DENSITY TEST STUDY

by

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Senior Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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ABSTRACT

This report presents the results of an investigation of the comparison of percent density determinations between dry, 4 in. square sawed samples and 4 in. wet cores measured in both the field and the lab. Recommendations are given concerning the relationship between one sample per test site and more than one, and how to estimate the maximum theoretical specific gravity used as a basis for the percent density. It is concluded that there is comparability between the percent density results from the dry plugs and those from the wet plugs once the latter are properly oven dried. However, because the percent density of the sawed plugs can be determined in the field, use of this method is recommended.

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INTRODUCTION

Virginia has used dry, sawed plugs in determining the density of bituminous concrete let to contract through maintenance schedules since 1978. The specification under which density has been accepted was developed based on the specific gravity of one plug per test site as determined by weighing in water and weighing in air.

The use of this specification, which includes both positive and negative price adjustments depending upon the distribution of the density results, has apparently resulted in an increased average density level and reduced variability. However, several questions have arisen as to how well the test procedure measures the air void content of the pavement.

Several pavements for which the average density results were in the 92% to 94% maximum theoretical density range (i.e., 6% to 8% air void content) have shown evidence of taking on quite a bit of water, particularly pavements made with I-2 mixes. This evidence indicates that the bulk density as determined by weighing in air and in water does not adequately measure the void content of the mix. Both ASTM(1) and AASHTO recommend using either paraffin-coated specimens (D 1188, T166) or saturated surface dry (SSD) specimens (D 2726, T166) for the determination of percent air voids. Since the use of paraffin-coated specimens is impractical in the field, it was decided that a study should be undertaken to compare specific gravities obtained by the SSD method with the bulk specific gravities determined as previously described.

Also, contractors have questioned if the use of dry, sawed plugs, even when cooled by propane, dry ice, or CO_2, may produce erroneous specific gravity results because of possible deformation. The question, then, is, Will wet cores produce more accurate specific gravity results than will dry, sawed plugs?

Other questions of concern are as follows:

1. Does the use of the average of two plugs per test site appreciably reduce the standard deviation as compared to the use of a single plug per test site?

2. Since the maximum theoretical specific gravity (MTSG) determined by the Rice method (ASTM D 2041, AASHTO T209) changes as the mix changes -- i.e., as the asphalt content and aggregate proportions change -- what MTSG should be used to determine the percent density?

PURPOSE

This study was initiated at the request of the Bituminous Research Advisory Committee to determine --

1. if bulk density accurately measures the air void content,

2. if wet cores more accurately measure the air void content than dry, sawed plugs,

3. if averaging the results of two plugs per test site reduces the standard deviation of the population over that obtained by using a single plug per test site, and

4. the MTSG that should be used to determine percent density.

STUDY APPROACH AND DISCUSSION

The study was conducted using historical data and data obtained from a research study.

Analysis of Historical Data

The historical data were used to estimate the standard deviation of the population obtained by averaging the results of tests of two sawed plugs per test site as is now a common procedure. Two other estimates of the standard deviation of the population were also made. One used the first individual test result and the other used both test results as individuals.

The definition of acceptable product in the specification was based on a standard deviation of 1.3% density as determined using one sample per test site, with the samples having been collected throughout the state. The analysis tested the statistical theory that predicts that the average of two samples per test site will reduce the estimated standard deviation below that obtained from the results of a single sample per test site.

The reason for taking two samples per test site was to reduce the within test variability, and common practice was to discard the results if the two samples differed by 2.0% or more.

The determination of the relationship between standard deviations of single samples and average of two samples was made in an analysis of 1983 data. Maintenance schedule data sheets were obtained from three districts and standard deviations were calculated by four methods. The standard deviations of the average of the two results per site (as in the present specification) were available from the computer printouts. Standard deviations were also calculated for the first result and for the two results per site used individually. Average standard deviations between the two results per test site were also calculated to obtain, in effect, a determination of the within test variability.

The historical data also presented the opportunity to examine the best method of determining what MTSG should be used.

