STATE OF FLORIDA

NUCLEAR DENSITY READINGS AND CORE DENSITIES: A COMPARATIVE STUDY

Research Report
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STATE MATERIALS OFFICE

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EXECUTIVE SUMMARY

This report summarizes the findings of an investigation performed to identify possible correlations between nuclear density gauge readings and core density results. The nuclear density data was collected on a Superpave section of Interstate Highway I-95 in Brevard County. Core samples were also obtained from this section for laboratory density determination. Five gauge units and three core density methods were considered. The relationships among the core density results were first analyzed. Then an investigation of the correlation among the different gauges used in this study was evaluated. Finally, the performance of each of the units with respect to the core density results was assessed.

The findings of this investigation indicated that the five nuclear gauge density units did not always produce similar results and did not consistently correlate with the core densities. In addition, the nuclear density testing variability did not only differ from gauge to gauge but also from location to location within each gauge. Therefore, directly substituting, at the present time, the nuclear gauges to core density for acceptance purposes may not be appropriate. However, since these findings apply only to the gauges used in this study, based on the data collected on this particular project, it is suggested that nuclear density testing variability be further assessed.

INTRODUCTION

Air void content of an asphalt mixture is an important factor that affects the performance of the pavement throughout its service life. High air voids in a finished pavement will adversely affect its durability and performance in various ways. Air filtration into a permeable pavement accelerates the aging or hardening process of the asphalt binder through oxidation. The penetration of excessive amounts of water into the pavement structure may induce stripping of the asphalt binder from the aggregate surface. Similarly, low air voids could lead to potential pavement distresses such as rutting and shoving. Therefore, it is of importance to ensure that the in-place air voids of a pavement are within an acceptable range.

The amount of voids in a HMA mixture is directly related to density. Thus, accurate control and measurement of pavement density are fundamental requirements for producing well performing pavements. Traditionally, the in-place pavement density has been determined using the core method. This procedure involves drilling full depth pavement cores at random locations, saw cutting the layer being tested from the underlaying material, and then measuring the bulk density of the core samples in the laboratory. Such a method is destructive and tends to be too time consuming to be used as an effective quality control tool. The need for faster and nondestructive methods of field density determination prompted the development of nuclear density gauges.

Nuclear gauges use the effects of Compton scattering and photoelectric absorption of gamma photons to read the in-place density of an HMA mixture. When the gamma photons from a small radioactive source penetrate a pavement, the energy transfer may not be complete, resulting in a portion of the photons being scattered back to the detectors located within the gauge. This gamma ray absorption and reflection process is known as the Compton effects. The level of absorption and scattering is a function of the number of electrons present in a given material, as is the density of the material. Thus, the number of gamma photons entering the gauge detectors can be related to density. This conversion is experimentally developed, based on a ratio between the number of photons detected in the pavement and the number of photons detected in a standard block of known density.

Nuclear gauges can be operated either in a backscatter or direct transmission mode. In the backscatter mode, both the source and the detectors are placed on the pavement surface. In the direct transmission mode, the source rod is placed at a desired depth in a pre-drilled hole in the pavement structure. When measuring asphalt pavement densities the backscatter mode is generally selected.

The advantages inherent in the determination of pavement density using the nuclear method include simplicity of performance, rapid results, and nondestructiveness. However, there has been a lack of confidence in the consistency and accuracy of nuclear gauges *(1, 2)*.

BACKGROUND

During its field implementation of Superpave, the Florida Department of Transportation (FDOT) initially specified the use of nuclear density gauges in the back-scatter mode for pavement density determination *(3)*. Following the construction of its first major Superpave project, it was noted that the completed pavement was excessively permeable. A subsequent investigation indicated that the actual in-place air void contents (based on roadway cores) were significantly higher than those estimated based on the readings of the nuclear density gauge *(4)*. This difference was attributed to the rough surface texture (macrotexture) of the coarse-graded Superpave pavement. At that point FDOT discontinued the use of nuclear gauges for acceptance on Superpave projects and changed the density specification to a core-based density procedure. This specification required that the pavement be cored at a frequency of one core taken randomly per 300 m. FDOT also believed that a more thorough investigation of nuclear gauge density readings under field conditions was needed to further assess the potential use of the gauge as an alternative to cores for acceptance or quality control purposes. To this end, the present study was initiated and its findings are summarized in this report.

EXPERIMENTAL PROGRAM AND DATA COLLECTION

The present study was initiated with the primary objective of identifying possible correlations between the nuclear density gauge readings and core density results. Density data was gathered on an I-95 Superpave project using five nuclear density gauges. Cores were also obtained from this section. For comparison purposes, core densities were determined in accordance to (1) the Florida test method FM 1-T 166 (Method A) *(5)*, (2) ASTM D 1188 using parafilm *(6)*, and (3) by dimensional analysis (weight and dimensions of each core sample were directly measured), respectively. Florida test method is similar to that of AASHTO T-166 procedure, with the exception of immersing test samples for a shorter time period (2±1 instead of 4±1 minutes).

Testing Locations Layout

FDOT specifications for acceptance and determination of payment with respect to density require that testing locations be randomly selected within each LOT at a specified frequency. For the purpose of this study, it was decided to perform additional density testing at a distance of 30 m from each "acceptance" location. Two LOTS were evaluated corresponding to a total of 10 test locations over a pavement section length of approximately 2800 m. The testing location stations are given in Table 1.

Project Description

The project site was a section of I-95 in Brevard County. This project was 47.831 km long, with a total of two lanes in the northbound roadway. The resurfacing portion of this project consisted of milling an average depth of 83 mm, followed by the placement of 50 mm of 12.5 mm and 40 mm of 9.5 mm coarse-graded Superpave mixes, and 20 mm of an open-graded friction course (FC-5). The Superpave mixes were designed using the standard Superpave mix design methodology, with the exception that the binder used was an AC-30 rather than a Performance Graded binder. The AC-30 would have met the requirements for a PG 67-22. The Contractor, MacAsphalt, Inc., designed the mix using limestone coarse aggregate from South Florida, granite screenings from Nova Scotia, and RAP milled from the project. The project was designed for 10-30 million ESALS (Traffic Level 5), with a pavement temperature of less than 39°C, resulting in an N_{des} of 152.

For the purpose of this investigation, the density testing was performed once the 50 mm layer of 12.5 mm mix was completed. The placement of the mix was accomplished with little difficulty using a rubber tired paver with hydraulic screed extensions, and compacted with two 13-metric ton and one 10-metric ton Caterpillar steel wheel rollers (breakdown and intermediate rollers, respectively), and a 9-metric ton finish roller.

Nuclear Density Measurements

In-situ pavement density measurements were taken using four different density gauge models (3401, 3440, 3450, and 4640 models), all manufactured by the same company. Two units of model 3440 were used. Thus, a total of five nuclear density gauge units were evaluated. Three units (3440, 3450, and 4640 models) were provided and operated by the manufacturer representatives. The contractor and the District supplied and operated models 3401 and 3440 (the second unit of 3440 model), respectively. All the units had Cesium^{137} as the source of radiation and all were operated in the backscatter mode. For this study, a one-minute reading time was adopted. According to the manufacturer, for one-minute readings the accuracy ranges from ±8 to ±16 kg/m^3 (±0.5 to ±1.0 pcf), depending on the thickness of the pavement layer considered. All calculations were performed within the gauge microprocessors.

