by Contractors for quality control of the in-place density of the compacted asphalt mat. The results from Test Section #2 in this study show that the variability of some nuclear gauges can be as high as the PQI gauges. The Troxler 4640B gauge had a standard deviation of 1.88 pcf, which was the same as the PQI 200 gauge.

3. Until nuclear and non-nuclear gauge technology have been shown to improve, additional test section evaluations comparing these non-destructive devices to cores should be put on hold.

REFERENCES

1. Choubane, B., P. B. Upshaw, G. A. Sholar, G. C. Page, J. A. Musselman. *Nuclear Density Readings and Core Densities: A Comparative Study*. Research report FL/DOT/SMO/98-418, Florida Department of Transportation, Gainesville, Fl., July, 1998.

2. Upshaw. P. B., B. Choubane, G. A. Sholar. Non-published report comparing cores to PQI 100 and Troxler 3430 gauges. Florida Department of Transportation, Gainesville, Fl., September, 1998.

Table 1 - Testing Methods for Each Gauge Type

Gauge Type	# Readings Taken at Each Core Location	Orientation of Gauge
Troxler 3450 (nuclear thin-lift)	4	All readings in the longitudinal direction of the roadway. Two readings at 0°. Two at 180°.
CPN MC3 (nuclear)	4	Four readings at 90° apart.
PQI 100 (electrical impedance)	5	All readings with gauge in longitudinal direction. One reading at center of core. The other four readings approximately 2" from the center at 45°, 135°, 225°, and 315°.
PQI 200 (electrical impedance)	5	Same as PQI 100.

Table 2 - Core Densities and Uncorrected Average Gauge Densities (Test Section #1)

Core #	Core Gmb	Core Density (pcf)	Troxler 3450 Avg.	CPN MC3 Avg.	PQI 100 Avg.	PQI 200 Avg.
A1	2.317	144.6	140.4	142.7	144.0	147.8
A2	2.294	143.1	138.8	142.2	145.2	148.2
A3	2.302	143.6	138.5	141.8	144.0	147.5
B1	2.327	145.2	140.9	143.1	145.1	148.4
B2	2.313	144.3	140.3	143.0	145.0	145.8
B3	2.336	145.8	143.5	145.2	142.3	143.4
B4	2.340	146.0	141.1	144.0	142.6	145.7
B5	2.310	144.2	142.2	144.2	143.6	145.1
C1	2.345	146.3	143.0	144.4	142.2	143.7
C2	2.357	147.1	143.9	145.2	142.2	143.9
C3	2.327	145.2	143.0	145.3	144.1	145.4
D1	2.272	141.8	139.8	141.1	142.1	145.3
D2	2.293	143.1	138.6	142.2	141.5	143.4
D3	2.280	142.3	138.9	141.1	145.8	148.5
E1	2.315	144.5	140.0	142.8	147.2	150.7
E2	2.299	143.5	138.7	142.6	144.7	147.4
E3	2.307	144.0	136.7	142.2	140.7	143.5
E4	2.325	145.1	141.2	144.0	146.1	148.1
E5	2.312	144.3	141.0	142.6	146.6	148.5
F1	2.291	142.9	137.8	141.2	147.5	150.2
F2	2.294	143.2	138.5	141.8	145.4	148.5
F3	2.294	143.1	140.6	141.9	147.7	150.9
G1	2.323	145.0	140.3	142.9	146.7	148.6
G2	2.323	145.0	141.3	144.0	146.6	148.9
G3	2.335	145.7	141.1	142.5	147.0	149.3
H1	2.318	144.6	140.8	142.6	150.1	152.2
H2	2.316	144.5	141.3	143.1	146.6	149.9
H3	2.330	145.4	141.8	146.3	142.7	145.6
H4	2.342	146.2	143.5	144.9	147.6	149.9
H5	2.330	145.4	141.6	143.8	147.1	149.5

Table 3 - Cores Used for Calculation of Correction Factors (Test Section #1)

Stratified Random Numbers for Correction Factor		
Range	Random #	Core ID
1 - 6	6	B3
7 - 12	9	C1
13 - 18	18	E4
19 - 24	22	F3
25 - 30	26	H1

Table 4 - Calculation of Correction Factor for Each Gauge (Test Section #1)

	Core	Troxler 3450		CPN MC3		PQI 100		PQI 200	
Core ID	Density (pcf)	Density	Difference	Density	Difference	Density	Difference	Density	Difference
B3	145.8	143.5	2.2	145.2	0.6	142.3	3.4	143.4	2.3
C1	146.3	143.0	3.4	144.4	1.9	142.2	4.1	143.7	2.7
E4	145.1	141.2	3.9	144.0	1.2	146.1	-1.0	148.1	-3.0
F3	143.1	140.6	2.6	141.9	1.3	147.7	-4.6	150.9	-7.8
H1	144.6	140.8	3.8	142.6	2.0	150.1	-5.5	152.2	-7.6
		Avg. Diff.	3.2	Avg. Diff.	1.4	Avg. Diff.	-0.7	Avg. Diff.	-2.7

Table 5 - Differences Between Core Densities and Corrected Average Gauge Densities (Test Section #1)