Research Study

The research study required field sampling and field and laboratory testing. Eight projects using an I-2 mix, six with S-5 mix, and one with S-6 mix were selected for the study, and each project was sampled at four locations. At each location two 4 in. x 4 in. dry sawed and two 4 in. wet core samples were taken. All samples were weighed in air and water to obtain bulk specific gravities then were surface dried and reweighed in air to obtain the SSD specific gravity in the field. This provided the data necessary for calculating the bulk and SSD specific gravities for the dry, sawed plugs. The determination of bulk and SSD specific gravities of the cores is more complicated. Because the coring operation forces water into the voids and this water must be removed to determine the dry weight, any specific gravities based on field measurements of cores will be inaccurate. The field information obtained in this study was gotten by determining how much water was forced into the cores. The specific gravities for the cores reported as field results are actually based on the oven dried weights obtained in the lab. As a practical matter it is illogical to make any field measurements on the cores since they contain water at that stage and must be taken into the lab to obtain the dry weights. Once in the lab, more accurate measurements can be made and thus the calculation of percent compaction will, in all probability, be more accurate.

All samples were brought into the lab, weighed in air, weighed in water, surfaced dried and reweighed, and, finally, dried in the oven at 230°F to a constant weight that was used as the dry weight of all laboratory results and of the field cores. (ASTM D 2726)

The primary considerations in this phase of the study were --

1. the difference in air voids (or, conversely, the percent density), as measured by the bulk and SSD methods, of the S-5 and I-2 mixes,

2. the voids filled with water by the wet coring method, and

3. the relationship between the results for dry, sawed samples and those wet cored.

For accurate estimates of the void content, the specific gravity should be based on the dry weight and SSD volume. The SSD volume is used because it measures the entire volume while the bulk volume measures only the solids and impermeable voids, and therefore underestimates the volume by not including the permeable voids.

RESULTS

Estimates of Standard Deviation

The average standard deviations are shown in Table 1.

Table 1

Average Standard Deviations
Percent Maximum Theoretical Density

District	σ_1[a]	σ_{all}[b]	$\sigma_{\bar{x}}$[c]	σ_w[d]
1	1.08	1.10	1.04	0.18
2	1.18	1.15	1.05	0.47
3	1.29	1.29	1.25	0.46

[a] σ_1 = standard deviation of first plug tested

[b] σ_{all} = standard deviation of both plugs individually

[c] $\sigma_{\bar{x}}$ = standard deviation of average of two plugs

[d] σ_w = average standard deviation within test site

Since the concept of the source of variability can be difficult to understand, additional explanation may be helpful. σ_1 and σ_{all} measure the overall variability; i.e., the variability contributed by the entire system. $\sigma_{\bar{x}}$, on the other hand, measures only the variability between test sites; i.e. it does not include any variability within test sites. σ_w is the variability due to the difference between the two tests at each test site.

The standard deviations are related by the formula

$$\sigma^2 \text{ overall} = \sigma^2 \text{ between test sites} + \sigma^2 \text{ within test sites,}$$

where

σ^2 overall = σ^2_1 or σ^2_{all},

σ^2 between test sites = $\sigma^2_{\bar{x}}$, and

σ^2 within test sites = σ^2_w .

If the σ_{all} is used as the estimate of the overall variability ($\sigma_{overall}$) in the above equation together with the within test variability (σ_w) to predict the between test variability ($\sigma_{\bar{x}}$), the relationships shown in Figure 1 are determined.

This figure shows, for example, that District 1 with a measured between test site variability ($\sigma_{\bar{x}}$) of 1.08 is very close to the predicted between test site variability of 1.06.

