
# An Investigation of the Cause of Variation in HMA Bulk Specific Gravity Test Results Using Non-Absorptive Aggregates



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# An Investigation of the Cause of Variation in HMA Bulk Specific Gravity Test Results Using Non-Absorptive Aggregates

**Prepared for:**

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*OF THE NATIONAL ACADEMIES*

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# CHAPTER 1: INTRODUCTION AND RESEARCH APPROACH

## 1.1 INTRODUCTION

The Superpave[1] mix design method relies on the volumetric properties of Hot Mix Asphalt (HMA) *(1)*. The desired compaction levels in the laboratory mix design are achieved by the use of gyratory compactors in accordance with AASHTO T312, Standard Test Method for Preparing and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor (SGC) *(2)*. The design computations and volumetric properties for laboratory compacted specimens require calculation of the relative density from the bulk ($G_{mb}$) and maximum ($G_{mm}$) specific gravity determinations. The relative density is a key factor in judging the performance and controlling the construction of HMA pavement. This property of HMA is often written into specifications and used to determine pay factors. Reducing the variation in relative density test results will improve construction control and reduce the potential for disputes between contractors and users.

This study was conducted to investigate the cause of variation in $G_{mb}$ test results. Several methods were evaluated including AASHTO T166, Standard Method of Test for Bulk Specific Gravity of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens (Method A) *(2)*, and ASTM D6752, Standard Method of Test for Bulk Specific Gravity and Density of Compacted Mixtures Using Automatic Vacuum Sealing Method *(3)*. A better understanding of the methods currently in use and the factors that influence the variation of $G_{mb}$ values may help standards developers to identify those methods and factors that have the greatest potential for reducing the variation of relative density test results.

### 1.1.1 Problem Statement

The first phase of Project 9-26 conducted by the AASHTO Materials Reference Laboratory (AMRL), herein referred to as the Phase 1 study, was reported in NCHRP Web Document 54 *(4)* and resulted in precision estimates for ASTM Test Method D2041, Standard Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Mixtures *(3)*, T166, and T312. These estimates indicated that the within laboratory variation in the bulk specific gravity, $G_{mb}$, test results ($S_r$ = 0.008 for 12.5-mm mixtures and 0.013 for 19.0-mm mixtures) was much greater than the variation in the maximum specific gravity, $G_{mm}$, test results ($S_r$ = 0.002). Consequently, the variation in $G_{mb}$ test results contributes to a greater extent to the variation in resulting relative density values calculated from $G_{mm}$ and $G_{mb}$ test results. For this reason, the researchers focused on the variation in $G_{mb}$ test results and recommended further investigation to determine if the difference in the within-laboratory variation or repeatability ($S_r$) of $G_{mb}$ test results reflected problems with T166 or actual variation in the density of the specimens tested, introduced by the specimen fabrication process specified in T312.

[1] "The Superpave System™" was developed under the Strategic Highway Research Program (SHRP).

The Superpave specimens tested in the Phase 1 study were fabricated by each participant according to procedures specified in AASHTO T312. The maximum specific gravity and bulk specific gravity data from the Phase 1 study were used to calculate air voids, and a d2s multilaboratory precision estimate of 1.7% was determined from the resulting air void data. The majority of this error was attributed to variations in the bulk specific gravity reported by the participants. Before attempting to reduce the variability in air void calculations, it would be helpful to know how much of the variability resulted from the specimen fabrication process (T312) and how much is inherent in test method (T166).

### 1.1.2 Research Objectives

This phase of NCHRP Project 9-26, herein referred to as the Phase 2 study, had the following objectives:

(a) Conduct a round-robin test program to determine the variability of T166 test results using pre-compacted 150-mm diameter test specimens in an attempt to eliminate the variability associated with specimen fabrication.
(b) Attempt to identify the cause(s) of variation in T166 test results.
(c) Compare the bulk densities obtained using D6752 to those obtained using T166.
(d) Attempt to identify the cause(s) of variation in D6752 test results.
(e) Compare the bulk densities obtained using the Troxler Core Reader *(5)* (referred to as Core Reader in this report) to those obtained using T166 and D6752.

## 1.2 SCOPE OF STUDY

This work was limited to an evaluation of test procedures that provide information on the bulk density of HMA made with non-absorptive aggregates. The following conditions limited the scope of the study:

(a) Use materials that conform to the Superpave mix specification.
(b) Use only one source of relatively non-absorptive aggregate. Use a 19.0-mm coarse gradation, a 12.5-mm fine gradation, and 9.5-mm fine gradation as specified in MP2-00, Standard Specification for Superpave Volumetric Mix Design *(6)*.
(c) Use a single performance graded neat PG 64-22 binder from a single source.

Specific tasks included in the study were as follows:

Task 1 -- Selection of Laboratories
Task 2 -- Sample Preparation
Task 3 -- Specimen Preparation
Task 4 -- Prepare Test Data Forms
Task 4 -- Visit Laboratories and Obtain Test Data
Task 5 -- Condition and Monitor Test Specimens between Tests
Task 6 -- Analyze Test Results
Task 7 -- Prepare Final Report

# CHAPTER 2: EXPERIMENTAL PLAN

## 2.1 OVERALL PLAN

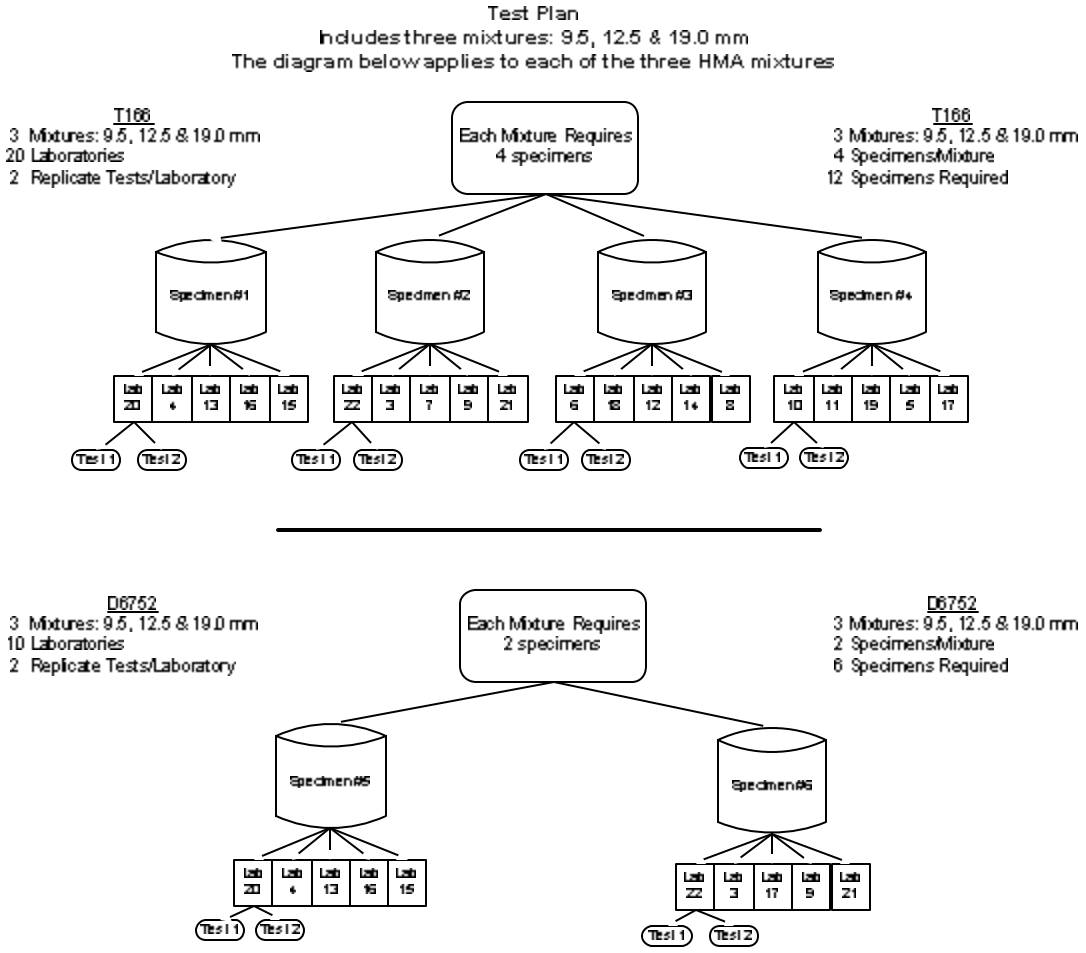
The overall experimental plan involved the following steps:

1. Design three Superpave mixtures using non-absorptive aggregate from the same source as used in Phase 1 of NCHRP 9-26. One mixture having a maximum aggregate size of 9.5 mm, another having a maximum aggregate size of 12.5 mm, and a third having a maximum aggregate size of 19.0 mm.
2. Prepare nine 150-mm diameter Superpave specimens for each mixture (9 X 3 = 27 compacted specimens).
3. Identify laboratories willing to participate in the study.
4. Identify four sets of specimens for T166 testing, each to include a 9.5-mm, a 12.5-mm, and a 19.0-mm specimen. *(3 specimens/set x 4 sets = 12 specimens)*
5. Identify two sets of specimens for D6752 testing, each to include a 9.5-mm, a 12.5-mm, and a 19.0-mm specimen. *(3 specimens/set x 2 sets = 6 specimens)*
6. Hold the remaining nine specimens, three for each mixture type, as spares, to replace any specimens that may become damaged.
7. Aluminum cylinders described in Section 2.4.3 were also taken to the laboratory to serve as control specimens.
8. Arrange to have an AMRL Laboratory Assessor visit each participating laboratory and invite the laboratory to perform tests on the appropriate specimen test set(s). Visit each laboratory twice. It is intended that the same specimens that were tested during the first visit be tested during the second visit.
9. Return the specimens tested to AMRL after each visit and condition them as described in Section 2.7 prior to the next visit.

The test plan is illustrated in Figure 1. The nested experiment was designed to permit separation of the effects of the T312 fabrication from the bulk specific gravity testing of the specimens. In general, test results include three components of error: a specimen component, a laboratory component and a test component. By fabricating all test specimens at the same facility using the same gyratory compactor, and by involving multiple specimens of each mixture in the test plan, it would be possible to minimize and measure the specimen component of error. By collecting and analyzing data from twenty laboratories for T166 the laboratory component of error (between laboratory error or reproducibility error) would be estimated. And, by having the laboratories perform replicate tests on each specimen, it would be possible to estimate the test component of error (within laboratory error or repeatability error).

The laboratory component of error (between laboratory error or reproducibility error) is of primary interest. This statistic would be compared to the T166 laboratory component statistic determined in the Phase 1 Study and any reduction in variability would be attributed to the specimen preparation procedure. An ideal experimental design would require all laboratories to test the same specimen of each material type. However, due to the time involved in conditioning a specimen after each test and the desire to evaluate

two test methods, T166 and D6752, it was decided to test six closely matched specimens of each material type. This experimental design will provide the data for the separate estimation of the three effects already noted, namely the specimen, the laboratory, and the test components. These components may be combined in various ways to answer the questions of interest in this study.



twenty laboratories able to conduct T166 and willing to participate, only ten were able to determine the bulk specific gravity of Superpave specimens according to ASTM D6752, the vacuum sealing method.

The twenty laboratories selected included nine State DOTs, two County materials test laboratories, seven private sector laboratories, AMRL, and an FHWA laboratory. Thirteen of the laboratories were accredited by the AAP for T166, seventeen received on-site assessments from AMRL, and nineteen participated in the AMRL HMA Gyratory Proficiency Sample Program.

## 2.3 SELECTION OF MATERIALS

### 2.3.1 Aggregates

The crushed limestone aggregate selected for the study came from a relatively uniform geologic formation of limestone in the Lafarge Stone Quarry located in Frederick, Maryland. The aggregate is being used in the on-going NCHRP Study 9-19, Superpave Support and Models Management, and was used in the NCHRP 9-26 Phase 1 study. Additionally, the State of Maryland has used the stone extensively in many of its highway projects and keeps a year-to-year record of the uniformity of material coming from the quarry that is measured in terms of tested properties. According to the records, the quarry has been in operation since 1859 and it has supplied about 150 million tons of stone since beginning operation.

Typical test properties of the coarse aggregate measured in the 2001-2002 timeframe and as recorded by the Maryland State Highway Administration are given below. The test methods used to determine the properties are not known.

- Bulk Specific Gravity = 2.71
- Percent Absorption = 0.3 percent
- Los Angeles Abrasion (percent loss) = 19 percent
- Loose Unit Weight = 87.8 pcf (1407 kg/m$^3$)
- Rodded Unit Weight = 95.7 pcf (1533 kg/m$^3$)

Testing performed on the aggregate by AMRL yielded the following results:

(a) Coarse Aggregate
- Water Absorption by AASHTO T85, Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate *(6)* = 0.5 – 1.0 percent
- Bulk Specific Gravity by AASHTO T85 = 2.67
- Effective Specific Gravity by AASHTO PP28, Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt (HMA) *(6)* = 2.71

(b) Fine Aggregate

- Water Absorption by AASHTO T84, Standard Method of Test for Specific Gravity and Absorption of Fine Aggregates *(2)* = 1.0 percent
- Bulk Specific Gravity by AASHTO T84 = 2.64

### 2.3.2 Asphalt Binder

The binder used in all three mixtures was a PG 64-22 grade asphalt binder obtained from the Chevron Refinery in Perth Amboy, New Jersey. This binder is one of the most commonly used grades in the United States and it has been used successfully on numerous research projects.

## 2.4 SPECIMEN PREPARATION

### 2.4.1 HMA Mixtures

The Superpave gyratory test specimens were prepared by AMRL in a laboratory located at the National Institute of Standards and Technology (NIST). Prior to compaction, loose HMA mixtures were individually prepared using procedures developed for the AMRL HMA Proficiency Sample Program *(7)*. The loose mixtures were then compacted using a Superpave Gyratory Compactor (SGC) according to the procedure described in T312.

The laboratory mix formulas shown in Table 1 were used to prepare the 9.5-mm, 12.5-mm, and 19.0-mm loose mixtures. Nine mixtures were prepared for each of the three mixture types. The 9.5-mm, 12.5-mm, and 19.0-mm mixtures resulted in the properties shown in Table 2.

**Table 1 – HMA Mixture Designs**

| Material | **9.5-mm Mix**, (g) | **12.5-mm Mix**, (g) | **19.0-mm Mix**, (g) |
|---|---|---|---|
| 19.0-mm aggregate | --- | --- | 1010 |
| 12.5-mm aggregate | --- | 450 | 990 |
| 9.5-mm aggregate | 480 | 740 | 460 |
| 4.75-mm aggregate | 1285 | 1265 | 545 |
| 2.36-mm aggregate | 1255 | 880 | 540 |
| Sand | 1500 | 1170 | 1155 |
| Mineral Filler | 150 | 185 | 20 |
| Binder | 230 | 200 | 195 |
| Total: | 4900 | 4890 | 4915 |

**Table 2 – HMA Mixture Properties**

| Property | 9.5-mm Mix | 12.5-mm Mix | 19.0-mm Mix |
|---|---|---|---|
| Design Asphalt Content (percent) | 4.69 | 4.09 | 3.97 |
| Effective Asphalt Content (percent) | 4.14 | 3.54 | 3.42 |
| Binder Absorption[1] (percent) | 0.6 | 0.6 | 0.6 |
| Max Specific Gravity[2] | 2.546 | 2.569 | 2.566 |
| Air Voids (percent) | 3.0 | 3.0 | 2.7 |

[1]Determined Using PP28 *(6)*
[2]Determined Using D2041 *(3)*

### 2.4.2 Gyratory Test Specimens

Each mixture was heated, mixed, and compacted according to T312. Each 150-mm diameter specimen was compacted to 100 gyrations using a SGC. Compacted specimens were permitted to cool in the mold for approximately fifteen minutes, then extruded from the mold. Once cooled, the bulk density of each specimen was determined according to T166.