			Including Correction Factor							
Core #	Core Gmb	Core Density (pcf)	Troxler 3450	Difference Core-Gauge	CPN MC3	Difference Core-Gauge	PQI 100	Difference Core-Gauge	PQI 200	Difference Core-Gauge
A1	2.317	144.6	143.5	1.0	144.0	0.5	143.3	1.3	145.1	-0.5
A2	2.294	143.1	142.0	1.1	143.6	-0.5	144.5	-1.3	145.5	-2.4
A3	2.302	143.6	141.7	1.9	143.2	0.4	143.3	0.3	144.8	-1.2
B1	2.327	145.2	144.0	1.2	144.5	0.7	144.4	0.8	145.8	-0.6
B2	2.313	144.3	143.4	0.9	144.3	0.0	144.3	0.0	143.1	1.3
B3	2.336	145.8	146.7	-0.9	146.5	-0.8	141.6	4.1	140.8	5.0
B4	2.340	146.0	144.3	1.7	145.4	0.7	141.9	4.2	143.1	3.0
B5	2.310	144.2	145.4	-1.2	145.6	-1.5	142.9	1.3	142.4	1.7
C1	2.345	146.3	146.1	0.2	145.8	0.5	141.5	4.8	141.0	5.3
C2	2.357	147.1	147.1	0.0	146.6	0.5	141.5	5.6	141.2	5.9
C3	2.327	145.2	146.1	-0.9	146.7	-1.4	143.4	1.8	142.7	2.5
D1	2.272	141.8	142.9	-1.1	142.5	-0.7	141.4	0.4	142.6	-0.8
D2	2.293	143.1	141.7	1.3	143.6	-0.5	140.8	2.3	140.7	2.3
D3	2.280	142.3	142.0	0.2	142.5	-0.2	145.1	-2.8	145.8	-3.5
E1	2.315	144.5	143.2	1.3	144.2	0.3	146.5	-2.0	148.1	-3.6
E2	2.299	143.5	141.9	1.6	143.9	-0.5	144.0	-0.6	144.7	-1.3
E3	2.307	144.0	139.9	4.1	143.6	0.4	140.0	4.0	140.9	3.1
E4	2.325	145.1	144.4	0.7	145.3	-0.2	145.4	-0.3	145.4	-0.3
E5	2.312	144.3	144.2	0.1	143.9	0.3	145.9	-1.6	145.8	-1.5
F1	2.291	142.9	141.0	2.0	142.6	0.3	146.8	-3.9	147.5	-4.6
F2	2.294	143.2	141.6	1.5	143.2	-0.1	144.7	-1.5	145.8	-2.7
F3	2.294	143.1	143.8	-0.6	143.3	-0.1	147.0	-3.9	148.2	-5.1
G1	2.323	145.0	143.5	1.5	144.3	0.7	146.0	-1.1	145.9	-1.0
G2	2.323	145.0	144.5	0.5	145.3	-0.4	145.9	-0.9	146.2	-1.3
G3	2.335	145.7	144.3	1.4	143.9	1.8	146.3	-0.6	146.6	-0.9
H1	2.318	144.6	144.0	0.7	144.0	0.6	149.4	-4.8	149.6	-4.9
H2	2.316	144.5	144.4	0.1	144.5	0.0	145.9	-1.4	147.2	-2.7
H3	2.330	145.4	145.0	0.4	147.7	-2.3	142.0	3.4	142.9	2.5
H4	2.342	146.2	146.7	-0.5	146.3	-0.1	146.9	-0.8	147.2	-1.0
H5	2.330	145.4	144.7	0.6	145.2	0.2	146.4	-1.0	146.8	-1.5
	Avg.	144.5	Avg.	0.693	Avg.	-0.048	Avg.	0.199	Avg.	-0.292
	Stdev	1.261	Stdev	1.121	Stdev	0.784	Stdev	2.667	Stdev	2.976

Table 6 - Differences Between Core Air Voids and Corrected Average Gauge Air Voids (Test Section #1)

Core #	Corrected Air Voids (Gmm = 2.380 from QC data)								
	Core	Troxler 3450	Difference	CPN MC-3	Difference	PQI 100	Difference	PQI 200	Difference
A1	2.66	3.36	-0.69	3.01	-0.35	3.54	-0.88	2.31	0.36
A2	3.62	4.38	-0.76	3.31	0.31	2.72	0.90	2.00	1.62
A3	3.29	4.59	-1.30	3.58	-0.29	3.50	-0.21	2.47	0.82
B1	2.24	3.02	-0.78	2.71	-0.46	2.77	-0.53	1.85	0.39
B2	2.80	3.42	-0.62	2.81	0.00	2.83	-0.02	3.65	-0.85
B3	1.86	1.22	0.64	1.33	0.53	4.65	-2.79	5.21	-3.36
B4	1.67	2.84	-1.16	2.12	-0.44	4.48	-2.81	3.67	-1.99
B5	2.93	2.13	0.80	1.95	0.98	3.80	-0.87	4.10	-1.17
C1	1.48	1.61	-0.13	1.83	-0.35	4.70	-3.22	5.07	-3.59
C2	0.95	0.97	-0.02	1.29	-0.34	4.73	-3.78	4.93	-3.98
C3	2.21	1.61	0.60	1.24	0.97	3.45	-1.24	3.91	-1.70
D1	4.52	3.76	0.76	4.07	0.45	4.82	-0.30	3.96	0.56
D2	3.67	4.57	-0.90	3.30	0.37	5.21	-1.55	5.23	-1.56
D3	4.21	4.37	-0.16	4.05	0.15	2.32	1.89	1.82	2.39
E1	2.72	3.59	-0.87	2.91	-0.19	1.36	1.36	0.30	2.42
E2	3.41	4.45	-1.04	3.08	0.33	3.03	0.38	2.55	0.86
E3	3.06	5.80	-2.74	3.33	-0.27	5.76	-2.71	5.15	-2.09
E4	2.29	2.77	-0.48	2.13	0.16	2.09	0.20	2.09	0.20
E5	2.85	2.94	-0.08	3.08	-0.22	1.76	1.09	1.83	1.02
F1	3.75	5.07	-1.32	3.97	-0.22	1.15	2.61	0.68	3.08
F2	3.60	4.64	-1.03	3.57	0.04	2.57	1.03	1.79	1.81
F3	3.61	3.21	0.41	3.53	0.08	1.01	2.60	0.19	3.42
G1	2.40	3.39	-1.00	2.84	-0.45	1.68	0.71	1.75	0.64
G2	2.39	2.72	-0.33	2.13	0.25	1.78	0.61	1.54	0.85
G3	1.91	2.84	-0.93	3.09	-1.19	1.51	0.40	1.30	0.61
H1	2.61	3.05	-0.44	3.03	-0.41	-0.59	3.21	-0.71	3.32
H2	2.70	2.75	-0.05	2.69	0.01	1.74	0.96	0.89	1.81
H3	2.09	2.38	-0.29	0.54	1.55	4.38	-2.29	3.76	-1.67
H4	1.59	1.24	0.35	1.50	0.09	1.06	0.53	0.89	0.70
H5	2.11	2.55	-0.44	2.22	-0.11	1.41	0.70	1.13	0.98
Avg.	2.71	Avg.	-0.47	Avg.	0.03	Avg.	-0.13	Avg.	0.20
Stdev	0.85	Stdev	0.75	Stdev	0.53	Stdev	1.80	Stdev	2.00