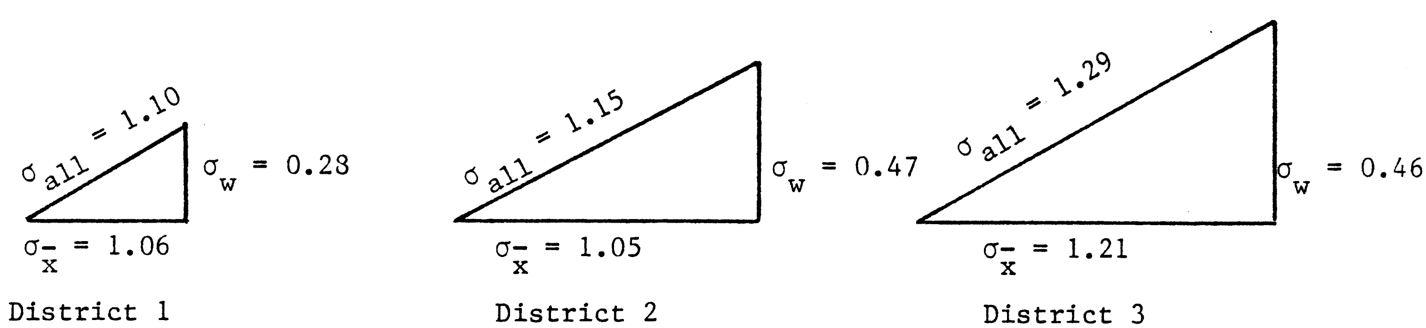

Figure 1. Relationship of standard deviations.

This analysis indicates several things. One, there is a great difference in within test site variabilities between District 1 and Districts 2 and 3. District 1 operates differently than the other two in that it has two material technicians that run all the density tests, whereas the other two districts rely on field inspectors to run the tests. This means that in Districts 2 and 3 there are many more operators and many more pieces of equipment, both of which influence variability.

Also, as shown in Figure 1 the standard deviation now being used is the between test site variability ($\sigma_{\bar{x}}$) as opposed to the overall variability. From a strictly statistical standpoint it does not appear to be efficient to take two samples at each location, since the between test site variability is so much larger than the within test site variability. However, from an engineering standpoint it does not take a great deal of time to take two samples from the same location and test both. The only reason for taking two samples per test site is to obtain the difference between the two samples as an indication of damaged or variable samples. If two samples are taken at each site, it seems logical to use each result individually in order to get a better estimate of the overall variability as compared to the between test site variability now being used.

Maximum Theoretical Specific Gravity

When the historical data supplied by Districts 2 and 3 in which the percent densities were obtained by bulk specific gravities run in the field were compared to those based on the SSD specific gravity run in the lab, it was found that the latter used a different MTSG than the field.

The MTSG, as mentioned previously, will change with the normal variability in asphalt content and the specific gravity of the aggregate blend. Therefore, there is no single MTSG but, as in percent density, a population of MTSG's with an average and standard deviation. The best estimate of the MTSG, which should be the one on which the percent density is based, is the population average. However, because short runs or changes can occur in the mix within a given job mix, a moving average may be the most appropriate average to use.

The historical data previously mentioned indicated that the MTSG used by the field was supplied by the district laboratory and was changed periodically; however, the one used in the laboratory was obtained on the plugs on which the percent density was measured. Therefore, there was a difference between the MTSG's used in the comparison. The average difference was 0.010, which can change the percent density by 0.4%.

To obtain the best estimate of the MTSG, it is recommended that a moving average be used under the following guidelines. At the start of the season, use the best available estimate of the MTSG. This may be the last MTSG used the previous year if the job mix and source of aggregates have not changed. If it is believed that this MTSG is not accurate and no mix can be obtained on which to run an MTSG, a calculated MTSG based on the job mix formula can be used at the start. However, this should not be used more than one or two days, and as soon as possible an MTSG should be run on the mix. Then, the next MTSG should be averaged with the first . This should be continued until 5 values have been averaged. When the sixth value is obtained, the first should be dropped and the average of the 2nd through 6th should be used. An example of this procedure is shown in Table 2, where it can be seen that the running average changed 0.023 over the time span of the ten MTSG results, and that the running average started high, decreased, and started getting higher again. The change of 0.023 can affect the percent density by about 0.8%. The decrease followed by an increase are typical of any normal distribution. Some districts provide the field MTSG values calculated to the hundredths rather than thousandths as shown in the table. Since the field scales weigh only to the nearest gram, specific gravities should be calculated to only three significant figures. Thus, the MTSG calculated to the hundredths is consistent.

