Statistical Evaluation of Nuclear Density Gauges Under Field Conditions

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Three field test locations (Texas, Virginia, and Nevada) were used to produce a data base of more than 900 nuclear density readings to investigate the precision of the American Society for Testing and Materials test method 2950. A combination of private, state, and county laboratories throughout the three states, as well as three gauge manufacturers, provided a total of 31 different gauges. Each field location consisted of 10 test sites and at least two different hot mix asphalt pavement conditions. Participating laboratories at each location tested the same test sites using 15-sec, 1-min, and 4-min readings. Test sites were cored after the nuclear density readings had been taken. Statistical analysis of the data showed that a 15-sec reading generated a similar density reading to either the 1-min or the 4-min readings. A two-way analysis of variance showed that all gauges and test sites were significantly different. Further statistical analysis showed variances generated by each test location to be dependent on each specific set of test conditions. Regression equations were developed for each gauge for each test location; nuclear density readings were correlated to densities determined from the bulk specific gravities of the corresponding cores. When considered as a group, gauges fail to generate an accurate regression equation. When considered individually, however, the gauges are capable of producing an r^2 of 0.8 or greater. Regression equations also appear to be dependent on test conditions. Correlations between r^2 and standard counts, date of last calibration, and average differences between cores and gauges showed no apparent trends.

Density of hot mix asphalt (HMA) pavements has been controlled by specifications since the 1890s (*1*). Early density control was accomplished by designating specific equipment, number of passes, and temperature of mixture at compaction. These procedural specifications gradually gave way to end result specifications. By 1967, approximately 80 percent of state highway departments designated some method of end result criteria (*2*).

End result specifications require the ability to evaluate the quality of the finished product accurately. Density has historically been one of the primary measurements used to assess the quality of a finished pavement. The density of the in-place material has typically been evaluated by taking a limited number of cores from the finished pavement, then determining the bulk specific gravities (BSGs).

Because end result specifications also typically impose strict financial penalties for noncompliance, it is essential to provide the contractor with notification of acceptance or rejection as quickly as possible. A typical time lapse between taking a core and notifying the contractor of the test results is 24 hr. In order to decrease this time between test and contractor notification, nuclear density gauges are becoming popular because of their quick, almost instantaneous results and ease of use.

The American Society for Testing and Materials (ASTM) developed a test method (ASTM D2950) in 1971 for use of these gauges for determining hot mix asphalt (HMA) density. Before the gauges can be used confidently for acceptance testing, however, their accuracy and the repeatability of test results from these gauges under field conditions need to be assessed.

RESEARCH PROGRAM

Three terms are used repeatedly throughout the remainder of the text. Location refers to one of the three geographic locations. Mat condition refers to physical variables such as mat thickness or HMA surface treatments. Test site refers to the actual sites tested for a particular mat condition.

The main objective of the research program was to develop a precision statement for use of the nuclear density gauge, as described in ASTM D2950. The design of testing programs for developing a precision statement is defined by ASTM C670 and ASTM C802. In general, precision statements are generated from a limited number of laboratories testing replicates of the same materials.

Because the nuclear density gauges are intended for field use only, obtaining replicates of the same material became a problem. Construction variables such as normal variations inherent between truckloads of materials, mixture temperature at time of compaction, aggregate segregation, and variations in mat thickness between test sites all combined to make it unlikely that replicates of materials could be obtained.

To minimize some of the problems previously described, test sites for each location were specifically biased. Test sites were chosen so that the pavement material tested was

1. Placed from the same truckload,
2. Within the same line of passages as the compaction equipment, and
3. Devoid of any visible signs of aggregate segregation.

The type and physical properties of aggregates, asphalts, bases, and construction variables, although held as constant as possible for individual locations, varied widely between locations. General mat thicknesses were chosen as a common link between locations. Test sites were separated by those mats 2.5 in. or less, and 3.5 in. or greater.

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Three locations for testing were chosen across the country: Galveston, Texas; McLean, Virginia; and Reno, Nevada. These field tests provided a data base of more than 900 test results generated by 31 laboratories for four specific pavement mat conditions. Various models of gauges from three gauge manufacturers were represented in this testing program.

A 3.5 inch thick or greater mat was not available for testing at the Reno, Nevada, location; two other mat conditions were chosen for evaluation at this location. One of these conditions was a heavily raveled surface, sanded as recommended by gauge manufacturers, and unsanded, as a comparison. The sanded versus unsanded comparison was designed as an attempt to evaluate the effectiveness of sand in reducing reading distortions caused by surface voids. The second condition was a surface sealed with coal tar emulsions. These seal coats had been applied to a portion of the surface of the 2.5-in. mat (Reno, Nevada); test sites for the sealed surface were located within 20 ft of the unsealed surface.