The first attempt to prepare suitable test specimens failed. The resulting specimens were judged to be unsuitable because the variability in the bulk densities for each of the mixture types, summarized in Table 3, was greater than the variability of the bulk density obtained during the Phase 1 study. An investigation into the cause of the increased variability revealed that the technician proportioning the material for the mixtures weighed out the sand portion from a dry stockpile rather than using the miniature stockpile method described in AASHTO T248, Standard Method for Reducing Samples of Aggregate to Testing Size *(2)*, as required.

**Table 3 - Bulk Density of HMA Specimens from Failed First Attempt**

| 9.5 mm Specimens | 12.5 mm Specimens | 19.0 mm Specimens |
|---|---|---|
| 2.345 | 2.447 | - - - |
| 2.330 | 2.429 | 2.428 |
| 2.356 | 2.445 | 2.455 |
| 2.358 | 2.464 | 2.444 |
| 2.400 | 2.411 | 2.456 |
| 2.357 | 2.484 | 2.461 |
| 2.370 | 2.427 | 2.478 |
| 2.368 | 2.493 | 2.424 |

New specimens were prepared using the miniature stock pile method to obtain the sand portion. Table 4 shows the properties of the resulting specimens. The resulting variability in bulk densities was judged to be small enough to reveal the contribution of error due to the compaction process. Table 5 shows a comparison of the variability in specimen bulk densities resulting from the first and second preparation attempts.

From the nine specimens in each mixture type, six specimens were selected as primary test specimens based on the closeness of agreement between $G_{mb}$ values. The remaining specimens were held as spares. Four of the six primary test specimens associated with each mixture were identified as T166 test specimens, and two were selected for use as D6752 test specimens. Specimens were selected to minimize the difference in average bulk specific gravity between the two test groups. The specimens were labeled as indicated in Table 4.

**Table 4 -Gyratory Test Specimen Properties**

| Preparation Sequence | Specimen I.D. | | Start of Testing AMRL T166 $G_{mb}$ | End of Testing AMRL T166 $G_{mb}$ | Absorption (Percent) | $G_{mb}$ $S_r$ |
|---|---|---|---|---|---|---|
| | T166 | D6752 | | | | |
| **9.5-mm Specimens** | | | | | | |
| 1 | | | 2.454 | 2.451 | 0.211 | |
| 2 | | | 2.490 | 2.488 | 0.117 | |
| 3 | 2 | | 2.471 | 2.470 | 0.192 | |
| 4 | 1 | | 2.458 | 2.459 | 0.292 | 0.013 |
| 5 | | 6 | 2.479 | 2.481 | 0.167 | |
| 6 | 3 | | 2.478 | 2.475 | 0.112 | |
| 7 | | | 2.453 | 2.452 | 0.232 | |
| 8 | 4 | | 2.473 | 2.473 | 0.147 | |
| 9 | | 5 | 2.458 | 2.458 | 0.196 | |
| **12.5-mm Specimens** | | | | | | |
| 1 | 1 | | 2.494 | 2.494 | 0.220 | |
| 2 | | | 2.482 | 2.483 | 0.306 | |
| 3 | 2 | | 2.499 | 2.499 | 0.267 | |
| 4 | 3 | | 2.493 | 2.493 | 0.245 | |
| 5 | | 5 | 2.495 | 2.497 | 0.328 | 0.011 |
| 6 | | | 2.483 | 2.483 | 0.270 | |
| 7 | | | 2.462 | 2.464 | 0.818 | |
| 8 | | 6 | 2.493 | 2.493 | 0.245 | |
| 9 | 4 | | 2.492 | 2.491 | 0.337 | |
| **19.0-mm Specimens** | | | | | | |
| 1 | | | 2.507 | 2.506 | 0.411 | |
| 2 | | 5 | 2.497 | 2.497 | 0.485 | |
| 3 | 1 | | 2.493 | 2.490 | 0.464 | |
| 4 | | | 2.511 | 2.510 | 0.400 | |
| 5 | | 6 | 2.494 | 2.498 | 0.529 | 0.007 |
| 6 | | | 2.485 | 2.486 | 0.523 | |
| 7 | 2 | | 2.495 | 2.494 | 0.613 | |
| 8 | 3 | | 2.497 | 2.497 | 0.444 | |
| 9 | 4 | | 2.497 | 2.498 | 0.413 | |

**Table 5 – Comparison of $G_{mb}$ Determined by Miniature Stock Pile Method (T248) and Scooping Method**

| Mixture | Scooping Method (Std. Dev. of $G_{mb}$ values) | Miniature Stock Pile Method (Std. Dev. of $G_{mb}$ values) |
|---|---|---|
| 9.5-mm | 0.020 | 0.013 |
| 12.5-mm | 0.029 | 0.011 |
| 19.0-mm | 0.019 | 0.008 |

### 2.4.3 Aluminum Cylinders

In addition to the HMA test specimens, four aluminum cylinders (Alloy 2024), approximately 110 mm in height, were cut from six inch diameter stock to serve as control specimens. Although the sides of the cylinders were smooth, the top and bottom included serrations that resulted from being cut with a horizontal band saw. The aluminum cylinders were labeled 1, 2, 3, and 4.

## 2.5 TEST PROTOCOLS AND DATA FORMS

All laboratory testing was performed according to T166 or D6752. In addition to recording the bulk specific gravity that resulted from each test, information about the test apparatus and test conditions was also recorded. The forms shown in Appendix A were used by the AMRL Laboratory Assessors during laboratory visits to record observations and test results.

In addition to the T166 and D6752 testing, AMRL made repeat determinations of the bulk density of all eighteen test specimens at their facility in Gaithersburg, MD using the Core Reader *(5)*.

## 2.6 LABORATORY VISITS

AMRL Laboratory Assessors visited all participating laboratories to deliver test specimens, observe test conditions and the test procedures, and record test results. Each participating laboratory was visited twice according to a planned schedule, with the second visit to a specific laboratory typically occurring two weeks after the first visit. The testing during each visit involved three T166 test specimens (9.5-mm, 12.5-mm, and 19.0-mm) and, where appropriate, three D6752 test specimens (9.5-mm, 12.5-mm, and 19.0-mm). The same test specimens were tested by a given laboratory on each of the two visits. In addition, each laboratory tested an aluminum cylinder for T166 and D6752, where appropriate. The four sets of T166 test specimens permitted up to four visits to take place simultaneously. Generally, a two week interval between tests on a specific set

of samples was scheduled to allow ample time for specimen conditioning, as described in Section 2.7, between tests. Laboratory visits began in July 2003 and ended in December 2003.

An AMRL Laboratory Assessor was assigned to each visit to ensure that testing was performed properly and to note any observed deviations from standard practice. Each Laboratory Assessor involved in the visits was instructed to:

- Verify that the laboratory is prepared to perform the tests.
- Verify that the laboratory is equipped to perform the tests and coach the technician(s) on how to properly perform the test(s).
- Observe the laboratory perform T166 on the three specimens.
- If the laboratory has the capability, observe the laboratory perform D6752 on the three specimens. AMRL provided plastic bags for all D6752 testing.
- Record test data, test conditions, and any deviations from the standard test method observed.
- Record bath temperature and immersion time, and describe the method of obtaining the saturated surface dry condition.

## 2.7 SPECIMEN CONDITIONING AND MONITORING

The test plan called for individual test specimens to be retested up to ten times. During each test, T166 requires the test specimen to be immersed in water for up to 300 seconds. For D6752, test specimens are vacuum sealed in a plastic bag and immersed in water. If the plastic bag leaks during the immersion process a significant amount of water can be forced into the specimen. In all cases, if meaningful repeat test results are to be obtained, any water must be removed from the specimen before it can be retested.

The specimen conditioning chamber shown in Figure 2 was constructed to prepare specimens for repeat testing. The chamber consisted of a rack for holding the specimens, four fans for circulating the air, and a dehumidifier. The humidity within the chamber was below 30 percent and the temperature within the chamber was between 25 and 30°C throughout the experiment. The test specimens remained in the chamber at all times except when they were removed for monitoring or testing. Foam lined coolers were used to transport specimens to laboratories for testing to minimize potential damage to the specimens.

**Figure 2 – Specimen Conditioning Chamber**

Prior to transporting the specimens to the laboratories for testing, the height of each specimen was measured to the nearest 0.01 mm, at four points roughly 90 degrees apart; the diameter of each specimen was measured to the nearest 0.01 mm, at two points on the top and two points on the bottom roughly 90 degrees apart; and, the mass of each specimen was determined to the nearest 0.1 g. A specimen was considered suitable for retest if: the current average height was within 0.5 mm of its original height; the current average diameter was within 0.5 mm of its original diameter; and the current mass was within 0.5 g of its original mass. The control charts in Appendix B were used to monitor and record the condition of the specimens.

During the course of the experiment, the specimens met the requirements for retest in all but four cases. The 9.5-mm specimens 1 (T166) and 5 (D6752), and the 12.5-mm specimens 5 (D6752) and 6 (D6752) all failed to meet the mass criteria at one or more points. In all four cases the magnitude of the deviations (less than 1.6 grams) was considered and the decision was made to continue using the specimen for test rather than substitute a spare specimen because it was believed that the introduction of additional specimens would confound the data analysis more than the minor specimen variation observed.

# CHAPTER 3: TEST RESULTS AND ANALYSIS

## 3.1 TEST DATA

The test data obtained in this study are shown in Appendix C. Tables C-1, C-2, C-3, and C-4 summarize the data for T166; Tables C-5, C-6, C-7, and C-8 show the data from D6752. Table C-9 lists the data from the Core Reader. Shaded cells in the data tables indicate data that were eliminated by the E691 analysis in the manner described in the Phase 1 study report *(4)*.

## 3.2 GRAPHICAL ANALYSIS OF THE DATA

Figures 3, 4, 5, and 6 display the bulk specific gravity data for test methods T166 and D6752. The data are displayed in a manner that permits a qualitative analysis of the experiment. Each graph uses a different color to distinguish the data from the six test specimens of a similar mix design. A circle indicates the data obtained during the first visit, and a triangle indicates the data obtained on the same specimen during the second visit. The scale interval of the y axis is the same for all four graphs to allow a visual comparison of the spread in data from one material to another. In all four figures, the points plotted for specimens 1 through 4 represent T166 data and the points plotted for specimens 5 and 6 represent D6752 data. The data for a given specimen are plotted in the order in which the specimen was tested to reveal any degradation in the specimen over time.

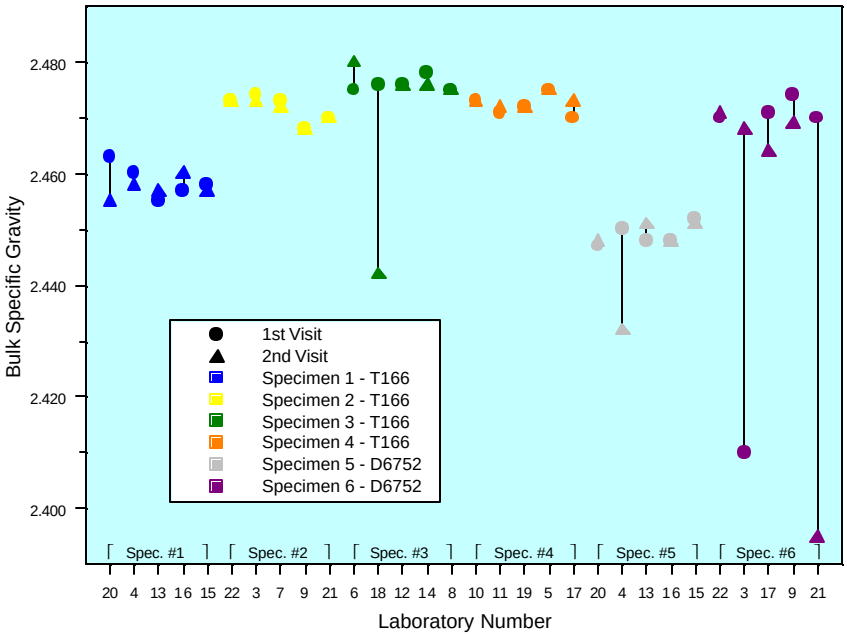



**Figure 3 - 9.5-mm Specimen Data**

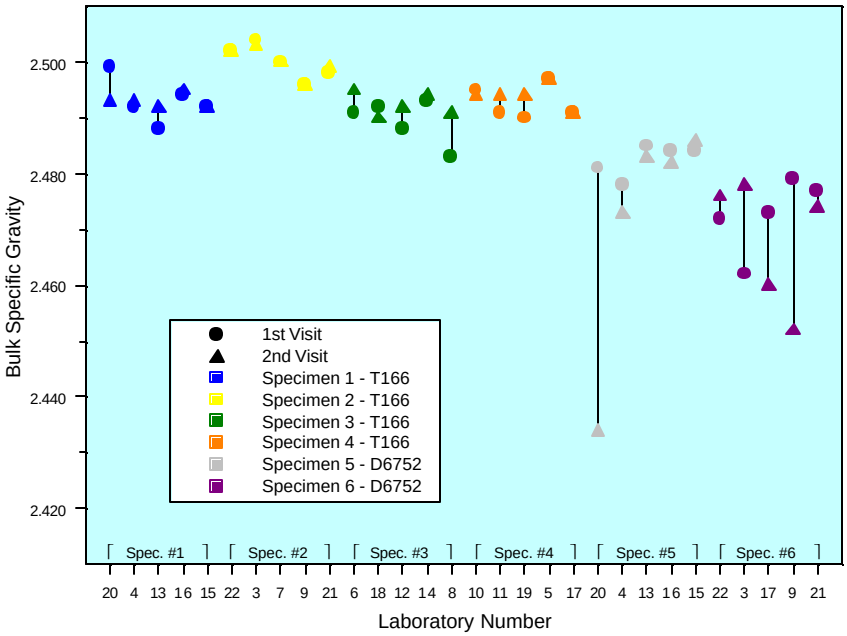



**Figure 4 - 12.5-mm Specimen Data**

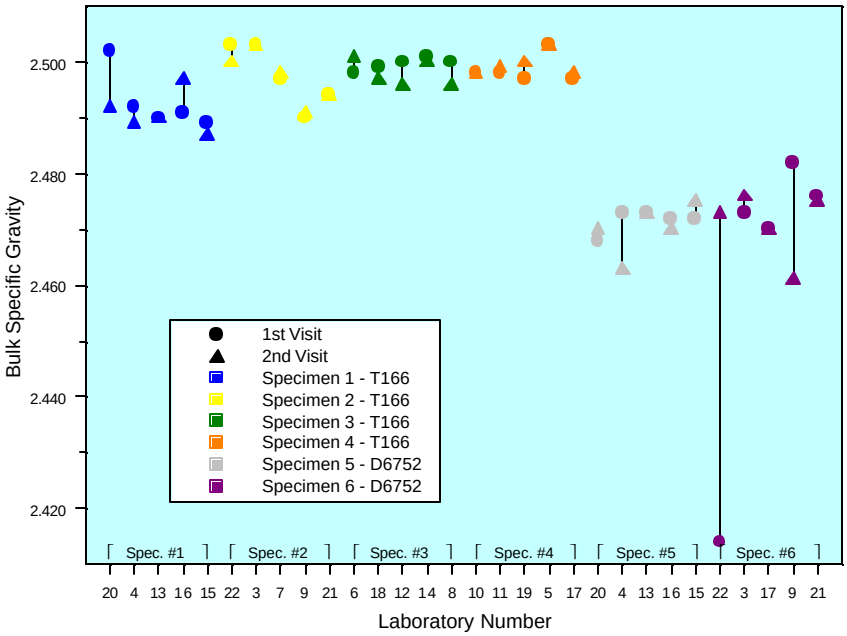



**Figure 5 - 19.0-mm Specimen Data**

The arrangement of the symbols for the paired data representing the first and second visits on all four figures is mixed implying that there is little or no replicate effect for any of the material types. Furthermore, the data points for the individual specimens plotted on the four figures show no definite trend from test to test; indicating no appreciable degradation of the specimens over time, or no test sequence effect.