During testing, care was taken to ensure that the gauges were firmly seated at each location. Readings were then taken in accordance with all manufacturer operating procedures. Readings were obtained with each of the five gauge units at the exact locations where cores were to be obtained. At each location, three readings were taken for each gauge, with the gauge completely lifted off the pavement surface then reseated in the same orientation prior to taking each replicate reading.

Core Density Measurements

Core samples were obtained immediately after the nuclear readings were taken to ensure that no changes in pavement density occurred between the time of the nuclear readings and the coring operation. The core samples were labeled and transferred to the State Materials Office. The cores were then cut to separate the Superpave overlay layer for density determination. The cutting was performed with a water-cooled masonry saw equipped with a diamond-tipped blade. After the wet saw cutting, the samples were thoroughly washed to remove any loose fine material resulting from the cutting process. All cores were then dried to constant weight at room temperature before being measured and weighed. As stated earlier, core densities were determined according to (1) the Florida test method FM 1-T 166, (2) ASTM D 1188 using parafilm, and (3) by direct calculation using the weight and volume measurements, respectively. The latter procedure is referred to hereafter as the dimensional method. A single operator was used throughout the laboratory testing of core samples.

ANALYSIS OF TEST RESULTS

The nuclear density measurements as collected during the course of this investigation are summarized in Table 1. The relationships among the core density results as determined using the three different methods were first considered. Then an investigation of the correlation among the different gauges used in this study was performed. Finally, the performance of each of the units with respect to the core density results was analyzed.

Core Density Measurements

The core density results as determined using the three different methods are given in Table 2. Plots of these results are also presented in Figures 1 to 3. These plots show that there is a linear relationship between each of the pairwise combinations of core density determination method. All the measurements fall near a straight line with relatively no dispersion about the line. This observation is also reflected by the high R-square values that ranged from 0.93 to 0.97. Moreover, the dimensional method resulted in comparatively lower density levels.

To further analyze the core density data, a one-way analysis of variance (ANOVA) was performed. The purpose of such an analysis was to evaluate if there was any evidence of real differences among the respective measurements by the three testing methods. The results of ANOVA are presented in Table 3. Letters t and r are used for the number of test methods and number of test locations, respectively. Thus, in this case $t = 3$ and $r = 10$. The calculated F value is compared with the critical F value for $t - 1$ and $t*(r-1)$ degrees of freedom to determine wether to accept the null hypothesis of no difference between the core density results as obtained using the three test methods. The critical F value for 2 and 27 degrees of freedom is 3.35 at the 0.05 probability level. Since, within the test range, the calculated F value exceeds the critical F, it can be concluded that there is evidence of real differences among the three methods of test for core density at a 95 percent confidence level. However this analysis of variance does not indicate which differences may be considered statistically significant. Therefore, a Duncan's multiple-range test was conducted, again at a 95 percent confidence level, to determine which of the three differences among the three ways of computing core density are significant and which are not. The test results, summarized in Table 4, show that, in comparison, the dimensional method resulted in statistically lower density values. However, the respective density results as determined using FM 1-T 166 and ASTM D 1188 were not significantly different, again within the test range. The corresponding difference in the resulting air voids, as shown in Table 5, ranges from 0.1 to 0.7 percent for a mix G_{mm} of 2.334, which is the average quality control G_{mm} value for the date the mix was placed.

Nuclear Density Measurements

One of the objectives of this investigation was also to evaluate the performance of the nuclear units in comparison to each other. Both the uncorrected (as read) and corrected readings were evaluated.

Uncorrected (As-Read) Nuclear Density Measurements

Thin lift density gauges, such as models 3450 and 4640, were developed to measure the pavement density without the influence of the underlying layers. As such, the density results would not require any correction. Therefore, the density data obtained during this investigation using the thin lift density gauge models 3450 and 4640 were analyzed to evaluate this assertion. The respective density average values as determined by these two gauges were compared using an analysis of the paired-difference experiment. The hypothesis concerning their equality (the difference between the respective average values is null) was tested using the Student t-test. The t value for the ten paired differences (10 reading locations) was calculated to be 13.85. The critical value of t based upon n - 1 = 9 degrees of freedom (n is the number of paired differences) and a level of significance $\alpha = 0.05$ is $t_\alpha = 2.306$. Since the calculated t exceeds this value, it can be inferred that, within the test range, the two gauges (models 3450 and 4640) were not reading the density at the same mean level.

Furthermore, Table 6 summarizes the within and between the two gauge reading range differences. It can be observed that the within density differences range from 6 to 45 kg/m^3 (corresponding to air void content ranges of 0.3 to 1.9 percent) for model 3450 and from 2 to 40 kg/m^3 for model 4640 (corresponding to air void content ranges of 0.1 to 1.7 percent). Such value ranges may be considered relatively high. The between gauge average density differences range, however, from 29 to 68 kg/m^3 (corresponding to air void content ranges of 1.3 to 2.9 percent). These differences, as also inferred from the above t-test results, are significant. All these findings indicate that the testing variability may differ from gauge to gauge and, within each gauge, from location to location.

Corrected Nuclear Density Measurements

An essential step of this subtask before the data analysis was to calibrate the nuclear gauge density readings to eliminate the possible effect of the underlying pavement layers during testing. Such a calibration would correct for the density of the underlying materials. A calibration factor was determined for each of the five gauges (with respect to each of the three core density methods) by comparing the bulk density of core samples obtained from three randomly selected locations (locations 1, 7 and 8) to the nuclear density readings at the same test sites. The complete description of the correction procedure as performed in Florida can be found in the *Asphalt Paving Technician Manual (7)*. The corrected nuclear density measurements are summarized in Table 7.

A one-way ANOVA was conducted to investigate if there is evidence of significant differences among each of the five sets of mean nuclear density measurements as corrected to each of the three core density methods. The findings of the ANOVA are illustrated in Table 8. In this case, letters t and r are used for the number of gauge units and number of test locations, respectively (t=5 and r=7). Again, the calculated F value is compared with the critical F value for t-1 and t*(r-1) degrees of freedom to determine wether to accept the null hypothesis of no difference between the five sets of nuclear density means. The critical F value for 4 and 30 degrees of freedom is 2.69 at the 0.05 probability level.

Table 8 indicates that, within the test range, the critical F value exceeds the calculated F in all cases. Therefore, it can be concluded that the experiment does not provide evidence of real differences among the means of the nuclear density gauge readings at a 95 percent confidence level. The ANOVA test results seem to indicate that all five nuclear units were reading at the same mean level, within the test range, whether these readings were corrected to the FM 1-T 166, dimensional or ASTM D 1188 core densities. However, Table 8 also shows that the gauge mean square is significantly lower than that of the error for all three cases. In such a case, the results are declared nonsignificant regardless of how small the value of calculated F. This observation could also be an indication of a spread in the data within each of the nuclear gauge readings.

To further evaluate the corrected density data, an analysis was performed to obtain ranges of the within and between gauge reading variability. The results of this analysis are summarized in Table 9. In addition, the corresponding within and between-nuclear gauge air void variations as determined using the mix G_{mm} of 2.334 at each test location are also plotted in Figures 4 and 5, respectively. Visual inspections of these two plots indicate erratic trends and little consistency in the respective percent of air void ranges from one location to another within and between gauges. A within-gauge air void content variation of up to 2.5 percent was recorded. The only gauge that seems to have a relatively consistent within air voids variation (ranging from 0.5 to 0.8 percent) is model 3440 (manufacturer). However, a similar unit operated by a District representative resulted in much more erratic differences. The comparison of the test data obtained using each of two model 3440 units seems to indicate that nuclear gauge density testing may be highly operator dependent.