Three durations of readings were taken at each test site: a 15-sec, 1-min, and 4-min reading. The gauges were not moved between these three readings nor were the probes retracted. This portion of the testing provided the data necessary to evaluate whether there were significant differences between the density readings obtained for the various durations.

Finally, the test sites were cored and the bulk specific gravities (ASTM 2726) were determined. Densities obtained from this testing were used as a comparison with the nuclear density gauge readings. Although densities determined from cores are affected by damage from the coring process and inherent testing variations associated with determining BSG, this is the traditional method of determining density. These densities were used as a datum against which the performance of the nuclear gauges was compared.

TESTING LOCATIONS

Each location and its specific test conditions are described in the following paragraphs. Testing control by University of Nevada-Reno personnel was limited to

1. Instructing that testing be performed according to ASTM D2950;
2. Designating orientation of gauge, when possible, by a template marking on the test site; and
3. Ensuring that gauge operators did not encroach on other test areas.

Galveston, Texas

A recent paving job for the Coast Guard in Galveston, Texas, just outside Houston provided 10 test sites on two different mat thicknesses: (a) 3.5 in. over limestone base, and (b) 2 in. over limestone base.

Five test sites were established approximately 25 ft apart on each mat. Six local laboratories and two gauge manufacturer representatives provided 15-sec, 1-min, and 4-min density readings for each test site. The eight gauges used for testing consisted of seven different models representing three manufacturers. The pavement was a parking lot that had not been opened to traffic. The HMA consisted of an AC-20 and crushed limestone coarse and fine aggregate.

Testing was conducted on September 3, 1986. Weather conditions were hot, humid, and clear.

McLean, Virginia

The Federal Highway Administration (FHWA) offered the use of their Accelerated Loading Facility (ALF) mats. Two mats were available:

- A 2-in. surface course over a 5-in. HMA base (an ALF test mat), and
- A 2.5-in. surface course over a gravel base (median between ALF test mats).

Five test sites approximately 35 ft apart were located on each mat. Nine laboratories and two gauge manufacturer representatives provided 15-sec, 1-min, and 4-min density readings. The 11 gauges used for testing consisted of five models representing two manufacturers. Because these mats were for test purposes only, no traffic had been allowed on them; ALF testing had not begun. The HMA base mixture was composed of an AC-20 with a 1-in. maximum nominal size aggregate. The surface mixture was made up of AC-20 and $^3/_8$-in. maximum nominal size aggregates. Gauge orientation was not specified with a template because of some surface irregularities on the 2.5-in. mat. Seating difficulties were encountered in several places with some gauge configurations.

Testing was conducted on September 16 and 17, 1986. Weather conditions were warm, breezy, and clear.

Reno, Nevada

Two University of Nevada-Reno parking lots were used at this location. The first was a recently paved, low-volume traffic parking lot. This provided one mat thickness of 2.5 in. over a gravel base. Four test sites were located on this mat approximately 45 ft apart. Another two test sites were located on the same parking lot, within 20 ft of the first four. HMA for these two sites had been treated with coal tar sealers.

A heavily raveled, high-volume-traffic parking lot was chosen for the remaining four test sites. Two of these sites had the surface sanded as required by gauge manufacturers. For comparison, the other two sites were not sanded.

Surface mixtures for both pavements consisted of an AR-4000 and a partially crushed river gravel. The absorption capacity of this aggregate was greater than 3 percent. The mix in the newer parking lot used $^3/_4$-in. nominal maximum-size aggregates. A coarser gradation was used in the surface that raveled. Eight laboratories provided test results for 15-sec, 1-min, and 4-min density readings. The eight gauges used for testing consisted of three models representing two manufacturers.

Testing was performed on January 30, 1987. The weather was chilly, windy, and cloudy. Pavement surfaces had been dry for at least 3 days before testing.

STATISTICS

Several statistical tests were used to evaluate the test results. These were (a) *t*-statistics, (b) two-way analysis of variance (ANOVA), and (c) ratio of variances.

The *t*-statistic, in this case a paired *t*-statistic, was used to determine whether there was a statistical difference between the 15-sec, 1-min, and 4-min readings. A two-way ANOVA was used to evaluate the influence of two factors within the same data base. The ratio of variances was used to determine whether there was a statistical difference between variances developed from different data bases.