The 9.5-mm test data plotted in Figure 3 does indicate that there was a specimen effect. Based on AMRL density measurements made before and after laboratory testing (Table 4), the initial densities of the four 9.5-mm, T166 specimens varied from 2.458 for specimen No.1 to 2.478 for specimen No. 3. This variation in density of the 9.5-mm specimens is clearly evident on the graph. Likewise, AMRL density data for the two 9.5-mm, D6752 specimens varied from 2.458 for specimen No. 5 to 2.481 for specimen No. 6. This variation in density is also reflected in the laboratory test data displayed on the graph. The difference in the density of the 9.5-mm specimens (0.023), as determined by AMRL, makes it difficult to detect the bias in the D6752 test results.

Figure 4 displays the data points for six 12.5-mm specimens. Unlike the 9.5-mm specimens, the difference in the densities of the six 12.5-mm specimens (0.008), as determined by AMRL, appears to be small enough to reveal bias in the D6752 test results when compared to the T166 test results. The difference in D6752 test results compared to T166 test results is more pronounced for the 19.0-mm specimens (Figure 5). The differences among the six 19.0-mm specimens as measured by the AMRL (0.008) were so small that the observed difference in the D6752 test results when compared to the

T166 test results would appear to represent a real difference. This is confirmed by the results from the statistical tests reported in Section 3.4.

The results of tests performed on the aluminum cylinders are shown in Figure 6. Four aluminum cylinders were included in the study. Aluminum specimens 1 and 2 were used by laboratories performing both T166 and D6752. All four cylinders were very similar in density. Figure 6 suggests that there was no appreciable bias in the D6752 test results obtained on the aluminum cylinders when compared to the T166 results. This is confirmed by the results from the statistical tests reported in Section 3.4.

It was observed that the size and number of specimen surface irregularities increased in the 9.5-mm, 12.5-mm and 19.0-mm specimens, respectively. The aluminum cylinders had virtually no surface irregularities. It is apparent from a study of Figures 3, 4, 5, and 6 that the $G_{mb}$ values obtained using T166 are higher than those obtained using D6752. The T166 $G_{mb}$ values may be higher than the D6752 $G_{mb}$ values because the plastic covering the D6752 specimens prohibits water from penetrating the crevices of the specimens. The discrepancy between the T166 and D6752 $G_{mb}$ values increases as the irregularity of the surface of the specimen increases. The difference between the average Gmb values for the aluminum, 9.5-mm, 12.5-mm and 19.0-mm specimens is 0.003, 0.013, 0.020, and 0.025 specific gravity units, respectively.

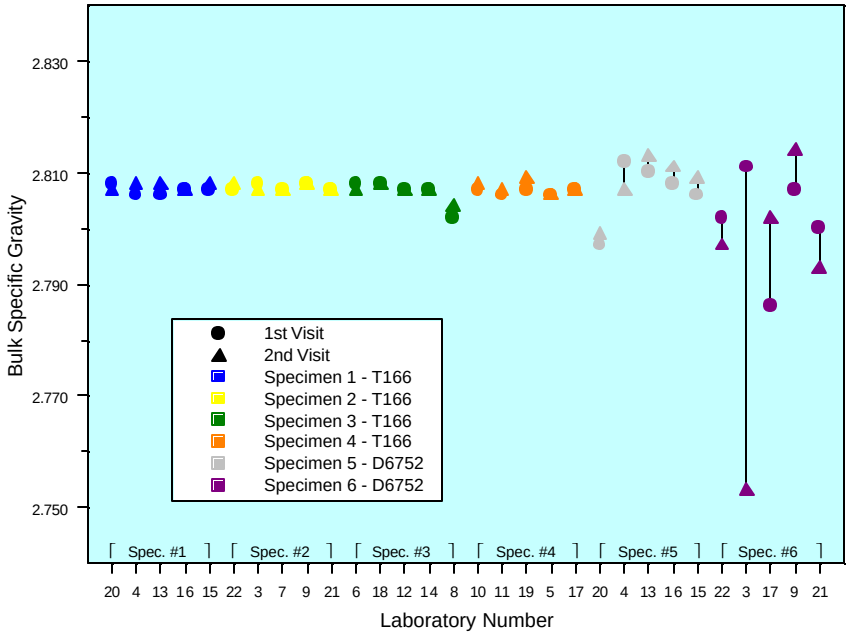



**Figure 6 - Aluminum Specimen Data**

A review of the data displayed on Figures 3, 4, and 5 indicates that, for all three HMA types, the within laboratory variation or repeatability of the laboratories testing the

second specimen was better than the within laboratory variation or repeatability of the laboratories in the other groups. Except for this, the plots do not suggest that there is a significant laboratory effect.

The data points displayed on Figures 3, 4, 5, and 6 indicate that the data for D6752 is more variable than the data for T166. Both the replicate laboratory results and the results between laboratories appear to be more dispersed, suggesting poorer repeatability and reproducibility for D6752 compared to T166. This is particularly apparent in the tests performed on the aluminum cylinders (Figure 6). It is also noted that when an erratic test occurs for D6752, it usually results in a low density value.

## 3.3 ANALYSIS OF VARIANCE

### 3.3.1 General

The experiment described in Section 2.1 may be regarded as two separate nested experiments: one experiment to evaluate T166, and another to evaluate D6752. The T166 analysis was performed on the data shown in Appendix C, Tables C-1, C-2, C-3, and C-4, Columns 1, 2, 3, and 7. The D6752 analysis was performed on the D6752 data shown in Appendix C, Tables C-5, C-6, C-7, and C-8, Columns 1, 2, 3, and 7. For the analysis, outliers were identified in the T166 and D6752 data using E691. The outlying data detected by E691 are highlighted in the data tables in Appendix C. All analyses were performed on the data remaining after the outlying data highlighted in Tables C-1 through C-8 were eliminated.

For both experiments, T166 and D6752, *Laboratories* are nested in the *Specimens*, and the *Specimens* are nested in the *Material Types*. For each data set, separate analyses were performed on each of the four material types using the Statistical Analysis System (SAS) statistical software package *(9)*. For each of these analyses the following statistical model was used:

$$\text{Measured } G_{mb}(I,J,K) = \text{Mu} + \text{Specimen}(I) + \text{Lab}(I,J) + \text{Error}(I,J,K)$$

Where:

Mu = the overall mean,
Specimen(I) = the effect of the $I^{th}$ Specimen,
Lab(I,J) = the effect of the $J^{th}$ Lab measuring the $I^{th}$ Specimen, and
Error(I,J,K) = the error in the $K^{th}$ measurement of the $I^{th}$ Specimen by the $J^{th}$ Lab.

Each of these components was modeled as a random variable with mean zero and a variance which is the property of interest in this study. The *"specimen effect"* may be regarded as the *"AMRL fabrication effect"*, the *"error effect"* as the *"pure measurement effect"*, and the *"Lab effect"* as the *"laboratory effect"*.

### 3.3.2 T166 Data Analysis

Table 6 gives the results of an analysis of T166 data using the SAS procedure "Nested" and the statistical model described above with the components of variance corresponding to the specimen, laboratory, and measurement error *(9)*.

**Table 6 - T166 Components of Variance**

| Material | Average $G_{mb}$ | Component | *df* | Variance of the Component | Percent of Total Variance | Std. Dev. of the Component | CV% of the Component |
|---|---|---|---|---|---|---|---|
| 9.5 mm | 2.469 | Specimen | 3 | 0.00006382 | 94% | 0.0080 | 0.324% |
| | | Lab | 15 | 0.00000109 | 2% | 0.0010 | 0.042% |
| | | Error | 19 | 0.00000324 | 5% | 0.0018 | 0.073% |
| 12.5 mm | 2.495 | Specimen | 3 | 0.00001252 | 63% | 0.0035 | 0.142% |
| | | Lab | 15 | 0.00000423 | 21% | 0.0021 | 0.082% |
| | | Error | 19 | 0.00000313 | 16% | 0.0018 | 0.071% |
| 19.0 mm | 2.497 | Specimen | 3 | 0.00001196 | 51% | 0.0035 | 0.138% |
| | | Lab | 15 | 0.00000853 | 36% | 0.0029 | 0.117% |
| | | Error | 19 | 0.00000308 | 13% | 0.0018 | 0.070% |
| Aluminum | 2.807 | Specimen | 3 | Negative | --- | --- | --- |
| | | Lab | 14 | 0.00000004 | 6% | 0.0019 | 0.007% |
| | | Error | 18 | 0.00000053 | 94% | 0.0007 | 0.026% |

Overall, it appears that the T166 $G_{mb}$ measurements were very precise. The *measurement errors* have standard deviations of 0.0018, 0.0018, 0.0018, and 0.0007, which translate into coefficients of variations (CV%) of 0.07%, 0.07%, 0.07% and 0.03%. These CV%s are estimated with good precision because they have 18 or 19 degrees of freedom (*df*). The first three CV%s are for HMA materials, which explains the close agreement. The fourth CV% was for the aluminum cylinders, which accounts for the added measurement precision. The fact that the estimate for the specimen "Component of Variance" is negative indicates that the four aluminum specimens are very similar.

The measurement error values are very small indicating that, for specimens with three percent air voids and 0.5 percent absorption, the T166 measurement of the $G_{mb}$ is a very precise process. The measurement error values are so small that it may be impracticable to attempt to find ways to improve T166.

The laboratory error values are about the same as the measurement error values. The laboratory error values for this study increase as the maximum size of the aggregate in the specimen increases. The error values represent 2%, 21%, and 36% of the total error for the 9.5, 12.5, and 19.0-mm specimens respectively. It is inconclusive if there would be a similar trend for mixtures of a different design.

The specimen error values are by far the largest, and clearly indicate that the variation in the specimens contributed the most to the variation in the $G_{mb}$ values. It should be noted that all of the specimens in the Phase 2 study were fabricated in one laboratory and then brought to individual laboratories for testing. Therefore, the specimen error component does not represent the ability of a group of laboratories to fabricate uniform specimens. It should be further noted that the six specimens, of each HMA material type, tested in the Phase 2 study were selected from the nine specimens fabricated to have the smallest variation in $G_{mb}$ (See Table 4). Fortunately, the ANOVA isolates the specimen error and makes it possible to eliminate it from the estimates of $S_r$ and $S_R$. Eliminating the specimen error simulates an experiment in which all participating laboratories test the same 9.5-mm, 12.5-mm, 19.0-mm and aluminum specimens.

Columns 8, 9, 10, and 11 in the data tables in Appendix C, show additional data that were collected during the laboratory visits. The data for T166 were analyzed and none of the factors was found to influence the $G_{mb}$ determinations significantly.

### 3.3.3 D6752 Data Analysis

Table 7 gives the results of an analysis of D6752 data using the SAS procedure "Nested" and the statistical model described above with the components corresponding to the specimen, laboratory, and measurement error.

**Table 7 - D6752 Components of Variance**

| Material | Average $G_{mb}$ | Component | *df* | Variance of the Component | Percent of Total Variance | Std. Dev. of the Component | CV% of the Component |
|---|---|---|---|---|---|---|---|
| 9.5 mm | 2.456 | Specimen | 1 | 0.0002460 | 91% | 0.0157 | 0.635% |
| | | Lab | 6 | negative | - - - | - - - | - - - |
| | | Error | 8 | 0.0000256 | 9% | 0.0051 | 0.205% |
| 12.5 mm | 2.475 | Specimen | 1 | 0.0000627 | 48% | 0.0079 | 0.317% |
| | | Lab | 7 | negative | - - - | - - - | - - - |
| | | Error | 9 | 0.0000676 | 52% | 0.0082 | 0.330% |
| 19.0 mm | 2.472 | Specimen | 1 | 0.0000006 | 2% | 0.0007 | 0.030% |
| | | Lab | 7 | negative | - - - | - - - | - - - |
| | | Error | 9 | 0.0000316 | 98% | 0.0056 | 0.225% |
| Aluminum | 2.804 | Specimen | 1 | 0.0000163 | 24% | 0.0040 | 0.144% |
| | | Lab | 7 | 0.0000268 | 40% | 0.0052 | 0.184% |
| | | Error | 9 | 0.0000242 | 36% | 0.0049 | 0.175% |

The D6752 $G_{mb}$ measurements were not quite as precise as the T166 measurements. The *measurement errors* have standard deviations of 0.0051, 0.0082, 0.0056, and 0.0049, which translate into coefficients of variations (CV%) of 0.21%, 0.33%, 0.23% and

0.18%. These CV%s are not estimated with as much precision as the T166 CV%s because they only have 8 or 9 degrees of freedom (*df*) since fewer laboratories conducted D6752. However, the fact that the CV%s for all four materials are about three times greater than the corresponding T166 CV%s indicates that it may be possible to improve the D6752 test procedure.

The negative values for the laboratory error component for the HMA specimens simply means that in the Phase 2 study the measurement error component and the specimen error component account for the major portion of the overall error. In other words, relative to the other two sources of error, the laboratory error component contributed very little to the total variation in $G_{mb}$ test results.

The specimen error values indicate that there were significant differences in the $G_{mb}$ for the two 9.5-mm test specimens. The two 12.5-mm specimens and the two 19.0-mm specimens are more closely matched than the two 9.5-mm specimens but not as closely matched as the specimens in the T166 experiment. With only two specimens for each material type, the D6752 information regarding the specimen error is not reliable.

Columns 8, 9, 10, and 11, in the data tables in Appendix C, show additional data that were collected during the laboratory visits. The data for D6752 were analyzed and none of the factors was found to influence the $G_{mb}$ determinations significantly.