Table 7 - Summary of Statistical Values (Test Section #1)

Statistic	Gauge Type			
	Troxler 3450	CPN MC3	PQI 100	PQI 200
Average Difference (pcf)	0.69	-0.05	0.20	-0.29
Average Difference (% air voids)	-0.47	0.03	-0.13	0.20
Standard Deviation (pcf)	1.12	0.78	2.67	2.98
Standard Deviation (% air voids)	0.75	0.53	1.80	2.00
Calculated t-value	3.387	-0.333	0.409	-0.537
Critical t-value (α = 0.05) 2-sided	2.045	2.045	2.045	2.045
R^2	0.61	0.68	0.003	0.03

Table 8 - Core Densities and Uncorrected Average Gauge Densities (Test Section #2)

Core #	Core Gmb	Core Density (pcf)	Troxler 3440 Avg.	Troxler 4640B Avg.	PQI 200 Avg.	CPN MC3 Avg.
A1	2.154	134.4	133.0	129.4	135.5	136.8
A2	2.110	131.7	134.0	131.5	133.1	137.4
A3	2.130	132.9	134.0	132.3	133.1	136.3
B1	2.162	134.9	134.4	133.3	134.8	139.3
B2	2.200	137.3	135.8		138.0	139.3
B3	2.204	137.5	135.2		135.6	137.3
B4	2.079	129.7	131.2		131.8	132.5
B5	2.097	130.8	132.8	128.0	131.2	134.0
C1	2.129	132.8	133.0	123.8	135.3	136.4
C2	2.108	131.5	132.5	128.4	135.9	136.3
C3	2.148	134.1	134.4	130.3	135.0	137.2
D1	2.169	135.3	137.0	130.2	136.2	138.6
D2	2.170	135.4	136.8	132.7	135.8	139.0
D3	2.155	134.5	137.1	132.8	135.8	138.4
E1	2.169	135.4	137.3	133.8	137.5	140.3
E2	2.182	136.1	136.3	132.1	137.4	140.1
E3	2.175	135.7	134.1	129.3	136.6	139.3
E4	2.159	134.7	136.2	132.8	136.5	139.0
E5	2.166	135.2	135.8	131.9	136.9	137.8
F1	2.156	134.5	137.5	131.0	137.7	137.3
F2	2.161	134.8	136.0	131.1	137.9	137.8
F3	2.152	134.3	137.1	131.0	137.8	137.2
G1	2.144	133.8	136.7	132.1	138.9	137.2
G2	2.129	132.8	135.2	127.5	139.3	136.2
G3	2.154	134.4	136.5	131.3	139.9	138.8
H1	2.178	135.9	138.1	131.6	134.4	136.6
H2	2.179	136.0	137.5	131.4	137.0	138.4
H3	2.141	133.6	134.5	130.6	136.0	137.7
H4	2.151	134.2	136.5	128.9	136.5	138.3
H5	2.170	135.4	137.9	133.1	136.3	138.7

Table 9 - Cores Used for Calculation of Correction Factors (Test Section #2)

Stratified Random Numbers for Correction Factor		
Range	Random #	Core ID
1 - 4	2	A2
8 - 12	9	C1
13 - 18	14	D3
19 - 24	22	F3
25 - 30	30	H5

Table 10 - Calculation of Correction Factor for Each Gauge (Test Section #2)

	Core	Troxler 3440		Troxler 4640B		PQI 200		CPN MC-3	
Core ID	Density (pcf)	Density	Difference	Density	Difference	Density	Difference	Density	Difference
A2	131.7	134.0	-2.3	131.5	0.2	133.1	-1.4	137.4	-5.7
C1	132.8	133.0	-0.1	123.8	9.1	135.3	-2.5	136.4	-3.6
D3	134.5	137.1	-2.6	132.8	1.7	135.8	-1.3	138.4	-3.9
F3	134.3	137.1	-2.8	131.0	3.3	137.8	-3.5	137.2	-2.9
H5	135.4	137.9	-2.5	133.1	2.3	136.3	-0.9	138.7	-3.3
		Avg. Diff.	-2.0	Avg. Diff.	3.3	Avg. Diff.	-1.9	Avg. Diff.	-3.9

Table 11 - Differences Between Core Densities and Corrected Average Gauge Densities (Test Section #2)