Paired *t*-Statistic

A paired *t*-statistic evaluates statistics derived for the differences between each set of test results. Each set must have a common factor such as the same sample or the same material. Test results would be handled as shown in the following table:

	Data Set 1	*Data Set 2*	*Difference*
1	A	A′	A − A′
2	B	B′	B − B′
3	C	C′	C − C′
4	D	D′	D − D′
5	E	E′	E − E′
6	F	F′	F − F′
			Calc. Average
			Calc. Std. Deviation

The paired *t*-statistic is calculated by

$$t = d/s$$

where d equals the average of the differences and s equals the standard deviation of the differences.

The more closely the data sets are related, the smaller the difference for each set of two. For two identical sets of data, the difference would be zero. Next, the table *t*-statistic value is found, using any *t*-table commonly presented in statistical textbooks. A comparison of the *t*-statistic calculated to the table is used to answer the question: Is the difference between the two sets of data significant? Conclusions are drawn as follows:

1. If the calculated *t*-statistic is greater than the table value, there is a statistical difference between the two sets of data; and
2. If the calculated *t*-statistic is less than the table value, there is no reason to suspect a difference between the data sets.

Two-Way ANOVA

When there are two variables (usually referred to as factors) within one data base, a two-way ANOVA is used. Data bases requiring the use of a two-way ANOVA are easy to spot just by the way the data are presented in a table. The following is a typical table:

		Factor 1							
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
	1	x	x	x	x	x	x	x	x
Factor 2	2	x	x	x	Data	x	x	x	x
	3	x	x	x	x	x	x	x	x

The results of a two-way ANOVA analysis are two calculated *F*-values. One *F*-value determines whether the variables in Factor 1 are statistically different. The second *F*-value determines whether the variables in Factor 2 are statistically different. Because the formulas for calculating these *F*-values are fairly complicated, the statistical software program MINITAB was used (*3*).

In order to use a two-way ANOVA, the data base must be complete. That is, each row and column must have the same number of data points. It was sometimes necessary to remove a row or column with missing data in order to meet this requirement.

Once the *F*-value has been calculated, a table *F*-value is found from a typical table supplied in any statistics book. To use these standard tables, it is necessary to understand several terms. These are

- Population size, n;
- Degrees of freedom, v;
- Level of confidence; and
- Level of significance.

The population size, n, is the number of samples tested. The degrees of freedom, v, is just n minus 1. The degrees of freedom are used to enter the table. The level of confidence and significance are related. A level of confidence is chosen by the investigator and is typically either 95 or 99 percent. This is a measure of how sure the investigator is that the final conclusion is correct. The level of significance is a measure of risk associated with a Type I error (i.e., rejecting a hypothesis when it is true). If investigators are 95 percent confident that their conclusions are correct, they are also willing to risk a 5 percent chance of a wrong conclusion. This 5 percent is the level of significance.

A conclusion is drawn by comparing the two *F*-values. The criteria for conclusions are the same as for the *t*-statistic:

1. If the calculated *F*-value is greater than the table value, there is a statistical difference between the column (or row) means.
2. If the calculated *F*-value is less than the table value, there is no reason to suspect a difference between the column (or row) means.

The interaction between individual gauges and individual test sites was not considered because an independence was assumed between the variables.

Ratio of Variances

Data bases with different variables, such as mat conditions, are compared by calculating an *F*-value. The *F*-value is a ratio of variances (i.e., standard deviation squared) and is calculated by

$$F\text{-value (calculated)} = s_1^2/s_2^2$$

where s_1^2 equals the largest of two variances being evaluated, and s_2^2 equals the variance of the other population.

A table *F*-value is then found and conclusions are drawn in a way similar to that used for the two-way ANOVA.

EVALUATION OF TEST RESULTS

Lengths of Readings

The first step in analyzing the data was to compare the densities determined by the three test durations: a 15-sec, 1-min, and 4-min density reading. A paired *t*-test was used for this comparison (Table 1) (*3*). A 99 percent significance level was used to determine the table *t*-value.

In all cases for all field locations there was no statistical difference between the 15-sec, 1-min, or 4-min readings. Because densities were not significantly different, regardless of length of time used to generate the reading, further analyses were limited to the 1-min reading. The 1-min reading was chosen because it was the one most commonly used in normal field practice.

Gauge and Site Difference

A two-way ANOVA was performed; the hypotheses tested by this analysis were as follows:

1. Did each gauge provide a statistically similar density value?
2. Was each test site on a specific mat representative of the same material?

The results are presented in Tables 2 and 3. At a 99 percent confidence level, all gauges and all test sites are significantly different. In other words, gauges provide significantly different density readings, and the test sites were not replicates of the same material as they were originally intended to be.

Within- and Between-Laboratory Differences

Because the test sites were statistically different, determining the within- and between-laboratory variance for the test method became difficult. The formulas for establishing these test variances are prescribed in ASTM C802, but this statistical approach assumes replicates of the same material. Because each test site was different there were no replicates in any of the data bases.

