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North Dakota DOT
Ohio DOT
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ABSTRACT

This report presents the results of a study to evaluate various mechanical devices for measuring maximum specific gravity (Gmm) of asphalt-aggregate mixtures and to determine the effect of change in the intensity of vibration of the mechanical agitators on Gmm measurements. Based on a Survey of the State Departments of Transportation, seven Gmm measuring devices were selected to be examined in this study. The selected devices were either the most commonly used brands of agitators or they were non-traditional setups with unique features. Gmm of laboratory-prepared and plant-produced mixtures ranging from 4.75-mm to 37.5-mm NMAS were measured. Along the Gmm measurements, the frequency and acceleration of vibration at each setting of the vibrating devices were determined to examine the relationship between Gmm and vibration properties. For possible refinement of Gmm measurement, the effect of change in the order of placing water and mixture in vacuum container and the effect of change in vacuum /agitation duration on Gmm and its variability was investigated. The results indicated that Gmm increases with the increase in intensity of vibration until Gmm reaches a highest value at a setting above which, the Gmm started to decrease. The stripping of asphalt is speculated to be the reason for the lower Gmm values at the higher vibration intensities since the water became significantly cloudy on or around the setting of the highest Gmm. The differences in Gmm from various devices/ methods and from various settings of each device were examined statistically and from practical point of view. The practical significance of the difference in Gmm was evaluated by examining the change in the air voids of the compacted mixtures. Based on the comparison of the air voids, statistical analysis of Gmm, and physical appearance of water, the optimum levels of the variables examined in this study were determined.

CHAPTER 1. INTRODUCTION AND RESEARCH APPROACH

1.1 Background

AASHTO T 209, "Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA)," test method covers the determination of the theoretical maximum specific gravity and density of uncompacted hot mix asphalt (HMA) [1]. The theoretical maximum specific gravities and densities of HMA are fundamental properties whose values are influenced by the composition of the mixtures in terms of types and amounts of aggregates and asphalt materials. Theoretical Maximum Specific Gravity property is used to calculate percent air voids in compacted HMA and provide target values for the compaction of HMA. Theoretical Maximum Specific Gravity is also essential when calculating the amount of asphalt binder absorbed by the internal porosity of the individual aggregate particles in HMA.

The AASHTO T 209 test procedure requires a vacuum be applied to a loose hot-mix asphalt (HMA) sample. The vacuum combined with either manual or mechanical agitation removes entrapped air in order to accurately determine the maximum specific gravity (Gmm). This value is used to determine both the air void content and in-place density of HMA. In-place density is commonly used in the acceptance and pay-factor determination of HMA.

Analysis of the AMRL Proficiency Sample Program data has demonstrated mechanical agitation provides less variation in test results when compared to manual agitation. However, several types of mechanical vibratory shakers are used to apply agitation. It is not known if these different devices provide significantly different results when compared to one another. In addition, the effect of change in intensity of vibration from various settings of the vibrating devices on Gmm measurements has not been explored.

The AASHTO Materials Reference Laboratory has conducted a research project to investigate the difference between the Gmm measured using the commonly used devices/methods and to determine the optimum frequency and acceleration levels of the mechanical agitation devices for accurate measurement of Gmm. For a possible refinement of Gmm measurement, the effect of other variables such as the effect of the order of placing water and mixture in vacuum container and the effect of changing the agitation/vacuum duration on Gmm was investigated.

1.2 Problem Statement

Deformation resistance and stability achievement greatly depend on the compaction of HMA. Theoretical maximum specific gravity and density values are used to calculate percent air voids, which provide target values for compaction of HMA. Various methods and devices, including several brands of mechanical agitators, are used for measuring the maximum density of asphalt mixtures. In addition, the mechanical agitation devices are manufactured to provide vibration on a wide range of frequency and acceleration. However, the difference in Gmm of various devices has not been examined and the effect of vibration levels on theoretical maximum specific gravity measurements has not been investigated. For the purpose of improving the

accuracy and precision of the test, the effect of several test variables such as the order of placing water and mixture in vacuum container and the duration of the agitation/vacuum on Gmm was also investigated.

1.3 Research Objectives

The overall goal of this study is to evaluate the effect of using various devices/methods on maximum specific gravity (Gmm) measurements. The objectives of the study are: 1) to compare the Gmm from manual and mechanical devices, 2) to investigate the relationship between the measured Gmm and the vibration properties of the mechanical vibratory tables and to determine an optimum vibration intensity of the vibrating devices, and 3) to evaluate the effect of several variables such as the order of placing water and mixture and the period of vacuum /agitation on Gmm measurements.

1.4 Scope of Study

The scope of the study involved the following major activities:

a) Conduct a survey of the State highway agencies to determine what specific mechanical equipment and methods are currently being practiced for determining the theoretical maximum specific gravity (Gmm) of asphalt mixtures (Chapter 2).

b) Based on the results of the survey, identify the most commonly used and the most unique equipment and methods utilized for measuring Gmm (Chapter 2 and 3).

c) Select a variety of laboratory-prepared and plant-produced asphalt mixtures for the study (Chapter 3):

   a. fine-graded, low traffic volume (< 1 million ESALs) Superpave mix;
   b. course-graded, high traffic volume Superpave mix (>30 million ESALs);
   c. gap-graded or SMA high traffic volume Superpave mix.

d) Conduct Gmm measurements using manual agitation and at several settings of various mechanical agitators (Chapter 4).

e) Evaluate the frequency, acceleration, and kinetic energy at various settings of the vibrating device (Chapter 4.1).

f) Evaluate practical and statistical significance of the differences between the Gmm from various settings of each vibratory device, zero vibration, and manual agitation and to determine the optimum setting of devices (Section 4.2).

g) Evaluate practical and statistical significance of the difference between the highest Gmm values from various mechanical devices and manual agitation. (Section 4.3)

h) Examine the relationship between the vibration properties of the vibrating devices and the highest Gmm produced by the device (Section 4.4).

i) Investigate the effect of the order of placing mixture and water in vacuum flask/bowl on Gmm measurement (Section 4.5).

j) Investigate the effect of changing the duration of vacuum/agitation process on Gmm measurement (Section 4.6).

k) Make conclusions and recommendations based on the findings in Chapter 4 (Chapter 5).

CHAPTER 2. SURVEY OF STATE DOT LABORATORIES

To identify the most commonly used devices and test methods, a survey of State departments of transportation were prepared and conducted. The survey included nine questions to identify the candidate devices for the study, to identify the level of operation of the devices by each state, and to determine any deviation of the state test methods from the AASHTO T 209. In addition to the Survey, phone conversations were conducted to obtain detailed information regarding the unique methods of test. The Thirty-five responses to the survey are organized and presented in Appendix A. The following sections provide some highlights of the results of the survey:

2.1 Survey Questions

To identify which devices are used most commonly, as well as any other important factors which might stem from variations in test methodology, a survey of State Departments of Transportation was conducted. The following questions were asked:

- What test method is used to determine Gmm?
- Is mechanical or manual agitation used?
- If using mechanical agitation, what setup is used?
- If using mechanical agitation, what brand and model of agitator is used?
- If using mechanical agitation, can the frequency of agitations be adjusted?
- If the frequency can be adjusted, how many distinct levels are available?
- If the frequency can be adjusted, what level is normally used?
    - What is the basis of this selection?
- If using a unique setup, can the lab assist AMRL in putting a similar unit together?

2.2 Test Methods

Generally, the laboratories utilized the standard AASHTO T 209 test method for testing maximum specific gravity of asphalt mixtures, although some states use a modified version of the AASHTO T 209 test method. The following are some brief descriptions of the differences among different state transportation departments test methods and AASHTO T 209.

2.2.1 Arizona

The Arizona DOT (ADOT) test method (ARIZ 417b) [2] was most recently revised in December 1987. ADOT method advocates the removal of entrapped air by subjecting the flask to a partial vacuum with a minimum of 20 inches mercury, instead of 1.08 ± 0.098 inches of mercury; and agitation of the contents manually only three or four times during the vacuum period, instead of once every two minutes. Also, weighing of the sample after the agitation is carried out at a temperature between 72 °F and 80 °F (23.9°C and 26.6°C), immediately after the agitation period is complete, instead of immersing the flask and the contents in water bath for 10 ± 1 minute.

2.2.2 Florida

Florida State DOT test method (FM 1-T 209) [3] was most recently revised in September 2007. The test method does not prescribe any mandatory conditioning for samples prepared in laboratories. Furthermore, Florida State DOT applies vacuum to reduce the residual pressure in the vacuum vessel to 30 ± 2 mm Hg, instead of 27 ± 2.5 mm Hg. The FDOT test method provides agitation using an orbital shaker table with a orbit of 3/4 inch (19.0 mm) with sufficient load capacity to shake at least two containers and specimens.

2.2.3 Idaho

The Idaho State DOT test method (T209_short) [4] was most recently revised in October 2007. Instead of measuring the dry mass of the sample directly, Idaho State DOT records the mass of the flask, including the cover, to the 0.1 g., then places the specimen in flasks and records the mass again, then takes the difference of these two masses to determine the mass of the sample. Furthermore, Idaho uses a petroleum gel to ensure a proper seal between the lid and the container. Modified version of Idaho State DOT Procedure includes instructions for both weigh-in air and weigh-in water methods.

2.2.4 Illinois

The Illinois State DOT test method (Ill-mod AASHTO T 209-05 #4) [5] was most recently revised in February 2008. This method applies the vacuum to reduce the residual pressure in the vacuum vessel to 30 ± 2.5 mm Hg, instead of 27 ± 2.5 mm Hg.

2.2.5 Indiana

The Indiana State Department of Transportation modified test procedure (T209 INDOT) [6], most recently modified in July 2002, mentions the use of both mechanical and manual agitation.

2.2.6 Minnesota

The Minnesota DOT test method (MNDOT 1807.0) [7] was most recently modified in August 2001. MNDOT differs from AASHTO by requiring the use of a cylindrical screen within the container and also makes use of a vacuum desiccator or a bell jar for a vacuum chamber. The mixture is placed around the cylindrical screen for better exposure to vacuum. Field samples are required to be dried to a constant weight at 110 ± 5°C (230 ± 9°F), instead of 105 ± 5°C (221 ± 9°F). Mass of container and screen is first measured prior to measuring mass of container, screen and sample, which replaces the process of measuring the weight of dry sample. Wetting agent is used proportionally before and after the agitation. Another remarkable difference in Minnesota method is that for determining the calibrated weight of the container, it is filled with water and a few drops of wetting agent and exposed to 3 minutes of vibration before the container is immersed in water.

2.2.7 New Mexico

The New Mexico DOT test method (T-209 NM) [8] was most recently modified in January 2009. New Mexico State Department of Transportation specifies that the container should be struck with a rubber mallet at 2 minute intervals during vacuum period, with 25 blows at 5 blows per 1/5 rotation along with the mechanical agitation, whereas AASHTO test method does not specify simultaneous manual and mechanical agitation; in addition, AASHTO T209 does not specify how many times and at what frequency the container should be struck for the manual agitation.

2.2.8 North Dakota

The North Dakota DOT test method (AASHTO T 209 NDDOT modified) [9] was most recently revised in May 2010. The NDDOT modification is to agitate for 15 minutes ± 30 seconds, instead of 15 ± 2 minutes; and after the agitation the flasks are immersed in water for 10 minutes ± 30 seconds, instead of 10 minutes ± 1 minute. The NDDOT provides agitation with an orbital shaker that is set at 225 to 250 rpm with a 3/4" throw. The North Dakota test method does not mention use of a wetting agent.

2.2.9 Ontario, Canada

The test method utilized by the Ontario Ministry of Transportation (LS-264 R19) [10] was revised in January 2001. The Ontario Ministry of Transportation procedure instructs to apply vacuum to reduce the residual pressure in the vacuum vessel to 30 ± 1 mm Hg, instead of 27 ± 2.5 mm Hg.

2.2.10 Washington

The Washington State DOT test method (WSDOT FOP for AASHTO T 209) [11] was modified in January 2007. Washington State Department of Transportation uses manual agitation with a mallet as well as mechanical agitation. WSDOT advises releasing of the vacuum within 10 to 15 seconds at the end of the vacuum period.

2.3 Summary of the Survey Responses

Brief summaries of the responses to each of the nine questions were compiled and is included below, sorted by question:

2.3.1 Question 1: What test method is used to determine Gmm?

From the total of 35 responses received, 24 states use AASHTO T 209 and 11 states use state test methods. The links to the state test methods are provided in the References section of the report.

2.3.2 Question 2: Is mechanical or manual agitation used?

Based on the 35 responses received, 6 states still use manual agitation and 29 states use mechanical agitation.

2.3.3 Question 3: If using mechanical agitation, what setup is used?

Based on the 35 responses, 32 states use traditional AASHTO T 209 setup and 3 states use unique setups. An example of the unique setup is the one used by the Minnesota DOT, in which a cylindrically formed mesh is placed in the middle of the test container and asphalt mixture is placed around the cylindrical mesh. The cylinder mesh is 4.75mm (#4) through 2.36mm (#8) opening, has diameter and height of approximately one-half those of the container, and has one end open. The open face of the cylindrical mesh is placed at the bottom of test container.

2.3.4 Question 4: If using mechanical agitation, what brand and model of agitator is used?

Based on the responses to the Question 4, five of the 29 laboratories using mechanical agitators use more than one brand of agitators. This results in total of 34 mechanical units, which fall in the following distribution:

- 7 Laboratories use Humboldt H- 1782, H-1756A, and H-3755 (0 to 10 adjustment)
- 6 Laboratories use Humboldt H-1756 and H-1755 (no adjustment)
- 7 Laboratories use Gilson (unlimited adjustment)
- 2 Laboratories use ELE (no adjustment)
- 3 Laboratories use vibrator from HMA lab supplies (no adjustment)
- 1 Laboratory uses pulley (no adjustment)
- 1 Laboratory uses Barnstead shaker (adjustable)
- 2 Laboratories uses Fasco M 7121-6088 (no adjustment)
- 3 Laboratories uses Syntron Vib-table (adjustable)
- 1 Laboratory uses Thermolyne (adjustable)
- 1 laboratory Endecotts E.V.S.1.(adjustable)

2.3.5 Question 5: If using mechanical agitation, can the frequency of agitations be adjusted?

Out of the total of 34 units (5 states use more than 1 unit), 19 units can be adjusted and 15 units cannot be adjusted (see responses to Question 4).

2.3.6 Question 6: If the frequency can be adjusted, how many distinct levels are available?

Out of the 19 units with adjustable dials, 8 units have unlimited adjustment and 11 units have 8 to 10 incremental adjustment levels.

2.3.7 Question 7: If the frequency can be adjusted, what level is normally used?

Out of the 19 units with adjustable dials, one unit is set to match the theoretical maximum gravity measurements from that unit to those from an un-adjustable unit, 6 units are set at maximum, 9 units are set at the middle, and 3 units are set at low.

2.3.8 Question 8: What is the basis of this selection?

The following categories are based on the total of 15 responses received to question 8:

- 4 laboratories based on no reason
- 3 laboratories based on feel or experience
- 3 laboratories based on maximum de-airation
- 2 laboratories based on repeatability of the measurement
- 1 laboratory based on gradation: finer mixes need more vibration
- 1 laboratory based on comparison between contractors and state laboratories
- 1 laboratory based on mimicking hand agitation

2.4 Selection of the Devices Based on Survey Results

Based on the results of the survey, the most commonly used brands of agitators were selected so that the findings would be pertinent to the widest number of labs. The most unique setups were also selected for the study to compare the application of the non-traditional methods to those of traditional methods. To that end, the following brands of agitating tables were selected for the investigation: Humboldt, Gilson, Syntron, Orbital, HMA, Aggregate Washer, and Corelok. The Humboldt, Gilson, and HMA tables were selected because they comprise over 80% of the devices used by the state laboratories. The Orbital shaker (similar to the Barnstead shaker), Aggregate Washer, and Corelok were selected despite being less common. However, these devices offer unique features in the Gmm measurements; therefore, it was important to investigate any differences between these devices and the traditional setups. The Syntron shaker was selected since it is used with the unique setup used by the Minnesota DOT.

CHAPTER 3. DESIGN AND EXECUTION OF THE STUDY

In order to provide target values for the compaction of HMA, it is essential to obtain a reliable measurement of theoretical maximum specific gravity (G_{mm}) and density of HMA samples. In this respect, a study was designed and conducted in which measurements of the theoretical maximum specific gravity of various mixture types were examined using different devices and at a variety of levels of agitation. The effect of factors such as the order of placing water and mixture in pycnometer and the vacuum/agitation duration on Gmm measurements were also investigated. The following sections will report on the design and execution of the study.

3.1 Test Apparatus

Based on the responses from the State Departments of Transportation (DOT) to the survey on the test methods and devices for the measurement of maximum theoretical specific gravity, seven devices were selected to be evaluated in the study. These include Gilson SGA-5R , Humboldt H-1782, Syntron shaking Table, HMA Lab Supply VA-2000, Orbital Shaker Table (SHKE 2000 table), Aggregate Drum Washer, and the Corelok vacuum sealing device. The selection of these devices was based on the prevalence of their use or the uniqueness of the agitation type they provide. Table 3-1 provides a brief description of each unit and Figure 3-1 illustrates the devices.

The setup used for measuring the theoretical maximum specific gravity includes an agitator, vacuum container, a vacuum bowl or vacuum flask (pycnometer), a balance, a vacuum pump, a moisture trap, a vacuum measurement device, a manometer, a bleeder valve, a thermometric device, a water bath, and a drying oven conforming to the requirements of Sections 6.2 to 6.11 of AASHTO T 209. An example of the testing arrangement is shown in Figure 3-2.