The comparative data of Table 9 also shows that the between-gauge air content variation (or density) are relatively high, ranging from 0.9 to 1.7 percent. In addition, this data seems to indicate that the correction of the two thin lift gauge density readings for the underlying layer reduced the maximum differences between gauge measurements.

Again, though these observations are based on a limited data (one project with three number of testing replicates per location and ten testing locations), they infer that the variability may differ from gauge to gauge and, within each gauge, from location to location.

Nuclear versus Core Density Comparisons

If the nuclear density gauges are to be considered for acceptance purposes, it is essential to assess their level of correlation with the core density method presently in use. Thus, the primary objective of this study was to compare the nuclear density readings with core densities. The density data was analyzed to evaluate the level of agreement between the gauge density readings and core densities. The uncorrected data of the two thin lift gauges was first analyzed. Then, the corrected density measurements as obtained using each of the five units were evaluated.

Uncorrected (As-Read) Nuclear Density Measurements

The results of the comparison between the uncorrected thin lift nuclear gauge readings and core density data are summarized in Table 10. Such a comparison is also illustrated in Figures 6 through 8. The data in these figures appears to be scattered, showing a large spread among the density data. The comparative plots also indicate that the core densities as measured using the Florida or ASTM methods tend to be consistently higher than the corresponding gauge readings as determined using model 4640. A corresponding difference in air void content of up to 4 percent was recorded. Moreover, the density data points seem to be evenly spread on both sides of the equality line when FM 1-T166 or ASTM D 1188 core densities were compared to those of model 3450 (the corresponding air void differences range from about 0 to 1.6 percent). The latter are however relatively higher than the core densities as determined by the dimensional method. In this case, the corresponding air void differences range from 0.7 to 3.5 percent.

Linear relationships between the average gauge and core densities were also obtained for each set of thin lift nuclear gauge and core density comparison. Corresponding coefficients of correlation, R^2, are given in Table 10. A comparison of the R-square values indicates that there appears to be a higher degree of correlation between core density methods than there is between the core and nuclear readings.

Corrected Nuclear Density Measurements

The results of the comparison between the corrected nuclear gauges (average of the three replicate readings per location) and core density test data, as related to each gauge model and each core density method, are summarized in Table 11. Such a comparison, in terms of air voids, is also illustrated in Figures 9 through 11. The data in these figures appears to be scattered, showing, at times, excessively large differences in percent air voids between the nuclear gauges and the core methods. A difference in air void content of more than 2 percent, within the same location, was recorded. The above plots also indicate that gauge model 3401 and 3440 (manufacturer) resulted in a narrower and more consistent range of air void differences. Incidently, the two model 3440 units had significantly different measurements. These findings seem, again, to infer that the nuclear density testing variability may differ from gauge to gauge, from location to location within each gauge, and may be highly operator dependent.

Linear relationships between the average gauge and core densities were also obtained for each set of nuclear gauge and core density comparison. Corresponding R-squares are included in Table 11, while those obtained for the core density methods are shown in Figures 1 through 3. A comparison of these R-square values indicates that there is a higher degree of correlation between core density methods than there is between the core and corrected nuclear readings. However, such a correlation improved when compared to that obtained in the case of uncorrected nuclear density data. This finding suggests the need to correct the readings of all nuclear gauges, including those for thin lift densities, to eliminate the possible effect of the underlying pavement layers during testing. Such a correction would account for the density of the underlying materials.

Earlier research has shown that the performance of nuclear gauges was not consistent from one project to another and that their accuracy was highly material-dependent *(1,2,8)*. Thus, it has to be noted that any discussion presented here applies only to the gauges used in this study, based on the data collected on this particular project.

CONCLUSIONS

An investigation of the correlation between nuclear density readings and core densities was performed. Five gauge units and three core density methods were considered. The relationships among the core density results were first analyzed. Then an investigation of the correlation among the different gauges used in this study was evaluated. Finally, the performance of each of the units with respect to the core density results was assessed. Based on the findings of this study and within the test range, the following conclusions can be drawn:

! Regression analyses indicated good correlations among the three core density methods. The dimensional method resulted in statistically lower density values while the respective density results as determined using FM 1-T 166 and ASTM D 1188 were not significantly different.

! A paired-difference analysis indicated that the respective uncorrected density average values as determined using the thin lift density gauge models 3450 and 4640 were statistically different. The differences in resulting air void contents between the two gauges ranged from 1.3 to 2.9 percent. However, when the density readings of the thin lift were corrected to consider the effects of the underlying layers, these differences were narrowed. This finding in combination with the results of the comparison between nuclear and core density data show that it is essential to correct the readings of all nuclear gauges, including the thin lift gauges, for the density of the underlying materials.

! The corrected nuclear gauge data showed relatively erratic trends and little consistency from one location to another within and between the gauges. A within-gauge air void content difference of up to 2.5 percent was recorded. The between-gauge air voids differed by 0.9 to 1.7 percent.

! The comparison of the test data obtained using each of two model 3440 units seems to infer that nuclear gauge density testing may be highly operator dependent.

! A comparison of the coefficient of correlations suggests a higher degree of correlation existed between core density methods than between the core and nuclear readings.

RECOMMENDATIONS

The findings of this investigation indicated that the five nuclear gauge density units did not always produce similar results and did not consistently correlate with the core densities. In addition, the nuclear density testing variability did not only differ from gauge to gauge but also from location to location within each gauge. Therefore, directly substituting, at the present time, the nuclear gauges to core density for acceptance purposes may not be appropriate. However, since these findings apply only to the gauges used in this study, based on the data collected on this particular project, it is suggested that the nuclear density testing variability be further assessed. The intent of such an assessment should not only be to correlate the nuclear density gauges to core densities, but also to develop potential acceptance limits and procedures specifically for nuclear gauges.

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Table 1 Nuclear Density Readings

Testing Location			Gauge Model														
			Model 3401			Model 3440 (D)*			Model 3440 (M)**			Model 3450			Model 4640		
LOT	Station	Location Number	Density Reading, kg/m³			Density Reading, kg/m³			Density Reading, kg/m³			Density Reading, kg/m³			Density Reading, kg/m³		
			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1	125+16	1	2227	2235	2243	2177	2188	2195	2182	2217	2204	2260	2236	2252	2188	2211	2191
	129+06	2	2231	2231	2227	2220	2185	2178	2191	2203	2204	2252	2233	2278	2204	2220	2201
	130+60	3	2183	2211	2203	2170	2140	2113	2172	2164	2178	2198	2196	2204	2161	2151	2153
	134+57	4	2146	2151	2162	2134	2154	2134	2153	2154	2142	2187	2188	2196	2113	2126	2153
	137+83	5	2215	2207	2219	2172	2195	2161	2196	2183	2193	2219	2227	2231	2203	2193	2193
	138+55	6	2127	2127	2127	2119	2121	2130	2105	2121	2122	2166	2161	2154	2108	2111	2103
2	139+61	7	2167	2146	2167	2126	2137	2130	2148	2113	2111	2142	2151	2158	2078	2090	2090
	144+46	8	2191	2183	2159	2142	2154	2132	2130	2158	2142	2187	2196	2195	2130	2116	2132
	145+79	9	2203	2175	2170	2143	2154	2158	2172	2159	2164	2191	2196	2190	2126	2126	2124
	148+98	10	2195	2195	2203	2164	2145	2145	2178	2167	2177	2203	2188	2196	2126	2127	2129