### 3.3.4 Estimating the Specimen Fabrication Effect

The specimen error estimates from the D6752 experiment, with only one degree of freedom, are not reliable. The specimen error estimates from the T166 experiment involving four specimens of each material type are much better. Therefore, only the data from the T166 experiment were compared to data from the Phase 1 study to estimate the specimen fabrication effect.

In the T166 nested experiment, the lowest level component, measurement error, is the most precise estimate. The measurement error is an estimate of the within laboratory precision ($S_r$) In the Phase 2 study the measurement error did not include any error associated with mixing or compacting. In the Phase 1 study, the measurement error, or within laboratory precision estimate ($S_r$), included within laboratory mixing and compacting error, since each laboratory compacted loose mixtures to obtain the test specimens.

In the Phase 2 study, the measurement error must be combined with the lab error to obtain a between laboratory precision estimate ($S_R$). Because the specimen effect has been isolated, this between laboratory precision estimate ($S_R$) does not include any error associated with specimen fabrication. In the Phase 1 study, the between laboratory precision estimate ($S_R$) includes specimen fabrication errors such as within laboratory mixing/compacting procedure errors as well as multilaboratory compacting variation due to different compactor manufacturers, compaction angles and compacting temperatures.

The Phase 2 study was designed to permit the specimen error to be separated from the $S_r$ and $S_R$ estimates. Therefore, the difference between the Phase 1 study test variation and the Phase 2 test variation is the specimen fabrication effect. Table 8 shows the additive effects of the error components for the Phase 2 study T166 experiment. The between laboratory precision estimate of primary interest is the estimate that does not include the specimen error. It is the within laboratory precision estimate and this between laboratory precision estimate that are compared with the Phase 1 study within laboratory and between laboratory precision estimates to evaluate the fabrication effect.

**Table 8 - T166 - Phase 2 Study Precision Estimates**

| Material | Test Method | Average $G_{mb}$ | Within Laboratory (Measurement Error) | | Between Laboratory (w/o Specimen Error) | | Between Laboratory (All Errors Included) | |
|---|---|---|---|---|---|---|---|---|
| | | | Std. Dev. | CV% | Std. Dev. | CV% | Std. Dev. | CV% |
| 9.5 mm | T166 | 2.469 | 0.0018 | 0.07% | 0.0021 | 0.08% | 0.0082 | 0.33% |
| 12.5 mm | T166 | 2.495 | 0.0018 | 0.07% | 0.0027 | 0.11% | 0.0045 | 0.18% |
| 19.0 mm | T166 | 2.497 | 0.0018 | 0.07% | 0.0035 | 0.14% | 0.0048 | 0.19% |
| Aluminum | T166 | 2.807 | 0.0007 | 0.03% | 0.0008 | 0.03% | 0.0008 | 0.03% |

The T166 Phase 1 and Phase 2 study precision estimates to be compared to determine the fabrication effect for the 12.5-mm and 19.0-mm mixtures are shown in Table 9. The Phase 2 study precision estimates for the 9.5-mm specimens were not considered because the Phase 1 study did not include 9.5-mm specimens. The smaller $S_r$ and $S_R$ estimates from the Phase 2 study indicate that the T312 specimen fabrication process, which was included in the Phase 1 study, introduces a significant amount of variability in the density of resulting specimens. The Phase 2 study $S_r$ estimates exclude any variation contributed by differences in compactors and, compared to the $S_r$ estimates from the Phase 1 study, indicate at least a fourfold increase in variability is caused by the fabrication process.

**Table 9 - Phase 1 and Phase 2 Comparisons**

| Material | Study | N | Average $G_{mb}$ | Within Lab ($S_r$) | | Between Lab ($S_R$) | |
|---|---|---|---|---|---|---|---|
| | | | | Std. Dev. | CV% | Std. Dev. | CV% |
| 12.5 mm | Phase 2 | 19 | 2.495 | 0.0018 | 0.07% | 0.0027 | 0.11% |
| | Phase 1 | 25 | 2.386 | 0.008 | 0.34% | 0.015 | 0.63% |
| | | | | | | | |
| 19.0 mm | Phase 2 | 19 | 2.497 | 0.0018 | 0.07% | 0.0035 | 0.14% |
| | Phase 1 | 24 | 2.398 | 0.013 | 0.54% | 0.014 | 0.58% |

Table 10 shows the results of the analysis to determine the specimen fabrication effect. The results indicate that approximately 90 percent of the variation in T166 bulk density test results for non-absorptive, 150-mm diameter, Superpave gyratory test specimens with a maximum aggregate size of 12.5 or 19.0 mm can be attributed to the mixing and compaction process. The fabrication effect may be somewhat exaggerated because the Phase 2 study testing was more tightly controlled than the Phase 1 study testing. However, even in a more loosely controlled experiment the fabrication effect would still be significant.

**Table 10 - The Fabrication Effect**

| Component/Error | 12.5-mm Specimens | | | |
|---|---|---|---|---|
| | Within Laboratory | | Between Laboratory | |
| | Variance of the Component | Percent of Total Variance | Variance of the Component | Percent of Total Variance |
| Measurement Error [1] | 0.00000313 | 5% | 0.00000313 | 1% |
| Lab Effect [1] | 0.00000423 | 6% | 0.00000423 | 2% |
| Mixing & Compacting Error [2] | 0.0000614 | 89% | 0.000235 | 97% |
| Total Error [3] | 0.0000687 | 100% | 0.000242 | 100% |
| | **19.0-mm Specimens** | | | |
| Measurement Error [1] | 0.00000308 | 2% | 0.00000308 | 2% |
| Lab Effect [1] | 0.00000853 | 5% | 0.00000853 | 4% |
| Mixing & Compacting Error [2] | 0.000172 | 93% | 0.000201 | 94% |
| Total Error [3] | 0.000183 | 100% | 0.000213 | 100% |

[1] From the Phase 2 study
[2] Mixing and Compacting Error = Total Error - (Measurement Error + Lab Effect)
[3] Calculated from the Phase 1 study $S_r$ and $S_R$ precision estimates adjusted for the Phase 2 study average $G_{mb}$, 12.5 mm (2.495), 19.0 mm (2.497).

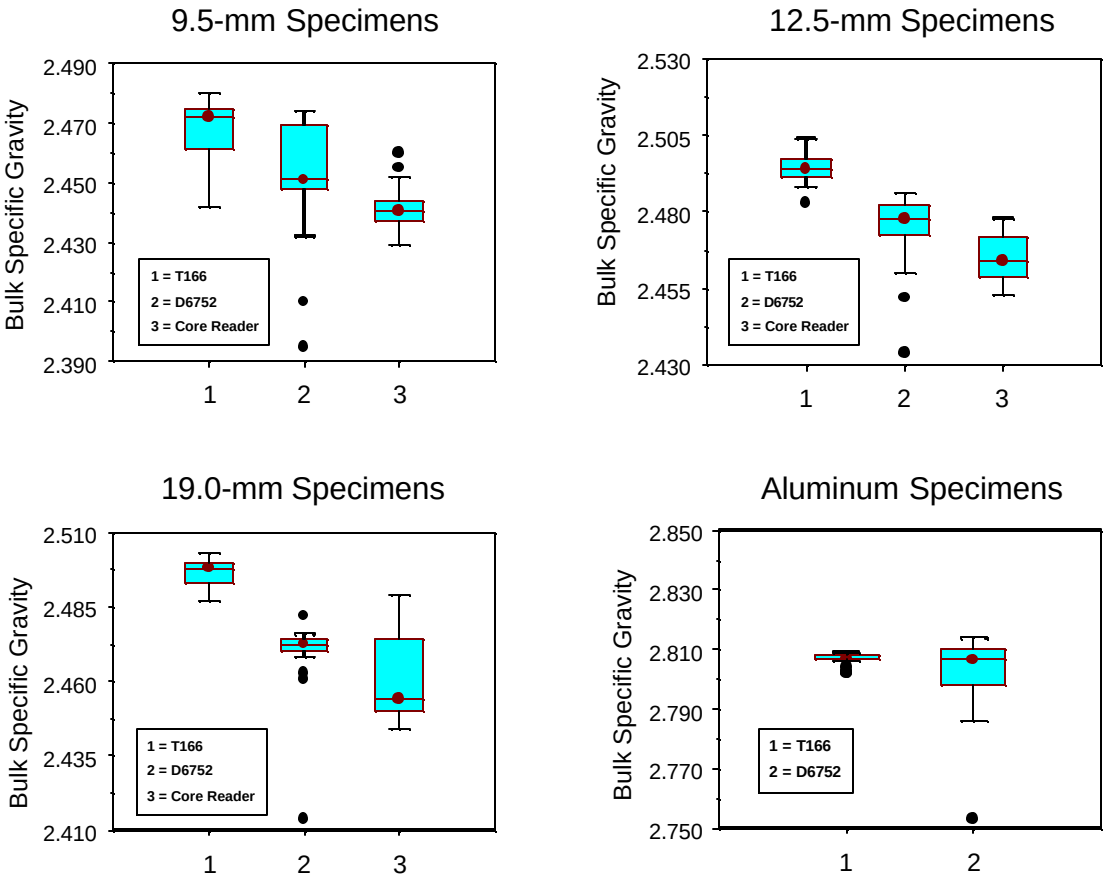
Unexpectedly, most of the variation seems to be in an individual laboratory's inability to produce uniform specimens (89 percent for 12.5-mm specimens and 93 percent for 19.0-mm specimens). The added variability resulting from use of different equipment, and mixing and compaction procedures in multiple laboratories does not appear to be very significant as indicated by the difference between within laboratory and between laboratory mixing and compacting error (8 percent for 12.5-mm specimens and 3 percent for 19.0-mm specimens).

T166 does an excellent job of determining the bulk density of the test specimens with three percent air voids and 0.5 percent absorption,. Any variation in $G_{mb}$ values determined in accordance with the procedures described in T166 probably indicates actual variation in the bulk density of the specimens tested**.**

### 3.4 TEST METHOD COMPARISON

For the comparative analysis, outliers were identified in the T166 and D6752 data using E691. The outlying data detected by E691 are shaded in the data tables in Appendix C. The results of tests for significance shown in Table 11 and the precision estimates given in Table 12 were obtained from analysis of data remaining after outliers were removed.

The box plots shown in Figure 7 compare the T166, D6752 and Core Reader test results for the three HMA mixture types and the T166 and D6752 test results on the aluminum cylinders *(10, 11).* The box plots for T166 and D6752 involved tests performed by multiple laboratories while the box plots for the Core Reader are based on tests performed by one laboratory (AMRL). The Core Reader device was not able to determine the density of the aluminum cylinders.




Note: Box plots for the Core Reader are based on test results from only one laboratory.

**Figure 7 - Test Method Comparison Using Box Plots *(10, 11)***

The box plots for the HMA specimens suggest that there are significant differences in the specimen densities measured by T166 and D6752, as described earlier in Section 3.2. The plots also show even greater differences in the densities determined using the Core Reader. The *T*-test results given in Table 11 indicate that these differences are statistically significant at the 1% confidence level. The box plots show a close agreement between the aluminum cylinders density obtained using T166 and D6752. This is confirmed by the lack of statistical significance in the *T*-test results shown in Table 11.

**Table 11 - Results of Tests for Significance on Bulk Specific Gravity Data**

| Specimens Tested | Data Compared | T test p-value for the *T* test of no differences in the true means. | F test p-value for the *F* test of no differences in the true variances. |
|---|---|---|---|
| 9.5-mm | T166 and D6752 | 0.1% | 1.2% |
| | T166 and Core Reader | 0.0% | 99.5% |
| | D6752 and Core Reader | 0.0% | 1.3% |
| 12.5-mm | T166 and D6752 | 0.0% | 0.0% |
| | T166 and Core Reader | 0.0% | 0.0% |
| | D6752 and Core Reader | 0.0% | 26.8% |
| 19.0-mm | T166 and D6752 | 0.0% | 20.0% |
| | T166 and Core Reader | 0.0% | 0.0% |
| | D6752 and Core Reader | 0.0% | 0.0% |
| Aluminum | T166 and D6752 | 9.3% | 0.0% |

Note: Shaded cells indicate significant differences at 1% Type 1 error rate level.

The data from this study clearly indicate that the test method used influences the $G_{mb}$ value obtained. To eliminate test method bias, when QC testing is based on $G_{mb}$, air void, or relative density values, it would seem appropriate that the test method used for determining the $G_{mb}$ value is the same as the method used to arrive at the mix design. It is unclear from this study how the test method would influence the $G_{mb}$ values on cores taken from pavement.

The box plots shown in Figure 7 support the results of the *F*-tests shown in Table 11. None of the comparisons of test variability made on the 9.5-mm specimens proved to be statistically significant at the 1% level. For the 12.5-mm specimens, *F*-tests comparing the variability of the T166 data with the D6752 data, and the T166 data with the Core Reader data indicated significant differences exist. For the 19.0-mm specimens significant differences in variability were detected between the T166 and Core Reader data, and the D6752 and Core Reader data. The *F*-test results in Table 11 confirm the obvious differences in the variability of T166 and D6752 test data for the aluminum cylinders, displayed on Figures 6 and 7.

Table 12 shows the averages and standard deviations that resulted from the analysis of T166, D6752 and Core Reader data. For the HMA mixtures, a rough comparison of the T166 repeatability and reproducibility (specimen error not included) standard deviations (0.002 and 0.003 respectively) with those for D6752 (0.006 and 0.007) and the Core Reader (0.004, repeatability only), indicates that T166 is an extremely good test for specimens with three percent air voids and 0.5 percent absorption,. This contention is reinforced by the extremely small variation shown for the aluminum control specimens (0.001 and 0.001).

**Table 12 - T166, D6752, and Core Reader Statistics from Phase 2 Study**

| Test Method | Material | Average $G_{mb}$ | Within Lab, $S_r$ | | Between Lab, $S_R$ | |
|---|---|---|---|---|---|---|
| | | | Std. Dev. | CV% | Std. Dev. | CV% |
| T166 | 9.5 mm | 2.469 | 0.0018 | 0.07 | 0.0021 | 0.08 |
| | 12.5 mm | 2.495 | 0.0018 | 0.07 | 0.0027 | 0.11 |
| | 19.0 mm | 2.497 | 0.0018 | 0.07 | 0.0035 | 0.14 |
| | Aluminum | 2.807 | 0.0007 | 0.03 | 0.0008 | 0.03 |
| D6752 | 9.5 mm | 2.456 | 0.0051 | 0.21 | 0.0051 | 0.21 |
| | 12.5 mm | 2.475 | 0.0082 | 0.33 | 0.0082 | 0.33 |
| | 19.0 mm | 2.472 | 0.0056 | 0.23 | 0.0056 | 0.23 |
| | Aluminum | 2.804 | 0.0049 | 0.18 | 0.0071 | 0.25 |
| Core Reader | 9.5 mm | 2.441 | 0.005 | 0.20 | - - - | - - - |
| | 12.5 mm | 2.465 | 0.003 | 0.12 | - - - | - - - |
| | 19.0 mm | 2.461 | 0.004 | 0.16 | - - - | - - - |
| | Aluminum | - - - | - - - | - - - | - - - | - - - |

Although not quite as good as T166, the variability of the data from D6752 is quite small. The data for the aluminum control specimens suggest that there is room for improvement for D6752. Pinholes in the bags were encountered during several of the tests in laboratories. In these cases the specimens absorbed considerable amounts of water, invalidating the test results. In all cases the test results were discarded and the specimens were retested. Although not observed, it is suspected that during immersion the plastic bag contacts the side of the bath or captures air bubbles resulting in erratic and usually lower densities. A further investigation is necessary to reveal the cause of the sometimes erratic results.