Frequency and amplitude measurements were made using a triaxial accelerometer, a signal conditioner, and "SignalView" computer software. An accelerometer produces an electrical signal which is a function of mechanical vibration. A signal conditioner obtains the voltage and acts as a transformer device between the accelerameter and the computer which processes and displays the signals. The acceleratometer was adhered on top of the vacuum container lid with the help of wax adhesive to capture the frequency and acceleration of vibration. The frequency measurements were recorded to the nearest 0.1 Hz and acceleration measurements were recorded to the nearest 0.01 m/s^2 in vertical, horizontal, and perpendicular axes. The axes shall be considered as such looking at the container from top down with the x-axis extending from the left to the right of the device, the y-axis perpendicular to the x-axis forming a plane parallel to the table, and the z-axis perpendicular to the x-y plane.

Table 3-1 Description of the units selected for the Refinement of AASHTO T 209 study

Unit	Manufacturer	Agitation Type	Description
Gilson Vibro-Deaerator SGA-5R	Gilson Co., Inc.	Vibratory	Has a dial for adjusting the frequency and amplitude of vibration. Different intensities are indicated by bars with different thickness. No number is associated with the bars.
Humboldt Vibrating Table H-1750	Humboldt Mfg. Co.	Vibratory	Has a dial for adjusting the frequency and amplitude of vibration. Different intensities are indicated by numbers on the dial from 1 to 10.
HMA Vibrating Table VA-2000	HMA Lab Supply	Vibratory	Has a fixed intensity; the most frequently used by the state DOTs.
Orbital Shaker SHKE 2000	Thermofisher Scientific	Orbital	Has an adjustable knob that controls the speed of the shaker platform in an orbital pattern in the range of 0 to 350 rpm.
Syntron			
Aggregate Drum Washer with vacuum lid.	Karol-Warner Co.	Rotary	Rotates slowly at the rate of 25 rpm and tumbles the loose mixture while the vacuum is applied.
Corelok device 130014	InstroTek, Inc.	No agitation-Vacuum sealing method	Corelok device vacuum-seals the loose asphalt mixture in a plastic bag.

Figure 3-1 Testing Apparatus used in this study

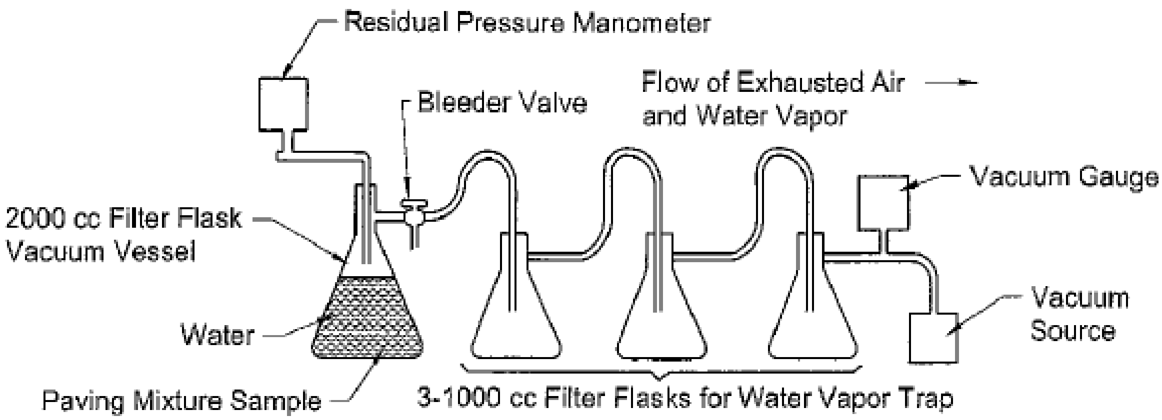

Figure 3-2 Example of Arrangement of Testing Apparatus as illustrated in AASHTO T 209 Test Method

3.2 Materials and Test Specimens

Test Specimens were either prepared in the laboratory or acquired from the field. Dense-graded 4.75-mm, 12.5-mm, 25.0-mm, and 37.5-mm nominal maximum aggregate size (NMAS) mixtures were prepared in laboratory. Dense-graded 9.5-mm and 19.0-mm NMAS mixtures were obtained from construction sites at the National Institute of Standards and Technology facility ground, and gap-graded (SMA) 9.5-mm, 19.0-mm, and 25.0-mm NMAS mixtures were obtained at construction sites in Richmond, Virginia. The mixture design of the dense-graded laboratory-prepared and plant produced mixtures are provided in Table 3-2; however, the mixture designs for the SMA mixtures were not provided by the contractor.

Plant produced samples were obtained conforming to the requirements of AASHTO T 168 [12] and stored in sealed boxes until the time of testing. To prepare the plant mixtures for testing, they were first heated in their boxes at 135 ± 5°C (275 ± 9°F) for about 2 hrs. The materials were then worked until a loose mixture condition was obtained. Both mechanical splitter and quartering methods were used to split the mixtures to the appropriate size for testing according to AASHTO R47 [13]. Mixtures were then dried in the oven at 105 ± 5°C (221 ± 9°F) to reach a constant mass, which is when the mass was within 0.1% of previous mass value measured in 15 minutes. The drying process usually took 15 to 30 min. HMA particles were further separated by hand so that the particles of the fine aggregate portion were not larger than 6.3 mm (1/4 in.). The mixtures were then cooled to room temperature before weighing and testing.

The laboratory mixtures were designed according to Superpave mix design procedure. Non absorptive Limestone-dolomite aggregate and PG 64-22 asphalt were mixed at 157°C and short-term conditioned for 2 hrs at 145°C according to AASHTO R30 [14]. The mixtures were then separated by hand so that the particles of the fine aggregate portion were not larger than 6.3-mm. Samples were then cooled to room temperature before weighing and testing.

Test specimens were prepared according to the weights in Table 3-3. As shown in the table, the 4.75-mm and 9.5-mm mixtures were prepared in 1500-g batches. The 12.5 mm mixture were prepared in 2000-g batches and the 19-mm and 25-mm mixtures were prepared in 2500-g batches. The 37.5-mm mixture was also prepared in 2000-g batches since the 4000 g batch weight that is required by AASHTO T209 for 37.5-mm and larger mixes could not fit in the flask or pycnometer. In this respect, four 2000-g specimens of 37.5-mm mixture were tested and the weight measurements from each of the two specimens were added and served as values for one replicate.

Table 3-2 Mix designs of the dense-graded laboratory-prepared and plant-produced mixtures

Sieve (mm)	Laboratory Prepared mixtures				Plant-Produced Mixture	
	4.75-mm Percent Passing (%)	12.0-mm Percent Passing (%)	25.0-mm Percent Passing (%)	37.5-mm Percent Passing (%)	9.5-mm Percent Passing (%)	19.0-mm Percent Passing (%)
50.00	100	100	100	100	100	100
37.50	100	100	100	97	100	100
25.00	100	100	97	91	100	100
19.00	100	100	86	78	100	98
12.50	100	92	71	59	100	87
9.50	100	78	63	45	94	74
4.75	93	52	45	29	53	37
2.36	67	34	29	19	33	27
1.18	44	22	18	12	22	20
0.60	23	15	11	8	14	15
0.30	16	11	7	5	10	10
0.15	11	7	5	4	7	7
0.075	8.0	4.4	4.4	3.6	6	5.1
AC %	5.8	5.2	4.0	3.6	5.2	4.4
D. B. Ratio	1.5	0.9	1.0	1.1	1.18	1.23

Table 3-3 Minimum Sample Sizes for the various mixtures in the study

Nominal Maximum Aggregate Size (mm)	Sample Weight (g)
4.75-mm and 9.5-mm	1500
12.5-mm and 37.5-mm	2000
19.0-mm and 25.0-mm	2500

3.3 Measurement Process

The theoretical maximum specific gravity (Gmm) measurements using vibratory, orbital, and rotary devices were conducted following AASHTO T 209. The cooled, separated particles of asphalt mixture were placed in a tared vacuum container and the dry mass of the sample was recorded. A sufficient amount of 25°C distilled water was then added to cover the sample completely. A deviation of the AASHTO T209 test method was also conducted on several mixtures in which the specified weight of the dry sample was added to the flask or pycnometer after water was placed in the container. The purpose of this practice was to examine the effect of the order of placing mixture and water on release of air and as a result on the Gmm measurement. After adding 0.001 percent of wetting agent, the container/flask was sealed and subjected to vibration at 27.5±2.5 mm Hg of vacuum for 15 minutes. For three of the mixtures, the agitation/vacuum time of 10 min, 20 min, and 25 min were also used with the Gilson vibratory device for examining the effect of agitation time on Gmm measurement.

Subsequent to the release of the vacuum, the container was either immersed in a distilled water bath for 10 minutes for mass measurement in water; or the flask was filled with distilled water, kept in the water bath for 10 minutes, and then dried and placed on scale for mass determination in the air. The weight measurements were obtained to the nearest 0.1 grams.

In addition to the weight measurements, the acceleration and frequency in the x, y and z axes of the vibrating tables were measured to the nearest 0.01 m/s^2 and 0.1 Hz, respectively. A 3-dimentional accelerometer, a data acquisition system, and analysis software were used for measuring the frequency and amplitude of the vibrating tables at approximately five minutes after starting the agitation. The measurements at each vibration setting of each vibratory device were performed in replicates. Figure 3-3 shows the 3-D accelerometer, its mounting position on the pycnometer lid, and typical acceleration signals in x-y- and z directions.

The Gmm measurement using the Corelok vacuum sealing device was conducted according to ASTM D6857 -09 “Standard Test Method for Maximum Specific Gravity and Density of Bituminous Paving Mixtures Using Automatic Vacuum Sealing Method” [15]. The specified weight of loose asphalt mixture was placed in special plastic bags of the vacuum sealing device. The bags were then sealed and subjected to a vacuum of 4 mm mercury. The weight of the dry sample in air, weight of the bag, and weight of mixture and bag in water were used to calculate Gmm of the mixture.

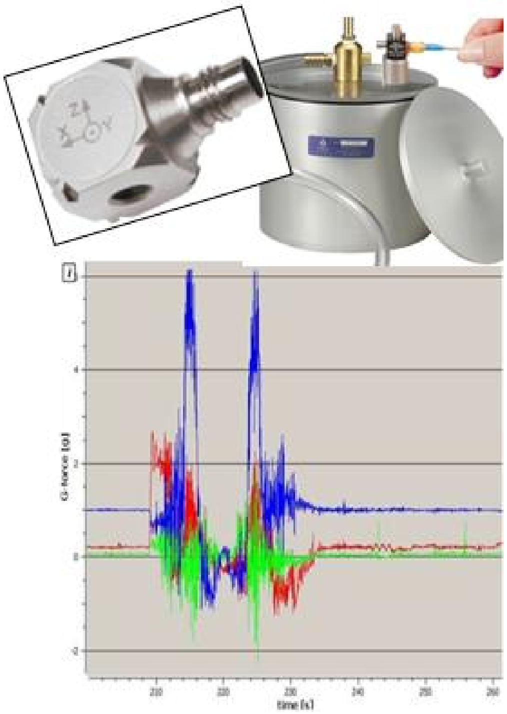

Figure 3-3- Triaxial accelerometer and typical acceleration measurements of the shaking tables in x, y, and z directions

3.4 Test Factorial

Table 3-4 provides the test factorial of the study. The effect of several variables on maximum specific gravity measurements was evaluated. The first evaluation was on the effect of vibration intensity on Gmm. Four of the shaking devices with variable settings (Humboldt, Gilson, Syntron, and Orbital) and all nine mixtures were used for this evaluation. The evaluation of effect of vibration intensity involved 36 mixture-device test combinations and is designated as “a” in the table. The second evaluation was on the effect of measuring device on Gmm. For this evaluation, four of the devices (Corelok, Aggregate Washer, HMA, and Humboldt) were evaluated using all nine mixtures, two of the devices (Gilson and Orbital) were evaluated using eight mixtures, and one of the devices (Syntron) was evaluated using seven mixtures. This evaluation included 56 mixture-device test combinations and is designated as “b” in the table. The third evaluation was on the comparison of manual and mechanical agitation. This evaluation was performed using four of the devices (Humboldt, Gilson, Orbital, and HMA) and all nine mixtures. The 36 mixture-device test combinations for this evaluation are designated as “c” in the table. The fourth evaluation is the effect of the order of placing water and mixture in pycnometer on Gmm measurement. For this evaluation, seven of the mixtures were each tested with three devices. The 21 mixture-device test combinations for this evaluation are designated as “d” in the table. Finally, the fifth evacuation was on the effect of vacuum/agitation period using one device (Gilson) and three mixtures. This evaluation consists of three mixture-device test combinations and is designated as “e” in the table. The results of the experiments in Table 3-4 will be discussed in Chapter 4.

Table 3-4 Experimental plan for evaluation of the effect of various factors on maximum specific gravity measurement; factors include (a) change in vibration, (b) equipment, (c) manual vs. mechanical, (d) order of placing water and mixture (e), and vacuum/agitation duration

Devices	Mixtures								
	Plant-Produced Dense-Graded		Plant-Produced Gap-Graded			Laboratory-Produced Dense-Graded			
	9.5-mm Percent Passing (%)	19.0-mm Percent Passing (%)	9.5-mm Percent Passing (%)	12.5-mm Percent Passing (%)	19.0-mm Percent Passing (%)	4.75-mm Percent Passing (%)	12.0-mm Percent Passing (%)	25.0-mm Percent Passing (%)	37.5-mm Percent Passing (%)
Humboldt Vibrating Table H-1750	a, b, c, d	a, b, c, d	a, b, c	a, b, c	a, b, c, d	a, b, c	a, b, c, d	a, b, c	a, b, c
Gilson Vibro-Deaerator SGA-5R	a, b, c, d	a, b, c	a, b, c, e	a, b, c, d, e	a, b, c, e	a, b, c, d	a, b, c	-	a, b, c
Syntron Concrete Shaking Table	a, b	a, b	a, b, d	a, b	a, b, d	a, b, d	a, b, d	-	-
Orbital Shaker SHKE 2000	a, b, c, d	a, b, c	a, b, c	a, b, c, d	a, b, c	a, b, c, d	a, b, c	a, b, c	-
HMA Vibrating Table VA-2000	b, c	b, c, d	b, c, d	b, c, d	b, c	b, c	b, c, d	b, c	b, c
Aggregate Drum Washer	b	b, d	b, d	b	b, d	b	b	b	b
Corelok device	b	b	b	b	b	b	b	b	b

a=Change in Vibration
b= Equipment Evaluation
c=Manual vs. Mechanical
d=Order of Placement
e=Agitation/Vacuum Duration

CHAPTER 4. TEST RESULTS AND ANALYSIS

The analysis of the results includes evaluation of the effect of several variables on Gmm measurements. The variables include vibration settings of mechanical agitators, agitation type (manual or mechanical), brand of mechanical agitators, order of placing water and mixture in pycnometer, and the duration of vacuum/agitation process. The relationship between the vibration properties of vibrating tables and the highest Gmm measured by them will also be examined.

The significance of the effect of the factors studied was evaluated statistically, physically, and from practical point of view. The physical significance was evaluated by observing the change in water cloudiness. The practical significance was evaluated by examining the change in air void values from the change in Gmm. The statistical significance was evaluated using either a Scheffe test for multivariate comparisons or paired t-test for two-variable comparisons.

4.1 Results of Vibration Measurements

Using an accelerameter, frequency and acceleration were measured in x, y, and z directions for the four vibratory devices of Humboldt, Gilson, Syntron, and HMA shaking tables. The frequency and acceleration data were collected for 10 seconds at 5 minutes into the 15 minute agitation period. Data was collected every 0.000605 seconds, providing 16,526 acceleration data points and 10 frequency data points. The acceleration data was used to calculate the kinetic energy of vibration using the kinetic energy equation: $KE = ½ mv^2$. Where m is the mass of the object, and v is the velocity of vibration. The velocity is calculated by integrating the acceleration data over the 10-sec. period. The energy values in the three directions were then summed to calculate the total kinetic energy. The total energy of vibration of different shaking tables was compared to examine if the same Gmm values would have resulted from the same energy of vibration. The graphs of vibration measurements can be found in Figure 4-1 through Figure 4-4 for the Humboldt, Gilson, Syntron, and HMA devices, respectively. The following observations can be made from the graphs:

Frequency, acceleration, and the energy of vibration of the Humboldt device are shown in Figure 4-1. As indicated from the figure, at each vibration setting, the frequency is the same in the x, y, and z directions. However, the acceleration and energy are not the same in all directions; they are the highest in the z direction and the lowest in the y direction. Figure 4-1 also shows that there is no noticeable change in vibration until Setting 5. The frequency, acceleration, and energy start increasing with the increase in the dial setting of the Humboldt device after Setting 4. A maximum frequency of 53 Hz, a maximum acceleration of 5.0 m/s^2, and the maximum kinetic energy of 50 Microjoules were achieved at Setting 8 and were maintained through Setting 10.

Figure 4-2 provides the vibration properties of the Gilson device. Similar to Humboldt, at each vibration setting, the frequency is the same in the x, y, and z directions. Also similar to Humboldt, the acceleration and energy are most prominent in the z direction and least prominent in the y direction. The difference between the vibration of the Gilson and Humboldt devices is in

the vibration trends. While Humboldt did not provide any noticeable acceleration up to setting 5, the acceleration of Gilson device was noticeable starting at Setting 1; with a steady increase in frequency, acceleration, and energy afterward. A maximum frequency of 52 Hz, a maximum acceleration of 7.2 m/s^2, and the maximum total kinetic energy of 90 Microjoules were achieved at the highest setting of 8.