* Model 3440 (D): operated by a District personnel

** Model 3440 (M): operated by a Manufacturer representative

Table 2 Core Density Results

Testing Location			Density, kg/m^3		
			Test Method		
LOT	Station	Number	FM 1-T 166	Dimensional	ASTM D 1188
1	125+16	1	2228	2179	2212
	129+06	2	2230	2173	2221
	130+60	3	2225	2176	2209
	134+57	4	2183	2124	2181
	137+83	5	2235	2187	2225
	138+55	6	2146	2073	2136
2	139+61	7	2182	2133	2165
	144+46	8	2202	2148	2190
	145+79	9	2191	2129	2180
	148+98	10	2201	2155	2193

Table 3 Analysis of Variance of Core Density Data

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	F
Test Method	t - 1 = 2	16655.4	8327.7	9.15
Error	t*(r-1) = 27	24569.8	909.99	
Total	29	41225.2		

Table 4 Results of Duncan's Multiple-Range Test on Core Density Data

Method of test	Means, kg/m^3	Grouping
FM 1-T 166	2202.3	A
Dimensional	2147.7	B
ASTM D 1188	2191.2	A

Note: Means with the same letter are not significantly different at a 95% confidence level

Table 5 Density and Air Void Ranges as Determined Using FM 1-T166 and ASTM D1188

Testing Location			Density, kg/m^3			Air Void
LOT	Station	Number	FM 1-T 166	ASTM D1188	Difference	Range, %
1	125+16	1	2228	2212	16	0.7
	129+06	2	2230	2221	9	0.4
	130+60	3	2225	2209	16	0.7
	134+57	4	2183	2181	2	0.1
	137+83	5	2235	2225	10	0.4
	138+55	6	2146	2136	10	0.4
	Average		2208	2197	11	0.5
2	139+61	7	2182	2165	17	0.7
	144+46	8	2202	2190	12	0.5
	145+79	9	2191	2180	11	0.5
	148+98	10	2201	2193	8	0.3
	Average		2194	2182	12	0.5

Table 6 Thin Lift Nuclear Density Test Readings Range

Testing Location			Within Gauge Range				Between Gauge Range	
			Model 3450		Model 4640			
LOT	Station	Number	Density kg/m^3	Air Void %	Density kg/m^3	Air Void %	Density kg/m^3	Air Void %
1	125+16	1	24	1.0	22	1.0	53	2.3
	129+06	2	45	1.9	19	0.8	46	2.0
	130+60	3	8	0.3	10	0.4	44	1.9
	134+57	4	10	0.4	40	1.7	60	2.6
	137+83	5	13	0.6	10	0.4	29	1.3
	138+55	6	11	0.5	8	0.3	53	2.3
	Average		18	0.8	18	0.8	48	2.0
2	139+61	7	16	0.7	13	0.6	64	2.8
	144+46	8	10	0.4	16	0.7	66	2.8
	145+79	9	6	0.3	2	0.1	67	2.9
	148+98	10	14	0.6	3	0.1	68	2.9
	Average		12	0.5	8	0.4	66	2.8

Table 7 Corrected Nuclear Density Measurements, kg/m^3

Location	Gauge Model														
	Model 3401			Model 3440 (D)			Model 3440 (M)			Model 3450			Model 4640		
	Correction to FM 1-T 166 Computed Core Densities														
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
2	2244	2244	2240	2271	2236	2229	2239	2250	2252	2259	2240	2284	2272	2288	2269
3	2196	2224	2216	2221	2191	2163	2220	2212	2226	2204	2203	2211	2229	2219	2221
4	2160	2164	2176	2184	2205	2184	2201	2202	2190	2193	2195	2203	2181	2193	2221
5	2228	2220	2232	2223	2245	2211	2244	2231	2241	2225	2233	2238	2270	2261	2261
6	2140	2140	2140	2170	2171	2181	2153	2169	2170	2172	2168	2161	2176	2179	2171
9	2216	2188	2184	2194	2205	2208	2220	2207	2212	2198	2203	2196	2193	2193	2192
10	2208	2208	2216	2215	2195	2195	2226	2215	2225	2209	2195	2203	2193	2195	2197
	Correction to Dimension Computed Core Densities														
2	2194	2194	2189	2220	2185	2178	2189	2200	2201	2208	2189	2234	2221	2237	2218
3	2146	2173	2165	2170	2140	2113	2169	2161	2176	2154	2152	2160	2178	2168	2170
4	2109	2114	2125	2134	2154	2134	2150	2152	2139	2142	2144	2152	2130	2143	2170
5	2178	2170	2181	2172	2194	2161	2193	2181	2190	2175	2183	2187	2220	2210	2210
6	2090	2090	2090	2119	2121	2130	2102	2118	2120	2122	2117	2110	2125	2128	2120
9	2165	2138	2133	2143	2154	2158	2169	2157	2161	2147	2152	2146	2143	2143	2141
10	2157	2157	2165	2164	2145	2145	2176	2165	2174	2158	2144	2152	2143	2144	2146
Correction to ASTM D 1188 Computed Core Densities															
2	2229	2229	2225	2256	2221	2214	2224	2235	2237	2244	2225	2269	2257	2273	2254
3	2181	2209	2201	2206	2176	2148	2205	2197	2211	2189	2188	2196	2214	2204	2206
4	2145	2149	2161	2169	2190	2169	2186	2187	2175	2178	2180	2188	2166	2178	2206
5	2213	2205	2217	2208	2230	2196	2229	2216	2226	2210	2218	2223	2255	2246	2246
6	2125	2125	2125	2155	2156	2166	2138	2154	2155	2157	2153	2146	2161	2164	2156
9	2201	2173	2169	2179	2190	2193	2205	2192	2197	2183	2188	2181	2178	2178	2177
10	2193	2193	2201	2200	2180	2180	2211	2200	2210	2194	2180	2188	2178	2180	2182

Table 8 Analysis of Variance of Corrected Nuclear Density Data

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	F
	Nuclear Density Readings Corrected to FM 1-T 166 Core Densities			
Gauge Unit	t - 1 = 4	1566.40	391.60	0.40
Error	t*(r-1) = 30	29736.57	991.22	
Total	34	31302.97		
	Nuclear Density Readings Corrected to Dimensional Core Densities			
Gauge Unit	4	1520.69	380.17	0.39
Error	30	29564.86	985.50	
Total	34	31085.54		
	Nuclear Density Readings Corrected to ASTM D 1188 Core Densities			
Gauge Unit	4	1566.40	391.60	0.40
Error	30	29736.57	991.22	
Total	34	31302.97		

Table 9 Ranges of Variability of Corrected Nuclear Density Measurements and Corresponding Air Voids

Location	Density and Air Void Difference Range											
	Within Gauge										Between Gauges	
	Gauge Model											
	3401		3440 (D)		3440 (M)		3450		4640			
	Density kg/m^3	% Air Voids	Density kg/m^3	% Air Voids	Density kg/m^3	% Air Voids	Density kg/m^3	% Air Voids	Density kg/m^3	% Air Voids	Density kg/m^3	% Air Voids
2	5	0.2	42	1.8	13	0.6	45	1.9	19	0.8	33	1.4
3	27	1.2	58	2.5	14	0.6	8	0.3	10	0.4	31	1.3
4	16	0.7	21	0.9	13	0.6	10	0.4	40	1.7	32	1.4
5	11	0.5	34	1.4	13	0.6	13	0.6	10	0.4	39	1.7
6	0	0.0	11	0.5	18	0.8	11	0.5	8	0.3	35	1.5
9	32	1.4	14	0.6	13	0.6	6	0.3	2	0.1	21	0.9
10	8	0.3	19	0.8	11	0.5	14	0.6	3	0.1	27	1.2