Within- and between-laboratory variances calculated by the ASTM method include not only testing variations but construction and materials variations as well (see Table 4). *F*-values were calculated and compared with table *F*-values to demonstrate the differences in variances when construction variables are included. Because the object of the research was to determine the variances associated with the test method only, no further analysis of these calculations will be discussed in this paper.

A different statistical approach was used to determine the variance inherent in the test method itself. A standard deviation for each test site was determined (see Table 5). Variances, calculated from these standard deviations, for each test site for a specific mat condition and location were then averaged. This provided the between-laboratory variance, test method only, shown in Table 6, which indicates that the test method only variances

1. Were different for mats 3.5 in. thick or greater;

TABLE 1 STATISTICAL EVALUATION OF LENGTH OF READINGS FOR DENSITIES DETERMINED BY NUCLEAR DENSITY GAUGES (99 PERCENT CONFIDENCE)

Description	*n*	Calculated *t* Values	Table *t* Value	Conclusion
3½ in. thick or greater AC mat				
Galveston, Texas				
15 sec vs. 1 min	40	2.46	2.714	No difference in densities
1 min vs. 4 min	40	−0.86	2.714	
McLean, Virginia				
15 sec vs. 1 min	50	1.45	2.682	No difference in densities
1 min vs. 4 min	55	1.51	2.671	
2½ in. thick or less AC mat				
Galveston, Texas				
15 sec vs. 1 min	35	0.16	2.714	No difference in densities
1 min vs. 4 min	30	1.43	2.714	
McLean, Virginia				
15 sec vs. 1 min	50	1.68	2.682	No difference in densities
1 min vs. 4 min	55	1.69	2.671	
Reno, Nevada				
15 sec vs. 1 min	28	0.23	2.771	No difference in densities
1 min vs. 4 min	20	−0.14	2.878	
Surface texture				
Sanded				
15 sec vs. 1 min	14	−0.21	3.012	No difference in densities
1 min vs. 4 min	10	1.48	3.250	
Unsanded				
15 sec vs. 1 min	14	−0.34	3.012	No difference in densities
1 min vs. 4 min	10	0.80	3.250	
Sealed surface				
15 sec vs. 1 min	14	1.82	3.012	No difference in densities
1 min vs. 4 min	10	0.66	3.250	

TABLE 2 STATISTICAL EVALUATION (TWO-WAY ANOVA) OF NUCLEAR DENSITY GAUGES (95 PERCENT CONFIDENCE)

Description	Degrees of Freedom	Calculated *F*-Values	Table *F*-Value	Conclusion
$3^1/_2$ in. thick or greater AC mat				
Galveston, Texas	7, 28	17.90	2.36	All gauges are different
McLean, Virginia	10, 40	7.88	2.08	
$2^1/_2$ in. thick or less AC mat				
Galveston, Texas	7, 28	6.37	2.36	All gauges are different
McLean, Virginia	10, 40	7.59	2.08	
Reno, Nevada	7, 21	36.69	2.49	
Surface texture				
Sanded	1, 7	24.08	3.79	All gauges are different
Unsanded	1, 7	91.20	3.79	
Sealed surface	1, 7	52.17	3.79	All gauges are different

TABLE 3 STATISTICAL EVALUATION (TWO-WAY ANOVA) OF TEST SITES FOR NUCLEAR DENSITY STUDY (95 PERCENT CONFIDENCE)

Description	Degrees of Freedom	Calculated *F*-Values	Table *F*-Value	Conclusion
$3^1/_2$ in. thick or greater AC mat				
Galveston, Texas	4, 28	12.82	2.71	All test sites are different
McLean, Virginia	4, 40	55.21	2.61	
$2^1/_2$ in. thick or less AC mat				
Galveston, Texas	4, 28	17.21	2.71	All test sites are different
McLean, Virginia	4, 40	23.14	2.61	
Reno, Nevada	3, 21	6.54	3.07	
Surface texture				
Sanded	1, 7	94.32	5.59	All test sites are different
Unsanded	1, 7	295.90	5.59	
Sealed surface	1, 7	114.39	5.59	All test sites are different

TABLE 4 VARIANCES AND *F*-VALUES INCLUDING CONSTRUCTION VARIATIONS CALCULATED ACCORDING TO ASTM C802 (95 PERCENT CONFIDENCE)