Figure 4-3 details the vibration data for the Syntron device. Unlike the previous devices, there are substantial differences in the directional frequencies. At Setting 3 and lower, the x and y directions are fairly close in magnitude, while the magnitude of the z direction is about half of this value. However, from Settings 4 until the peaks at Setting 8, the magnitude of the z direction increases drastically, while the x and y magnitudes changed far less. Although the frequency data peaked at Setting 8 with frequencies of 63, 119, and 629 Hz in the x, y, and z directions respectively, the maximum acceleration and energy occurred at Setting 9. The maximum acceleration and total energy for this setting are 76.3 m/s^2 and 4307 Microjoules, respectively.

Figure 4-4 shows the vibration data for the HMA device that operates at a fixed setting. While the vibration frequencies in x, y, and z directions are the same, there are differences in the directional accelerations and energies. The acceleration and energy in y and z directions are relatively close in magnitude, while the magnitude in the x direction is considerably less. The maximum acceleration and total energy for the HMA device are 26 m/s^2 and 1400 Microjoules, respectively.

As noticed above, the vibration properties of various devices are very different. As shown from the comparison of the total energy from Syntron and Humboldt devices, the total energy from one device could be as much as 10 times higher than that of the other device. In the next sections the effect of different vibration intensities on the Gmm measurement will be investigated.

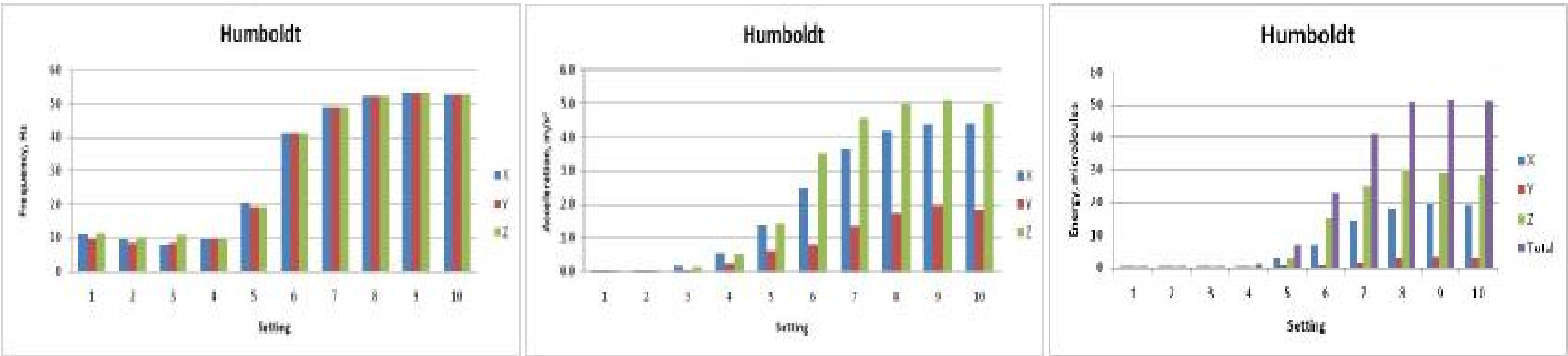

Figure 4-1- Frequency, acceleration, and energy graphs for various settings of the Humboldt device

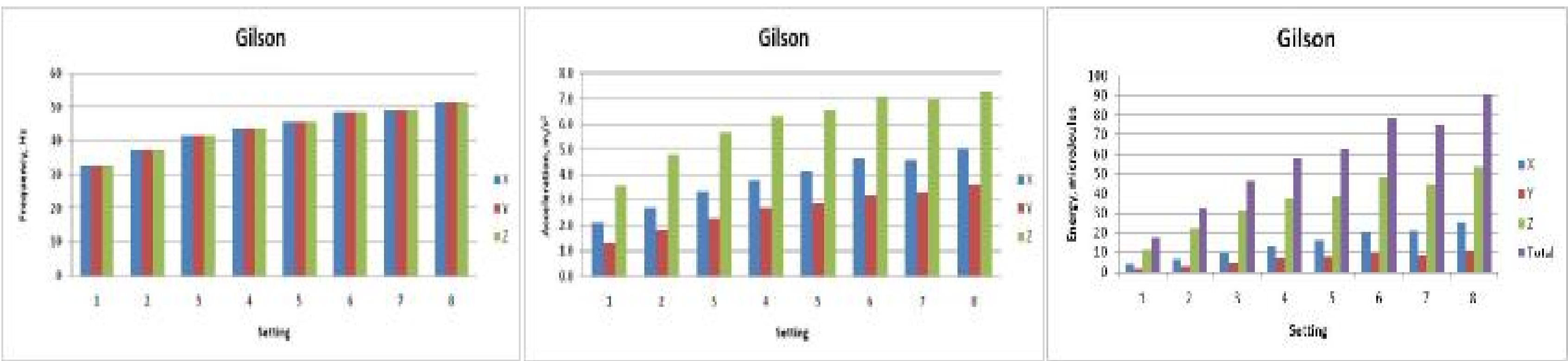

Figure 4-2- Frequency, acceleration, and energy graphs for various settings of the Gilson device

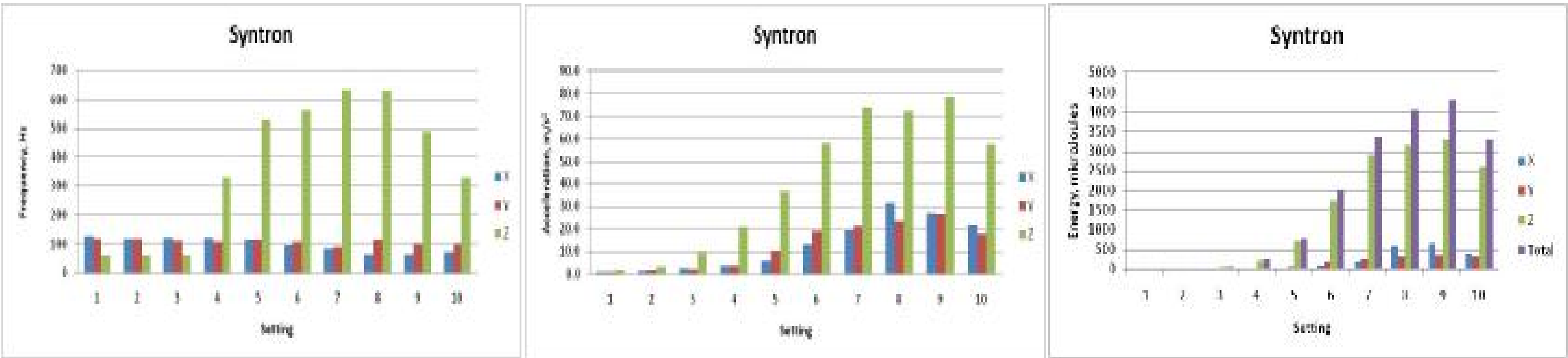

Figure 4-3- Frequency, acceleration, and energy graphs for various settings of the Syntron device

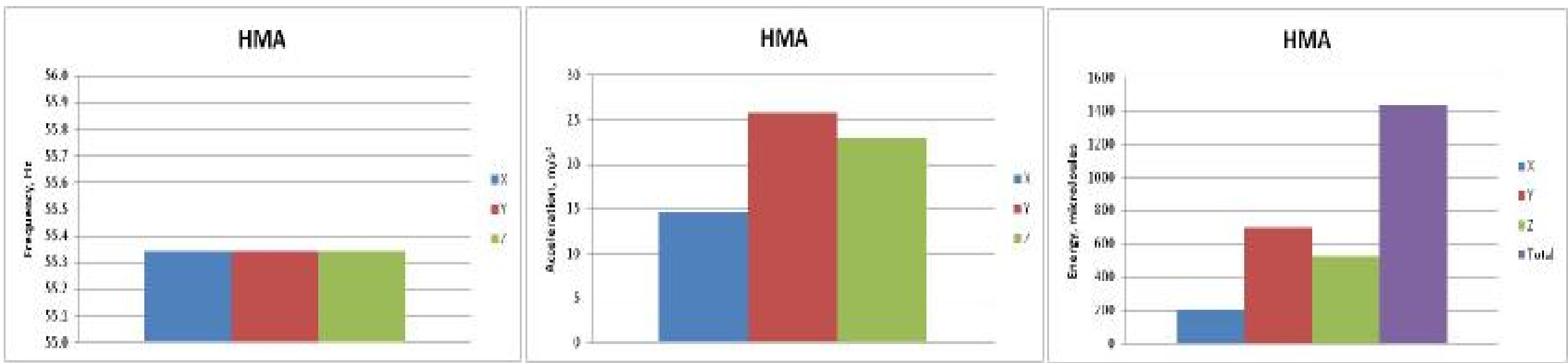

Figure 4-4- Frequency, acceleration, and energy graphs for the HMA device

4.2 Gmm Measurements at Various Settings of Vibrating Tables

Four vibratory tables with variable settings were used for evaluating the effect of vibration intensity on the Gmm measurements: Humboldt, Gilson, Syntron, and Orbital shaker. The Gmm measurements were conducted at several settings of the vibrating devices and at zero and manual agitation as well. The comparison of the Gmm at various settings would indicate if there is a systematic change of Gmm and its variability with change in vibration setting. While measurements at zero agitation were performed along with all four mechanical devices, the manual agitation was only performed with three out of the four device setups. The Minnesota DOT setup that was used with the Syntron concrete shaker was not utilized for manual agitation since it was not practical to strike or shake its bell jar vacuum chamber.

To examine the physical significance of the vibration intensity, the changes in clarity of water with changes in intensity of vibration were observed. Excessively dark water would be an indication of asphalt stripping that might have been caused by intensive vibration of the shaking tables.

The practical significance of the change in Gmm was examined using the calculated air voids values. For calculating the air voids, a bulk specific gravity (Gmb) that would result in 4 % ± 1% air voids was assumed for each mixture. Although a change of more than ±0.5% in air voids is typically significant, in this study a change in air voids of greater than 0.2% is considered practically significant. The reason for this is to allow for the variability in Gmb measurement, which is assumed a constant for each mixture.

The statistical significance of the difference between the Gmm values was examined using a Scheffe test [16]. Whenever Multivariate Analysis of Variance (MANOVA) rejects the null hypothesis, the Scheffe method will find which comparison yielded the significant difference. A Scheffe test was conducted to compare the Gmm values resulted from various settings of each device. The comparison of the computed F from Scheffe test with the critical F values would determine if the difference between Gmm of each pair of vibration setting was significant.

To determine the optimum vibration setting, the results of physical evaluation and statistical analysis are taken into account. The setting that provides the highest Gmm without significantly polluting the water is considered as the optimum setting for a device. The Statistical tests on Gmm and comparison of the computed air void values will be used for selecting an optimum setting of a device that would result in not significantly different Gmm from the highest Gmm of several mixtures.

The significance of the difference between the Gmm from manual agitation and the highest Gmm obtained with a mechanical device will also be evaluated statistically and from practical stand point. If the difference between manual and mechanical Gmm of a mixture is significant, then use of manual agitation will not be recommended for that particular mixture.

In the following sections, the analysis of the measurement results using four vibrating tables with variable settings will be discussed. Based on the observation in this section, optimum settings of the vibrating devices for reliable and accurate measurement of Gmm of nine asphalt mixtures would be recommended.

4.2.1 Humboldt

The Humboldt device has 11 discrete vibration levels of 0 to 10. Based on the results of the states' survey, provided in Chapter 2, Setting 5 (mid-range) and Setting 10 (maximum) are commonly used with the Humboldt device. The Gmm of field and laboratory mixtures were measured at various settings of the Humboldt device and the resulted highest Gmm values were compared with the Gmm from manual agitation and from the settings commonly used by the states as discussed here.

4.2.1.1 Dense-Graded Field Mixtures

The Gmm of the two field dense-graded 9.5-mm surface mixture and a 19.5-mm binder mixture were measured using the Humboldt device. For the 19.0-mm mixture, the measurements were conducted at all 11 settings of the device. For the 9.5-mm mixture, the measurements at Settings 1 through 4 were omitted since the changes in Gmm at these settings with respect to the zero setting were very small.

As shown in Figure 4-5, the Gmm of the mixtures increased with the increase in the setting of the device until Gmm reached a maximum. Further increases in vibration intensity resulted in decreases of Gmm. For the 9.5-mm mixture the highest Gmm of 2.512 was achieved at Setting 8 and for the 19.0-mm mixture, the highest Gmm of 2.536 was achieved at Setting 7 of the Humboldt device. Figure 4-5 also shows that for the 9.5-mm mixture, Gmm from manual agitation (2.506) was equivalent to Gmm at Setting 5 and for the 19.0-mm mixture; the Gmm from manual agitation (2.525) was equivalent to Gmm from Setting 4.

The change in water clarity was monitored to examine the physical effect of vibration on the mixtures. The level of discoloration of water is considered a factor in determining the optimum vibration setting of the device. The visual observation of water indicated that for both mixtures water remained clear up to Setting 6. At Setting 7 water became slightly cloudy, and at Settings 8, 9 and 10 water was significantly cloudy.

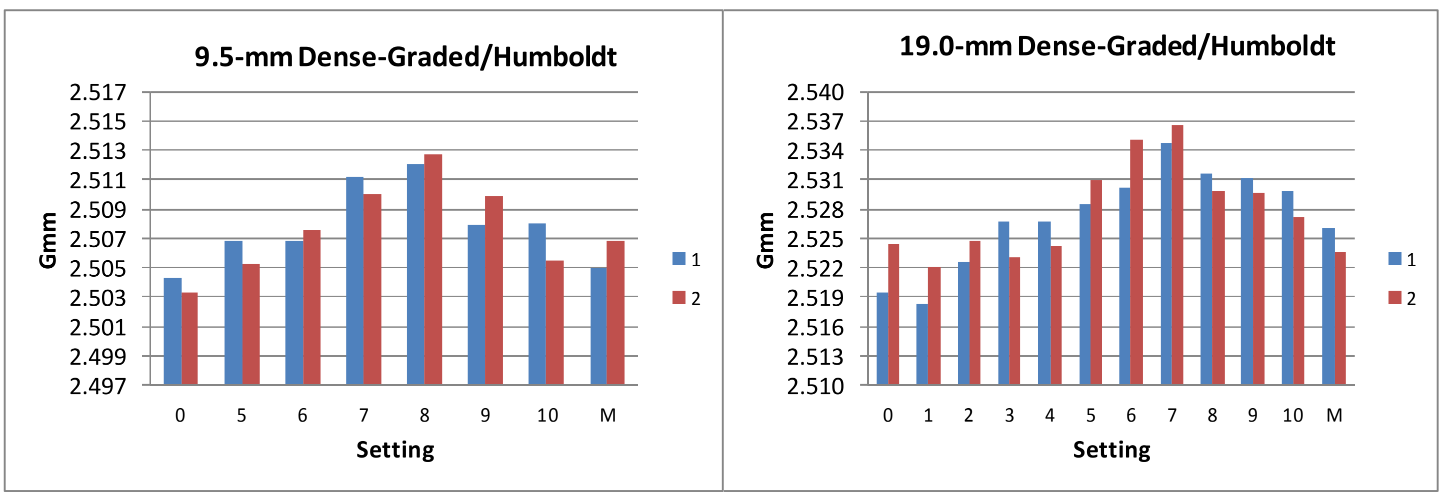

Figure 4-5- Gmm of dense-graded field mixtures at various settings for Humboldt device

The differences in replicate Gmm values at different settings would indicate if there is a relationship between vibration setting and measurement variability. As shown in Figure 4-6, the differences in Gmm of two replicates at various settings do not follow a defined trend as a function of the intensity of vibration. However, the differences between replicate measurements of the 19.0-mm mixture are larger than those of the 9.5-mm mixture. Nevertheless, the difference between replicate measurements of both mixtures at every setting of the

device was smaller than 0.005, which is significantly smaller than the acceptable difference between two replicate measurements specified in AASHTO T 209.

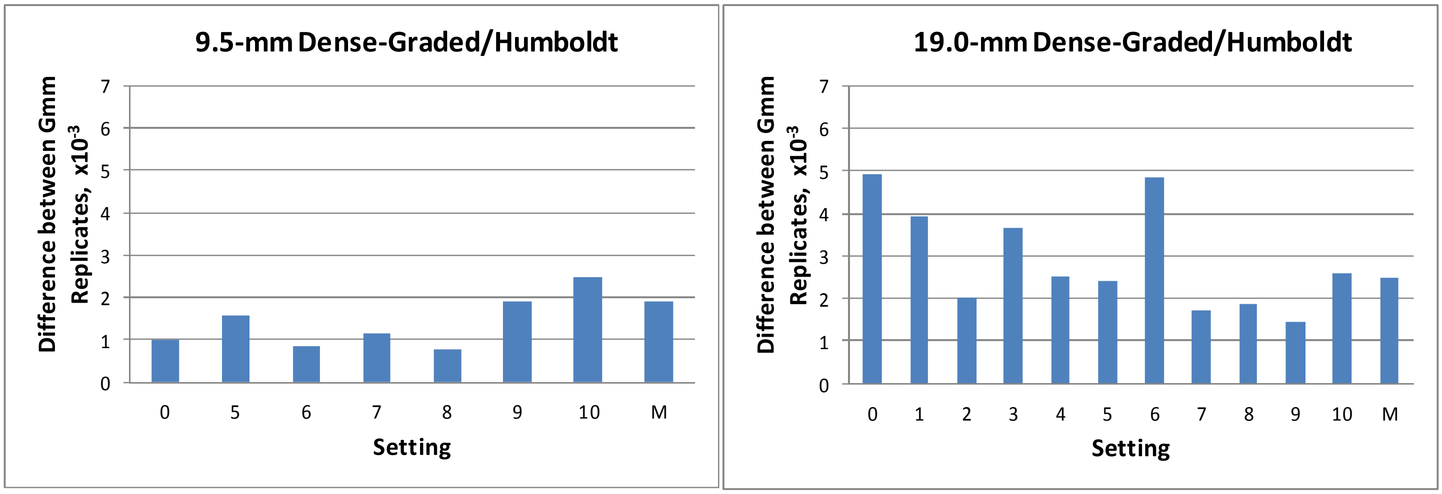

Figure 4-6- Difference between Gmm replicates of dense-graded field mixtures at various settings for Humboldt device

The practical significance of the difference between the highest Gmm and those from the settings of specific importance was examined by comparing the calculated air void values. The air void values computed from Gmm measurements are shown in Figure 4-7. The bulk specific gravity values of 2.404 and 2.422 were assumed for calculating the air voids of 9.5-mm and 19.0-mm mixtures, respectively. The differences between the air voids from the highest Gmm and those from Setting 5, Setting 10, and manual agitation, which are commonly used by DOTs are provided in Table 4-1. As shown in the table, the difference between the air voids from the highest Gmm and from Gmm of manual agitation is 0.25% for 9.5-mm and 0.41% for 19.0-mm mixtures. Also shown in Table 4-1, the difference in air voids from using the highest Gmm and Gmm at mid-range agitation (Setting 5) is 0.24% and 0.22% for 9.5-mm and 19.0-mm mixtures, respectively. Moreover, the difference between air voids from the highest Gmm and Gmm of the maximum setting (Setting 10) is 0.21% and 0.27% for 9.5-mm and 19.0-mm mixtures, respectively. Considering other source of variability in measuring air voids, use of manual agitation and use of mid-range and maximum settings could result in significantly lower air voids than the actual air voids of the compacted 9.5-mm and 19.0-mm mixtures.