Table 10 Comparative Results Between Uncorrected Nuclear Gauges and Core Density Data

	Density, kg/m³			Air Void,	Density, kg/m³			Air Void,
	Core	Nuclear	Range	%	Core	Nuclear	Range	%
Location	FM 1-T 166 vs. Gauge 3450				FM 1-T 166 vs. Gauge 4640			
1	2228	2250	22	0.9	2228	2197	31	1.3
2	2230	2254	24	1.0	2230	2208	22	0.9
3	2225	2199	26	1.1	2225	2155	70	3.0
4	2183	2190	7	0.3	2183	2130	53	2.3
5	2235	2226	10	0.4	2235	2196	39	1.7
6	2146	2160	14	0.6	2146	2107	39	1.7
7	2182	2150	32	1.4	2182	2086	96	4.1
8	2202	2192	10	0.4	2202	2126	76	3.3
9	2191	2192	1	0.1	2191	2125	66	2.8
10	2201	2196	5	0.2	2201	2127	74	3.2
Linear Coef. of Correlation, R^2 = 0.69					Linear Coef. of Correlation, R^2 = 0.70			
	Dimensional vs. Gauge 3450				Dimensional vs. Gauge 4640			
1	2179	2250	71	3.0	2179	2197	18	0.8
2	2173	2254	81	3.5	2173	2208	35	1.5
3	2176	2199	23	1.0	2176	2155	21	0.9
4	2124	2190	66	2.8	2124	2130	6	0.3
5	2187	2226	39	1.7	2187	2196	9	0.4
6	2073	2160	87	3.8	2073	2107	34	1.5
7	2133	2150	17	0.7	2133	2086	47	2.0
8	2148	2192	44	1.9	2148	2126	22	0.9
9	2129	2192	63	2.7	2129	2125	4	0.2
10	2155	2196	41	1.7	2155	2127	28	1.2
Linear Coef. of Correlation, R^2 = 0.57					Linear Coef. of Correlation, R^2 = 0.57			
	ASTM D 1188 vs. Gauge 3450 Test Results				ASTM D 1188 vs. Gauge 4640 Test Results			
1	2212	2250	38	1.6	2212	2197	15	0.7
2	2221	2254	33	1.4	2221	2208	13	0.5
3	2209	2199	10	0.4	2209	2155	54	2.3
4	2181	2190	9	0.4	2181	2130	51	2.2
5	2225	2226	1	0.0	2225	2196	29	1.2
6	2136	2160	24	1.0	2136	2107	29	1.2
7	2165	2150	15	0.6	2165	2086	79	3.4
8	2190	2192	2	0.1	2190	2126	64	2.7
9	2180	2192	12	0.5	2180	2125	55	2.4
10	2193	2196	3	0.1	2193	2127	66	2.8
Linear Coef. of Correlation, R^2 = 0.74					Linear Coef. of Correlation, R^2 = 0.75			

Table 11 Comparative Results Between Corrected Nuclear Gauges and Core Density Data

	Range Differences Between FM 1-T 166 and Nuclear Gauge									
	Nuclear Gauge Model									
	3401		3440 (D)		3440 (M)		3450		4640	
Location	Density kg/m^3	% Air Voids	Density kg/m^3	% Air Voids	Density kg/m^3	% Air Voids	Density kg/m^3	% Air Voids	Density kg/m^3	% Air Voids
2	13	0.6	15	0.6	17	0.7	31	1.3	46	2.0
3	13	0.6	33	1.4	6	0.2	19	0.8	2	0.1
4	17	0.7	8	0.4	15	0.6	14	0.6	15	0.7
5	8	0.4	9	0.4	4	0.2	3	0.1	29	1.2
6	6	0.2	28	1.2	18	0.8	21	0.9	29	1.3
9	5	0.2	11	0.5	22	0.9	8	0.3	2	0.1
10	9	0.4	1	0.0	21	0.9	1	0.1	6	0.3
R^2	0.90		0.61		0.90		0.74		0.75	
	Range Differences Between Dimensional and Nuclear Gauge									
2	19	0.8	21	0.9	24	1.0	37	1.6	52	2.3
3	15	0.6	35	1.5	7	0.3	21	0.9	4	0.2
4	8	0.4	17	0.7	23	1.0	22	1.0	23	1.0
5	11	0.5	11	0.5	1	0.0	6	0.2	26	1.1
6	17	0.7	50	2.2	40	1.7	43	1.9	52	2.2
9	16	0.7	23	1.0	33	1.4	19	0.8	13	0.6
10	5	0.2	4	0.2	16	0.7	3	0.1	11	0.5
R^2	0.87		0.53		0.88		0.65		0.64	
	Range Differences Between ASTM D 1188 and Nuclear Gauge									
2	7	0.3	9	0.4	11	0.5	25	1.1	40	1.7
3	12	0.5	32	1.4	5	0.2	18	0.8	1	0.1
4	30	1.3	5	0.2	2	0.1	1	0.0	2	0.1
5	13	0.6	14	0.6	1	0.1	8	0.3	24	1.0
6	11	0.5	23	1.0	13	0.6	16	0.7	24	1.0
9	1	0.0	7	0.3	18	0.8	4	0.2	2	0.1
10	2	0.1	6	0.3	14	0.6	6	0.2	13	0.6
R^2	0.90		0.66		0.92		0.78		0.76	