Table 2

Example of Moving Average, $\bar{X}_5$, for MTSG

Sample No.	MTSG	Total[a]		X_5 MTSG
1	2.685[b]	2.685		2.685
2	2.660	5.345	÷ 2 =	2.672
3	2.655	8.000	÷ 3 =	2.667
4	2.658	10.658	÷ 4 =	2.664
5	2.666	13.324	÷ 5 =	2.665
6	2.670	13.309[c]	÷ 5 =	2.662
7	2.681	13.330	÷ 5 =	2.666
8	2.674	13.349	÷ 5 =	2.670
9	2.682	13.373	÷ 5 =	2.675
10	2.685	13.391	÷ 5 =	2.678

[a]Total = sum of no more than five results

[b]Four significant figures can be used only if scales measure to 0.1g

[c]13.309 = 13.324 - 2.685 + 2.670

SSD Density Vs. Bulk Percent Density

Although the bulk density (as defined herein) has been used as the standard test for determining density under the specification, according to the ASTM and AASHTO the SSD density is more appropriate as an estimate of voids. The correlation of low voids with improved pavement performance was the basis for the specification. The first analysis made in the research study data was a comparison of the SSD vs. bulk densities of th sawed plugs as measured in the field. Table 3 shows the percent compaction of the bulk and SSD methods.

Table 3

Field Bulk vs. SSD Results on Sawed Plugs, Percent Compaction

Route	Bulk	SSD	Diff.
		I-2	
221	94.8	92.2	2.6
653	92.7	92.4	0.3
207	90.9	88.4	2.5
24	95.7	95.2	0.5
460	94.3	93.7	0.6
649	93.4	92.8	0.6
11	91.9	89.4	2.5
81	91.2	89.5	1.7
$\bar{X}$	93.1	91.7	1.4
		S-5	
58	93.3	91.7	1.6
8	94.1	93.3	0.8
699	90.2	89.6	0.6
17	90.9	90.7	0.2
95	93.3	92.8	0.5
29	91.1	89.6	1.5
$\bar{X}$	92.2	91.2	0.9
		S-6	
29	91.2	87.7	3.5

As the results in Table 3 indicate, the difference between the bulk and the SSD determinations varies considerably even within mix type. The greatest difference is 3.5% for the S-6 mix and the least is 0.2%for an S-5 mix.

Based on logic one would expect that the difference would be greater on mixes having the lower bulk percent compaction, because these would be expected to allow more water to enter the voids. This did not happen. There is no correlation within mix type between either measure of percent compaction and the differences. This means that it is not possible to obtain a correction factor from the bulk determination to use to obtain an estimate of the SSD density.

As expected, however, the S-6 and I-2 mixes have higher average differences than the S-5 mix because their gradations produce more open mixes.

Although determining the level of compaction in relationship to the specification was not part of this study, if the SSD method is used in the future, consideration must be given the maximum achievable absolute density.

The present target percent compaction of 92.5% will certainly be harder to obtain when the SSD method is used. Table 3 shows that for five of the eight I-2 mixes there would be no problem with a target value of 92.0% nor for two of the six S-5 mixes.

Although density variability was not measured in this study because of the few samples per project, the average standard deviation for the last year was 1.1%. Therefore, a slightly lower standard deviation than the one presently used should be considered.

It is, therefore, recommended that the specification require that density measurements be made by the SSD method and that an acceptable product be defined as a population average of 92.0% and standard deviation of 1.2%. This modified specification expressed in terms of acceptable product and with price adjustments is shown in Figure 2.