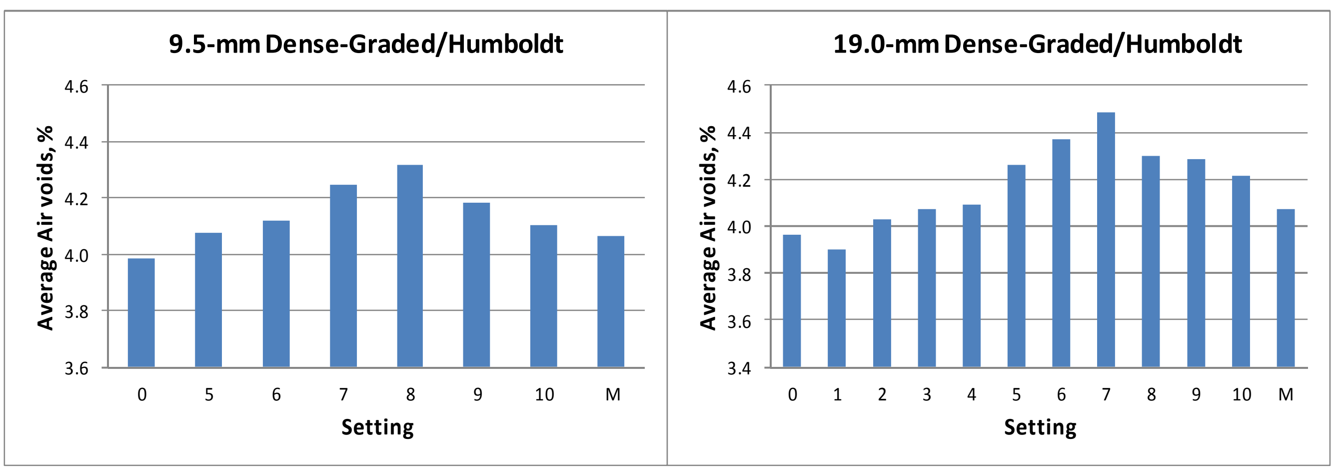

Figure 4-7- Air voids of dense-graded field mixtures at various settings for Humboldt device

Table 4-1- Gmm values using Humboldt device at settings of specific importance (setting of highest Gmm, manual agitation, mid-range setting, and maximum setting) and the differences between air voids resulted from measurements at the various settings

Mixture Type	Setting of Maximum Gmm	Gmm, Highest	Gmm, Manual Agitation	Gmm, Mid-Range Setting (Setting 5)	Gmm, Maximum Setting (Setting 10)	Difference in Air Voids, Highest and Manual (%)	Difference in Air Voids, Highest and Setting 5 (%)	Difference in Air Voids, Highest and Setting 10 (%)
9.5-mm	8	2.512	2.506	2.506	2.507	0.25	0.24	0.21
19.0-mm	7	2.536	2.525	2.530	2.529	0.41	0.22	0.27

The significance of the differences between Gmm measurements from various settings was also evaluated statistically. The Scheffe test was conducted to evaluate the statistical significance of the differences. Table 4-2 and Table 4-3 provide the computed F values for comparison of Gmm. The shaded cells in the tables indicate that the computed F values are greater than the critical F value and therefore, the difference between Gmm values from those pairs of vibration settings are significant. For the 9.5-mm mixture, the comparison of the computed F from Table 4-2 and critical F value of 3.500 for 5% level of significance and degrees of freedom (DOF) of 7 and 8 indicates that the highest Gmm value from Setting 8 is significantly different from those of Settings 0 through 5, Setting 10, and Manual agitation. Gmm of Setting 8 is not statistically different from those of Settings 6, 7, and 9.

Table 4-3 shows the computed F values for 19.0-mm mixture. The comparison of the computed F with the critical F value of 2.723 for 5% level of significance and DOF of 11 and 12 indicates that the highest Gmm from Setting 7 is significantly greater than those of Settings 0 through 2. The rest of the settings provide statistically the same Gmm as that of Setting 7.

Based on the results from statistical analysis and from comparison of the air voids, the manual agitation and mid-range and Maximum settings (Settings 5 and 10) of the Humboldt device would most likely provide significantly lower air voids than the highest achieved air voids for the 9.5-mm mixture. However, for the 19.0-mm mixture the statistical analysis, indicated that the highest Gmm of Setting 7 was statistically the same as that of manual agitation and of mid-range and maximum settings. This might indicate that manual agitation and lower agitation settings would be adequate for measuring Gmm of the coarser mixtures.

Table 4-2- Computed F values for comparison of Gmm of 9.5-mm dense-graded field mixture at various vibration settings of Humboldt device; Critical F value=3.500 and DOF= (7, 8) for 5% level of significance

Setting	0	5	6	7	8	9	10
5	0.608						
6	1.351	0.147					
7	5.415	2.395	1.356				
8	8.640	4.665	3.158	0.375			
9	3.045	0.932	0.339	0.339	1.427		
10	1.041	0.058	0.020	1.708	3.684	0.525	
M	0.522	0.003	0.193	2.574	4.915	1.045	0.089

Table 4-3- Computed F values for comparison of Gmm of 19.0-mm dense-graded field mixture at various vibration settings of Humboldt device; Critical F value=2.723 and DOF= (11, 12) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8	9	10
1	0.053										
2	0.058	0.224									
3	0.175	0.421	0.031								
4	0.238	0.517	0.061	0.005							
5	1.195	1.754	0.725	0.456	0.366						
6	2.197	2.936	1.539	1.133	0.989	0.151					
7	3.640	4.575	2.776	2.220	2.016	0.664	0.181				
8	1.488	2.106	0.957	0.643	0.536	0.016	0.069	0.473			
9	1.405	2.006	0.890	0.589	0.486	0.008	0.088	0.522	0.001		
10	0.832	1.307	0.449	0.244	0.180	0.033	0.325	0.991	0.095	0.124	
M	0.162	0.402	0.026	0.000	0.007	0.477	1.166	2.266	0.668	0.613	0.260

Since water was significantly cloudy at Settings 8 and higher, the possibility of using Setting 7 for 9.5-mm mixture was investigated. The F values from comparison of Gmm of Setting 7 and 8 in Table 4-2 indicates that Settings 7 and 8 produce statistically the same Gmm for 9.5-mm mixture. The differences in air voids of the 9.5-mm mixture indicated that the difference between the air voids from Settings 7 and 8 is 0.07 %, which is not considered practically significant. Based on the small difference in the Gmm of the 9.5-mm mixture at Setting 7 and Setting 8, Setting 7 of Humboldt is recommended as the optimum operation setting of the device for measuring Gmm of the of 9.5-mm and 19.0-mm dense-graded field mixtures. Setting 7 corresponds to the frequency, accelerations, and the kinetic energy values provided in Table 4-4.

Table 4-4- Frequency, acceleration, and kinetic energy of the Humboldt device at the Setting 7 for measuring Gmm of dense-graded field mixtures

Vibration Properties	X	Y	Z	Total
Frequency, Hz	48.7	48.7	48.7	-
Acceleration, m/s^2	3.66	1.35	4.59	-
Energy (x 10^{-5}), Joule	1.34	0.161	2.33	3.84

4.2.1.2 SMA Field Mixtures

The Gmm of the three gap-graded (SMA) mixtures of 9.5-mm, 12.5-mm, and 19.0-mm NMAS were measured using the Humboldt device. Since there was no noticeable change in the vibration level of the device up to Setting 4, the measurements were conducted at Settings 5 through 10. The following are the results from testing the SMA mixtures using the Humboldt device:

As shown in Figure 4-8 the highest Gmm of the 9.5-mm and 12.5-mm mixtures (2.647 and 2.466, respectively) were achieved at Setting 8 and the highest Gmm of the 19.0-mm mixture (2.448) was achieved at Setting 9. The Gmm of the 9.5-mm and 12.5-mm from manual agitation was equivalent to those from Setting 5 (2.641 and 2.459, respectively) and the Gmm of the 19.0-mm mixture was equivalent to that of Setting 6 (2.439).

The change in water clarity was monitored to examine the physical effect of vibration on the mixtures. The visual observation of the water indicated that for all three mixtures water remained clear up to setting 6. At Settings 7 and 8, water became slightly cloudy, and at Settings 9 and 10, water became significantly cloudy.

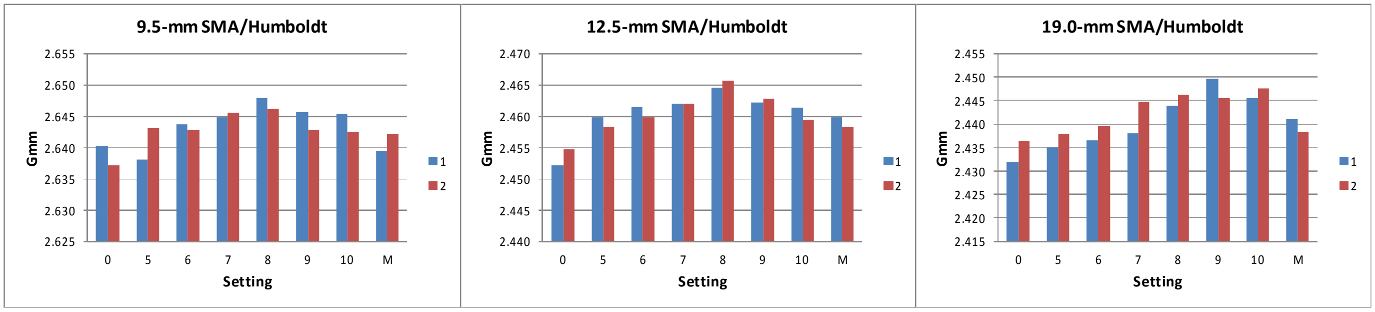

Figure 4-8- Gmm of SMA Mixtures at various settings of the Humboldt device

The differences in replicate Gmm values at different settings would indicate if there is a relationship between vibration setting and measurement variability. As shown in Figure 4-9, the differences in Gmm of two replicates at various settings do not indicate a defined trend as a function of vibration setting. However, the differences between replicate measurements of the 19.0-mm mixture are larger than those of the 9.5-mm and 12.5-mm mixtures. Nevertheless, Figure 4-9 shows that at every setting of the table, the difference between replicate measurements of the three mixtures was smaller than 0.007, which is significantly smaller than the acceptable difference between two replicate measurements specified in AASHTO T 209.

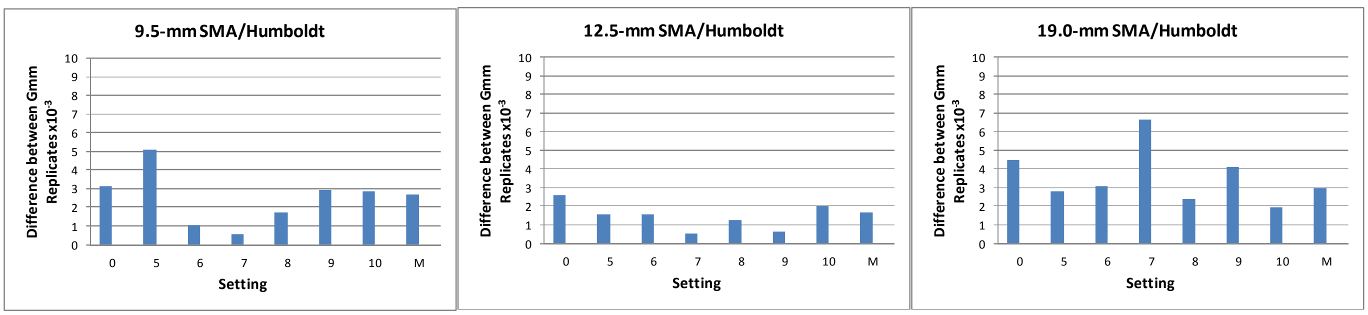

Figure 4-9- Difference between two Gmm replicates of SMA Mixtures at various settings of the Humboldt device

The practical significance of the difference between the highest Gmm and Gmm of the settings of specific importance was examined by comparing the calculated air void values. The air void values computed from the Gmm measurements are shown Figure 4-10. Bulk specific values of 2.532, 2.357, and 2.339 were assumed for calculating the air voids of the 9.5-mm, 12.5-mm, and 19.0-mm SMA mixtures, respectively. The differences between the air voids are provided in Table 4-5. As shown in Table 4-5, the difference between air voids from the highest Gmm and Gmm of manual agitation is in the range of 0.23%- 0.30%, the difference between the air voids from the highest Gmm and Gmm of mid-range agitation is in the range of 0.23%- 0.45%, and the difference between the air voids from the highest Gmm and that of the maximum setting (Setting 10) is in the range of 0.05 to 0.20. Considering other sources of variability in measuring air voids, using mid-range and manual settings would most likely provide significantly lower air voids than those of the compacted SMA mixtures. However, operating the Humboldt device at the maximum setting would produce practically the same Gmm as the highest Gmm.

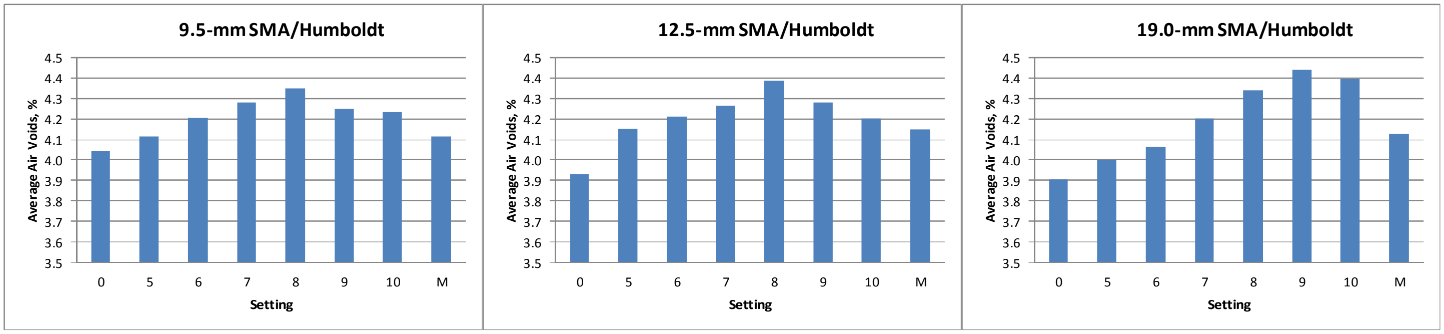

Figure 4-10- Air voids of SMA Mixtures at various settings of the Humboldt device

Table 4-5- Gmm values using Humboldt at settings of specific importance (setting of highest Gmm, manual agitation, mid-range and maximum settings) and the differences in air voids resulted from measurements at the various settings

Mixture Type	Setting of Maximum Gmm	Gmm, Highest	Gmm, Manual Agitation	Gmm, Mid-Range Setting (Setting 5)	Gmm, Maximum Setting (Setting 10)	Difference in Air Voids, Highest and Manual, %	Difference in Air Voids, Highest and Setting 5, %	Difference in Air Voids, Highest and Setting 10, %
9.5-mm	8	2.647	2.642	2.641	2.644	0.23	0.23	0.11
12.5-mm	8	2.465	2.459	2.459	2.461	0.25	0.25	0.20
19.0-mm	9	2.448	2.441	2.437	2.446	0.30	0.45	0.05

The significance of the differences between Gmm measurements from various settings were also evaluated statistically. Table 4-6 through Table 4-8 provide the computed F values from the Scheffe test for comparison of Gmm values of SMA mixtures at various settings of the Humboldt device. A shaded cell indicates that the computed F value is greater than the critical F value and therefore, the difference between Gmm values from the paired comparison is significant. For the 9.5-mm mixture, the comparison of the computed F from Table 4-6 and critical F value of 3.500 indicates that for 5% level of significance the Gmm values from manual agitation and those of various settings are statistically the same. For the 12.5-mm mixture, the shaded cells in Table 4-7 indicates that the highest Gmm of 12.5-mm mixture from Setting 8 is significantly greater than those of Setting 0, Setting 5, and manual agitation. The rest of the settings provide statistically the same Gmm values as that of Setting 8. For the 19.0-mm SMA mixture, the shaded cell in Table 4-8 indicates that the highest Gmm of 19.0-mm mixture from Setting 9 is only significantly greater than that of zero agitation.