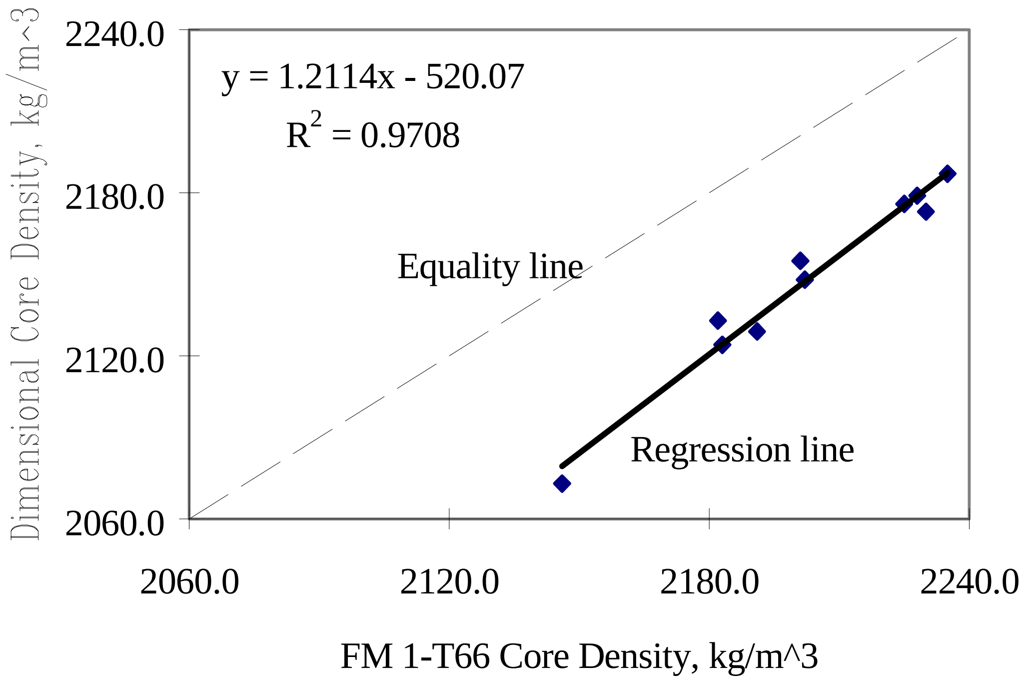

Figure 1 Plot of dimensional method and FM 1-T 166 core density results

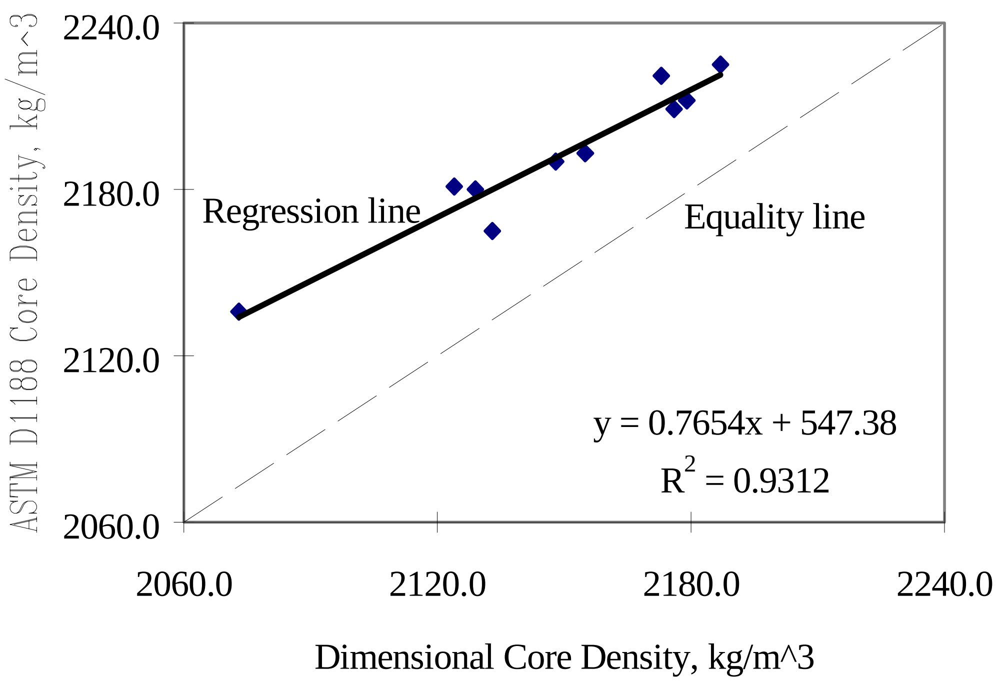

Figure 2 Plot of dimensional method and ASTM D1188 core density results

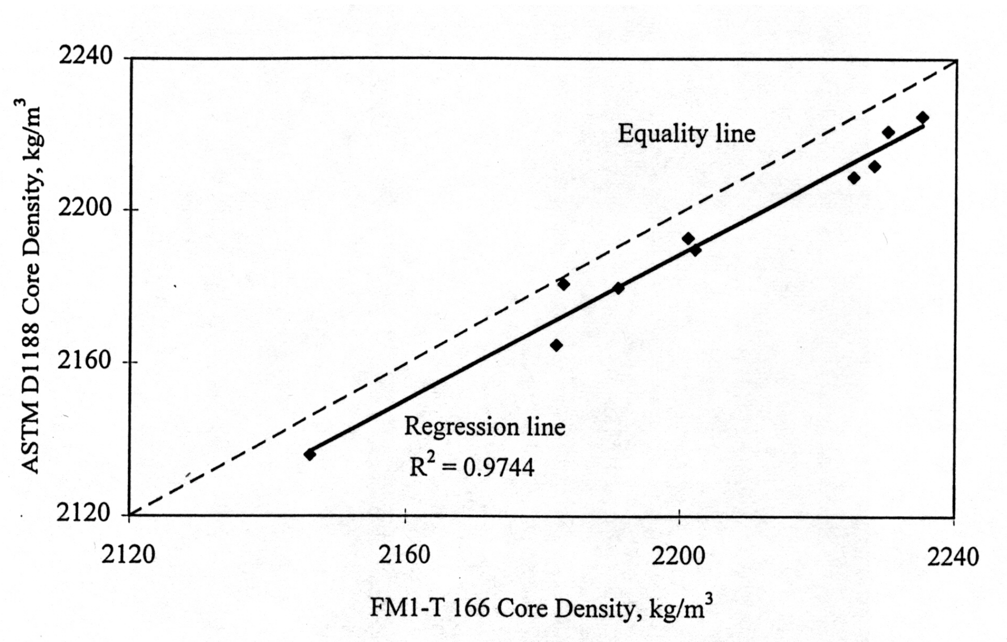

Figure 3 Plot of ASTM D1188 and FM1-T 166 core density results

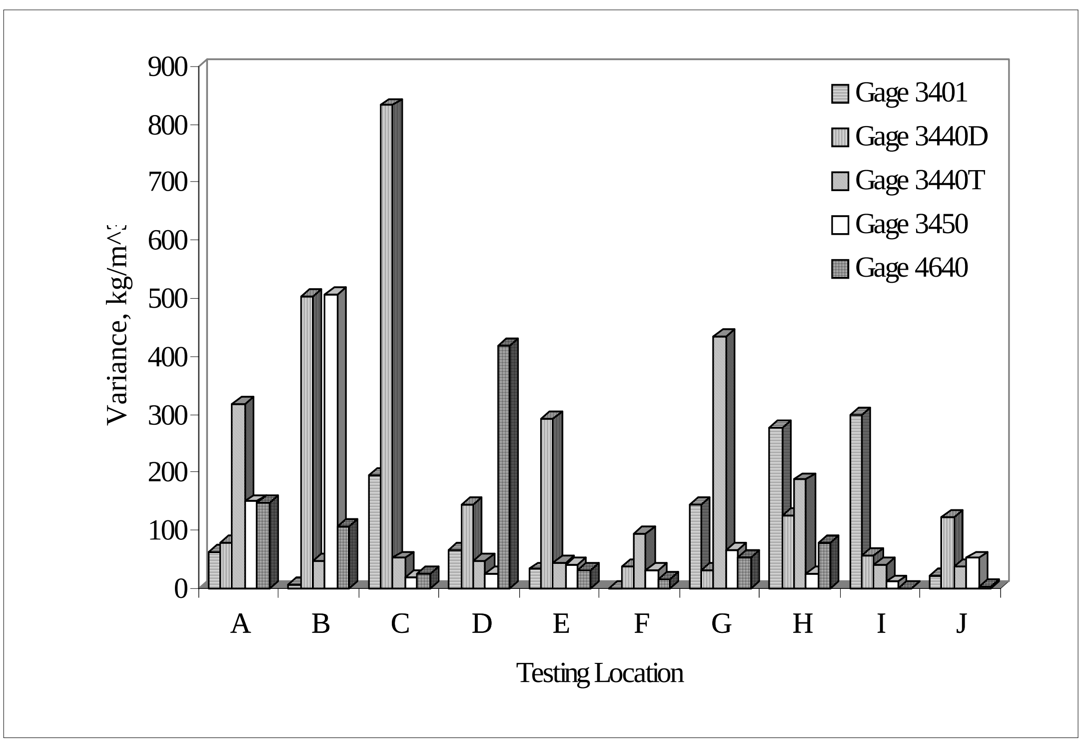

Figure 4 Plot of within-nuclear gauge variances at each test location