			Including Correction Factor							
Core #	Core Gmb	Core Density (pcf)	Troxler 3440	Difference Core-Gauge	Troxler 4640B	Difference Core-Gauge	PQI 200	Difference Core-Gauge	CPN MC-3	Difference Core-Gauge
A1	2.154	134.4	131.0	3.4	132.7	1.7	133.6	0.9	133.0	1.5
A2	2.110	131.7	131.9	-0.2	134.8	-3.1	131.2	0.5	133.5	-1.8
A3	2.130	132.9	131.9	1.0	135.6	-2.7	131.2	1.7	132.5	0.4
B1	2.162	134.9	132.3	2.6	136.6	-1.6	132.9	2.1	135.4	-0.5
B2	2.200	137.3	133.8	3.5			136.0	1.2	135.5	1.8
B3	2.204	137.5	133.1	4.4			133.7	3.9	133.4	4.1
B4	2.079	129.7	129.2	0.6			129.9	-0.2	128.6	1.2
B5	2.097	130.8	130.7	0.1	131.3	-0.5	129.3	1.6	130.1	0.8
C1	2.129	132.8	130.9	1.9	127.1	5.7	133.4	-0.5	132.5	0.3
C2	2.108	131.5	130.4	1.1	131.7	-0.2	134.0	-2.5	132.4	-0.9
C3	2.148	134.1	132.3	1.7	133.6	0.4	133.1	1.0	133.4	0.7
D1	2.169	135.3	135.0	0.4	133.5	1.9	134.3	1.1	134.8	0.6
D2	2.170	135.4	134.7	0.7	136.0	-0.6	133.9	1.5	135.2	0.2
D3	2.155	134.5	135.0	-0.5	136.1	-1.7	133.9	0.6	134.5	0.0
E1	2.169	135.4	135.2	0.2	137.1	-1.7	135.5	-0.2	136.4	-1.0
E2	2.182	136.1	134.2	1.9	135.4	0.7	135.5	0.7	136.3	-0.1
E3	2.175	135.7	132.0	3.7	132.6	3.1	134.6	1.0	135.5	0.2
E4	2.159	134.7	134.1	0.6	136.1	-1.4	134.6	0.1	135.1	-0.4
E5	2.166	135.2	133.8	1.4	135.2	0.0	135.0	0.2	133.9	1.3
F1	2.156	134.5	135.4	-0.9	134.3	0.3	135.8	-1.3	133.5	1.1
F2	2.161	134.8	134.0	0.9	134.4	0.4	136.0	-1.2	133.9	0.9
F3	2.152	134.3	135.0	-0.7	134.3	0.0	135.9	-1.6	133.4	0.9
G1	2.144	133.8	134.6	-0.8	135.4	-1.7	137.0	-3.2	133.3	0.5
G2	2.129	132.8	133.1	-0.3	130.8	2.0	137.4	-4.6	132.4	0.5
G3	2.154	134.4	134.5	-0.1	134.6	-0.2	138.0	-3.6	134.9	-0.5
H1	2.178	135.9	136.1	-0.2	134.9	1.0	132.5	3.4	132.8	3.1
H2	2.179	136.0	135.4	0.6	134.7	1.3	135.1	0.9	134.5	1.5
H3	2.141	133.6	132.4	1.1	133.9	-0.4	134.1	-0.5	133.8	-0.2
H4	2.151	134.2	134.4	-0.2	132.2	2.0	134.6	-0.4	134.4	-0.2
H5	2.170	135.4	135.8	-0.4	136.4	-1.0	134.4	1.0	134.8	0.6
	Avg.	134.3	Avg.	0.917	Avg.	0.138	Avg.	0.118	Avg.	0.549
	Stdev	1.769	Stdev	1.433	Stdev	1.879	Stdev	1.879	Stdev	1.171

Table 12 - Differences Between Core Air Voids and Corrected Average Gauge Air Voids (Test Section #2)

Core #	Corrected Air Voids (Gmm = 2.252 from QC data)								
	Core	Troxler 3440	Difference	Troxler 4640B	Difference	PQI 200	Difference	CPN MC-3	Difference
A1	4.34	6.79	-2.45	5.54	-1.19	4.95	-0.61	5.38	-1.04
A2	6.29	6.12	0.17	4.08	2.21	6.66	-0.37	4.99	1.30
A3	5.44	6.14	-0.70	3.49	1.95	6.62	-1.18	5.73	-0.30
B1	3.99	5.85	-1.86	2.82	1.17	5.45	-1.46	3.66	0.33
B2	2.32	4.82	-2.49			3.19	-0.86	3.61	-1.28
B3	2.12	5.26	-3.14			4.87	-2.74	5.06	-2.94
B4	7.67	8.07	-0.40			7.54	0.13	8.50	-0.83
B5	6.89	6.97	-0.08	6.53	0.36	8.01	-1.12	7.43	-0.54
C1	5.48	6.83	-1.35	9.56	-4.08	5.09	0.38	5.69	-0.21
C2	6.41	7.20	-0.79	6.28	0.13	4.65	1.76	5.76	0.65
C3	4.61	5.85	-1.24	4.91	-0.31	5.31	-0.70	5.10	-0.49
D1	3.69	3.96	-0.27	5.02	-1.33	4.44	-0.75	4.10	-0.41
D2	3.65	4.13	-0.47	3.24	0.41	4.74	-1.09	3.82	-0.17
D3	4.30	3.93	0.37	3.12	1.18	4.72	-0.42	4.30	0.00
E1	3.68	3.79	-0.11	2.44	1.23	3.54	0.13	2.95	0.73
E2	3.13	4.50	-1.37	3.62	-0.49	3.60	-0.47	3.04	0.09
E3	3.44	6.05	-2.61	5.64	-2.20	4.18	-0.74	3.61	-0.17
E4	4.12	4.57	-0.44	3.15	0.97	4.23	-0.10	3.84	0.29
E5	3.80	4.80	-1.00	3.81	-0.01	3.96	-0.16	4.71	-0.91
F1	4.26	3.63	0.64	4.45	-0.19	3.36	0.91	5.03	-0.77
F2	4.06	4.68	-0.62	4.35	-0.29	3.23	0.83	4.71	-0.65
F3	4.44	3.93	0.51	4.45	-0.01	3.32	1.13	5.10	-0.66
G1	4.79	4.20	0.60	3.62	1.18	2.49	2.30	5.14	-0.34
G2	5.48	5.28	0.20	6.93	-1.45	2.22	3.26	5.81	-0.33
G3	4.34	4.30	0.04	4.19	0.16	1.81	2.53	4.00	0.34
H1	3.30	3.18	0.12	3.99	-0.69	5.69	-2.39	5.53	-2.22
H2	3.22	3.64	-0.42	4.13	-0.91	3.88	-0.66	4.28	-1.06
H3	4.95	5.76	-0.81	4.68	0.27	4.57	0.38	4.78	0.17
H4	4.48	4.36	0.13	5.89	-1.41	4.20	0.28	4.35	0.13
H5	3.64	3.34	0.29	2.94	0.70	4.35	-0.72	4.07	-0.43
Avg.	4.41	Avg.	-0.65	Avg.	-0.10	Avg.	-0.08	Avg.	-0.39
Stdev	1.26	Stdev	1.02	Stdev	1.34	Stdev	1.34	Stdev	0.83