Table 4-6- Computed F values for comparison of Gmm of 9.5-mm SMA field mixture at various vibration settings of Humboldt device; Critical F value=3.500 and DOF= (7, 8) for 5% level of significance

Setting	0	5	6	7	8	9	10
5	0.148						
6	0.767	0.242					
7	1.572	0.756	0.143				
8	2.558	1.476	0.523	0.119			
9	1.151	0.474	0.039	0.033	0.277		
10	1.027	0.396	0.019	0.058	0.343	0.004	
M	0.159	0.000	0.227	0.731	1.440	0.454	0.377

Table 4-7- Computed F values for comparison of Gmm of 12.5-mm SMA field mixture at various vibration settings of Humboldt device; Critical F value=3.500 and DOF= (7, 8) for 5% level of significance

Setting	0	5	6	7	8	9	10
5	3.656						
6	5.942	0.276					
7	8.315	0.944	0.199				
8	15.579	4.142	2.279	1.131			
9	9.203	1.258	0.355	0.023	0.834		
10	5.406	0.171	0.013	0.312	2.631	0.502	
M	3.578	0.000	0.298	0.984	4.225	1.305	0.188

Table 4-8- Computed F values for comparison of Gmm of 19.0-mm SMA field mixture at various vibration settings of Humboldt device; Critical F value=3.500 and DOF= (7, 8) for 5% level of significance

Setting	0	5	6	7	8	9	10
5	0.122						
6	0.320	0.047					
7	1.103	0.492	0.235				
8	2.408	1.447	0.973	0.252			
9	3.627	2.419	1.793	0.730	0.124		
10	3.079	1.976	1.414	0.496	0.041	0.022	
M	0.630	0.198	0.052	0.066	0.574	1.233	0.923

Since water became significantly cloudy at Setting 9, the possibility of using Setting 8 instead of Setting 9 for the 19.0-mm SMA mixture was examined. The difference between the air voids from the two settings is 0.1 %, which is practically insignificant. The F values in Table 4-8 also shows that the Gmm values from Setting 8 and 9 are statistically the same. Therefore, it is recommended to conduct the Gmm measurement of the 19.0-mm mixture at Setting 8.

Based on the highest achieved Gmm of the 9.5-mm and 12.5-mm mixtures at Setting 8 and the small difference between the Gmm from Settings 8 and 9 for the 19.0 mixtures, Setting 8 of the Humboldt device is recommended as the optimum operation setting of the device for measuring Gmm of the SMA mixtures. This setting corresponds to the frequency, acceleration, and energy data found in Table 4-9.

Table 4-9- Frequency, acceleration, and kinetic energy of the Humboldt shaking device at Setting 8 for measuring Gmm of SMA mixtures

Vibration Properties	X	Y	Z	Total
Frequency, Hz	52.8	52.8	52.8	-
Acceleration, m/s^2	4.29	1.84	5.04	-
Energy (x 10^{-5}), Joule	1.82	0.31	2.71	4.84

4.2.1.3 Dense-Graded Laboratory Mixtures

The Gmm of 4.75-mm, 12.5-mm, 25.0-mm, and 37.5-mm laboratory dense-graded mixtures were measured at Settings 4 through 10 of the Hamburg device. As shown in Figure 4-11, the highest Gmm of the 4.75-mm mixture (2.557) was achieved at the maximum setting (Setting 10), the highest Gmm of the 12.5-mm

mixture (2.580) was obtained at Setting 8, and the highest Gmm of the 25.0-mm and 37.5-mm mixtures (2.617, 2.629, respectively) were achieved at Setting 9 of Humboldt device. Figure 4-11 also shows that for the 4.75-mm and 12.5-mm mixtures, the Gmm from manual agitation (2.548 and 2.572, respectively) is equivalent to the Gmm from Setting 5 and for the 25.0-mm and 37.5-mm mixtures, the Gmm from manual agitation (2.610 and 2.625, respectively) are equivalent to that from Setting 6. This might indicate that in the coarser mixtures, manual agitation produce Gmm that are equivalent to those from higher agitation levels than in the finer mixtures.

The change in water clarity was monitored to examine the physical effect of vibration on the mixtures. The observation of water cloudiness indicated that the water did not become significantly cloudy at any of the settings. For the four mixtures mixture, water was slightly cloudy at the settings of the highest Gmm, which are Setting 10 for the 4.75-mm mixture, Setting 8 for the 12.5-mm mixture and Setting 9 for the 25.0-mm and 37.5-mm mixtures.

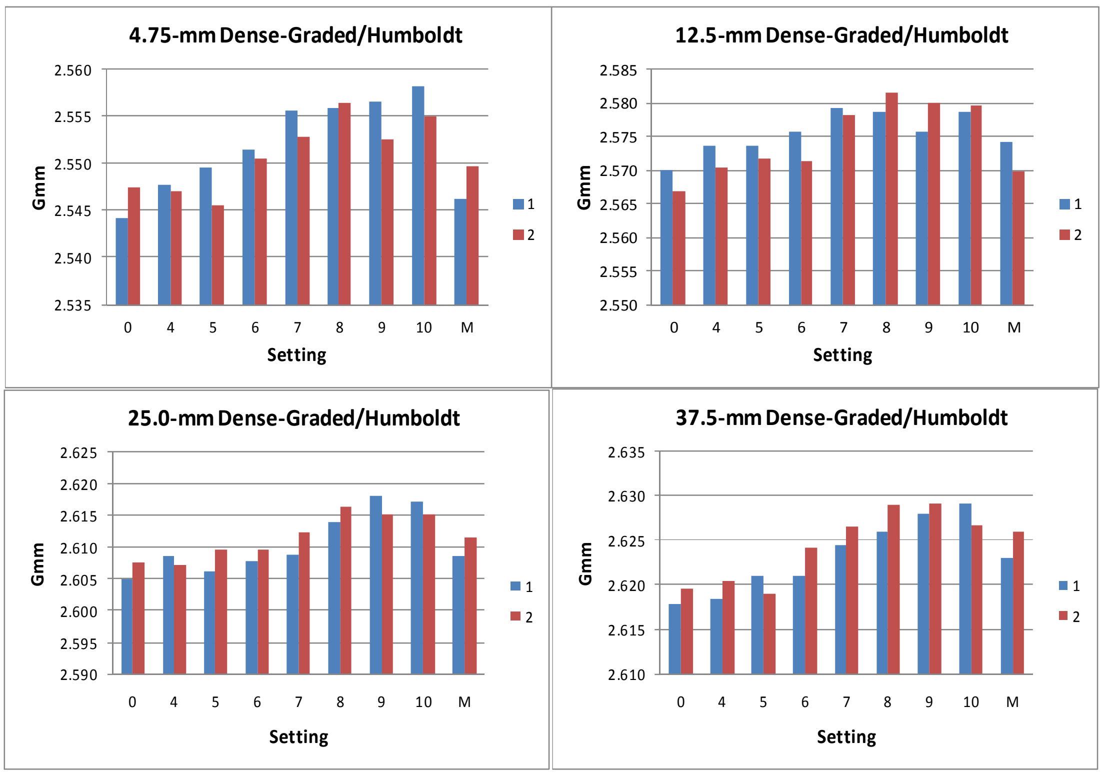

Figure 4-11- Gmm of dense-graded laboratory-prepared mixtures at various settings for the Humboldt device

The differences in replicate Gmm values at different settings would indicate if there is a relationship between vibration setting and measurement variability. As shown in Figure 4-12, the difference in Gmm of two replicates at various settings does not follow a defined trend as a function of vibration setting. Figure 4-12 also shows that at every setting of the table, the difference between replicate measurements was smaller than 0.005, which is significantly smaller than the acceptable difference between two replicate measurements specified in AASHTO T 209.

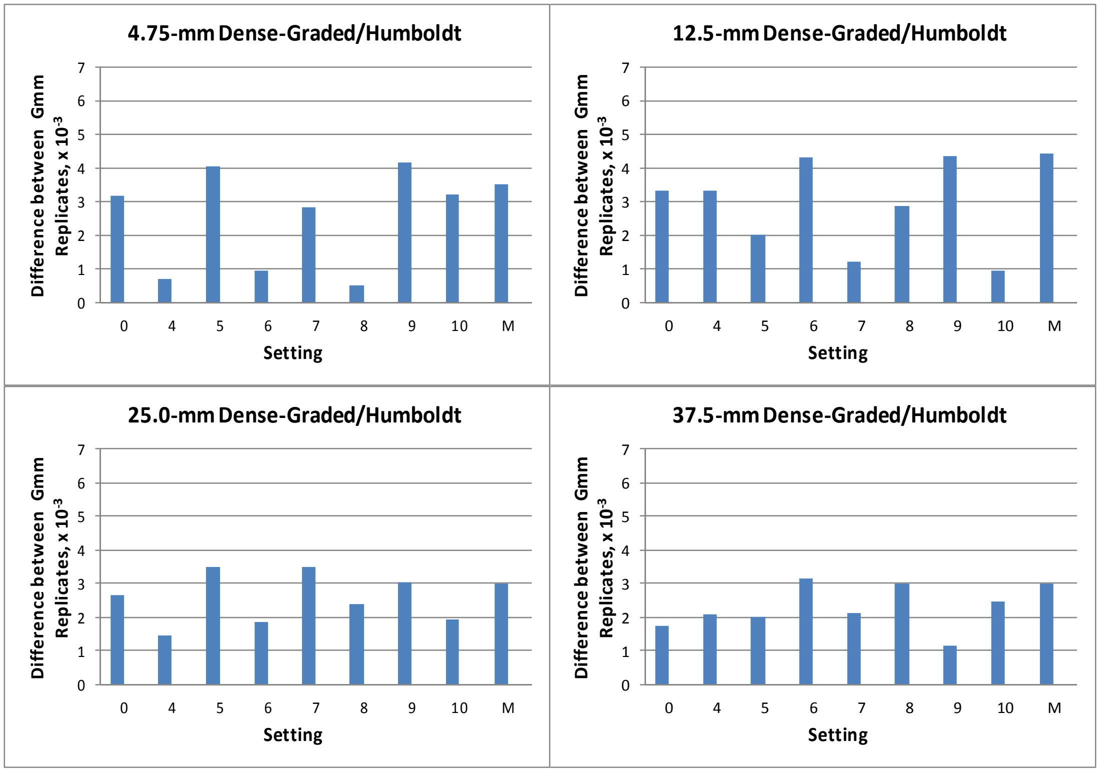

Figure 4-12- Difference between replicate Gmm of laboratory-prepared mixtures at various settings for the Humboldt device

The practical significance of the difference between the highest Gmm and Gmm of the settings of specific importance was examined by evaluating the differences between their corresponding air void values. Figure 4-13 shows the change in air voids with change in the settings of the Humboldt device. Bulk specific values of 2.444, 2.466, 2.502, and 2.515 were assumed for calculating the air voids of 4.75-mm, 12.5-mm, 25.0-mm, and 37.5-mm mixtures, respectively. Table 4-10 provides the differences between the air voids from the highest Gmm and those from the most important settings. The difference between the air voids that resulted from the highest Gmm and those from manual agitation indicates a difference of 0.30 % for the 4.75-mm and 12.5-mm mixtures and a difference of 0.24% and 0.15% for the 25.0-mm and 37.5-mm mixtures, respectively. Considering other sources of variability in measuring the air voids, these differences could be significant. Therefore, from practical point of view, for obtaining the highest Gmm of mixtures, use of manual agitation is not recommended for measuring Gmm of dense-graded laboratory mixtures.

Table 4-10 also provides the differences between air voids from the highest Gmm and those from Setting 5 and Setting 10, which are commonly used by the state laboratories. As shown in the table, for the 4.75-mm, 25.0-mm, and 37.5-mm mixtures, the difference between the highest air voids and those from Setting 5 (the mid-range setting) is on average 0.30%, which could be significant. The difference between the highest air voids and those from Setting 10 (maximum setting) is on average 0.03%, which is not practically significant. This indicates that it might be preferable to operate the Humboldt device at its higher settings to achieve the highest Gmm of laboratory prepared dense-graded mixtures.

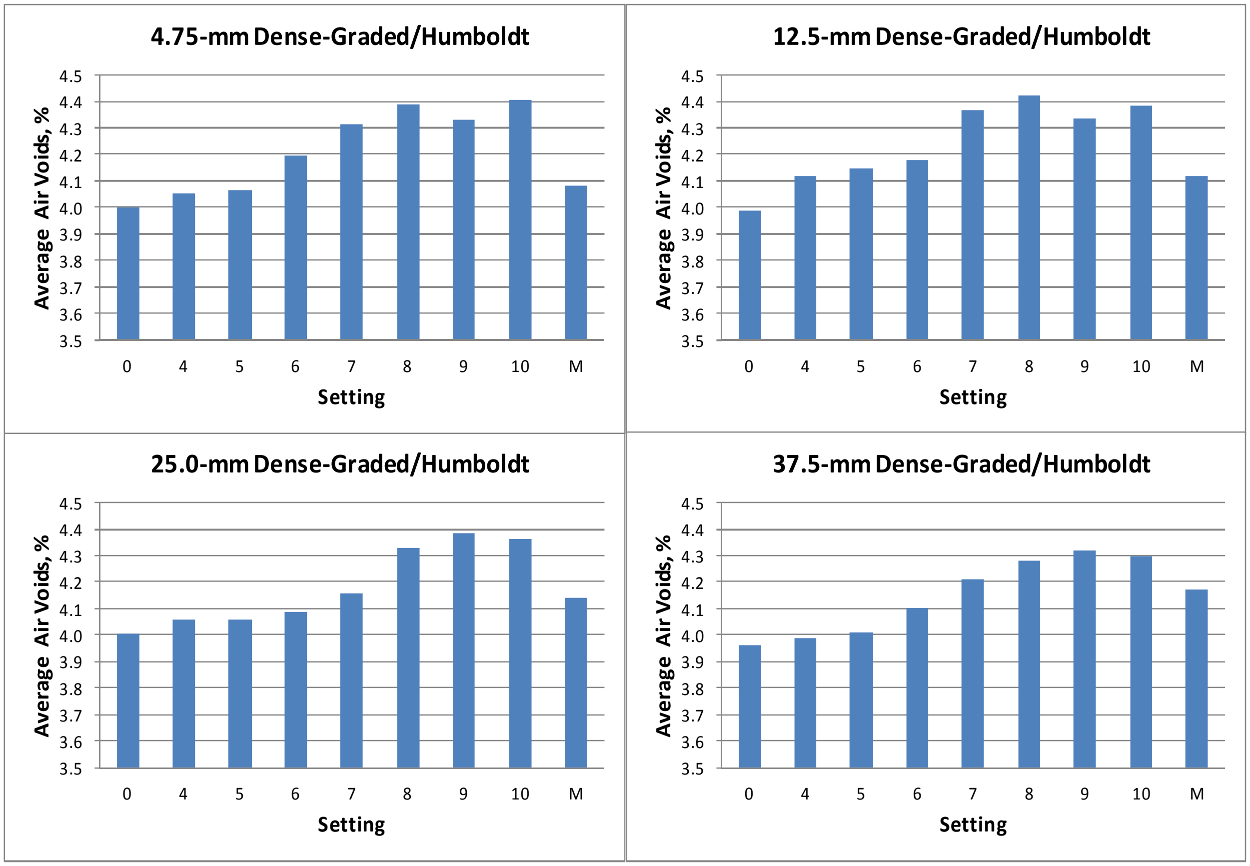

Figure 4-13- Air voids of the laboratory-prepared mixtures at various settings for the Humboldt device

Table 4-10- Gmm values using Humboldt at settings of specific importance (setting of highest Gmm, manual agitation, mid-range setting, and maximum setting) and the differences in air voids resulted from measurements at the various settings

Mixture Type	Setting of Highest Gmm	Gmm, Highest	Gmm, Manual Agitation	Gmm, Mid-Range Setting (Setting 5)	Gmm, Maximum Setting (Setting 10)	Difference in Air Voids, Highest and Manual, %	Difference in Air Voids, Highest and Setting 5, %	Difference in Air Voids, Highest and Setting 10, %
4.75-mm	10	2.557	2.548	2.548	2.557	0.30	0.32	0.02
12.5-mm	8	2.580	2.572	2.573	2.579	0.30	0.28	0.03
25.0-mm	9	2.617	2.610	2.608	2.616	0.24	0.32	0.02
37.5-mm	9	2.629	2.625	2.620	2.628	0.15	0.31	0.02

The significance of the differences between Gmm measurements from various settings were also evaluated statistically. Table 4-11 through Table 4-14 provide the computed F values from the Scheffe test. As indicated from the comparison of the computed and critical F values, for either SMA mixtures, the differences between the highest Gmm and those from manual agitation, Setting 5, and Setting 10 are not statistically significant. However, use of manual agitation and mid-range settings are not recommended for the SMA mixtures due to the potential significance of the difference in air voids.