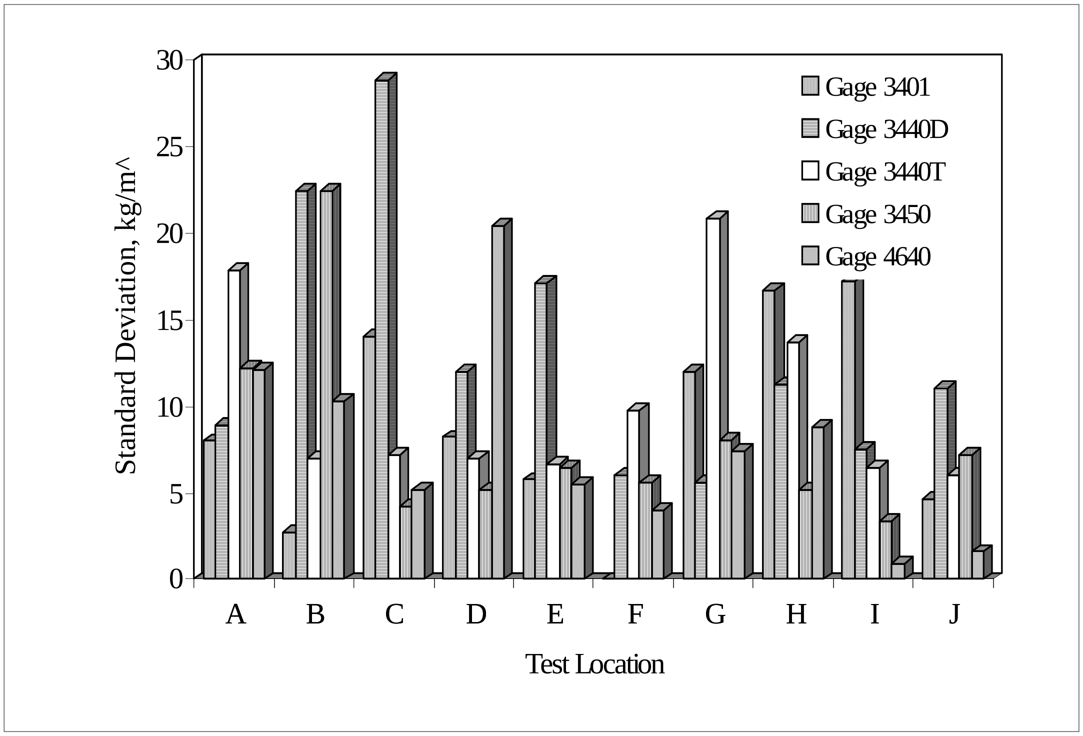

Figure 5 Plot of within-nuclear gauge standard deviations at each test location

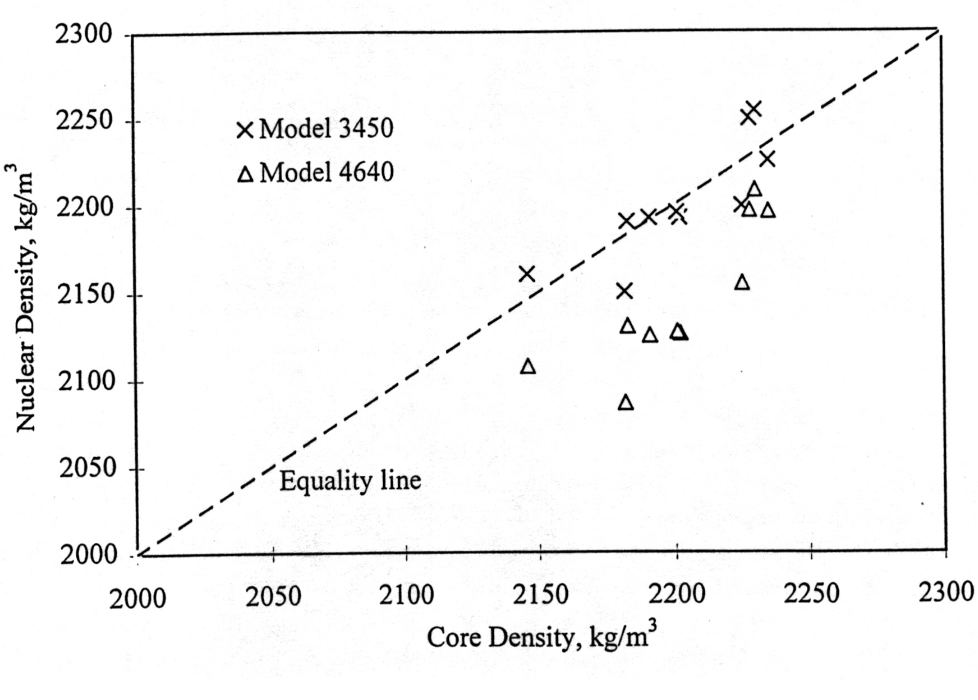

Figure 6 Plot of dimensional method core densities and nuclear gauge readings

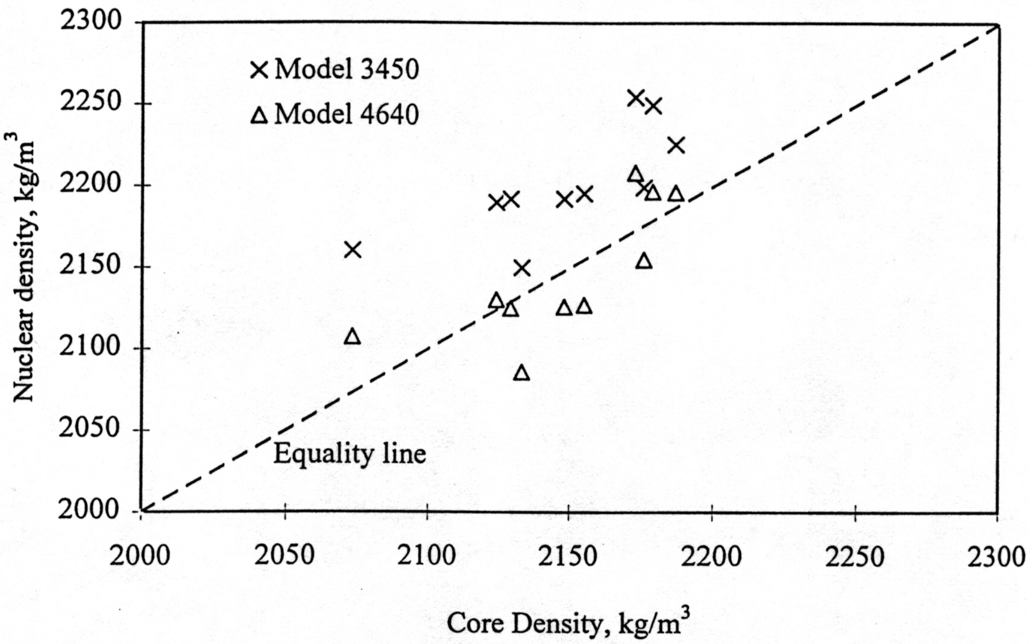

Figure 7 Plot of ASTM method core densities and nuclear gauge readings

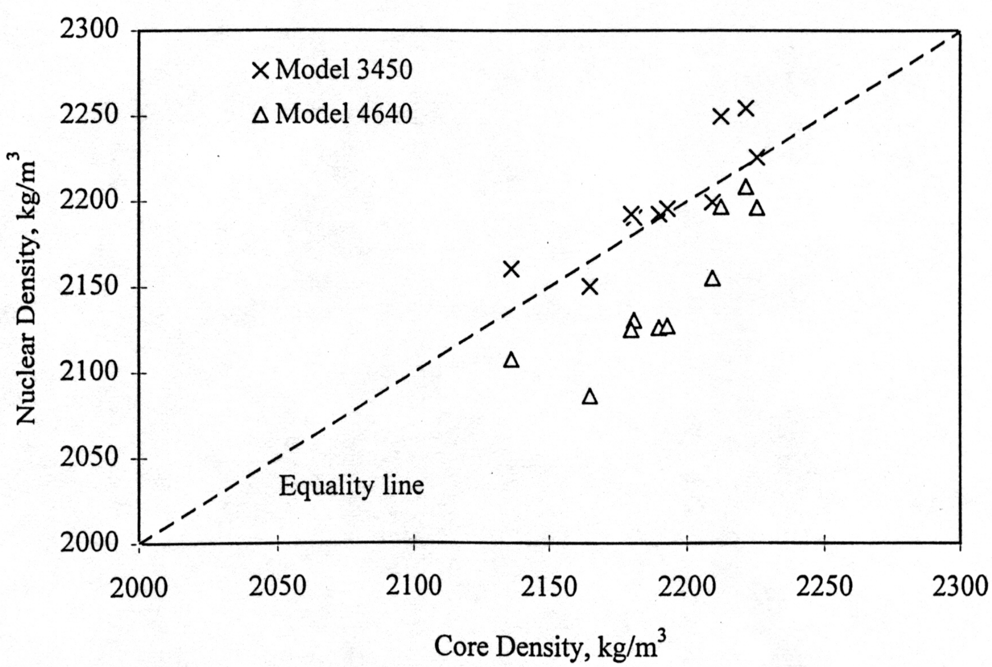

Figure 8 Plot of Florida method core densities and nuclear gauge readings