For the 9.5-mm and 12.5-mm specimens, the repeatability standard deviations for the Core Reader resulting from tests performed by multiple operators on different days and are comparable to those for D6752. A comparison of reproducibility from the Core Reader was not possible since the testing did not involve multiple laboratories.

The estimates shown in Table 12 are not suitable as precision estimates because they do not include the specimen fabrication component.

# CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

## 4.1 GENERAL

This study, which was a follow up to NCHRP 9-26, Phase 1, was conducted to evaluate the performance of two methods used to determine the bulk density of Superpave Gyratory specimens compacted using one SGC. The variability in $G_{mb}$ test results from this Phase 2 study, which eliminated the mixing and fabrication process, was compared to the variability of $G_{mb}$ results from the Phase 1 study to reveal how much of the variability resulted from the specimen fabrication process (T312) and how much is inherent in the test method methods evaluated. Specimen bulk density was determined by test methods T166, D6752, and a Troxler Core Reader. The study conclusions and recommendations are as follows.

### 4.1.1 AASHTO T166, Standard Test Method for Bulk Specific Gravity of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens

#### Conclusions

1. For 9.5, 12.5, and 19.0-mm mixtures containing non-absorptive aggregates, T166 is an excellent method for the determining bulk specific gravity ($G_{mb}$). The measurement error values are very small (0.0018) indicating that, for specimens with three percent air voids and 0.5 percent absorption, the T166 measurement of the $G_{mb}$ is a very precise process. The measurement error values are so small that it may be impracticable to attempt to find ways to improve T166.

2. For 9.5, 12.5, and 19.0-mm mixtures containing non-absorptive aggregates, the bulk specific gravity ($G_{mb}$) values obtained using T166 (2.469, 2.495, and 2.497) are significantly higher than those obtained using D6752 (2.456, 2.475, and 2.472).

3. For 12.5 and 19.0-mm mixtures containing non-absorptive aggregates, approximately 90 percent of the variation in T166 bulk density test results for 150-mm diameter, Superpave gyratory test specimens can be attributed to the mixing and compaction process.

4. For 12.5 and 19.0-mm mixtures containing non-absorptive aggregates, most of the variation in T166 test results can be attributed to an individual laboratory's inability to produce uniform specimens. The added variability resulting from use of different equipment, and mixing and compaction procedures in multiple laboratories does not appear to be very significant.

#### Recommendations

1. There are no recommended changes for T166.

2. If T166 is used to determine the bulk specific gravity of specimens during the mix design process, it should also be used in quality control testing.

### 4.1.2 ASTM D6752, Standard Method of Test for Bulk Specific Gravity and Density of Compacted Mixtures Using Automatic Vacuum Sealing Method

**Conclusions**

1. For 9.5, 12.5, and 19.0-mm mixtures containing non-absorptive aggregates, the within laboratory (WL) and between laboratory (BL) coefficients of variation for D6752 (WL: 0.21%, 0.33% and 0.23%, BL: 0.21%, 0.33% and 0.23%) are not as good as the within laboratory and between laboratory coefficients of variation for T166 (WL: 0.07%, 0.07% and 0.07%, BL: 0.08%, 0.11% and 0.14%).

2. For 9.5, 12.5, and 19.0-mm mixtures containing non-absorptive aggregates, the bulk specific gravity ($G_{mb}$) values obtained, from specimens with three percent air voids and 0.5 percent absorption, using D6752 (2.456, 2.475, and 2.472) are significantly lower than those obtained using T166 (2.469, 2.495, and 2.497).

3. Although not as good as T166, the variability of the data from D6752 is quite small. However, the fact that the CV%s for all four materials are about three times greater than the corresponding T166 CV%s indicates that it may be possible to improve the D6752 test procedure.

4. For 9.5, 12.5, and 19.0-mm mixtures containing non-absorptive aggregates, when D6752 testing errors occur, they result in densities that are considerably lower than the expected density.

5. The plastic bags specified in D6752 are susceptible to leakage due to pin holes.

6. It may not be possible to dry back specimens that take on water during immersion.

**Recommendations**

1. Changes to D6752 to improve its precision should be investigated. Specific concerns include the durability of the plastic bags (susceptibility to pin holes), possibility of the bag contacting the side of the bath, and air being trapped under the bag while immersed.

2. If D6752 is used to determine the bulk specific gravity of specimens during the mix design process it should also be used in quality control testing.

### 4.1.3 Specimen Fabrication Process

#### Conclusions

1. For 9.5, 12.5, and 19.0-mm mixtures containing non-absorptive aggregates, using the miniature stock pile method described in AASHTO T248 to obtain the sand portion of the mix, produces more uniform specimens.

2. For 9.5, 12.5, and 19.0-mm mixtures containing non-absorptive aggregates, the T312 fabrication process introduces a significant amount of error into the HMA mix design process.

#### Recommendations

1. Any AASHTO methods requiring uniform HMA mixtures should consider specifying use of the miniature stock pile method described in T248 to obtain the sand portion of individually prepared mixtures.

2. Changes to the specimen fabrication process described in T312 should be considered. Specific factors to investigate include: mixture preparation, mixture temperature, method of introducing the mixture into the mold, angle of compaction, diameter of the specimen, and differences in compactors.

## REFERENCES


1. Cominsky, R.J., Huber, G.A., Kennedy, T.W., and Anderson, R.M., "The Superpave Mix Design Manual for New Construction and Overlays," Strategic Highway Research Program, SHRP-A-407, 1994.
2. AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing (Part 2 – Tests), Twenty-First Edition, American Association of State Highway and Transportation Officials, Washington, DC, 2003.
3. ASTM Book of Standards, Vol. 04.03, Road and Paving Materials, West Conshohocken, PA, 2003.
4. Spellerberg, P.A., Savage, D.A., and Pielert, J.H., "Precision Estimates of Selected Volumetric Properties of HMA Using Non-Absorptive Aggregate," NCHRP Web Document 54, 2003.
5. Troxler Web Site: http://www.troxlerlabs.com
6. American Association of State Highway and Transportation Officials, "Provisional Standards," Annual Editions 1993-2003.
7. AMRL Web Site: http://www.nist.gov/amrl
8. Pielert, J.H. and Spellerberg, P.A., "AASHTO Materials Reference Laboratory – Thirty Years of Service to the Transportation Community," TR News, Number 183, Transportation Research Board, Washington, DC, March-April 1996, pages 22-28.
9. Statistical Analysis System Web Site: http://www.tutorialusa.com/sas/html
10. Tukey, John W., "Exploratory Data Analysis," Addison Wesley, Reading, Massachusetts, 1977.
11. Dataplot Website: http://www.itl.nist.gov/div898/software/dataplot.html/summary.htm

# Appendix A

## Data Forms

### NCHRP 9-26(2) - T166 Data Sheet

Laboratory Name: _____ City: _____ State: ___ Date: _____ Time: _____

Laboratory No. _____ 1st Visit ? ☐ 2nd Visit ? ☐ Ambient Temperature: _____ °C Humidity: High ? ☐ Low ? ☐

| **T166** | 9.5 mm | 12.5 mm | 19.0 mm | Aluminum |
|---|---|---|---|---|
| Specimen ID | | | | |
| Water Temp. nearest 0.1°C | | | | |
| Air Dry Mass (nearest 0.1g) | | | | |
| Weight in Water (nearest 0.1g) | | | | |
| SSD Mass (nearest 0.1g) | | | | |
| Bulk Sp. Gr. ($G_{mb}$) | | | | |
| Time Immersed (sec.) | | | | |
| Time from Removal from the Water to SSD Weight (sec.) | | | | |

Balance readability?: 1g ☐ 0.1g ☐ 0.01g ☐

Specimen Suspension: Diameter of the Wire? _____ No. of times the wire breaks the surface? ____

Is the Bath Fitted with a Constant Overflow Device? **Yes** ☐ **No** ☐

Describe the specimen blotting method:

Comments:

AMRL Representative: _____ Tech. Name _____

**Figure A-1, Data Form for T166**

## NCHRP 9-26(2) - D6752 Data Sheet

Laboratory Name: _____ City: _____ State: ___

Date: _____ Time: _____ Laboratory No. _____ 1st Visit ? ☐ 2nd Visit ? ☐

Ambient Temperature: _____ °C Humidity: High ? ☐ Low ? ☐

| **D6752** | 9.5 mm | 12.5 mm | 19.0 mm | Alum |
|---|---|---|---|---|
| Specimen ID | | | | |
| Water Temp. nearest 0.1°C | | | | |
| (A) Mass of the Bag (0.1g) | | | | |
| (B) Dry Specimen Mass before Sealing (0.1g) | | | | |
| (C) Sealed Specimen Weight in Water (0.1g) | | | | |
| (D) Dry Specimen Mass after Water Submersion (0.1g) | | | | |
| (E) Ratio B/A (0.01) | | | | |
| (F) Bag Volume Correction from Table (0.001) | | | | |
| (G) Total Volume (A+D) - C (0.1) | | | | |
| (H) Volume of Bag A/F (0.1) | | | | |
| (I) Volume of Specimen G-H (0.1) | | | | |
| (J) Bulk Sp.Gr. ($G_{mb}$) B/I (0.001) | | | | |
| Time Immersed (sec.) | | | | |

Balance readability?: 1g ☐ 0.1g ☐ 0.01g ☐

Specimen Suspension: Diameter of the Wire? _____

Number of times the wire breaks the surface? ____

Is the Bath Fitted with a Constant Overflow Device? **Yes** ☐ **No** ☐

Describe the Bath's Dimensions, Shape etc.:

Comments:

AMRL Representative: _____ Tech. Name _____

**Figure A-2, Data Form for D6752**

# Appendix B
## Control Charts

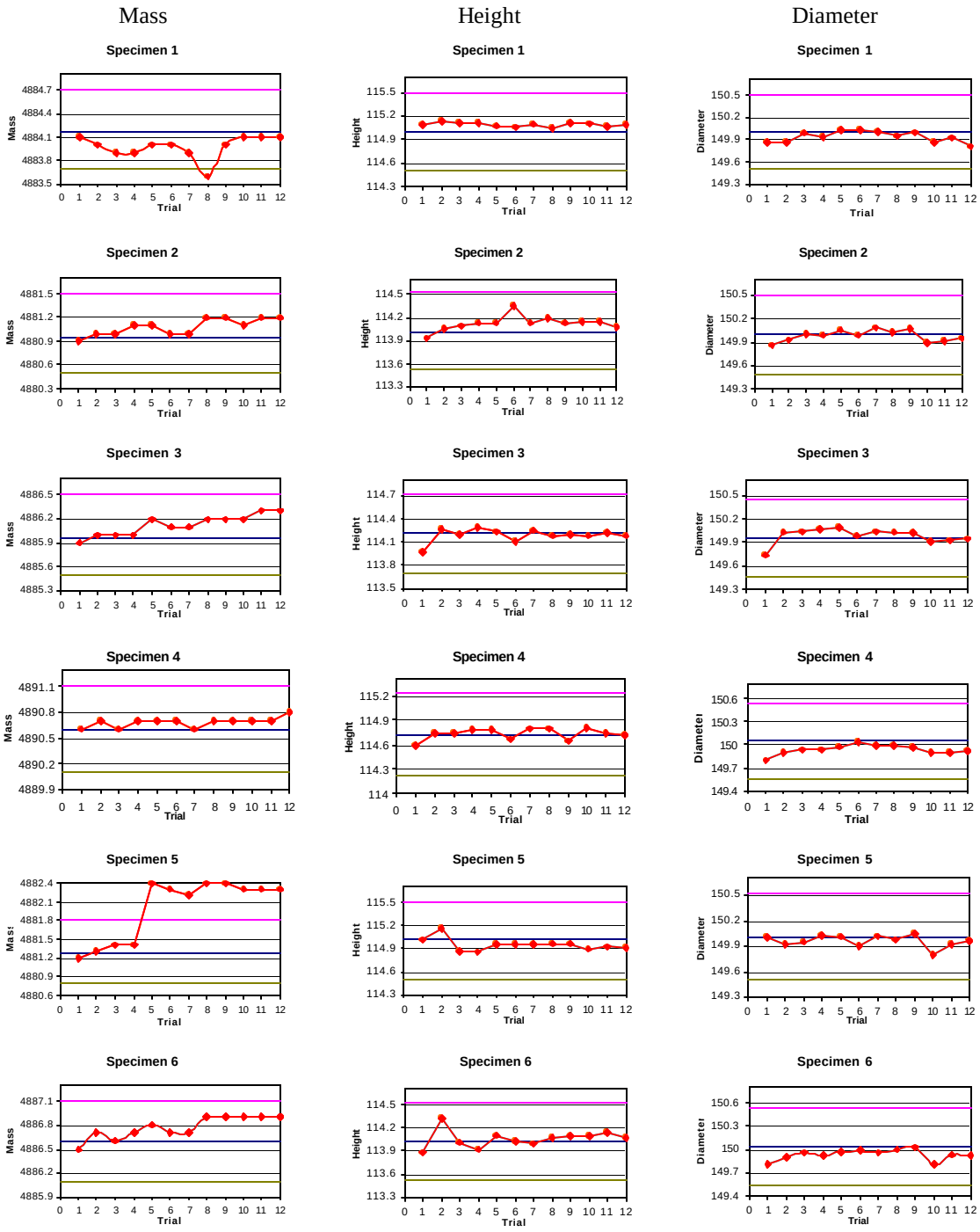



**Figure B-1, 9.5-mm HMA Specimen Control Charts**

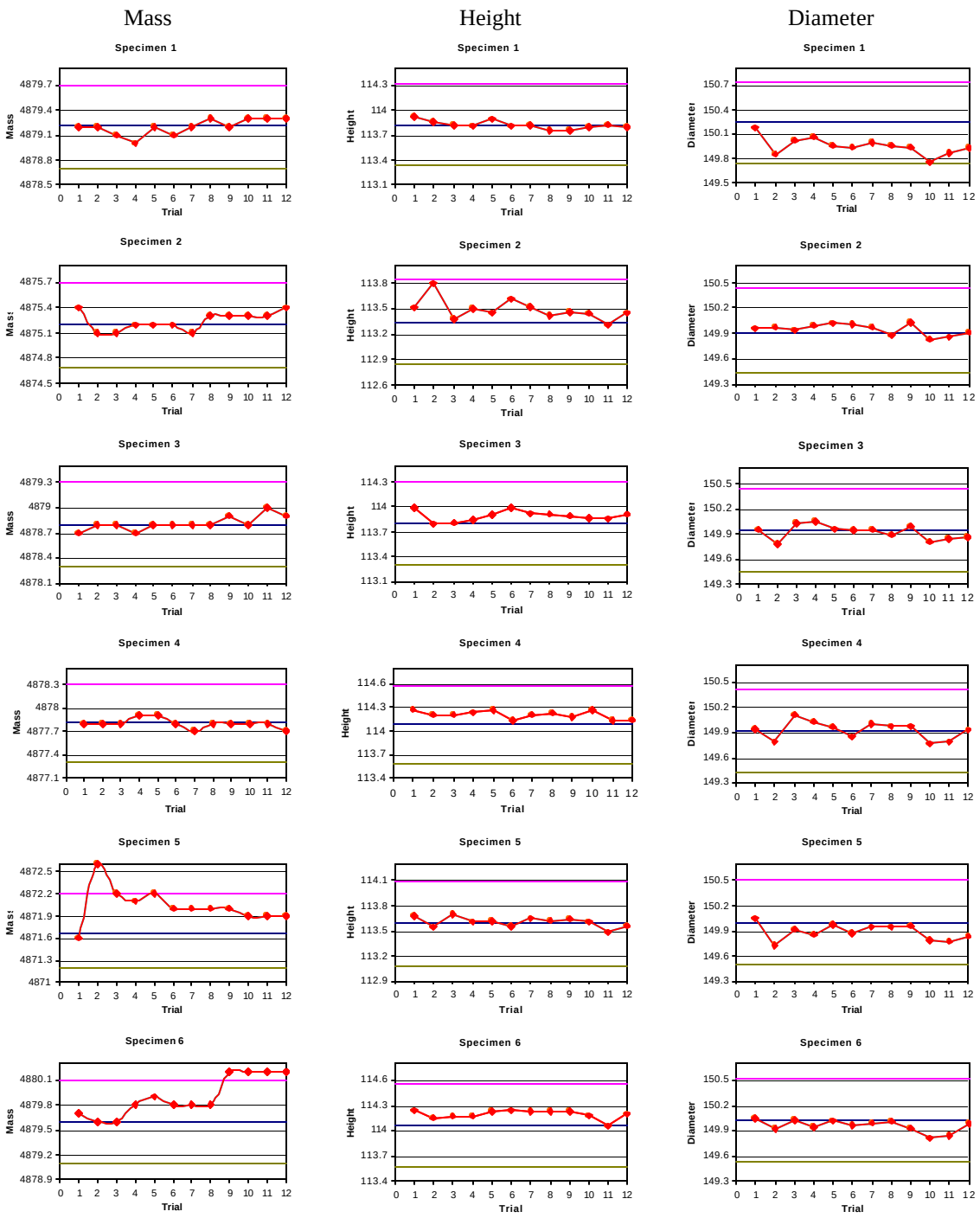



**Figure B-2, 12.5-mm HMA Specimen Control Charts**

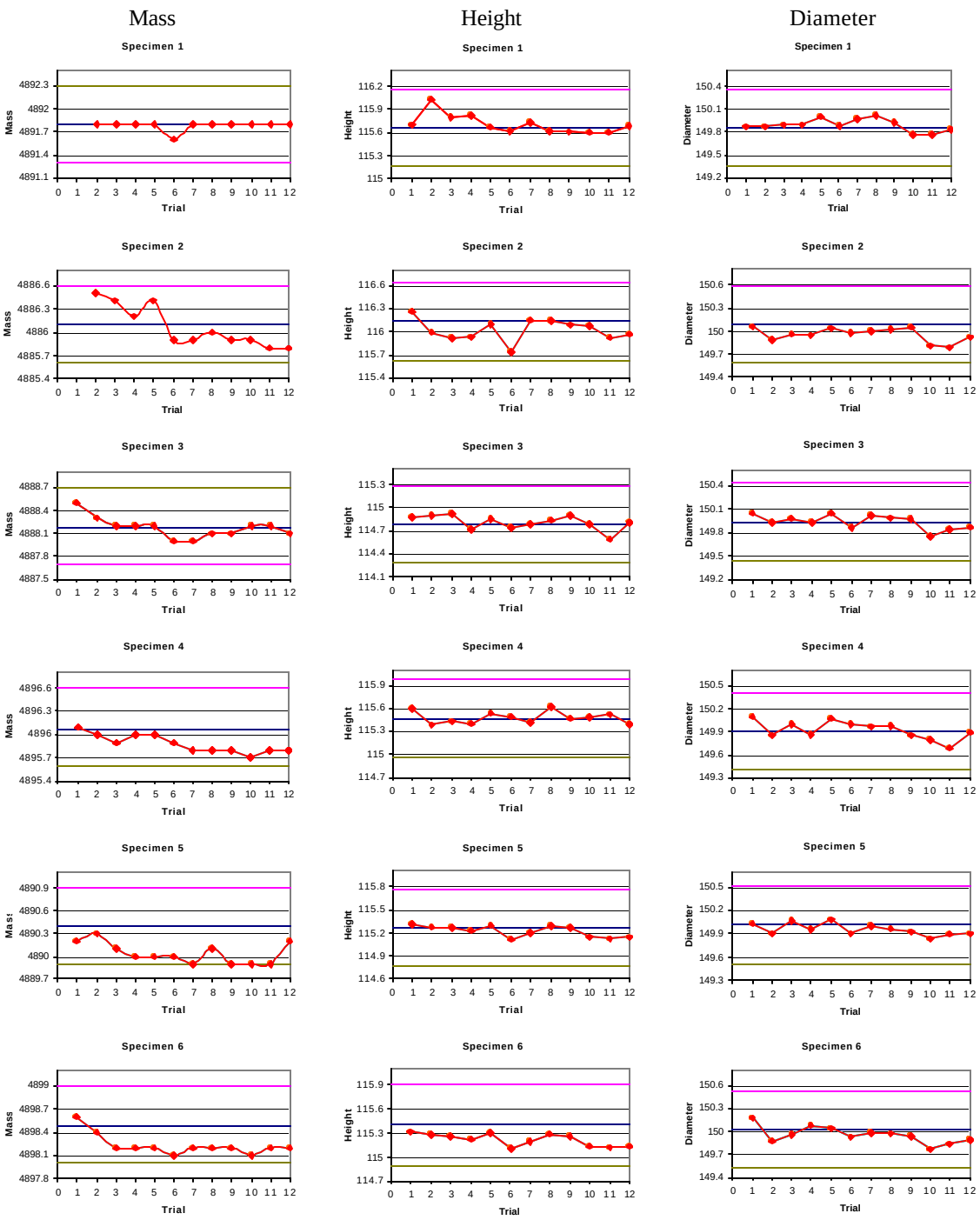



**Figure B-3, 19.0-mm HMA Specimen Control Charts**

# Appendix C

## Test Results

**Table C-1, T166, 9.5-mm Specimen Data**

| Laboratory No. | Replicate No. | Specimen No. | Air Dry Mass (g) | Weight in Water (g) | SSD Mass (g) | Bulk Sp. Gr. | Lab Temp. (Deg. C) | Bath Temp (Deg. C) | Time Immersed (sec.) | Time to SSD (sec.) |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 1 | 2 | 4880.9 | 2910.9 | 4883.7 | 2.474 | 23.3 | 25.8 | 190 | 25 |
| | 2 | | 4881.0 | 2910.8 | 4884.3 | 2.473 | 28.0 | 25.3 | 276 | 26 |
| 4 | 1 | 1 | 4888.9 | 2902.4 | 4889.6 | 2.460 | 20.4 | 25.2 | 206 | 14 |
| | 2 | | 4884.1 | 2902.5 | 4889.8 | 2.458 | 22.9 | 25.2 | 224 | 35 |
| 5 | 1 | 4 | 4890.8 | 2918.8 | 4894.6 | 2.475 | 21.0 | 25.1 | 240 | 12 |
| | 2 | | 4890.8 | 2918.8 | 4895.2 | 2.475 | 18.7 | 25.6 | 240 | 5 |
| 6 | 1 | 3 | 4885.9 | 2915.9 | 4889.9 | 2.475 | 26.3 | 26.1 | 200 | 30 |
| | 2 | | 4886.0 | 2918.0 | 4888.3 | 2.480 | 25.6 | 24.4 | 300 | 30 |
| 7 | 1 | 2 | 4880.3 | 2908.8 | 4882.6 | 2.473 | 23.2 | 25.1 | 218 | 33 |
| | 2 | | 4880.1 | 2908.1 | 4882.6 | 2.472 | 26.2 | 25.0 | 219 | 26 |
| 8 | 1 | 3 | 4887.7 | 2914.2 | 4889.3 | 2.475 | 26.6 | 24.6 | 194 | 56 |
| | 2 | | 4887.5 | 2913.9 | 4888.7 | 2.475 | 21.3 | 25.6 | 191 | 38 |
| 9 | 1 | 2 | 4881.5 | 2908.7 | 4886.4 | 2.468 | 24.5 | 25.3 | 240 | 7 |
| | 2 | | 4881.5 | 2908.6 | 4886.4 | 2.468 | 21.1 | 24.9 | 255 | 9 |
| 10 | 1 | 4 | 4890.4 | 2915.9 | 4893.2 | 2.473 | 24.3 | 24.9 | 210 | 10 |
| | 2 | | 4890.5 | 2915.8 | 4893.4 | 2.473 | 21.5 | 22.5 | 250 | 15 |
| 11 | 1 | 4 | 4888.3 | 2912.0 | 4890.5 | 2.471 | 22.4 | 24.2 | 240 | 5 |
| | 2 | | 4888.3 | 2913.1 | 4890.7 | 2.472 | 24.2 | 24.8 | 265 | 20 |
| 12 | 1 | 3 | 4885.7 | 2915.4 | 4888.3 | 2.476 | 21.6 | 24.2 | 250 | 20 |
| | 2 | | 4885.8 | 2915.4 | 4888.5 | 2.476 | 21.0 | 24.8 | 256 | 16 |
| 13 | 1 | 1 | 4884.7 | 2901.9 | 4891.7 | 2.455 | 25.0 | 24.9 | 285 | 17 |
| | 2 | | 4884.1 | 2902.3 | 4890.0 | 2.457 | 24.5 | 25.4 | 217 | 23 |
| 14 | 1 | 3 | 4885.6 | 2915.1 | 4886.6 | 2.478 | 21.9 | 24.8 | 240 | 16 |
| | 2 | | 4885.6 | 2913.9 | 4887.0 | 2.476 | 21.3 | 24.6 | 219 | 22 |
| 15 | 1 | 1 | 4884.6 | 2902.1 | 4889.2 | 2.458 | 19.5 | 24.2 | 238 | 16 |
| | 2 | | 4884.6 | 2901.3 | 4889.2 | 2.457 | 21.0 | 24.6 | 196 | 15 |
| 16 | 1 | 1 | 4885.3 | 2904.0 | 4892.2 | 2.457 | 21.6 | 25.1 | 240 | 12 |
| | 2 | | 4885.2 | 2906.1 | 4891.8 | 2.460 | 20.2 | 24.5 | 199 | 26 |
| 17 | 1 | 4 | 4890.7 | 2913.2 | 4893.5 | 2.470 | 19.2 | 25.0 | 180 | 10 |
| | 2 | | 4890.8 | 2915.6 | 4893.1 | 2.473 | 16.6 | 24.8 | 180 | 10 |
| 18 | 1 | 3 | 4886.0 | 2916.2 | 4889.2 | 2.476 | 20.1 | 25.3 | 244 | 4 |
| | 2 | | 4867.4 | 2897.1 | 4889.9 | 2.442 | 23.5 | 25.9 | 255 | 10 |
| 19 | 1 | 4 | 4891.3 | 2916.4 | 4895.3 | 2.472 | 18.3 | 25.0 | 210 | 60 |
| | 2 | | 4891.8 | 2918.2 | 4896.9 | 2.472 | 20.2 | 25.6 | 316 | 45 |
| 20 | 1 | 1 | 4884.1 | 2906.6 | 4889.8 | 2.463 | 21.7 | 24.8 | 240 | 30 |
| | 2 | | 4884.1 | 2903.4 | 4893.2 | 2.455 | 23.4 | 24.8 | 240 | 12 |
| 21 | 1 | 2 | 4881.4 | 2907.7 | 4884.1 | 2.470 | 21.0 | 24.5 | 182 | 6 |
| | 2 | | 4881.5 | 2907.9 | 4884.1 | 2.470 | 21.2 | 24.4 | 195 | 9 |
| 22 | 1 | 2 | 4880.5 | 2908.9 | 4882.3 | 2.473 | 22.5 | 24.5 | 243 | 20 |
| | 2 | | 4880.7 | 2909.0 | 4882.7 | 2.473 | 20.5 | 24.7 | 225 | 35 |

Note: Shading indicates data that were identified as outliers by ASTM E691.