Description	*n*	Variance	Calculated *F*-Value	Table *F*-Value
Within laboratory variance (ASTM C802)				
$3^1/_2$ in. thick or greater AC mat				
Galveston, Texas	40	5.83	1.03	1.63
McLean, Virginia	55	6.03		
$2^1/_2$ in. thick or less AC mat				
Galveston, Texas	40	12.50	4.06 Tex./Nev.	1.79
McLean, Virginia	55	7.75	2.52 Va./Nev.	1.76
Reno, Nevada	32	3.08	1.62 Tex./Va.	1.62
Surface texture				
Sanded	16	17.60	1.53	2.40
Unsanded	16	27.00		
Sealed surface[a]	16	10.80	3.51	2.01
Between laboratory variance (ASTM C802)				
$3^1/_2$ in. thick or greater AC mat				
Galveston, Texas	40	14.31	1.87	1.63
McLean, Virginia	55	7.46		
$2^1/_2$ in. thick or less AC mat				
Galveston, Texas	40	17.65	1.70 Nev./Va.	1.67
McLean, Virginia	55	11.65	1.52 Tex./Va.	1.76
Reno, Nevada	32	19.77	1.12 Nev./Tex.	1.74
Surface texture				
Sanded	16	34.33	1.73	2.40
Unsanded	16	59.51		
Sealed surface[a]	16	29.38	1.49	2.01

[a] The unsealed surface was the 2.5-in. Reno, Nevada, mat.

TABLE 5 STATISTICS FOR INDIVIDUAL TEST SITES (1-MIN READING)

Test Site	Number of Data Points	Average (pfc)	Standard Deviation (pfc)
Galveston, Texas			
1	8	139.9	3.44
2	8	140.8	3.86
3	8	140.2	3.46
4	8	136.7	2.89
5	8	142.2	3.17
6	8	136.6	1.81
7	8	134.7	3.16
8	8	140.2	3.58
9	8	140.0	3.29
10	8	141.7	3.12
McLean, Virginia			
1	11	155.8	1.56
2	11	155.4	1.84
3	11	155.4	1.32
4	11	156.8	1.39
5	11	151.0	1.62
6	11	149.6	2.55
7	11	146.0	3.79
8	11	150.9	1.72
9	11	146.0	1.44
10	11	150.0	1.98
Reno, Nevada			
1	8	133.0	3.56
2	8	132.4	4.48
3	8	130.3	3.62
4	8	132.8	4.17
5	8	130.0	3.05
6	8	124.3	4.60
7	8	124.6	4.95
8	8	117.3	5.75
9	8	130.0	4.18
10	8	134.5	3.95

2. Varied, depending on location, for mats 2.5 in. thick or less;
3. Were the same for either sanded or unsanded surfaces; and
4. Were the same for either sealed or unsealed surfaces.

TABLE 7 BULK SPECIFIC GRAVITIES OF CORES

Description	Bulk Specific Gravity				
$2^1/_2$ in. thick or less					
Galveston, Texas	140.50	140.52	146.45	145.67	146.27
McLean, Virginia	148.01	144.01	150.13	146.14	154.50
Reno, Nevada	136.03	136.48	135.41	135.61	
$3^1/_2$ in. thick or greater					
Galveston, Texas	147.03	145.29	146.25	141.04	147.48
McLean, Virginia	158.81	154.81	155.31	155.88	155.56

Laboratory (Cores) Versus Field Results

The next task was to determine the correlation between the BSGs of the cores and the nuclear density gauge readings. Again, only the 1-min readings were used for comparison. Because the gauges were statistically different, each gauge had to be compared individually with the BSGs of the cores. The BSGs of the cores for selected locations are shown in Table 7. Correlation between the nuclear gauges and the cores was accomplished by calculating regression equations for each mat condition for each gauge. Because the sanded versus unsanded surfaces and the coal tar sealer did not significantly affect the variances, these test sites were eliminated from the regression calculations.

Regression equation constants are shown in Table 8. Several interesting observations can be made from an examination of these results. First, slopes of the regression lines (i.e., *b*) can be either close to zero or negative (see Table 8). This can be explained for the most part by looking at the densities as determined by the BSGs of the cores for each mat (see Table 6). The mats for both the 2-in. HMA over 5-in. HMA base for McLean, Virginia, and the 2.5-in. HMA over gravel for Reno, Nevada, show very little difference in densities between test sites determined from BSGs of cores. The resulting attempt to develop a regression equation for a point explains the erratic regression results. Regression equation comparisons were limited to those mats exhibiting a larger range of densities.