Table 13 - Summary of Statistical Values (Test Section #2)

Statistic	Gauge Type			
	Troxler 3440	Troxler 4640B	PQI 200	CPN MC3
Average Difference (pcf)	0.92	0.14	0.12	0.55
Average Difference (% air voids)	-0.65	-0.10	-0.08	-0.39
Standard Deviation (pcf)	1.43	1.88	1.88	1.17
Standard Deviation (% air voids)	1.02	1.34	1.34	0.83
Calculated t-value	3.504	0.382	0.343	2.566
Critical t-value ($\alpha = 0.05$) 2-sided	2.045	2.056	2.045	2.045
R^2	0.46	0.27	0.26	0.59

Table 14 - t-test Results with Alternate Set of Five Cores Used for Correction Factor (Test Section #2)

Statistic	Gauge Type			
	Troxler 3440	Troxler 4640B	PQI 200	CPN MC3
Calculated t-value	-4.723	-1.964	0.862	0.867
Critical t-value ($\alpha = 0.05$) 2-sided	2.045	2.056	2.045	2.045

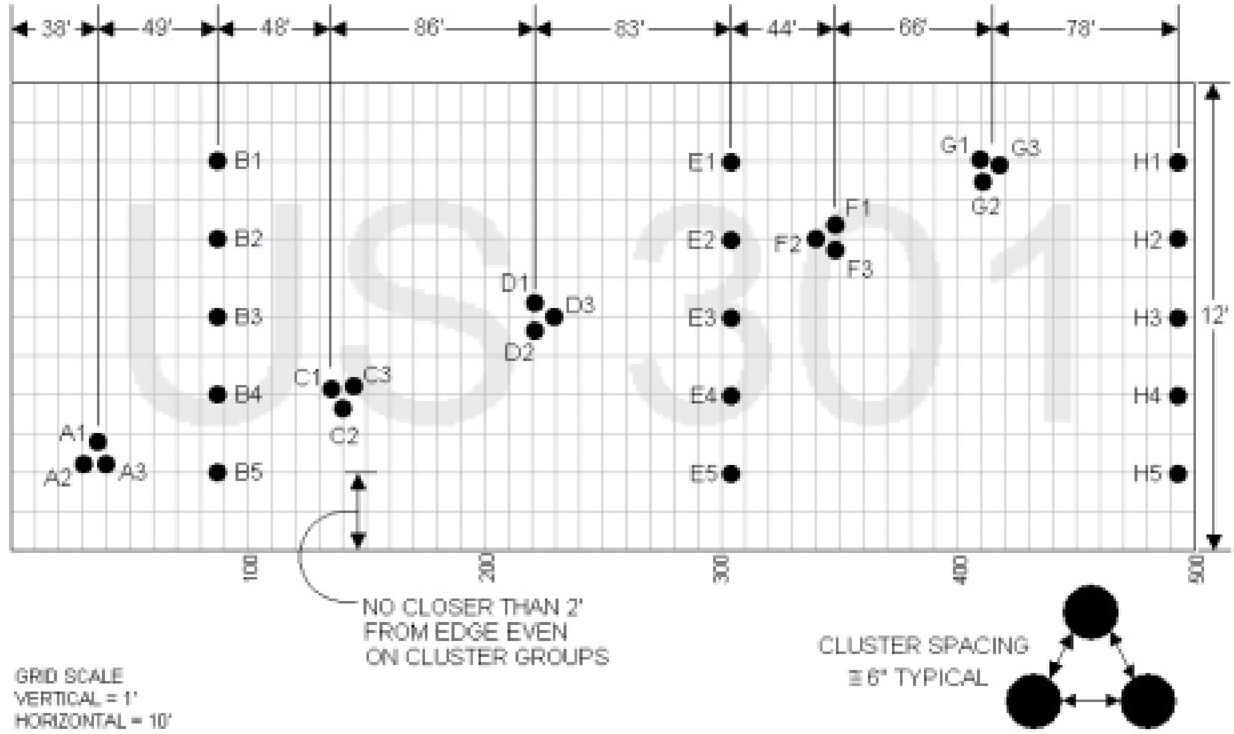

Figure 1 - Coring Pattern for Test Section #1

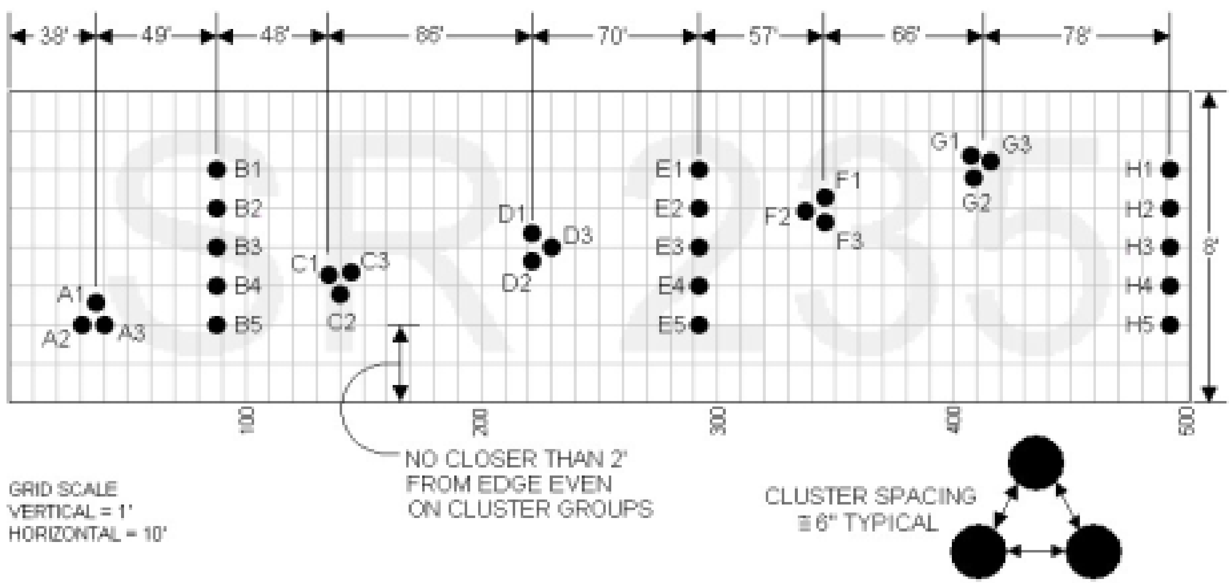

Figure 2 - Coring Pattern for Test Section #2

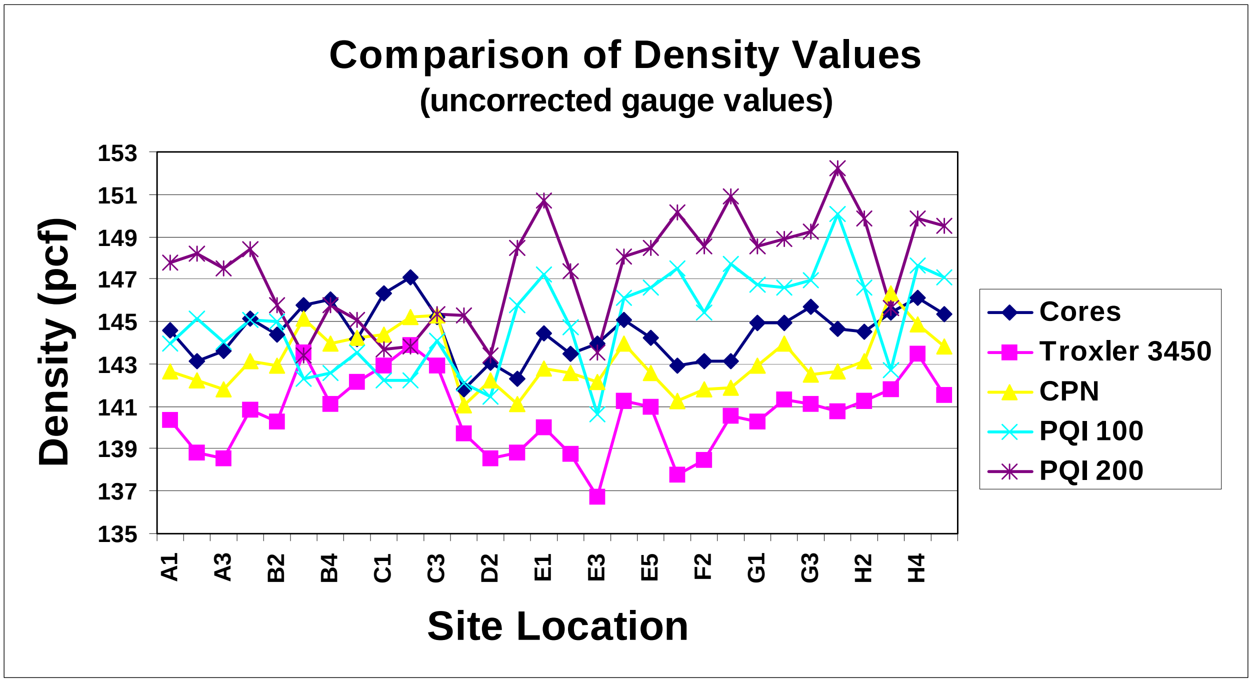

Figure 3 - Plot of Core and Uncorrected Average Gauge Density Values for Test Section #1