Table 4-11- Computed F values for comparison of Gmm of 4.75-mm dense-graded laboratory mixture at various vibration settings of Humboldt device; Critical F value=3.230 and DOF= (8, 9) for 5% level of significance

Setting	0	4	5	6	7	8	9	10
4	0.060							
5	0.078	0.001						
6	0.705	0.355	0.314					
7	1.881	1.271	1.193	0.283				
8	2.848	2.084	1.983	0.719	0.100			
9	2.022	1.388	1.306	0.339	0.003	0.070		
10	3.069	2.274	2.169	0.832	0.145	0.004	0.109	
M	0.123	0.011	0.005	0.239	1.043	1.788	1.149	1.965

Table 4-12- Computed F values for comparison of Gmm of 12.5-mm dense-graded laboratory mixture at various vibration settings of Humboldt device; Critical F value=3.230 and DOF= (8, 9) for 5% level of significance

Setting	0	4	5	6	7	8	9	10
4	0.199							
5	0.278	0.007						
6	0.397	0.034	0.011					
7	1.643	0.699	0.569	0.424				
8	2.110	1.014	0.855	0.676	0.029			
9	1.374	0.528	0.415	0.293	0.012	0.079		
10	1.771	0.783	0.645	0.490	0.002	0.015	0.025	
M	0.197	0.000	0.007	0.035	0.703	1.018	0.531	0.787

Table 4-13- Computed F values for comparison of Gmm of 25.0-mm dense-graded laboratory mixture at various vibration settings of Humboldt device; Critical F value=3.230 and DOF= (8, 9) for 5% level of significance

Setting	0	4	5	6	7	8	9	10
4	0.069							
5	0.069	0.000						
6	0.165	0.021	0.021					
7	0.549	0.229	0.229	0.112				
8	2.421	1.673	1.673	1.323	0.664			
9	3.281	2.399	2.399	1.976	1.146	0.065		
10	2.942	2.110	2.110	1.714	0.949	0.025	0.009	
M	0.435	0.157	0.157	0.064	0.007	0.804	1.327	1.115

Table 4-14- Computed F values for comparison of Gmm of 37.5-mm dense-graded laboratory mixture at various vibration settings of Humboldt device; Critical F value=3.230 and DOF= (8, 9) for 5% level of significance

Setting	0	4	5	6	7	8	9	10
4	0.020							
5	0.068	0.014						
6	0.624	0.420	0.281					
7	1.942	1.567	1.285	0.364				
8	3.263	2.771	2.391	1.034	0.171			
9	4.100	3.546	3.115	1.526	0.399	0.048		
10	3.555	3.041	2.642	1.201	0.242	0.006	0.019	
M	1.411	1.094	0.861	0.159	0.042	0.383	0.701	0.487

The possibility of using one vibration setting for all four dense-graded laboratory mixtures was explored. For that, the highest Gmm of each mixture was compared with Gmm at the settings that produced highest Gmm of other mixtures. As shown in Table 4-15, the differences between the air voids of the mixtures resulted from the settings of highest Gmm are below 0.1 %, which is not considered significant. This is also confirmed statistically, where comparison of Gmm from Settings 8, 9, and 10 in Table 4-11 through Table 4-14 provided F-values that are smaller than the critical F value.

Table 4-15- Gmm of the laboratory prepared dense-graded mixtures at the settings of Humboldt which resulted in the highest Gmm of one or more of the mixtures and the differences between the air voids resulted from those settings

Mixture Type	Setting of Highest Gmm	Gmm, Setting 8	Gmm, Setting 9	Gmm, Setting 10	Difference in Air Voids, Highest and Setting 8, %	Difference in Air Voids, Highest and Setting 9, %	Difference in Air Voids, Highest and Setting 10, %
4.75-mm	10	2.556	2.555	2.557	0.01	0.08	0.00
12.5-mm	8	2.580	2.578	2.579	0.00	0.08	0.04
25.0-mm	9	2.615	2.617	2.616	0.05	0.00	0.02
37.5-mm	9	2.628	2.629	2.628	0.04	0.00	0.03

Based on the highest achieved Gmm of the four laboratory mixtures at Settings of 8, 9, and 10 and based on the similarity of the air voids from Setting 8 through Setting 10, Setting 8 of the Humboldt device is recommended as the optimum operation setting for measuring the Gmm of laboratory prepared dense-graded mixtures. At Setting 8, water was only slightly cloudy. The vibration properties of Humboldt at Setting 8 were previously provided in Table 4-9.

4.2.2 Gilson

The Gilson device has an adjustable dial for a continuous increase of the vibration level. Eight marks of 1 through 8 were made at approximately equal intervals on the dial of the device to represent eight discrete levels of vibration. Based on the results of the states' survey reported in Chapter 2, the middle and maximum range of the Gilson device are commonly operated in the state laboratories. The Gmm of field and laboratory mixtures were measured at various settings of the Gilson device and the resulted highest Gmm values were compared with the Gmm from manual agitation and from the settings commonly used by the states as discussed here.

4.2.2.1 Dense-Graded Field Mixtures

The Gmm of the 9.5-mm and 19.0-mm dense-graded field mixtures were measured at Settings 1 through 8 and at zero and manual agitations as well. Figure 4-14 shows the measured Gmm values. As shown in the figure, the highest Gmm of 2.515 and 2.536 for 9.5-mm and 19.0-mm mixtures were achieved at Settings 6 and 7 of the Gilson device, respectively. The Gmm values from manual agitation were equivalent to Gmm values from Setting 3 for both mixtures (2.507 and 2.527 for the 9.5-mm and 19.0-mm mixtures, respectively).

The change in water clarity was monitored to examine the physical effect of vibration on the mixtures. The visual observation indicated that water remained clear up to Setting 4. From Setting 5 through Setting 6 water became slightly cloudy, and at Setting 7 and Setting 8 water became significantly cloudy.

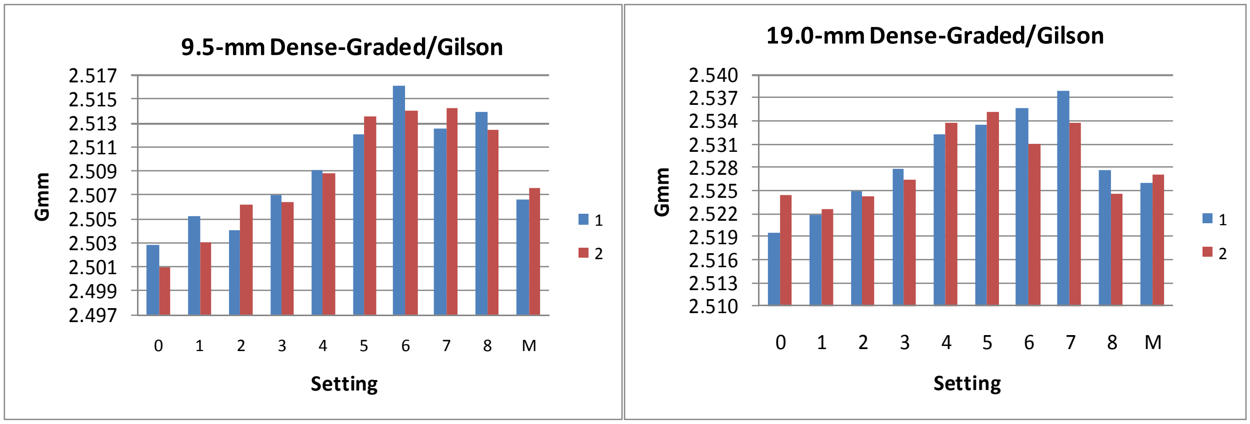

Figure 4-14- Gmm of dense-graded field mixtures at various settings for Gilson device

Figure 4-15 shows the differences between the two replicate Gmm values at various settings of Gilson. While there is no defined trend between the variability of measurements and the intensity of vibration, higher variability is observed at high Gmm values for the 19.5-mm mixture. Nevertheless, the difference between replicates at any setting is smaller than 0.005, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

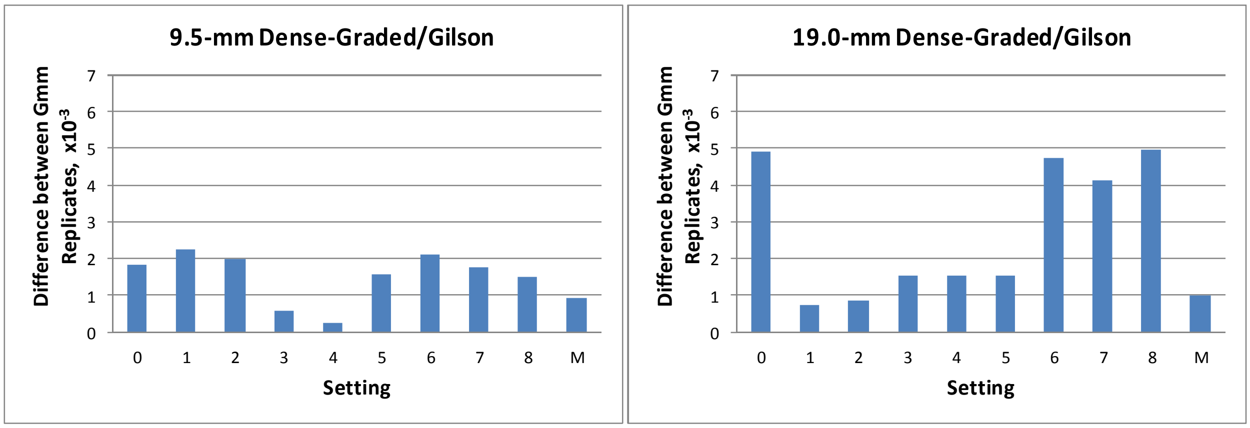

Figure 4-15- Difference between Gmm replicates of dense-graded field mixtures at various settings for Gilson device

The practical significance of the difference between the highest Gmm and those from the settings of specific importance was examined by comparing the calculated air void values. Figure 4-16 shows the computed air voids. Bulk specific values of 2.404 and 2.422 were assumed for calculating the air voids of 9.5-mm and 19.0-mm mixtures, respectively. Table 4-16 shows the difference between the air voids from the highest Gmm and those from the most commonly used agitation levels. As shown in Table 4-16, the difference between air voids of the highest Gmm and Gmm of manual agitation is 0.31% and 0.35% for the 9.5-mm and 19.0-mm mixtures, respectively. Considering other sources of variability in measuring air voids, use of manual agitation for either mixture would most likely result in significantly lower air voids than the actual air voids of the compacted mixture.

Also shown in the table is the difference between air voids from the highest Gmm and that of mid-range agitation (Setting 4), which is 0.23 % for the 9.5-mm mixture and 0.11 % for the 19.0-mm mixture. This might indicate that use of mid-range setting would most probably result in significantly lower air voids for the 9.5-mm mixture ; however, for the 19.0-mm mixture, the mid-range setting would produce similar air voids as Setting 7.

Table 4-16 also shows that the difference between air voids from the highest Gmm and that of maximum setting (Setting 8) is 0.07% for the 9.5-mm mixture and 0.24% for the 19.0-mm mixture. This might indicate that for finer mixtures, the Gilson device can be operated at maximum setting to achieve similar air voids as when operated at Setting 6. However, for the 19.0 mm mixture, the maximum setting would most likely result in stripping of asphalt and provide significantly lower air voids than the actual air voids of the compacted mixture.

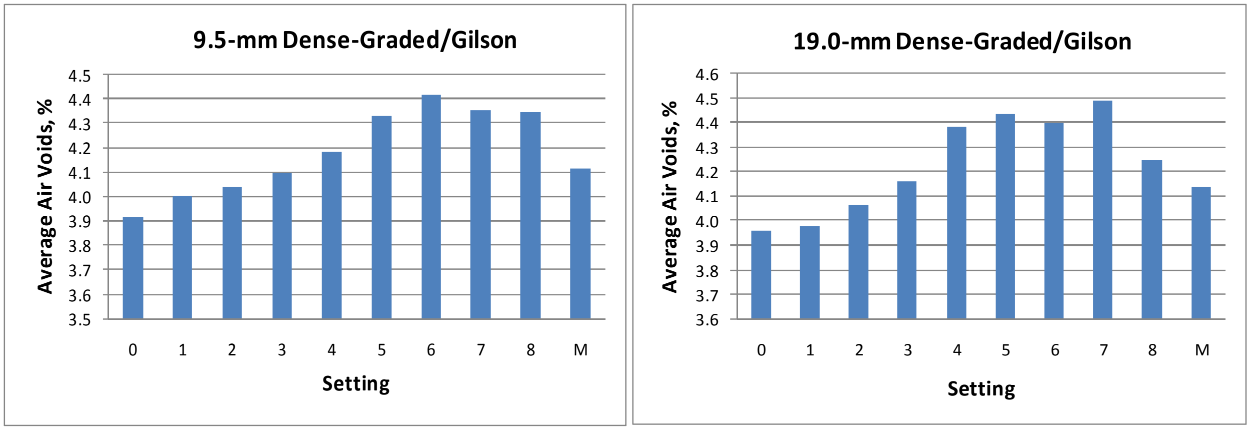

Figure 4-16- Air voids of dense-graded field mixtures at various settings for Gilson device

Table 4-16- Gmm values using Gilson device at settings of specific importance (setting of highest Gmm, manual agitation, mid-range setting, and maximum setting) and the differences in air voids resulted from measurements at various settings

Mixture Type	Setting of Maximum Gmm	Gmm, Highest	Gmm, Manual Agitation	Gmm, Mid-Range Setting (Setting 4)	Gmm, Maximum Setting (Setting 8)	Difference in Air Voids, Highest and Manual, %	Difference in Air Voids, Highest and Setting 4, %	Difference in Air Voids, Highest and Setting 8, %
9.5-mm	6	2.515	2.507	2.509	2.513	0.31	0.23	0.07
19.0-mm	7	2.536	2.527	2.533	2.529	0.35	0.11	0.24

The significance of the difference between Gmm measurements from various settings of Gilson device were also evaluated statistically. Table 4-17 and Table 4-18 provide the computed F values from the Scheffe test for statistical comparison of Gmm values. As shown in Table 4-17, the highest Gmm of 9.5 mm mixture from Setting 6 is significantly different from Gmm of zero and manual agitation and significantly different from those of Setting 1 through 4; however, statistically the same as those from Setting 5 through 8. Conversely, the F values in Table 4-18 show that for 19.0-mm mixture the highest Gmm from Setting 7 is only different from those of zero agitation and Setting 1. The rest of the settings provide statistically the same Gmm as that of Setting 7. This agrees with previous observations that manual and lower vibration levels might provide adequately high Gmm values for the coarser mixtures.

Table 4-17- Computed F values for comparison of Gmm of 9.5-mm dense-graded field mixture at various vibration settings of Gilson device; Critical F value=3.020 and DOF= (9, 10) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8
1	0.447								
2	0.898	0.078							
3	1.957	0.534	0.203						
4	4.334	1.997	1.286	0.466					
5	10.280	6.440	5.100	3.266	1.264				
6	14.971	10.245	8.534	6.103	3.195	0.440			
7	11.407	7.338	5.903	3.915	1.679	0.029	0.242		
8	11.001	7.013	5.611	3.678	1.525	0.012	0.305	0.004	
M	2.315	0.728	0.329	0.015	0.314	2.838	5.512	3.444	3.223

Table 4-18- Computed F values for comparison of Gmm of 19.0-mm dense-graded field mixture at various vibration settings of Gilson device; Critical F value=3.020 and DOF= (9, 10) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8
1	0.003								
2	0.162	0.121							
3	0.612	0.530	0.144						
4	2.807	2.629	1.620	0.798					
5	3.535	3.334	2.182	1.205	0.042				
6	3.001	2.816	1.768	0.903	0.003	0.022			
7	4.400	4.176	2.873	1.731	0.178	0.047	0.134		
8	1.249	1.130	0.511	0.112	0.312	0.582	0.378	0.961	
M	0.496	0.422	0.091	0.006	0.944	1.383	1.057	1.942	0.171

Since water was significantly cloudy at Settings 7 and higher, the possibility of using Setting 6 for 19.0-mm mixture was investigated. It was observed from both air void values and from statistical results that for measuring the 19.0-mm mixture, lower settings (up to Setting 4) would result in not significantly different Gmm than the highest Gmm. Therefore, Setting 6 can be used for accurate measurement of Gmm for both 9.5-mm and 19.0-mm dense-graded field mixtures. The Setting 6 corresponds to the frequency, acceleration, and kinetic energy values in Table 4-19.

Table 4-19- Frequency, acceleration, and kinetic energy of the Gilson shaking device at Setting 6 for measuring Gmm of dense-graded field mixtures

Vibration Properties	X	Y	Z	Total
Frequency, Hz	48.7	48.7	48.7	-
Acceleration, m/s^2	4.60	3.26	7.01	-
Energy (x 10^{-5}), Joule	2.11	0.95	4.90	7.97

4.2.2.2 SMA Field Mixtures

The three SMA mixtures of 9.5-mm, 12.5-mm, and 19.0-mm NMAS were tested using Gilson device. The Gmm of the mixtures were measured at Setting 1 through 8. For all mixtures, the measurements were also made at zero and manual agitations. As shown in Figure 4-17, the highest Gmm values of 2.649, 2.463, 2.447 for the 9.5-mm, 12.5-mm, and 19.0-mm mixtures, respectively, were achieved at Setting 7 of the Gilson device. For the SMA mixtures, the Gmm values from manual agitation were equivalent to Gmm values in the range of Setting 3 through 5. The change in water clarity was monitored to examine the physical effect of vibration on the mixtures. The observation of the water indicated that up to Setting 4, the water remained clear. From Setting 5 to Setting 7, the water became slightly cloudy, and at Setting 8, the water became significantly cloudy.