Comparisons limited to the 2.5 in. over gravel mats for Texas and Virginia and the 3.5-in. Texas mat show it is quite

TABLE 6 AVERAGE PER SITE VARIANCES AND *F*-VALUES (VARIANCES FOR TEST METHOD ONLY: 95 PERCENT CONFIDENCE)

Description	*n*	Variance	Calculated *F*-Value	Table *F*-Value
Between laboratory variance-test method only				
$3^1/_2$ in. thick or greater AC mat				
Galveston, Texas	40	11.42	4.72	1.63
McLean, Virginia	55	2.42		
$2^1/_2$ in. thick or less AC mat				
Galveston, Texas	40	9.33	3.04 Nev./Va.	1.67
McLean, Virginia	55	5.96	1.94 Tex./Va.	1.76
Reno, Nevada	32	18.09	1.57 Nev./Tex.	1.74
Surface texture				
Sanded	16	17.41	1.89	2.40
Unsanded	16	32.87		
Sealed surface[a]	16	18.80	1.04	2.01

[a] The unsealed surface was the 2.5-in. Reno, Nevada, mat.

possible to achieve a coefficient of determination (r^2) of .80 to .90 (see Table 8). Yet examination of the regression constants shows a wide range of y intercepts. This is further evidence that each gauge, although capable of producing accurate results, does so in an individual manner different from other gauges.

A visual comparison of three correlations between BSGs of cores and nuclear gauge readings is presented in Figures 1 and 2. Individual nuclear density readings for three laboratories are shown in Figure 1. This figure shows what appears to be little correlation between nuclear density readings and densities of cores. Figure 2 separates these data into individual regression lines for each laboratory. The multitude of y-intercepts should be noted. The laboratories selected for this comparison had gauges that produced at least a .80 r^2.

Although a gauge can produce an r^2 of .80 to .90, the same gauge does not appear to give the same r^2 when the mat conditions are changed (see Table 8 and Figure 3). Even when the gauges yield acceptable r^2 values, the regression equations appear to be different for each mat condition. This variation is shown in a comparison of Figure 2 with Figure 4. The same gauges produced the regression lines shown in these figures; only the mat conditions changed. An analysis of covariance to determine whether the slopes and intercepts were statistically different was not within the scope of this research program. Such an analysis should be conducted before definite conclusions can be stated.

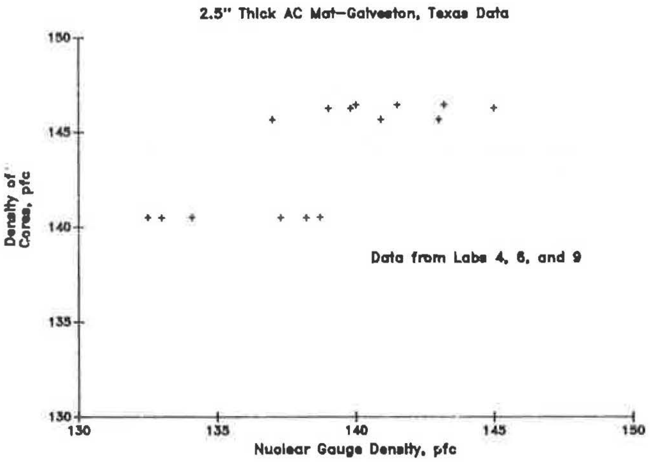

FIGURE 1 Comparison of core density with nuclear gauge density.

The wide range of r^2 values prompted a search for possible causes. Comparisons were tried for r^2 and standard counts (see Table 9 and Figure 5), date of last calibration (Table 9 and Figure 6), and average of the difference between each gauge's density reading and the corresponding BSG (Table 9 and Figure 7). No trend between r^2 and either standard count or date of calibration was evident. Gauges that yielded the largest average difference between nuclear density

TABLE 8 REGRESSION EQUATION CONSTANTS FOR EACH NUCLEAR DENSITY GAUGE FOR 2½ IN. THICK OR LESS AND 3½ IN. THICK OR GREATER MATS

Laboratory Identification Number	2½ in. thick or less			3½ in. thick or greater		
	r^2	a	b	r^2	a	b
Galveston, Texas						
1	.74	25.301	0.850	.99	–	–
3	.18	87.166	0.423	.82	2.431	1.061
4	.95	24.075	0.879	.45	30.660	0.844
6	.94	2.530	0.998	.78	27.335	0.831
9	.82	16.622	0.917	.83	18.519	0.898
10	.30	99.233	0.324	.19	80.920	0.456
11	.82	47.858	0.691	.31	83.562	0.441
12	.88	34.055	0.782	.35	77.935	0.479
McLean, Virginia						
13	.27	46.303	0.672	.08	118.030	1.061
14	.64	−103.763	1.695	.01	165.080	−0.058
15	.48	−10.497	1.066	.11	127.352	0.184
16	.05	106.509	0.287	.01	150.756	0.034
17	.44	−10.893	1.066	.11	123.628	0.209
18	.16	−40.092	1.265	.17	122.884	0.214
19	.81	0.180	1.021	.15	121.251	0.227
20	.57	61.127	0.598	.02	169.735	−0.089
21	.85	−50.880	1.362	.35	91.389	0.423
22	.59	−83.062	1.557	.02	142.300	0.089
23	.71	−51.262	1.338	.01	167.464	−0.073
Reno, Nevada						
27	.22	113.182	0.171			
29	.55	166.035	−0.244			
30	.62	179.059	−0.316			
31	.01	138.445	−0.020			
32	.71	79.274	0.426			
33	.34	119.900	0.121			
34	.08	143.666	−0.058			

NOTE: Regression equation: $y = a + bx$, where a equals y-intercept and b equals slope.