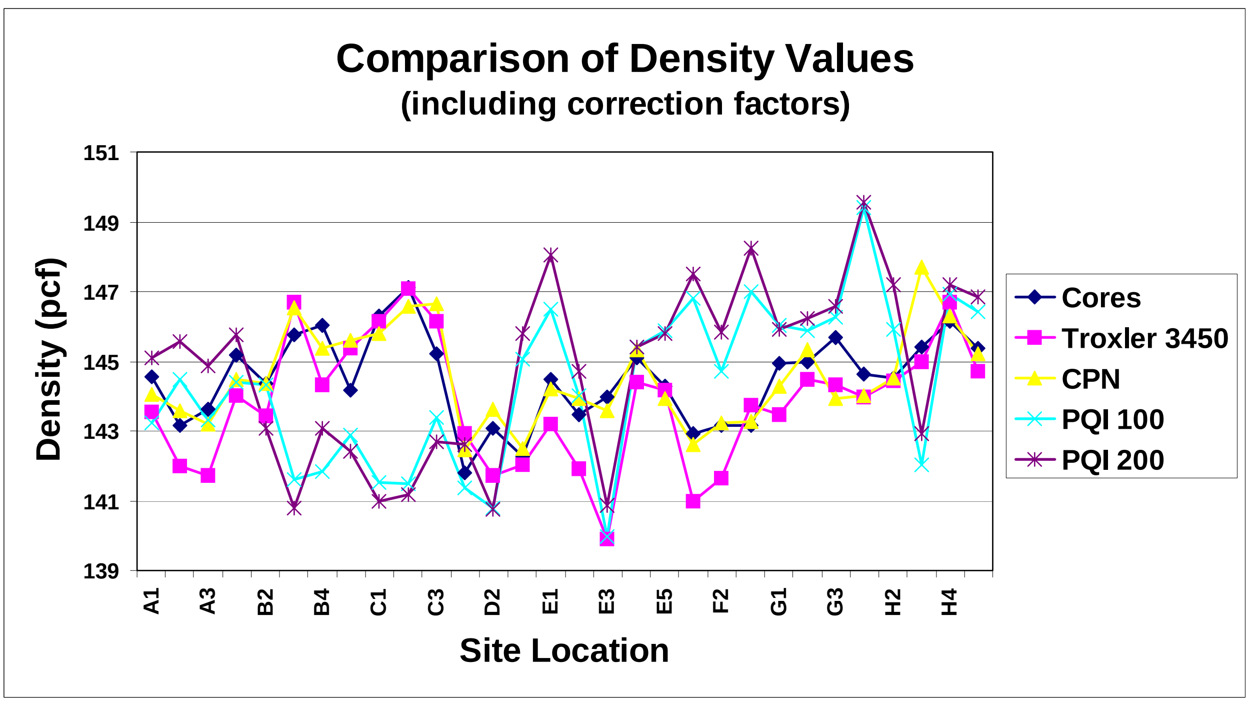

Figure 4 - Plot of Core and Corrected Average Gauge Density Values for Test Section #1

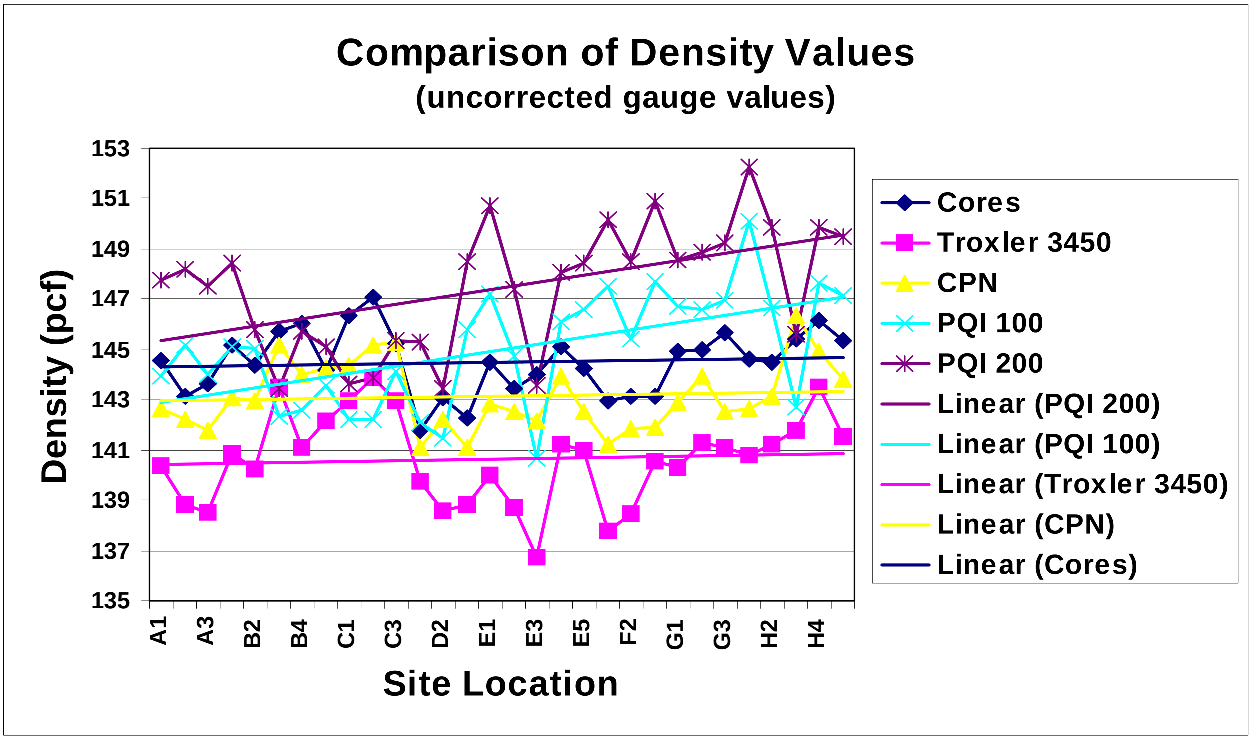

Figure 5 - Plot of Core and Uncorrected Average Gauge Density Values and Trendlines for Test Section #1