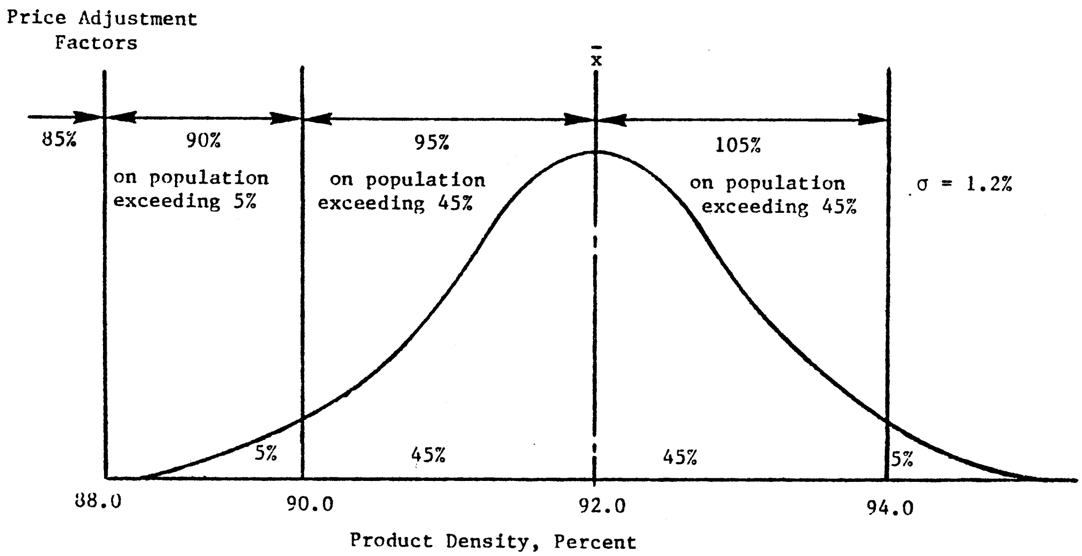

Figure 2. Acceptable product with price adjustment factors using SSD method.

Percent Density of Plugs, Field vs. Lab Results

Before comparing plug and core densities, it is of interest to compare the percent compaction results of the field tests and lab tests of the sawed plugs. For the lab percent compaction the plugs had to be dried to a constant weight to avoid any effects of weighing them in water in the field. Shown in Table 4 is a random example of the "dry" weights of the plugs from one project, first as an actual dry weight in the field, next as a pseudo dry weight in the lab in which the plugs still contained some water from the field weighing in water (this weight was obtained for explanatory purposes and was not used in any calculation), and, lastly, the dry weight from oven drying.

As Table 4 shows, the plugs contained an average of 0.4 gram of water when brought into the lab and weighed. During oven drying, the plugs lost an average of 0.4 gram to return to the same average as determined in the field. (This, of course, did not happen on an individual basis.) These results indicate that for this project (1) the field dry weights are accurate and (2) that after weighing in water the plugs must be thoroughly oven dried in the lab before an accurate dry weight can be determined. Although on average the plugs did not absorb much water in this project, on some projects as much as 8 grams were absorbed.

One more analysis is of interest before proceeding to a comparison of the percent compaction of the plugs. Since it is simple to obtain the dry weight in the field or in the lab, the only obstacle to obtaining an accurate specific gravity is in the volume measurement, and this is the cause of the difference between the bulk and SSD specific gravities. Table 5 shows the volume determinations for the plugs from the same project as above. Points of interest in these results are that the volumes measured by both the bulk and SSD methods compare well from field to lab, and (2) as expected, the SSD volumes are slightly higher than the bulk volumes, which results in less percent compaction and reflects the difference shown in Table 3. This difference between bulk and SSD volumes is greater in the more absorbent mixes.

The comparison between field and lab percent compaction results is shown in Table 6. These data confirm that the field measurements are as accurate as those made in the lab, particularly when the SSD method is used. Therefore, for sawed plugs either field or laboratory measurements can be used for the enforcement of specifications. It must be remembered, however, that if the samples are weighed in water in the field, they must be oven dried before specific gravities can be checked in the lab.