## Table C-2, T166, 12.5-mm Specimen Data

| Laboratory No. | Replicate No. | Specimen No. | Air Dry Mass (g) | Weight in Water (g) | SSD Mass (g) | Bulk Sp. Gr. | Lab Temp. (Deg. C) | Bath Temp (Deg. C) | Time Immersed (sec.) | Time to SSD (sec.) |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 1 | 2 | 4875.1 | 2931.9 | 4878.8 | 2.504 | 23.3 | 25.8 | 190 | 40 |
| | 2 | | 4875.1 | 2931.4 | 4879.2 | 2.503 | 28.0 | 25.4 | 275 | 23 |
| 4 | 1 | 1 | 4879.2 | 2926.8 | 4884.5 | 2.492 | 20.4 | 25.2 | 213 | 22 |
| | 2 | | 4879.2 | 2927.7 | 4885.2 | 2.493 | 22.9 | 25.2 | 227 | 16 |
| 5 | 1 | 4 | 4877.9 | 2929.4 | 4883.1 | 2.497 | 21.0 | 25.1 | 240 | 5 |
| | 2 | | 4877.6 | 2931.1 | 4884.2 | 2.497 | 18.7 | 25.6 | 240 | 4 |
| 6 | 1 | 3 | 4878.6 | 2926.6 | 4885.2 | 2.491 | 26.3 | 26.1 | 245 | 30 |
| | 2 | | 4878.8 | 2928.6 | 4883.8 | 2.495 | 25.6 | 24.4 | 300 | 40 |
| 7 | 1 | 2 | 4874.5 | 2928.2 | 4877.9 | 2.500 | 23.2 | 25.1 | 210 | 26 |
| | 2 | | 4874.1 | 2928.1 | 4877.9 | 2.500 | 26.2 | 25.0 | 196 | 25 |
| 8 | 1 | 3 | 4880.5 | 2917.3 | 4882.9 | 2.483 | 26.6 | 24.2 | 209 | 48 |
| | 2 | | 4879.9 | 2923.7 | 4882.4 | 2.491 | 21.3 | 25.3 | 180 | 35 |
| 9 | 1 | 2 | 4875.6 | 2928.8 | 4882.2 | 2.496 | 24.5 | 25.2 | 251 | 10 |
| | 2 | | 4875.6 | 2929.2 | 4882.2 | 2.496 | 21.1 | 24.9 | 260 | 13 |
| 10 | 1 | 4 | 4877.7 | 2927.3 | 4882.5 | 2.495 | 24.3 | 24.9 | 240 | 12 |
| | 2 | | 4877.8 | 2927.2 | 4883.3 | 2.494 | 21.5 | 25.0 | 230 | 15 |
| 11 | 1 | 4 | 4875.6 | 2922.2 | 4879.5 | 2.491 | 22.4 | 24.2 | 238 | 3 |
| | 2 | | 4875.5 | 2924.8 | 4879.7 | 2.494 | 24.2 | 24.8 | 260 | 12 |
| 12 | 1 | 3 | 4878.4 | 2926.2 | 4886.6 | 2.488 | 21.6 | 24.2 | 256 | 15 |
| | 2 | | 4878.4 | 2925.0 | 4883.0 | 2.492 | 21.0 | 24.7 | 248 | 15 |
| 13 | 1 | 1 | 4880.1 | 2925.5 | 4887.3 | 2.488 | 25.0 | 24.9 | 280 | 21 |
| | 2 | | 4879.4 | 2927.4 | 4885.6 | 2.492 | 24.5 | 25.5 | 217 | 40 |
| 14 | 1 | 3 | 4878.1 | 2924.1 | 4880.5 | 2.493 | 21.9 | 24.8 | 240 | 15 |
| | 2 | | 4878.3 | 2924.7 | 4881.0 | 2.494 | 21.3 | 24.6 | 218 | 21 |
| 15 | 1 | 1 | 4880.0 | 2926.1 | 4884.6 | 2.492 | 19.5 | 24.1 | 236 | 22 |
| | 2 | | 4879.9 | 2926.1 | 4884.7 | 2.492 | 21.0 | 24.6 | 217 | 17 |
| 16 | 1 | 1 | 4880.6 | 2930.7 | 4887.7 | 2.494 | 21.6 | 25.1 | 240 | 15 |
| | 2 | | 4880.5 | 2931.9 | 4888.2 | 2.495 | 20.2 | 24.5 | 216 | 22 |
| 17 | 1 | 4 | 4877.7 | 2924.8 | 4882.9 | 2.491 | 19.2 | 24.8 | 180 | 10 |
| | 2 | | 4877.7 | 2925.0 | 4883.1 | 2.491 | 16.6 | 24.7 | 180 | 10 |
| 18 | 1 | 3 | 4878.7 | 2925.9 | 4883.4 | 2.492 | 20.1 | 25.4 | 243 | 4 |
| | 2 | | 4878.6 | 2925.4 | 4884.4 | 2.490 | 23.5 | 25.9 | 254 | 10 |
| 19 | 1 | 4 | 4878.2 | 2927.4 | 4886.7 | 2.490 | 18.3 | 25.0 | 210 | 60 |
| | 2 | | 4878.8 | 2927.9 | 4883.9 | 2.494 | 20.2 | 25.6 | 321 | 33 |
| 20 | 1 | 1 | 4879.3 | 2931.4 | 4884.1 | 2.499 | 21.7 | 24.8 | 240 | 60 |
| | 2 | | 4879.3 | 2926.9 | 4884.1 | 2.493 | 23.4 | 24.8 | 215 | 30 |
| 21 | 1 | 2 | 4875.5 | 2928.7 | 4880.1 | 2.498 | 21.0 | 24.5 | 196 | 10 |
| | 2 | | 4875.6 | 2928.7 | 4879.9 | 2.499 | 21.2 | 24.5 | 187 | 9 |
| 22 | 1 | 2 | 4874.7 | 2929.0 | 4877.0 | 2.502 | 22.5 | 24.5 | 250 | 51 |
| | 2 | | 4874.7 | 2929.2 | 4877.6 | 2.502 | 20.5 | 24.7 | 220 | 30 |

Note: Shading indicates data that were identified as outliers by ASTM E691.

## Table C-3, T166, 19.0-mm Specimen Data

| Laboratory No. | Replicate No. | Specimen No. | Air Dry Mass (g) | Weight in Water (g) | SSD Mass (g) | Bulk Sp. Gr. | Lab Temp. (Deg. C) | Bath Temp (Deg. C) | Time Immersed (sec.) | Time to SSD (sec.) |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 1 | 2 | 4886.2 | 2944.6 | 4897.1 | 2.503 | 23.3 | 25.8 | 197 | 27 |
| | 2 | | 4886.3 | 2943.9 | 4896.4 | 2.503 | 28.0 | 25.4 | 279 | 35 |
| 4 | 1 | 1 | 4891.8 | 2938.1 | 4901.3 | 2.492 | 20.4 | 25.2 | 185 | 20 |
| | 2 | | 4891.8 | 2939.2 | 4904.6 | 2.489 | 22.9 | 25.2 | 224 | 28 |
| 5 | 1 | 4 | 4895.8 | 2948.5 | 4904.5 | 2.503 | 21.0 | 25.1 | 240 | 6 |
| | 2 | | 4895.8 | 2948.5 | 4904.2 | 2.503 | 18.7 | 25.6 | 240 | 5 |
| 6 | 1 | 3 | 4888.2 | 2941.7 | 4898.2 | 2.498 | 26.3 | 26.1 | 240 | 30 |
| | 2 | | 4888.3 | 2940.1 | 4894.8 | 2.501 | 25.6 | 24.5 | 300 | 30 |
| 7 | 1 | 2 | 4885.4 | 2938.7 | 4894.9 | 2.497 | 23.2 | 25.3 | 199 | 25 |
| | 2 | | 4884.9 | 2937.5 | 4893.4 | 2.498 | 26.2 | 24.8 | 203 | 27 |
| 8 | 1 | 3 | 4889.7 | 2938.7 | 4894.5 | 2.500 | 26.6 | 24.7 | 196 | 36 |
| | 2 | | 4889.2 | 2935.8 | 4894.4 | 2.496 | 21.3 | 25.5 | 187 | 29 |
| 9 | 1 | 2 | 4886.2 | 2939.7 | 4902.1 | 2.490 | 24.5 | 25.2 | 228 | 7 |
| | 2 | | 4886.3 | 2940.1 | 4901.3 | 2.491 | 21.1 | 24.9 | 245 | 9 |
| 10 | 1 | 4 | 4895.9 | 2943.8 | 4903.5 | 2.498 | 24.3 | 24.9 | 240 | 15 |
| | 2 | | 4896.0 | 2943.4 | 4903.6 | 2.498 | 21.5 | 24.9 | 245 | 15 |
| 11 | 1 | 4 | 4893.7 | 2939.2 | 4898.6 | 2.498 | 22.4 | 24.2 | 240 | 5 |
| | 2 | | 4893.5 | 2941.0 | 4899.0 | 2.499 | 24.2 | 24.8 | 250 | 15 |
| 12 | 1 | 3 | 4887.7 | 2939.6 | 4894.7 | 2.500 | 21.6 | 24.5 | 240 | 26 |
| | 2 | | 4887.7 | 2936.7 | 4894.7 | 2.496 | 21.0 | 24.6 | 250 | 15 |
| 13 | 1 | 1 | 4892.6 | 2939.3 | 4904.2 | 2.490 | 25.0 | 24.9 | 300 | 30 |
| | 2 | | 4892.0 | 2938.4 | 4903.3 | 2.490 | 24.5 | 25.5 | 228 | 26 |
| 14 | 1 | 3 | 4887.6 | 2937.9 | 4892.0 | 2.501 | 21.9 | 24.8 | 240 | 18 |
| | 2 | | 4887.5 | 2938.6 | 4893.4 | 2.500 | 21.3 | 24.6 | 238 | 21 |
| 15 | 1 | 1 | 4892.3 | 2936.9 | 4902.7 | 2.489 | 19.5 | 24.1 | 249 | 26 |
| | 2 | | 4892.4 | 2936.2 | 4903.3 | 2.487 | 21.0 | 24.6 | 284 | 25 |
| 16 | 1 | 1 | 4893.1 | 2941.2 | 4905.4 | 2.491 | 21.6 | 25.1 | 240 | 13 |
| | 2 | | 4893.0 | 2945.6 | 4904.9 | 2.497 | 20.2 | 24.8 | 201 | 21 |
| 17 | 1 | 4 | 4895.9 | 2942.1 | 4902.6 | 2.497 | 19.2 | 24.6 | 180 | 10 |
| | 2 | | 4895.9 | 2941.6 | 4901.6 | 2.498 | 16.6 | 24.6 | 180 | 10 |
| 18 | 1 | 3 | 4888.0 | 2940.0 | 4896.3 | 2.499 | 20.1 | 25.4 | 243 | 5 |
| | 2 | | 4888.1 | 2938.4 | 4895.8 | 2.497 | 23.5 | 25.9 | 254 | 8 |
| 19 | 1 | 4 | 4896.2 | 2942.8 | 4903.9 | 2.497 | 18.3 | 25.0 | 210 | 60 |
| | 2 | | 4896.8 | 2944.9 | 4903.4 | 2.500 | 20.2 | 25.6 | 276 | 103 |
| 20 | 1 | 1 | 4892.1 | 2944.4 | 4899.8 | 2.502 | 21.7 | 24.9 | 240 | 55 |
| | 2 | | 4891.9 | 2939.4 | 4902.3 | 2.492 | 23.4 | 24.7 | 235 | 20 |
| 21 | 1 | 2 | 4886.0 | 2939.6 | 4898.5 | 2.494 | 21.0 | 24.5 | 196 | 10 |
| | 2 | | 4886.0 | 2937.8 | 4896.8 | 2.494 | 21.2 | 24.5 | 190 | 10 |
| 22 | 1 | 2 | 4887.7 | 2941.3 | 4894.2 | 2.503 | 22.5 | 24.6 | 256 | 43 |
| | 2 | | 4886.0 | 2938.2 | 4892.7 | 2.500 | 20.5 | 24.7 | 215 | 30 |

Note: Shading indicates data that were identified as outliers by ASTM E691.

## Table C-4, T166, Aluminum Specimen Data

| Laboratory No. | Replicate No. | Specimen No. | Air Dry Mass (g) | Weight in Water (g) | SSD Mass (g) | Bulk Sp. Gr. | Lab Temp. (Deg. C) | Bath Temp (Deg. C) | Time Immersed (sec.) | Time to SSD (sec.) |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 1 | 2 | 5500.2 | 3541.7 | 5500.7 | 2.808 | 23.3 | 25.8 | 52 | 22 |
| | 2 | | 5500.5 | 3541.2 | 5500.5 | 2.807 | 28.0 | 25.3 | 280 | 39 |
| 4 | 1 | 1 | 5494.2 | 3536.1 | 5494.1 | 2.806 | 20.4 | 25.3 | 183 | 18 |
| | 2 | | 5494.3 | 3537.6 | 5494.3 | 2.808 | 22.9 | 25.2 | 197 | 50 |
| 5 | 1 | 4 | 5427.2 | 3493.6 | 5427.5 | 2.806 | 21.0 | 25.1 | 240 | 7 |
| | 2 | | 5427.0 | 3493.9 | 5427.7 | 2.806 | 18.7 | 25.6 | 240 | 4 |
| 6 | 1 | 3 | 5506.5 | 3545.6 | 5506.7 | 2.808 | 26.3 | 26.1 | 210 | 30 |
| | 2 | | 5506.5 | 3544.7 | 5506.5 | 2.807 | 25.6 | 24.5 | 300 | 25 |
| 7 | 1 | 2 | 5499.3 | 3540.5 | 5499.5 | 2.807 | 23.2 | 25.5 | 203 | 28 |
| | 2 | | 5499.2 | 3540.0 | 5499.2 | 2.807 | 26.2 | 24.2 | 200 | 24 |
| 8 | 1 | 3 | 5508.3 | 3542.9 | 5508.4 | 2.802 | 26.6 | 24.9 | 190 | 31 |
| | 2 | | 5508.0 | 3543.8 | 5507.9 | 2.804 | 21.3 | 25.6 | 191 | 39 |
| 9 | 1 | 2 | 5500.5 | 3542.0 | 5500.8 | 2.808 | 24.5 | 25.3 | 225 | 10 |
| | 2 | | 5500.5 | 3542.3 | 5501.0 | 2.808 | 21.1 | 24.9 | 208 | 7 |
| 10 | 1 | 4 | 5427.2 | 3494.3 | 5427.5 | 2.807 | 24.3 | 24.9 | 240 | 12 |
| | 2 | | 5427.3 | 3494.4 | 5427.5 | 2.808 | 21.5 | 24.9 | 240 | 15 |
| 11 | 1 | 4 | 5424.7 | 3491.7 | 5424.9 | 2.806 | 22.4 | 24.2 | 239 | 4 |
| | 2 | | 5424.5 | 3492.0 | 5424.7 | 2.807 | 24.2 | 24.7 | 250 | 9 |
| 12 | 1 | 3 | 5506.2 | 3544.7 | 5506.2 | 2.807 | 21.6 | 24.2 | 250 | 15 |
| | 2 | | 5506.2 | 3545.4 | 5507.1 | 2.807 | 21.0 | 24.7 | 252 | 15 |
| 13 | 1 | 1 | 5495.1 | 3537.2 | 5495.3 | 2.806 | 25.0 | 24.8 | 300 | 22 |
| | 2 | | 5494.4 | 3538.0 | 5494.9 | 2.808 | 24.5 | 25.4 | 240 | 32 |
| 14 | 1 | 3 | 5505.8 | 3544.2 | 5505.9 | 2.807 | 21.9 | 24.8 | 240 | 15 |
| | 2 | | 5505.9 | 3544.3 | 5506.0 | 2.807 | 21.3 | 24.7 | 239 | 22 |
| 15 | 1 | 1 | 5494.8 | 3537.9 | 5495.3 | 2.807 | 19.5 | 24.2 | 242 | 16 |
| | 2 | | 5494.7 | 3537.9 | 5495.0 | 2.808 | 21.0 | 24.6 | 192 | 16 |
| 16 | 1 | 1 | 5495.7 | 3538.1 | 5495.9 | 2.807 | 21.6 | 25.1 | 240 | 13 |
| | 2 | | 5495.5 | 3537.9 | 5495.7 | 2.807 | 20.2 | 24.5 | 208 | 26 |
| 17 | 1 | 4 | 5426.8 | 3491.3 | 5428.1 | 2.802 | 19.2 | 25.7 | 180 | 10 |
| | 2 | | 5426.7 | 3492.1 | 5428.0 | 2.803 | 16.6 | 25.4 | 180 | 10 |
| 18 | 1 | 3 | 5506.9 | 3545.8 | 5507.2 | 2.808 | 20.1 | 25.4 | 240 | 6 |
| | 2 | | 5506.5 | 3545.5 | 5506.7 | 2.808 | 23.5 | 25.9 | 248 | 11 |
| 19 | 1 | 4 | 5427.8 | 3493.8 | 5427.8 | 2.807 | 18.3 | 25.0 | 210 | 60 |
| | 2 | | 5428.4 | 3495.8 | 5428.4 | 2.809 | 20.2 | 25.6 | 243 | 87 |
| 20 | 1 | 1 | 5494.3 | 3537.4 | 5494.3 | 2.808 | 21.7 | 25.0 | 240 | 50 |
| | 2 | | 5494.4 | 3537.4 | 5494.5 | 2.807 | 23.4 | 24.7 | 225 | 20 |
| 21 | 1 | 2 | 5500.5 | 3541.0 | 5500.6 | 2.807 | 21.0 | 24.5 | 183 | 10 |
| | 2 | | 5500.5 | 3540.8 | 5500.4 | 2.807 | 21.2 | 24.6 | 189 | 10 |
| 22 | 1 | 2 | 5500.0 | 3540.9 | 5500.0 | 2.807 | 22.5 | 24.6 | 259 | 18 |
| | 2 | | 5500.0 | 3541.2 | 5500.1 | 2.808 | 20.5 | 24.7 | 220 | 35 |

Note: Shading indicates data that were identified as outliers by ASTM E691.