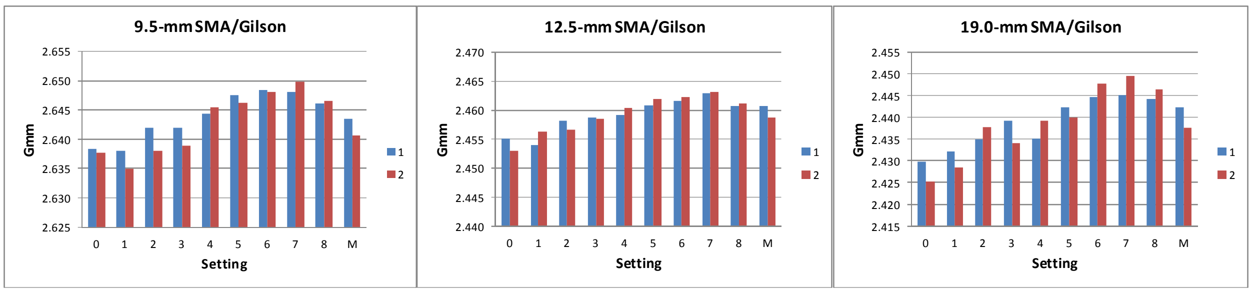

Figure 4-17-Gmm of SMA Mixtures at various settings of the Gilson device

The differences between the two replicate Gmm values at various settings of the Gilson device is shown in Figure 4-18. As shown in the figure, there is no defined trend between the variability of measurement and the intensity of vibration. However, the differences between replicates are larger for the 19.0-mm mixtures. Nevertheless, the difference between replicates at any setting is smaller than 0.007, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

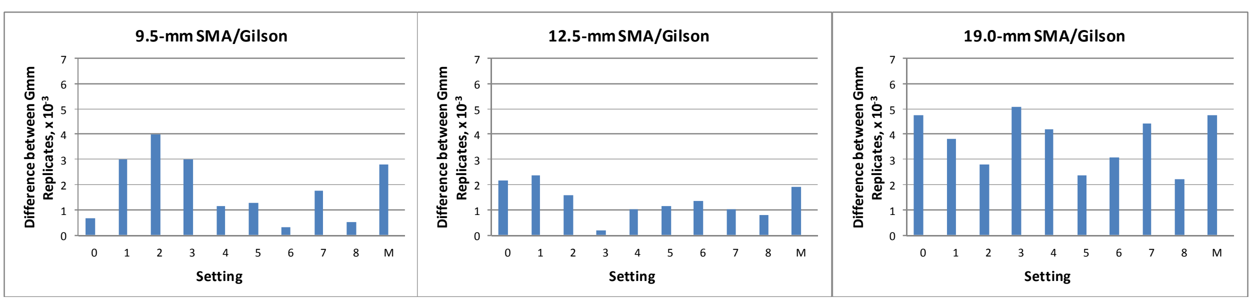

Figure 4-18-Difference between Gmm replicates of SMA Mixtures at various settings of the Gilson device

The practical significance of the difference between the highest Gmm and those from settings of specific importance was examined by comparing the calculated air void values. Figure 4-19 shows the air void values. Bulk specific values of 2.532, 2.357, and 2.339 were assumed for calculating the air voids of 9.5-mm, 12.5-mm, and 19.0-mm SMA mixtures, respectively. Table 4-20 shows the difference between the air voids from the highest Gmm and the Gmm of the most commonly used settings. As shown in the table, the difference between the air voids from the highest Gmm and the Gmm of maximum setting (Setting 7) is in the range of 0.08 to 0.10, which is not practically significant. The difference between air voids using the highest Gmm and using the Gmm from manual agitation could be significant for the 9.5-mm and 19.0-mm mixtures with the difference of 0.25% and 0.28%, respectively. The difference between using the highest Gmm and using the Gmm from mid-range agitation (Setting 4) could be significant for the 19.0-mm mixture with the difference of 39%.

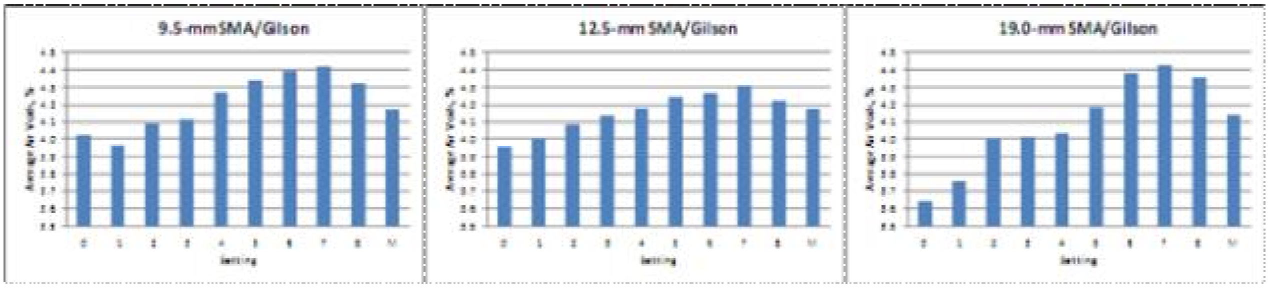

Figure 4-19-Air voids of SMA Mixtures at various settings of the Gilson device

Table 4-20- Gmm values of SMA mixtures using Gilson at settings of specific importance (setting of highest Gmm, manual agitation, mid-range setting, and maximum setting) and the differences in air voids resulted from the measurements

Mixture Type	Setting of Maximum Gmm	Gmm, Highest	Gmm, Manual Agitation	Gmm, Mid-Range Setting (Setting 5)	Gmm, Maximum Setting (Setting 8)	Difference in Air Voids, Highest and Manual, %	Difference in Air Voids, Highest and Setting 4, %	Difference in Air Voids, Highest and Setting 8, %
9.5-mm	7	2.649	2.642	2.645	2.646	0.25	0.15	0.10
12.5-mm	7	2.463	2.459	2.459	2.461	0.13	0.13	0.08
19.0-mm	7	2.447	2.439	2.437	2.445	0.28	0.39	0.09

The significance of the difference between Gmm measurements from various settings of the Gilson device were also evaluated statistically. Table 4-21 through Table 4-23 provide the computed F values from the Scheffe test for statistical comparison of Gmm values. As shown in the tables, the highest Gmm of the SMA mixtures from Setting 7 is statistically the same as those from manual agitation, mid-range setting (Setting 4), and maximum agitation (Setting 8). Based on the results from Scheffe test, manual agitation, mid-range, and maximum settings would provide statistically the same Gmm as that from Setting 7. However, from practical point of view, the differences between air voids from Setting 7 and those from mid-range setting and manual agitation could become significant if adding the variability from bulk specific gravity measurements.

Table 4-21- Computed F values for comparison of Gmm of 9.5-mm SMA field mixture at various vibration settings of Gilson device; F value=3.020 and DOF= (9, 10) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8
1	0.103								
2	0.181	0.558							
3	0.284	0.729	0.011						
4	2.181	3.233	1.105	0.892					
5	3.550	4.863	2.126	1.827	0.166				
6	4.833	6.348	3.142	2.775	0.521	0.099			
7	5.487	7.095	3.673	3.276	0.749	0.210	0.021		
8	3.167	4.414	1.833	1.555	0.092	0.011	0.175	0.317	
M	0.772	1.440	0.205	0.120	0.358	1.011	1.742	2.143	0.812

Table 4-22- Computed F values for comparison of Gmm of 12.5-mm SMA field mixture at various vibration settings of Gilson device; F value=3.020 and DOF= (9, 10) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8
1	0.013								
2	0.911	0.704							
3	1.037	0.816	0.004						
4	2.116	1.794	0.250	0.190					
5	3.838	3.399	1.009	0.884	0.255				
6	6.348	5.781	2.450	2.253	1.134	0.314			
7	7.169	6.566	2.970	2.752	1.496	0.516	0.025		
8	5.223	4.709	1.772	1.605	0.690	0.106	0.055	0.154	
M	2.092	1.772	0.242	0.183	0.000	0.263	1.152	1.516	0.704

Table 4-23- Computed F values for comparison of Gmm of 19.0-mm dense-graded field mixture at various vibration settings of Gilson device; F value=3.020 and DOF= (9, 10) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8
1	0.119								
2	1.197	0.562							
3	1.262	0.606	0.001						
4	1.430	0.724	0.010	0.005					
5	2.790	1.757	0.332	0.299	0.225				
6	5.182	3.732	1.397	1.329	1.168	0.367			
7	5.835	4.289	1.746	1.670	1.489	0.556	0.019		
8	4.783	3.394	1.194	1.131	0.983	0.267	0.008	0.052	
M	2.327	1.394	0.186	0.162	0.109	0.021	0.564	0.792	0.438

Since the highest Gmm was produced at Setting 7 and since water was only slightly cloudy at this setting, Setting 7 of the Gilson device is recommended as the optimum operation setting of the SMA mixtures. The Setting 7 of the Gilson device corresponds to the frequency, acceleration, and energy data found in Table 4-24.

Table 4-24- Frequency, acceleration, and kinetic energy of the Gilson shaking device at the Setting 7 for measuring Gmm of SMA mixtures

Vibration Properties	X	Y	Z	Total
Frequency, Hz	49.0	49.0	49.0	-
Acceleration, m/s^2	4.57	3.33	6.96	-
Energy ($\times 10^{-5}$), Joule	2.11	0.91	4.70	7.72

4.2.2.3 Dense-Graded Laboratory Mixtures

The Gmm of 4.75-mm, 12.5-mm, and 37.5-mm dense-graded laboratory mixtures were measured at Settings 1 through 8, and at zero and manual agitations. As shown in Figure 4-20, the highest Gmm of 2.555, 2.580, and 2.631 of the 4.75-mm, 12.5-mm, and 37.5-mm mixtures were achieved at Setting 7, 6, and 6 of the Gilson device, respectively. For all three dense-graded laboratory mixtures, the manual agitation resulted in

Gmm values that were equivalent or less than the Gmm values from Setting 2. The investigation of water clarity revealed that for the 4.75-mm mixture, water became cloudy at Setting 8, and for the 12.5 mm and 37.5-mm mixtures, water became cloudy at Settings 7 and 6, respectively.

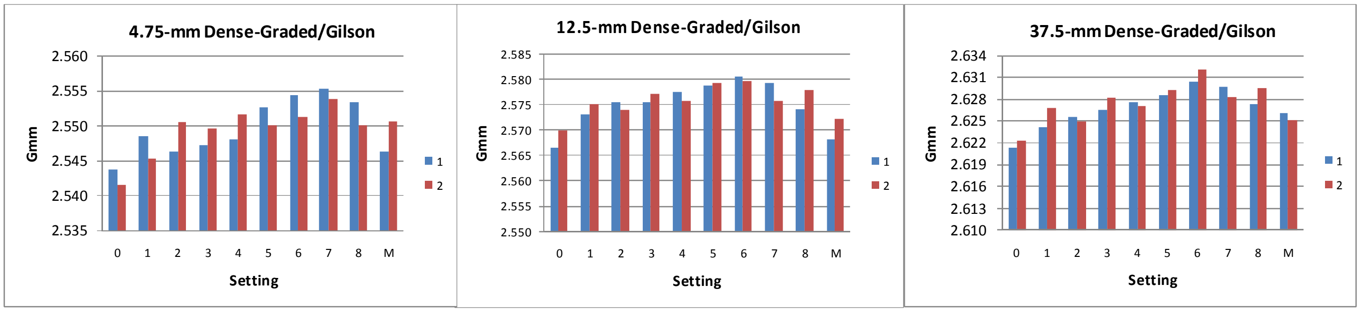

Figure 4-20- Gmm of dense-graded laboratory-prepared mixtures at various settings for the Gilson device

Figure 4-21 shows the differences between the two replicate Gmm values at various settings of the Gilson device. While there is no defined trend between the variability of measurement and the intensity of vibration, a smaller variability at the settings of higher Gmm is observed for the 12.5-mm mixture. Figure 4-21 also shows that the variability of the 37.5-mm mixture is less than those of the 4.75-mm and 12.5-mm mixtures, which might be attributed to the better release of air in coarser mixtures. Nevertheless, the difference between replicates at any setting is smaller than 0.005, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

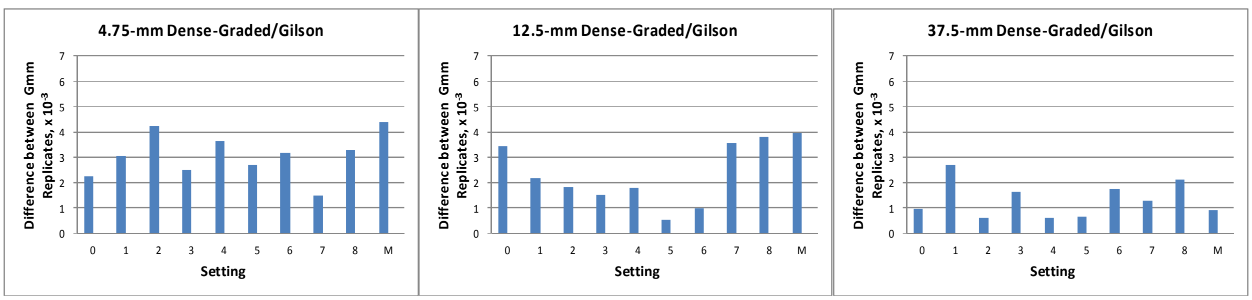

Figure 4-21- Difference between replicate Gmm of laboratory-prepared mixtures at various settings for the Gilson device

The practical significance of the difference between the highest Gmm and those from settings of specific importance was examined by comparing the calculated air void values. Figure 4-22 provides the air voids calculated from the measured Gmm values. The bulk specific values of 2.444, 2.466, and 2.515 were assumed for calculating the air voids of the 4.75-mm, 12.5-mm, and 37.5-mm mixtures, respectively. The difference between the air voids from the highest Gmm and those from the mid-range setting, maximum setting, and the manual agitation are provided in Table 4-25. As shown in the table, the difference between the air voids using the highest Gmm and that of mid-range agitation (Setting 4) is in the range of 0.12% to 0.18%. The difference between the air voids from the highest Gmm and those from the maximum setting (Setting 8) is in the range of 0.10% to 0.15 %. The difference between the air voids from the highest Gmm and those from manual agitation is in the range of 0.20% to 0.37%. Therefore, from practical point of view the use of Gmm from manual agitation could result in significantly lower air voids of the compacted mixtures.

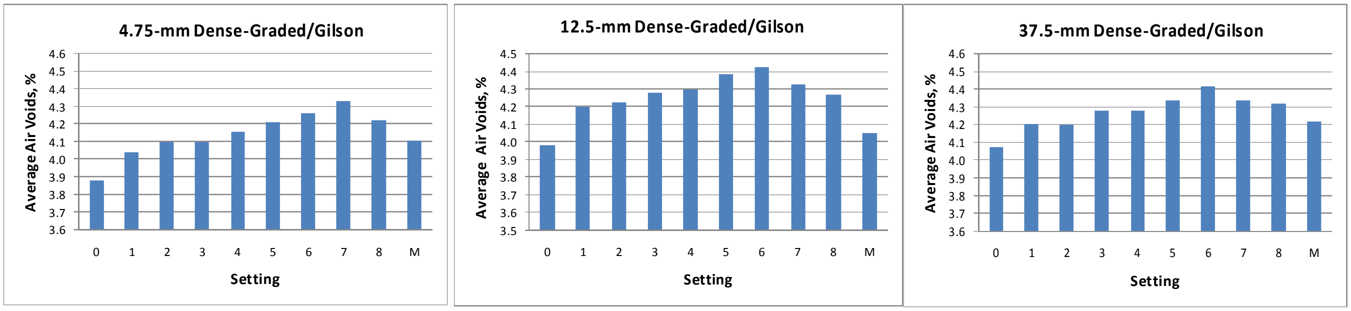

Figure 4-22- Air voids of the laboratory-prepared mixtures at various settings for the Gilson device

Table 4-25- Gmm values of dense-graded laboratory mixtures using Gilson at settings of specific importance (setting of highest Gmm, manual agitation, mid-range setting, and maximum setting) and the differences in air voids resulted from the measurements

Mixture Type	Setting of Maximum Gmm	Gmm, Highest	Gmm, Manual Agitation	Gmm, Mid-Range Setting (Setting 4)	Gmm, Maximum Setting (Setting 8)	Difference in Air Voids, Highest and Manual, %	Difference in Air Voids, Highest and Setting 4, %	Difference in Air Voids, Highest and Setting 8, %
4.75-mm	7	2.555	2.548	2.550	2.552	0.23	0.18	0.11
12.5-mm	6	2.580	2.570	2.577	2.576	0.37	0.12	0.15
37.5-mm	6	2.631	2.626	2.627	2.628	0.20	0.14	0.10

The statistical significance of the difference between Gmm from various settings is evaluated using a Scheffe test. Table 4-26 through Table 4-28 provide the computed F values for comparison of Gmm of various settings. As indicated from the comparison of the computed and critical F values, the difference between the highest Gmm and that from manual agitation is significant for the 12.5-mm and 37.5-mm mixtures and not significant for the 4.75-mm mixture. The F-values for comparison of the highest Gmm with the Gmm of Setting 4 and Gmm of Setting 8 show that the highest Gmm values are statistically the same as those from the mid-range and maximum settings. Based on the results from statistical comparison and evaluation of the air void values, use of manual agitation for the dense-graded laboratory mixtures is not recommended.