Table 4

Dry Weight of Plugs in Grams
Route 95 S-5

Sample	Field	Lab-Air Dried	Lab-Oven Dried
1A	911	910.4	910.3
B	903	903.8	903.8
2A	872	971.4	870.3
B	871	868.6	867.7
3A	919	921.8	921.5
B	991	991.4	991.2
4A	969	969.9	969.6
B	942	943.8	943.5
Average	922.2	922.6	922.2

Table 5

Volume Measurements of Plugs in cc
Route 95 S-5

Sample	Field Bulk	Field SSD	Lab Bulk	Lab SSD
1A	399	400	395.5	396.5
B	394	396	392.4	393.2
2A	392	396	394.7	397.5
B	392	396	392.7	395.3
3A	397	399	399.3	400.3
B	430	432	429.6	430.9
4A	430	432	428.9	430.3
B	416	418	417.3	418.4
Average	406.2	408.6	406.3	407.8

Table 6

Field vs. Lab Percent Compaction of Dry Plugs

Route	Bulk		SSD	
	Field	Lab	Field	Lab
I-2				
221	94.8	95.1	92.2	92.5
653	92.7	93.6	92.4	92.8
207	90.9	91.5	88.4	88.3
24	95.7	95.5	95.2	94.9
460	94.3	95.1	93.7	93.8
649	93.4	94.1	92.8	93.2
11	91.9	91.6	89.4	89.3
81	91.2	91.2	89.5	89.7
Average	93.1	93.5	91.7	91.8

Table 6 continued

Route	Bulk		SSD	
	Field	Lab	Field	Lab
		S-5		
58	93.3	94.0	91.7	92.1
8	94.1	93.7	93.3	93.0
699	90.2	90.6	89.6	89.6
17	90.9	91.2	90.7	90.8
95	93.3	93.3	92.8	93.0
29	91.1	91.4	89.6	88.8
Average	92.2	92.4	91.2	91.2
		S-6		
29	91.2	90.7	87.7	87.0

Plug vs. Core Comparison

As stated earlier, contractors have questioned if the use of dry sawed plugs, even when cooled properly, may produce erroneous specific gravities because of possible deformation. They apparently feel that drilling cores cooled with water will provide samples having less deformation.

As also stated earlier, the complicating feature of wet coring is the amount of water that is forced into the voids and effectively replaces air. For the specific gravity determination, the weight in air then must be an oven dry weight. This change in weight is shown in Table 7 by the weight in air in the field containing the water forced in by drilling, the weight in air in the lab that still contains some water, and, finally, the weight after oven drying. These three determinations can be compared to those for plugs shown previously in Table 4.

The average core weights in Table 7 show that the drilling forced 9.1 grams of water into the cores and that 3.9 grams still remained when the samples were first weighed in the lab. This water in the voids makes an appreciable difference in the weight of the specimens, which affects the percent compaction.

The data in Table 8 show that the volumes determined by the bulk method do not agree as closely as those determined by the SSD method. The SSD volume is also the correct volume; i.e., the volume including the voids permeated by water. On the other hand, the bulk volumes underestimate the true volume because the volume once occupied by voids is filled with water and is not measured.

Table 7

Dry Weight of Cores in grams
Route 95 S-5

Sample	Field	Lab-Air Dried	Lab-Oven Dried
1A	695	690.0	687.4
B	677	676.5	674.5
2A	605	595.7	590.3
B	602	593.7	587.6
3A	670	667.4	664.7
B	646	645.9	644.5
4A	685	676.0	670.5
B	680	673.3	667.9
Average	657.5	652.3	648.5

Table 8

Volume Measurement of Cores in cc

	Field		Lab	
Sample	Bulk	SSD	Bulk	SSD
1A	295	301	298.4	301.5
B	292	296	293.8	296.2
2A	256	271	264.4	271.1
B	255	269	264.1	271.5
3A	284	290	286.8	290.0
B	277	280	277.9	279.8
4A	288	302	294.1	300.6
B	287	300	293.1	299.2
Average	279.2	288.6	284.1	288.7

Table 9 shows the comparison between the plugs and cores based on SSD measurements. The results in Table 9 show that there is no significant difference between the percent compaction as measured by cores compared to that measured by plugs. Although the average results of the cores in the I-2 and S-5 mixes were slightly lower than the corresponding average results of the plugs, they were not significantly different.