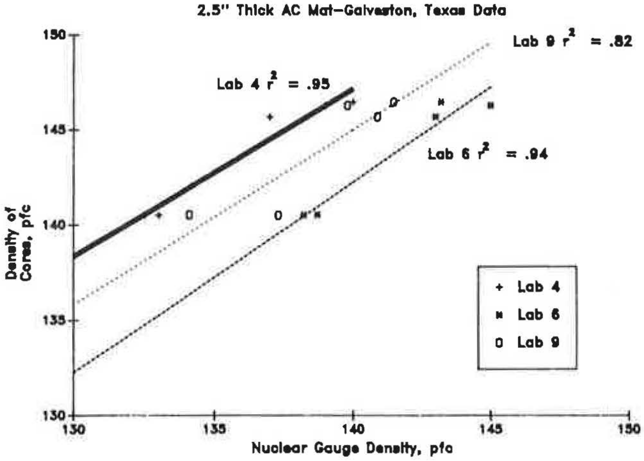

FIGURE 2 Regression lines for three gauges.

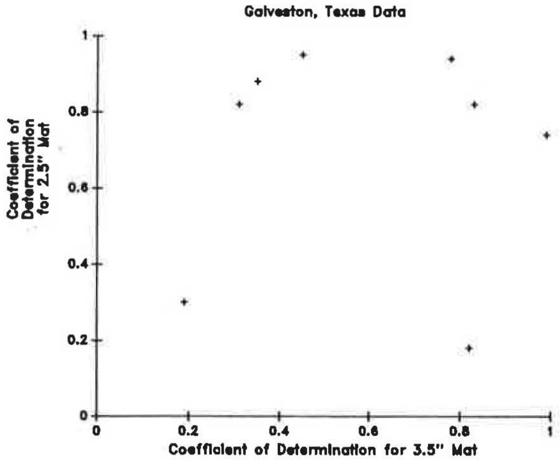

FIGURE 3 Comparison of coefficients of determination for various mat conditions.

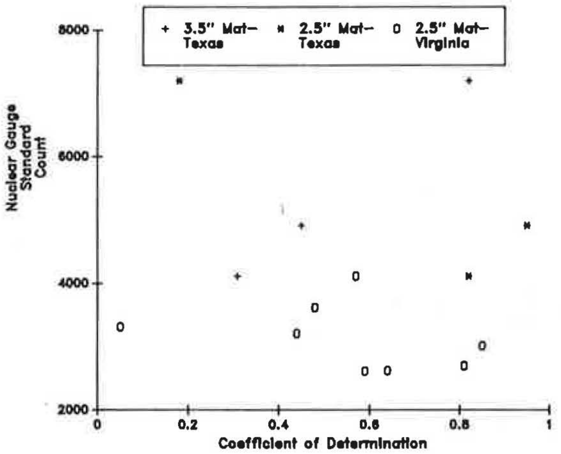

FIGURE 5 Comparison of coefficient of determination with gauge standard counts.

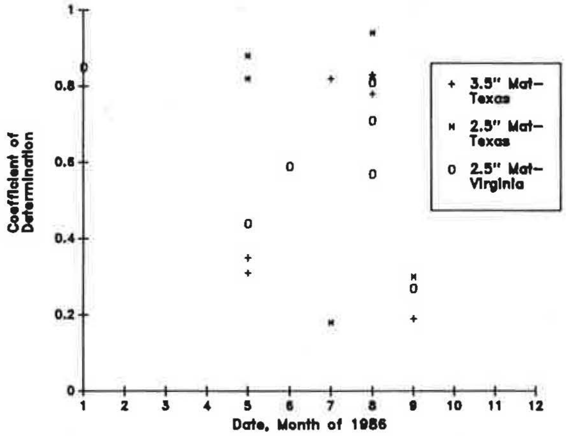

FIGURE 6 Comparison of coefficient of determination with date of last gauge calibration.