**Table C-5, D6752, 9.5-mm Specimen Data**

| Laboratory No. | Replicate No. | Specimen No. | Dry mass (g) | Wt of sealed specimen in water (g) | Dry Spec. after Submersion (g) | Bulk Sp. Gr. | Lab Temp. (Deg. C) | Bath Temp (Deg. C) | Time Immersed (sec.) |
|---|---|---|---|---|---|---|---|---|---|
| 3 | 1 | 6 | 4886.5 | 2838.1 | 4886.9 | 2.410 | 22.2 | 25.8 | 108 |
| | 2 | | 4886.7 | 2885.5 | 4886.8 | 2.468 | 28.0 | 25.2 | 74 |
| 4 | 1 | 5 | 4881.3 | 2869.6 | 4882.9 | 2.450 | 20.5 | 25.5 | 251 |
| | 2 | | 4882.3 | 2853.9 | 4882.3 | 2.432 | 20.0 | 25.1 | 60 |
| 9 | 1 | 6 | 4887.0 | 2890.6 | 4887.0 | 2.474 | 22.7 | 25.4 | 168 |
| | 2 | | 4887.1 | 2886.5 | 4887.0 | 2.469 | 21.1 | 25.1 | 140 |
| 13 | 1 | 5 | 4883.3 | 2867.6 | 4883.6 | 2.448 | 25.0 | 24.9 | 210 |
| | 2 | | 4882.5 | 2870.3 | 4883.4 | 2.451 | 24.5 | 25.2 | 156 |
| 15 | 1 | 5 | 4883.0 | 2870.3 | 4882.9 | 2.452 | 19.5 | 24.5 | 302 |
| | 2 | | 4883.0 | 2869.5 | 4883.0 | 2.451 | 20.8 | 24.7 | 170 |
| 16 | 1 | 5 | 4883.6 | 2867.6 | 4883.7 | 2.448 | 21.6 | 25.3 | 240 |
| | 2 | | 4883.5 | 2867.8 | 4883.5 | 2.448 | 20.2 | 24.5 | 116 |
| 17 | 1 | 6 | 4886.5 | 2887.5 | 4886.5 | 2.471 | 21.3 | 24.8 | 132 |
| | 2 | | 4886.7 | 2882.0 | 4886.7 | 2.464 | 22.3 | 24.1 | 106 |
| 20 | 1 | 5 | 4881.5 | 2865.4 | 4881.5 | 2.447 | 21.4 | 24.8 | 65 |
| | 2 | | 4881.6 | 2866.1 | 4881.7 | 2.448 | 23.6 | 24.7 | 60 |
| 21 | 1 | 6 | 4887.1 | 2887.1 | 4887.1 | 2.470 | 21.0 | 24.5 | 189 |
| | 2 | | 4887.1 | 2827.8 | 4889.6 | 2.395 | 21.2 | 24.5 | 189 |
| 22 | 1 | 6 | 4886.1 | 2886.7 | 4886.1 | 2.470 | 22.7 | 24.7 | 272 |
| | 2 | | 4886.2 | 2887.5 | 4886.3 | 2.471 | 20.2 | 24.8 | 80 |

Note: Shading indicates data that were identified as outliers by ASTM E691.

**Table C-6, D6752, 12.5-mm Specimen Data**

| Laboratory No. | Replicate No. | Specimen No. | Dry mass (g) | Wt of sealed specimen in water (g) | Dry Spec. after Submersion (g) | Bulk Sp. Gr. | Lab Temp. (Deg. C) | Bath Temp (Deg. C) | Time Immersed (sec.) |
|---|---|---|---|---|---|---|---|---|---|
| 3 | 1 | 6 | 4879.6 | 2878.0 | 4881.4 | 2.462 | 22.2 | 25.8 | 124 |
| | 2 | | 4879.7 | 2889.6 | 4879.8 | 2.478 | 28.0 | 25.3 | 96 |
| 4 | 1 | 5 | 4872.3 | 2886.6 | 4873.6 | 2.478 | 20.5 | 25.0 | 121 |
| | 2 | | 4872.4 | 2881.0 | 4872.3 | 2.473 | 22.9 | 25.0 | 210 |
| 9 | 1 | 6 | 4880.2 | 2890.5 | 4880.2 | 2.479 | 22.7 | 25.4 | 105 |
| | 2 | | 4880.2 | 2868.7 | 4880.4 | 2.452 | 21.1 | 25.0 | 185 |
| 13 | 1 | 5 | 4873.0 | 2890.8 | 4873.0 | 2.485 | 25.0 | 24.9 | 170 |
| | 2 | | 4872.4 | 2888.8 | 4872.3 | 2.483 | 24.5 | 25.3 | 104 |
| 15 | 1 | 5 | 4872.7 | 2890.3 | 4872.7 | 2.484 | 19.5 | 24.5 | 285 |
| | 2 | | 4872.6 | 2891.6 | 4872.6 | 2.486 | 20.8 | 24.6 | 221 |
| 16 | 1 | 5 | 4873.3 | 2890.2 | 4873.3 | 2.484 | 21.6 | 25.3 | 240 |
| | 2 | | 4873.3 | 2888.9 | 4873.2 | 2.482 | 20.2 | 24.5 | 129 |
| 17 | 1 | 6 | 4879.6 | 2885.3 | 4879.6 | 2.473 | 21.3 | 24.8 | 75 |
| | 2 | | 4879.9 | 2875.1 | 4879.9 | 2.460 | 22.3 | 24.0 | 105 |
| 20 | 1 | 5 | 4872.3 | 2887.7 | 4872.4 | 2.481 | 22.0 | 24.5 | 35 |
| | 2 | | 4782.7 | 2889.0 | 4874.5 | 2.434 | 23.6 | 24.7 | 50 |
| 21 | 1 | 6 | 4880.3 | 2889.2 | 4880.3 | 2.477 | 21.0 | 24.5 | 190 |
| | 2 | | 4880.4 | 2886.5 | 4880.6 | 2.474 | 21.2 | 24.6 | 183 |
| 22 | 1 | 6 | 4879.2 | 2884.4 | 4879.2 | 2.472 | 22.7 | 24.7 | 235 |
| | 2 | | 4879.4 | 2887.5 | 4879.4 | 2.476 | 20.2 | 24.8 | 80 |

Note: Shading indicates data that were identified as outliers by ASTM E691.

**Table C-7, D6752, 19.0-mm Specimen Data**

| Laboratory No. | Replicate No. | Specimen No. | Dry mass (g) | Wt of sealed specimen in water (g) | Dry Spec. after Submersion (g) | Bulk Sp. Gr. | Lab Temp. (Deg. C) | Bath Temp (Deg. C) | Time Immersed (sec.) |
|---|---|---|---|---|---|---|---|---|---|
| 3 | 1 | 6 | 4898.0 | 2896.2 | 4898.0 | 2.473 | 22.2 | 25.8 | 53 |
| | 2 | | 4898.2 | 2898.8 | 4898.5 | 2.476 | 28.0 | 25.3 | 76 |
| 4 | 1 | 5 | 4890.2 | 2891.2 | 4890.1 | 2.473 | 20.5 | 25.1 | 230 |
| | 2 | | 4890.1 | 2884.5 | 4890.8 | 2.463 | 22.9 | 24.9 | 104 |
| 9 | 1 | 6 | 4898.4 | 2903.1 | 4898.3 | 2.482 | 22.7 | 25.4 | 409 |
| | 2 | | 4898.5 | 2886.9 | 4898.4 | 2.461 | 21.1 | 25.0 | 184 |
| 13 | 1 | 5 | 4890.7 | 2891.6 | 4890.8 | 2.473 | 25.0 | 24.9 | 165 |
| | 2 | | 4890.2 | 2891.5 | 4890.2 | 2.473 | 24.5 | 25.4 | 130 |
| 15 | 1 | 5 | 4890.5 | 2893.9 | 4893.2 | 2.472 | 19.5 | 24.3 | 252 |
| | 2 | | 4890.6 | 2893.2 | 4890.6 | 2.475 | 20.8 | 24.6 | 247 |
| 16 | 1 | 5 | 4891.2 | 2891.4 | 4891.2 | 2.472 | 21.6 | 25.3 | 240 |
| | 2 | | 4891.1 | 2890.2 | 4891.2 | 2.470 | 20.2 | 24.6 | 125 |
| 17 | 1 | 6 | 4897.7 | 2893.9 | 4897.7 | 2.470 | 21.3 | 24.6 | 84 |
| | 2 | | 4897.9 | 2893.7 | 4897.8 | 2.470 | 22.3 | 24.1 | 82 |
| 20 | 1 | 5 | 4890.3 | 2887.8 | 4890.4 | 2.468 | 21.4 | 24.6 | 60 |
| | 2 | | 4890.3 | 2889.0 | 4890.4 | 2.470 | 23.6 | 24.7 | 50 |
| 21 | 1 | 6 | 4898.3 | 2898.8 | 4898.4 | 2.476 | 21.0 | 24.5 | 188 |
| | 2 | | 4898.2 | 2897.9 | 4898.2 | 2.475 | 21.2 | 24.5 | 183 |
| 22 | 1 | 6 | 4897.9 | 2847.9 | 4898.3 | 2.414 | 22.7 | 24.7 | 242 |
| | 2 | | 4897.9 | 2896.1 | 4897.9 | 2.473 | 20.2 | 24.8 | 70 |

Note: Shading indicates data that were identified as outliers by ASTM E691.

**Table C-8, D6752, Aluminum Specimen Data**

| Laboratory No. | Replicate No. | Specimen No. | Dry mass (g) | Wt of sealed specimen in water (g) | Dry Spec. after Submersion (g) | Bulk Sp. Gr. | Lab Temp. (Deg. C) | Bath Temp (Deg. C) | Time Immersed (sec.) |
|---|---|---|---|---|---|---|---|---|---|
| 3 | 1 | 2 | 5500.3 | 3519.7 | 5500.2 | 2.811 | 22.2 | 25.9 | 73 |
| | 2 | | 5500.3 | 3479.3 | 5500.6 | 2.753 | 28.0 | 25.0 | 126 |
| 4 | 1 | 1 | 5494.2 | 3517.1 | 5494.2 | 2.812 | 20.5 | 25.3 | 232 |
| | 2 | | 5494.2 | 3513.7 | 5494.3 | 2.807 | 22.9 | 25.3 | 180 |
| 9 | 1 | 2 | 5500.5 | 3517.5 | 5500.5 | 2.807 | 22.7 | 25.4 | 122 |
| | 2 | | 5500.3 | 3521.9 | 5500.4 | 2.814 | 21.1 | 25.1 | 196 |
| 13 | 1 | 1 | 5495.2 | 3515.8 | 5495.0 | 2.810 | 25.0 | 24.8 | 210 |
| | 2 | | 5494.5 | 3517.6 | 5494.4 | 2.813 | 24.5 | 25.2 | 165 |
| 15 | 1 | 1 | 5494.8 | 3513.3 | 5494.9 | 2.806 | 19.5 | 24.6 | 245 |
| | 2 | | 5494.7 | 3515.1 | 5494.7 | 2.809 | 20.8 | 24.7 | 390 |
| 16 | 1 | 1 | 5495.6 | 3515.6 | 5495.6 | 2.808 | 21.6 | 25.3 | 240 |
| | 2 | | 5495.6 | 3517.2 | 5495.5 | 2.811 | 20.2 | 24.4 | 212 |
| 17 | 1 | 2 | 5500.1 | 3502.1 | 5500.0 | 2.786 | 21.3 | 25.0 | 138 |
| | 2 | | 5499.9 | 3514.3 | 5499.8 | 2.802 | 22.3 | 24.3 | 153 |
| 20 | 1 | 1 | 5494.3 | 3506.8 | 5494.3 | 2.797 | 21.4 | 24.8 | 60 |
| | 2 | | 5494.4 | 3508.0 | 5494.4 | 2.799 | 23.6 | 24.7 | 50 |
| 21 | 1 | 2 | 5500.5 | 3512.6 | 5500.5 | 2.800 | 21.0 | 24.5 | 182 |
| | 2 | | 5500.5 | 3507.8 | 5500.5 | 2.793 | 21.2 | 24.8 | 182 |
| 22 | 1 | 2 | 5500.0 | 3513.2 | 5500.0 | 2.802 | 22.7 | 24.7 | 217 |
| | 2 | | 5500.1 | 3510.3 | 5500.1 | 2.797 | 20.2 | 25 | 150 |

Note: Shading indicates data that were identified as outliers by ASTM E691.

**Table C-9 - Core Reader Test Results**

| | | Date Tested | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Specimens | ID | 9/5/2003 | 9/15/2003 | 9/16/2003 | 9/17/2003 | 9/17/2003 | 9/29/2003 | $S_r$ | Avg. $S_r$ |
| 9.5-mm | 1 | 2.430 | 2.433 | 2.437 | 2.439 | 2.443 | 2.444 | 0.0055 | 0.0044 |
| | 2 | 2.438 | 2.443 | 2.440 | 2.439 | 2.437 | 2.442 | 0.0023 | |
| | 3 | 2.444 | 2.451 | 2.450 | 2.460 | 2.447 | 2.452 | 0.0054 | |
| | 4 | 2.440 | 2.455 | 2.444 | 2.441 | 2.447 | 2.443 | 0.0055 | |
| | 5 | 2.432 | 2.438 | 2.432 | 2.429 | 2.429 | 2.432 | 0.0033 | |
| | 6 | 2.442 | 2.431 | 2.439 | 2.440 | 2.441 | 2.444 | 0.0045 | |
| 12.5-mm | 1 | 2.468 | 2.470 | 2.466 | 2.464 | 2.463 | 2.465 | 0.0029 | 0.0029 |
| | 2 | 2.473 | 2.472 | 2.478 | 2.477 | 2.478 | 2.476 | 0.0026 | |
| | 3 | 2.458 | 2.464 | 2.466 | 2.461 | 2.459 | 2.462 | 0.0030 | |
| | 4 | 2.459 | 2.454 | 2.457 | 2.455 | 2.459 | 2.454 | 0.0023 | |
| | 5 | 2.468 | 2.472 | 2.471 | 2.470 | 2.472 | 2.474 | 0.0020 | |
| | 6 | 2.456 | 2.464 | 2.459 | 2.455 | 2.453 | 2.464 | 0.0047 | |
| 19.0-mm | 1 | 2.444 | 2.453 | 2.458 | 2.444 | 2.444 | 2.452 | 0.0065 | 0.0037 |
| | 2 | 2.444 | 2.444 | 2.448 | 2.450 | 2.450 | 2.447 | 0.0027 | |
| | 3 | 2.481 | 2.487 | 2.486 | 2.489 | 2.485 | 2.486 | 0.0027 | |
| | 4 | 2.451 | 2.463 | 2.456 | 2.456 | 2.454 | 2.454 | 0.0040 | |
| | 5 | 2.451 | 2.456 | 2.450 | 2.454 | 2.450 | 2.453 | 0.0024 | |
| | 6 | 2.470 | 2.480 | 2.475 | 2.473 | 2.470 | 2.477 | 0.0040 | |