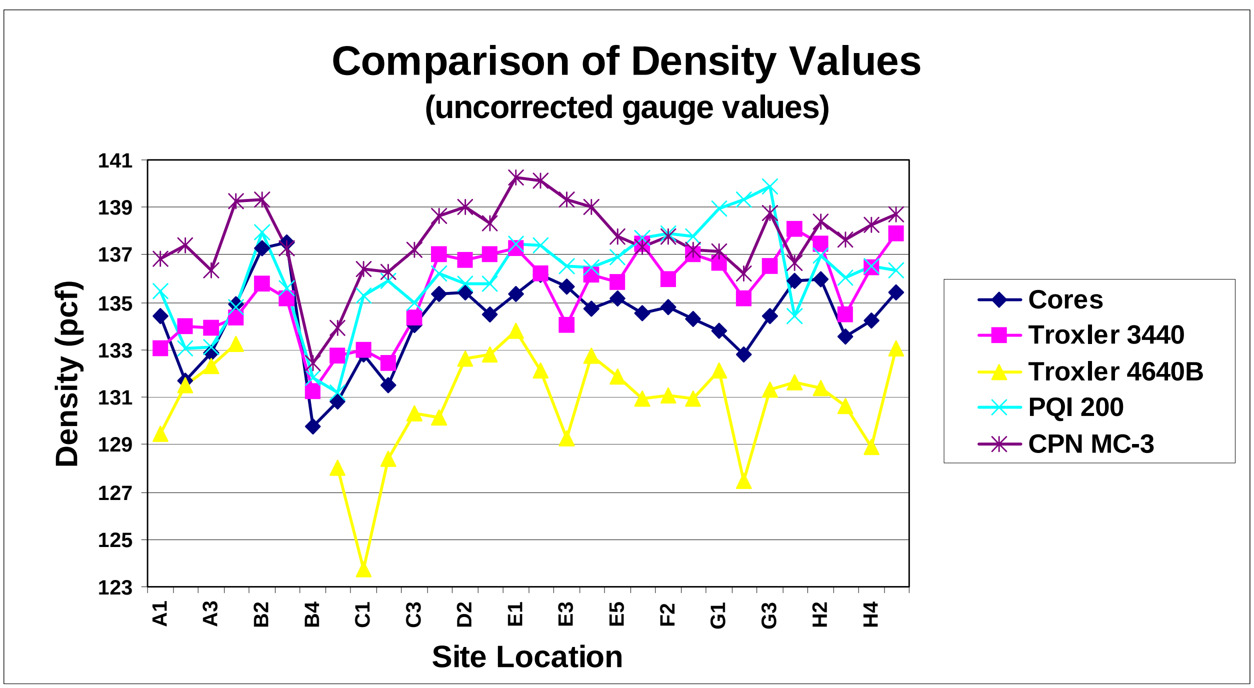

Figure 6 - Plot of Core and Uncorrected Average Gauge Density Values for Test Section #2

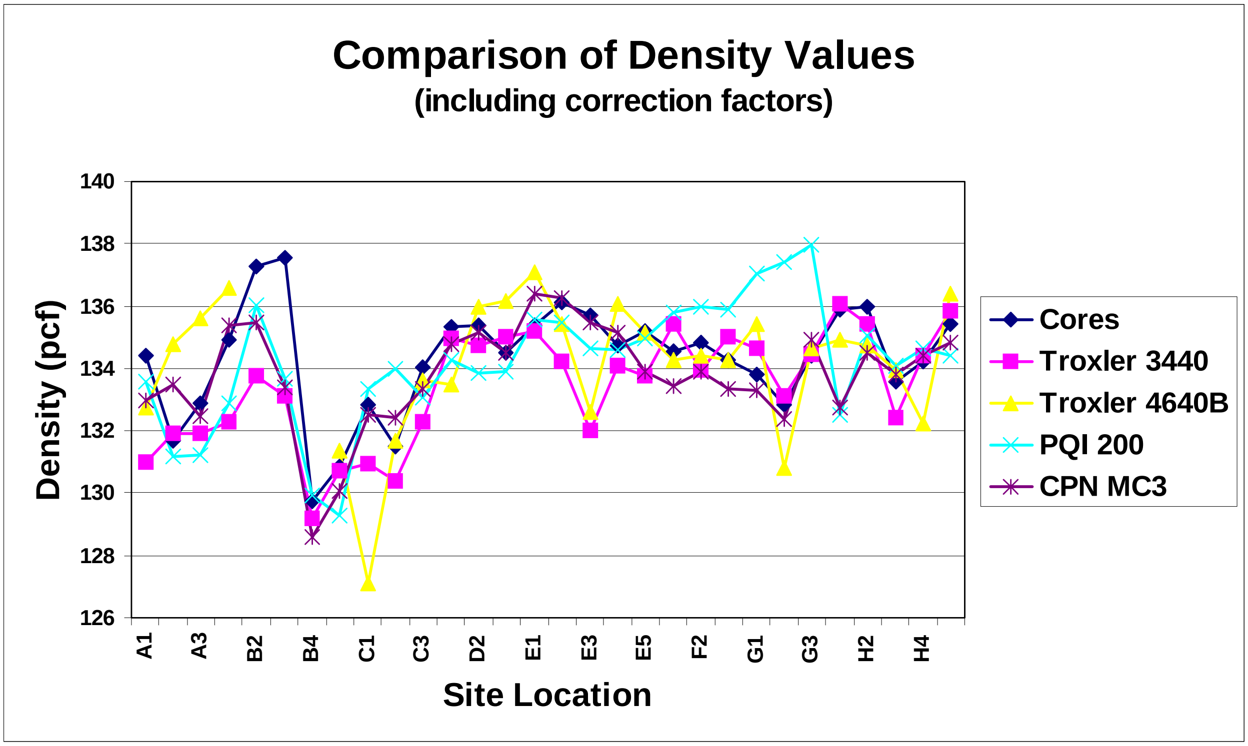

Figure 7 - Plot of Core and Corrected Average Gauge Density Values for Test Section #2