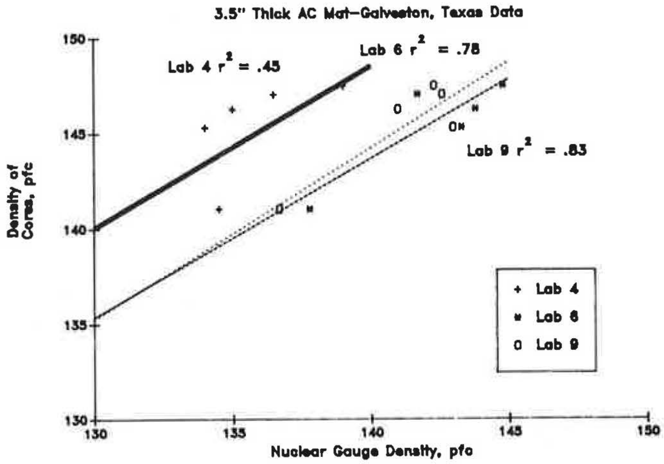

FIGURE 4 Regression lines for three gauges: 3.5-in-thick AC mat.

TABLE 9 COMPARISON OF COEFFICIENT OF DETERMINATION, STANDARD COUNTS, CALIBRATION DATES, AND AVERAGE DIFFERENCES BETWEEN BULK SPECIFIC GRAVITIES OF CORES AND NUCLEAR DENSITY READINGS

Laboratory Identification Number	r^2		Standard Count	Calibration Date	Average Difference Between Core BSG and Gauge	
	2½ in.	3½ in.			2½ in.	3½ in.
Galveston, Texas						
1	.74	.99	–	–	4.6	5.4
3	.18	.82	7200	7-23-86	9.4	10.6
4	.95	.45	4912	–	7.0	9.6
6	.94	.78	–	8-1-86	2.2	3.1
9	.82	.83	–	8-85	5.0	4.3
10	.30	.19	–	9-3-86	8.0	4.4
11	.82	.31	4110	5-86	4.4	5.5
12	.88	.35	–	5-86	3.0	4.8
McLean, Virginia						
13	.27		–	9-9-86	–3.7	
14	.64		2624	–	–0.2	
15	.48		3618	–	–0.7	
16	.05		3311	–	1.7	
17	.44		3208	5-24-86	–1.0	
18	.16		–	1985	–0.6	
19	.81		2699	8-86	3.3	
20	.57		4114	8-30-86	2.2	
21	.85		3015	1-20-86	2.2	
22	.59		2616	6-9-86	–0.2	
23	.71		–	8-86	–0.7	

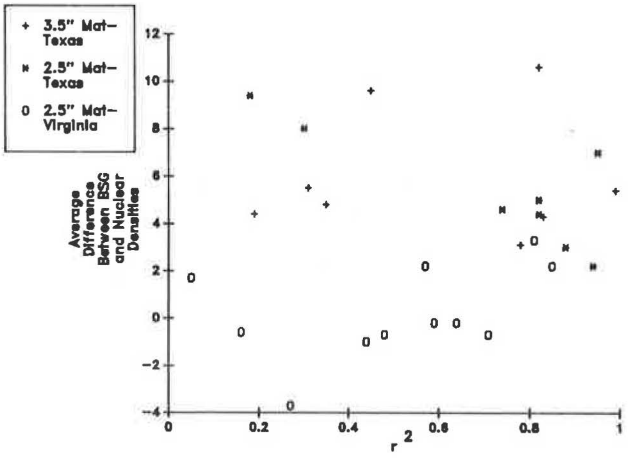

FIGURE 7 Comparison of coefficients of determination with average differences between BSG and nuclear densities.

reading and the corresponding BSG of the core could provide results just as accurate as those with the least difference.

CONCLUSIONS

Conclusions from this research are as follows:

1. Nuclear gauge reading durations of 15 sec, 1 min, or 4 min do not produce significantly different density readings.
2. Variance in density measurements, calculated in any manner, is a function of specific site conditions.
3. Sealing the surface of a pavement with a coal tar does not influence variance.
4. Each gauge, although capable of providing accurate correlations with BSG, appears to have its own individual regression equation.
5. Gauge regression equations appear to be dependent on site conditions.
6. Neither standard count nor date of calibration appears to be related to the r^2 of a given gauge.
7. There appears to be no relationship between the r^2 and the average of the difference between each core density and its corresponding nuclear gauge reading.

ACKNOWLEDGMENTS

The sponsorship of this research program by the National Asphalt Pavement Association is gratefully appreciated. This research project could not have been successful without the generous donation of technician time and equipment by all the participating laboratories.

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Publication of this paper sponsored by Committee on Quality Assurance and Acceptance Procedures.