Table 9

Plug vs. Core Comparison Using SSD, Percent Compaction

	Field			Lab		
Route	Plug	Core	Diff.	Plug	Core	Diff.
I-2						
221	92.2	92.0	-0.2	92.5	91.3	-1.2
653	92.4	91.9	-0.5	92.8	92.4	-0.4
207	88.4	88.9	+0.5	88.3	88.7	+0.4
24	95.2	94.6	-0.6	94.9	95.3	+0.4
460	93.7	93.8	+0.1	93.8	93.3	-0.5
649	92.8	92.5	-0.3	93.2	92.9	-0.3
11	89.4	89.0	-0.4	89.3	89.0	-0.3
81	89.5	89.5	0.0	89.7	89.6	-0.2
Average	91.7	91.5	-0.2	91.8	91.5	-0.3
S-5						
58	91.7	92.4	+0.7	92.1	92.8	+0.7
8	93.3	93.0	-0.3	93.0	93.2	+0.2
699	89.6	89.4	-0.2	89.6	89.4	-0.2
17	90.7	90.4	-0.3	90.8	90.2	-0.6
95	92.8	92.3	-0.5	93.0	92.3	-0.7
29	89.6	87.8	-1.6	88.8	87.4	-1.4
Average	91.2	90.9	-0.3	91.2	90.9	-0.3
S-6						
29	87.7	87.9	+0.2	87.0	87.5	+0.5

The practical conclusion to be drawn from the analyses is that either cores or plugs can be used to estimate the percent compaction of the pavement. However, if cores are used, they must be taken into a lab and thoroughly dried in an oven before a valid specific gravity determination can be made. Thus the time involved to produce a result becomes important.

CONCLUSIONS

1. The averaging of two density results does reduce the overall standard deviation and effectively determines a "between test" variability.

2. Different and variable maximum theoretical specific gravities are being used for determining percent density.

3. The SSD method of determining percent compaction results in a lower and more accurate value than does the bulk method presently used.

4. When weighed in water in the field, sawed plugs retain some of the water and it can be removed for laboratory testing only by thorough oven drying.

5. The volume determinations of sawed plugs made in the field and in the lab are equally valid. The volumes from the SSD determinations are significantly higher and more accurate than those of the bulk determinations.

6. For sawed plugs, field measurements are as accurate as laboratory measurements.

7. Wet core drilling forces an appreciable amount of water into the core and this can be removed only by thorough oven drying. This water in the core creates an error in any field weight in air measurement, which, in turn, would produce an error in a subsequent percent compaction determination.

8. Wet core drilling does not affect the volume determination of the core sample as much as it does the weight.

9. Samples taken by either dry sawing or wet coring produce comparable percent compaction results by the SSD method, when the wet core sample is thoroughly oven dried before the weight in air determination is made.

RECOMMENDATIONS

1. One 4-in. sample should be taken per test site. As an alternative, if it is judged that within test variability is a problem and that differences greater than 2.0% between two comparison samples will be discarded, then each density result should be used individually and not as an average as is now done.

2. A moving average of five maximum theoretical specific gravity determinations should be used to obtain a percent compaction.

3. The SSD method of determining the specific gravity should be used.

4. The desirable properties of percent compaction distributions should be modified to be an average of 92.0% and a standard deviation of 1.2% in conjunction with the SSD method, with price adjustments as shown in Figure 2.

5. Although both 4 in. square dry sawed samples and 4 in. core samples produce comparable results, because of the longer time to obtain the core results, it is recommended that the approved method continue to be the sawed plugs. Core samples, properly dried, may be used if a dispute arises concerning possible deformation of the plugs.

6. Because both sawed and cored samples are hard to remove from surface treated pavements, and because many of the roads carrying low traffic volumes have surface treatments prior to overlaying, the density specification should be waived on those roads having surface treated surfaces.

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