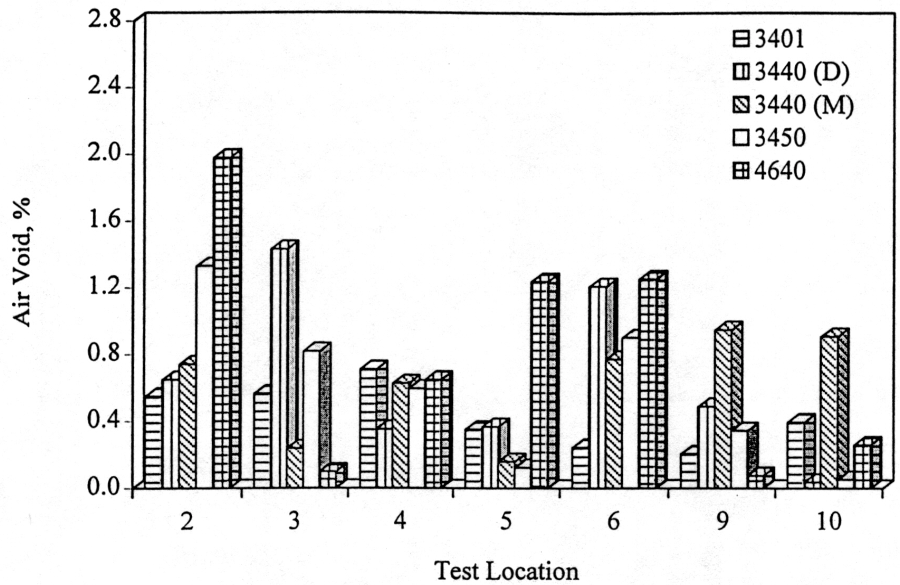

Figure 9 Illustrative differences in resulting air voids between FM 1-T 166 and nuclear methods

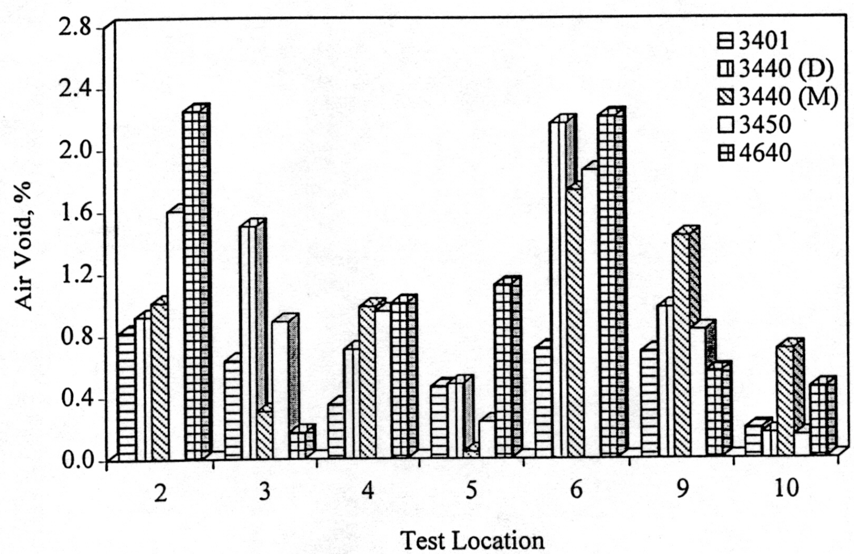

Figure 10 Illustrative differences in resulting air voids between dimensional and nuclear methods

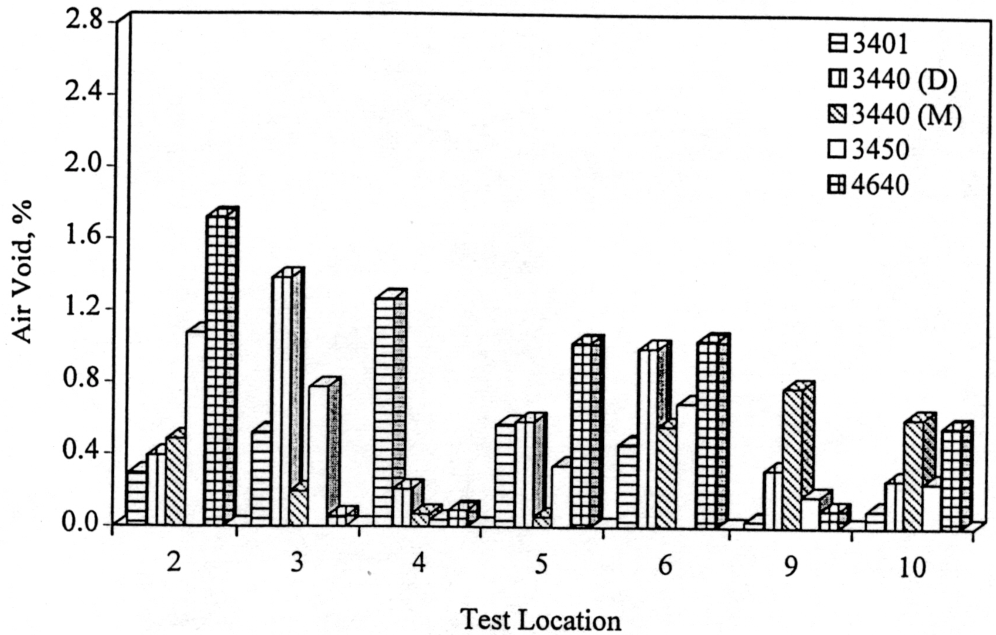

Figure 11 Illustrative differences in resulting air voids between ASTM D1188 and nuclear methods