Table 4-26- Computed F values for comparison of Gmm of 4.75-mm dense-graded laboratory mixture at various vibration settings of Gilson device; F value=3.020 and DOF= (9, 10) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8
1	0.404								
2	0.738	0.050							
3	0.738	0.050	0.000						
4	1.171	0.199	0.050	0.050					
5	1.708	0.451	0.201	0.201	0.051				
6	2.285	0.767	0.426	0.426	0.184	0.042			
7	3.169	1.309	0.848	0.849	0.487	0.224	0.072		
8	1.827	0.512	0.243	0.243	0.073	0.002	0.026	0.184	
M	0.762	0.056	0.000	0.000	0.044	0.189	0.408	0.823	0.229

Table 4-27- Computed F values for comparison of Gmm of 12.5-mm dense-graded laboratory mixture at various vibration settings of Gilson device; F value=3.020 and DOF= (9, 10) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8
1	1.112								
2	1.361	0.013							
3	2.072	0.148	0.074						
4	2.299	0.213	0.122	0.006					
5	3.792	0.797	0.609	0.258	0.186				
6	4.517	1.146	0.919	0.470	0.371	0.032			
7	2.752	0.365	0.242	0.048	0.020	0.083	0.217		
8	1.937	0.114	0.051	0.002	0.015	0.309	0.538	0.071	
M	0.100	0.545	0.724	1.262	1.440	2.661	3.273	1.803	1.157

Table 4-28- Computed F values for comparison of Gmm of 37.5-mm dense-graded laboratory mixture at various vibration settings of Gilson device; F value=3.020 and DOF= (9, 10) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8
1	1.345								
2	1.236	0.002							
3	3.126	0.370	0.430						
4	3.153	0.380	0.441	0.000					
5	5.145	1.229	1.337	0.250	0.243				
6	9.060	3.424	3.603	1.543	1.523	0.550			
7	5.313	1.312	1.424	0.288	0.280	0.001	0.497		
8	4.531	0.939	1.034	0.130	0.125	0.019	0.777	0.031	
M	1.488	0.004	0.012	0.301	0.309	1.099	3.205	1.178	0.826

The possibility of selecting one optimum setting of Gilson device for the dense-graded laboratory mixtures was investigated. As showed earlier, for the 37.5-mm mixture, the water was significantly cloudy at Setting 6; therefore possibility of using Setting 5 for the three mixtures is examined. Table 4-29 shows the differences between the air voids resulted from Setting 5 and those of Settings 6 and 7, which provided the highest Gmm of one or more of the mixtures. As indicated from the table, the difference between the air voids from the three settings for the three mixtures is below 0.11%, which is not considered practically significant. This is also reinforced by the results of statistical analysis in Table 4-26 through Table 4-28, where the computed F values from comparison of Gmm of Settings 5, 6, and 7 are smaller than the critical F value. Considering the small difference between the air voids resulted from Settings 5 and those of Settings 6 and 7, Setting 5 is recommended for 4.75-mm, 12.5-mm, and 25.0-mm mixtures. The vibration properties of Gilson at Setting 5 can be found in Table 4-30.

Table 4-29- Gmm of the laboratory prepared dense-graded mixtures at settings of Gilson device which resulted in the highest Gmm and the differences between the air voids resulted from those settings and from Setting 5

Mixture Type	Setting of Maximum Gmm	Gmm, Setting 6	Gmm, Setting 7	Difference in Air Voids, Highest and Setting 5, %	Difference in Air Voids, Highest and Setting 6, %	Difference in Air Voids, Highest and Setting 7, %
4.75-mm	7	2.553	2.555	0.11	0.07	0.00
12.5-mm	6	2.580	2.573	0.03	0.00	0.10
37.5-mm	6	2.631	2.629	0.08	0.00	0.08

Table 4-30- Frequency, acceleration, and kinetic energy of the Gilson shaking device at Setting 5 for measuring Gmm of dense-graded laboratory mixtures

Vibration Properties	X	Y	Z	Total
Frequency, Hz	48.7	48.7	48.7	-
Acceleration, m/s^2	4.54	2.89	7.59	-
Energy (x 10^{-5}), Joule	2.00	0.81	5.75	8.56

4.2.3 Syntron

The Syntron concrete shaker can be operated at ten discrete settings of 1 through 10. Based on the results of the state survey reported in Chapter 2, the Syntron device is commonly operated at Setting 5 in the state laboratories. While measurements at zero agitation were performed along other settings, the manual agitation was not performed. The reason was that it was not practical to strike or shake the bell jar vacuum chamber of the Minnesota setup, which was used with the Syntron concrete shaker. The following observations were made from the Gmm measurements:

4.2.3.1 Dense-Graded Field Mixtures

Figure 4-23 shows the Gmm values at various settings of the Syntron device. As shown in the figure, the highest Gmm of 2.513 and 2.534 for the 9.5-mm and 19.0-mm mixtures, respectively, were achieved at Setting 7 of the Syntron table. The visual observation of the water indicated that water remained clear through Setting 4. At Settings 5 through 8 and at Setting 10, water was slightly cloudy and at Setting 9 water was significantly cloudy.

Figure 4-24 shows the differences between the two replicate Gmm values at various settings of the Syntron device. As indicated from the figures there are no defined trends between the variability of measurements and the intensity of vibration. Figure 4-24 also shows that the difference between replicates at any setting is smaller than 0.004, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

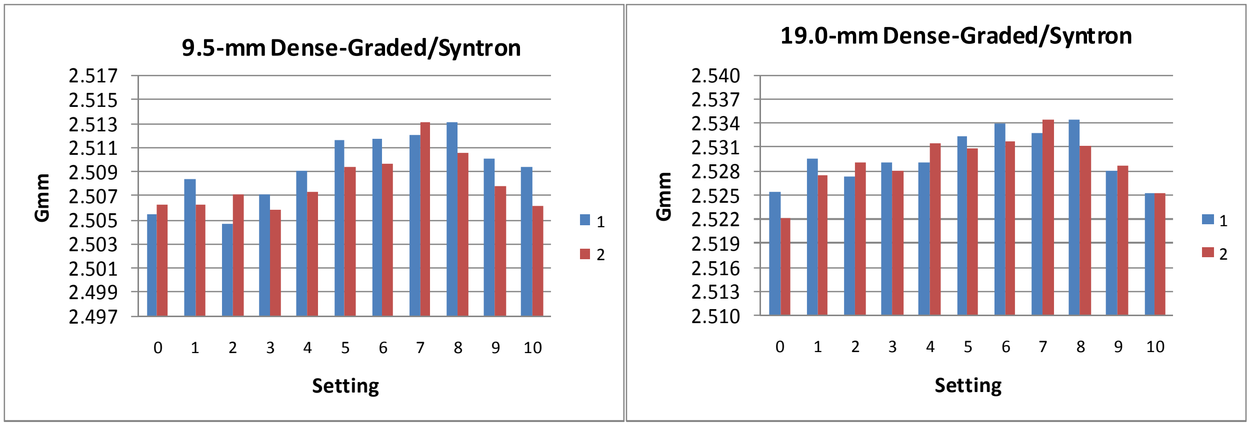

Figure 4-23- Gmm of dense-graded field mixtures at various settings for Syntron device

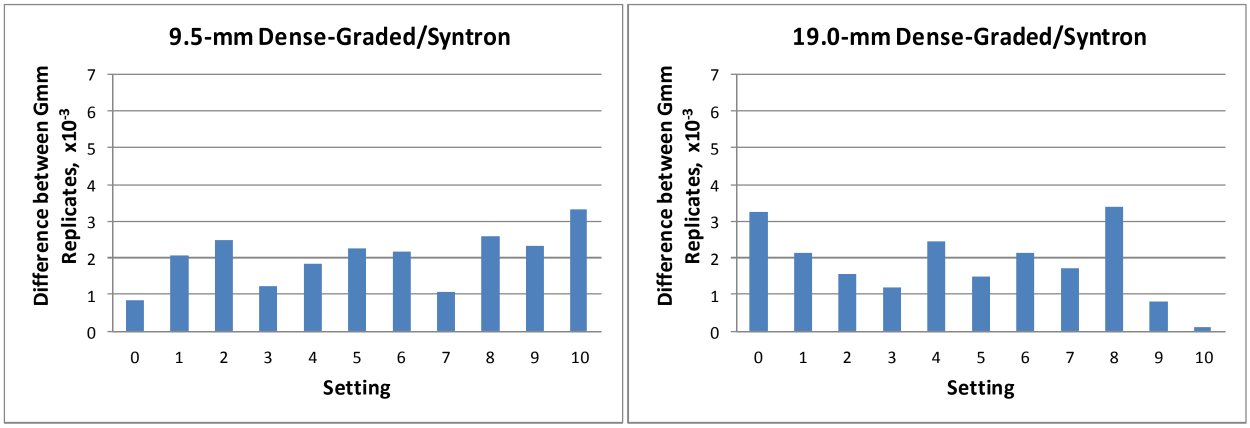

Figure 4-24- Difference between replicate Gmm of dense-graded mixtures at various settings for Syntron device

The practical significance of the difference between the highest Gmm and those from the settings of specific importance was examined by comparing the calculated air void values. Figure 4-25 shows the computed air voids using the measured Gmm values. Bulk specific values of 2.404 and 2.422 were assumed for calculating the air voids of 9.5-mm and 19.0-mm mixtures, respectively. Table 4-31 provides the differences between the air voids from the highest Gmm and that from Setting 5, which is commonly used by the state laboratories. As shown in the table, the difference between the air voids resulted from the highest Gmm (Setting 7) and that from Setting 5 is 0.07% for the 9.5mm mixture and 0.08% for the 19.0mm mixture; neither which are considered practically significant.

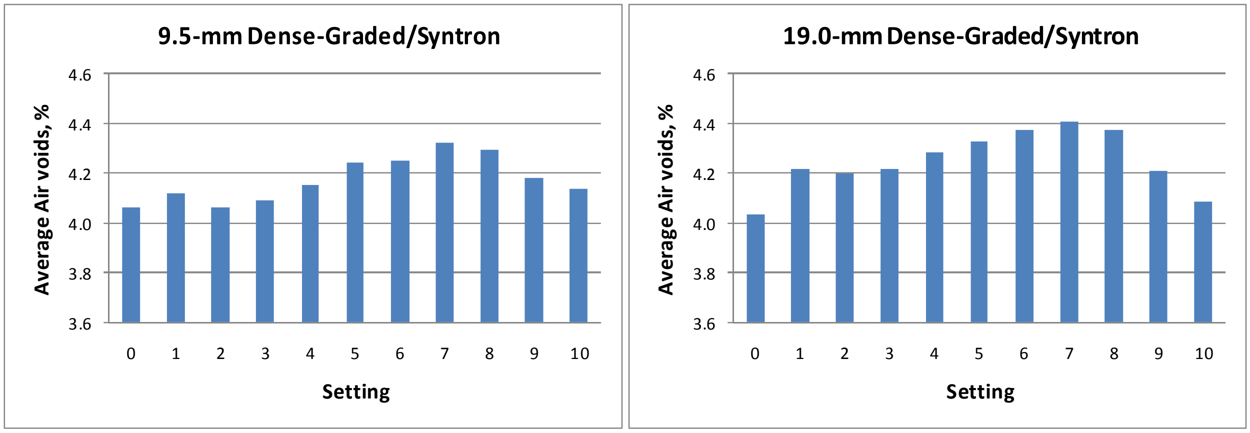

Figure 4-25- Air voids of dense-graded field mixtures at various settings for Syntron device

Table 4-31- Gmm values using Syntron device at settings of specific importance (setting of highest Gmm and mid-range setting) and differences in air voids resulted from the measurements

Mixture Type	Setting of Highest Gmm	Gmm, Highest	Gmm, Mid-Range Setting (Setting 5)	Difference between Air Voids from Setting of Highest Gmm and Setting 5, %
9.5-mm	7	2.513	2.510	0.07
19.0-mm	7	2.534	2.532	0.08

The significance of the difference between Gmm values from various settings was also examined statistically using a Scheffe test. Table 4-32 and Table 4-33 provide the computed F values. As indicated from the tables, for the 9.5-mm mixture, the differences between Gmm values from various settings are not significant. For the 19.0-mm mixture, the differences between the highest Gmm and only those from Setting 10 and zero are statistically significant.

Table 4-32- Computed F values for comparison of Gmm of 9.5-mm dense-graded field mixture at various vibration settings of Syntron device; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8	9
1	0.093									
2	0.000	0.093								
3	0.017	0.030	0.017							
4	0.237	0.033	0.237	0.127						
5	0.934	0.438	0.934	0.699	0.230					
6	1.021	0.499	1.021	0.775	0.274	0.002				
7	1.970	1.208	1.970	1.621	0.840	0.191	0.154			
8	1.552	0.886	1.552	1.244	0.576	0.078	0.055	0.025		
9	0.415	0.116	0.415	0.264	0.025	0.104	0.134	0.576	0.362	
10	0.160	0.009	0.160	0.073	0.008	0.321	0.373	1.007	0.716	0.060

Table 4-33- Computed F values for comparison of Gmm of 19.0-mm dense-graded field mixture at various vibration settings of Syntron device; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8	9
1	1.044									
2	0.902	0.005								
3	1.046	0.000	0.005							
4	1.987	0.150	0.211	0.150						
5	2.817	0.431	0.531	0.430	0.072					
6	3.819	0.869	1.009	0.868	0.297	0.076				
7	4.501	1.209	1.373	1.207	0.506	0.196	0.028			
8	3.817	0.868	1.007	0.866	0.296	0.076	0.000	0.028		
9	0.975	0.001	0.001	0.001	0.178	0.477	0.934	1.286	0.933	
10	0.095	0.509	0.412	0.511	1.213	1.877	2.709	3.287	2.707	0.461

Based on achieving the highest Gmm and based on the clarity of water, Setting 7 is recommended as the optimum operational setting of the Syntron device for measuring Gmm of 9.5-mm and 19.0-mm dense graded field mixtures. This setting corresponds to the frequency, acceleration, and kinetic energy values in Table 4-34.

Table 4-34- Frequency, acceleration, and kinetic energy of the Syntron shaking device at the Setting 7 for measuring Gmm of dense-graded field mixtures

Vibration Properties	X	Y	Z	Total
Frequency, Hz	73.8	103.4	630.6	-
Acceleration, m/s^2	25.3	22.5	72.7	-
Energy (x 10^{-5}), Joule	16.3	25.0	244.1	285.4

4.2.3.2 SMA Field Mixtures

The Gmm of the 9.5-mm, 12.5-mm and 19.0-mm SMA mixtures were measured at Setting 1 through 10 of the Syntron table. The measurements were also conducted at zero agitation. As shown in Figure 4-26, the highest Gmm of the 9.5-mm (2.646), 12.5-mm (2.464), and 19.0-mm (2.448) mixtures were achieved at Settings 8, 7, and 9 of the Syntron table, respectively. The visual observation of the water indicated that the water remained clear through Setting 5. At Setting 6 through 8 and at Setting 10, the water became slightly cloudy, and at Setting 9, the water was significantly cloudy.

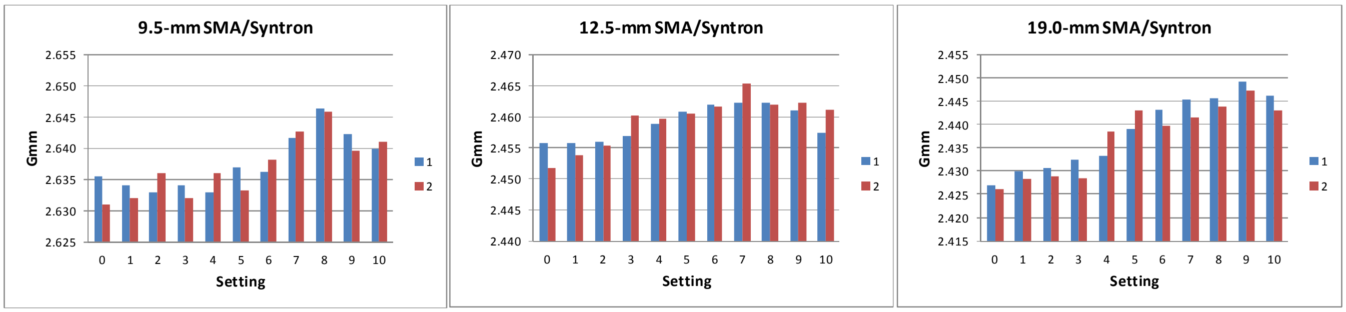

Figure 4-26-Gmm of SMA Mixtures at various settings of the Syntron device

The differences between the two replicate Gmm values at various settings of the Syntron device are shown in Figure 4-27. As shown, there is no defined trend between the variability of measurement and the intensity of vibration. However, the differences between replicates of the 19.0-mm mixtures are larger than those of the other mixtures. Nevertheless, the difference between replicates at any setting is smaller than 0.007, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

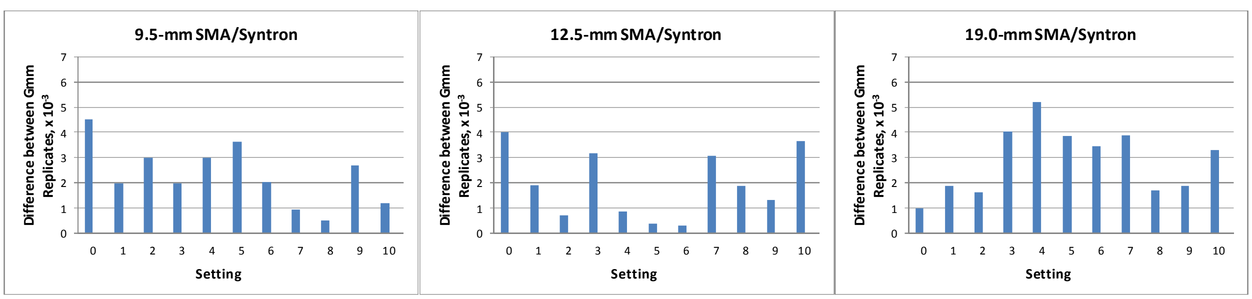

Figure 4-27-Difference between Gmm replicates of SMA Mixtures at various settings of the Syntron device

The practical significance of the difference between the highest Gmm and those from the settings of specific importance was examined by comparing the calculated air voids. The air voids of the mixtures resulted from various settings of Syntron device are shown in Figure 4-28. Bulk specific values of 2.532, 2.357, and 2.339 were assumed for calculating the air voids of the 9.5-mm, 12.5,-mm, and 19.0-mm mixtures, respectively. The differences between the air voids from the highest Gmm and that of Setting 5, which is most commonly used by the state laboratories, are provided in Table 4-35. As shown in the table, the difference between the air voids using the Gmm from Setting 5 (mid-range) and the highest Gmm is 0.40%, 0.15%, and 0.30% for the 9.5-mm, 12.5-mm, and 19.0-mm mixtures, respectively. Considering other sources of variability in measuring air voids, using the mid-range setting of 5, would most probably result in significantly lower air voids than the actual air voids of the 9.5-mm and 19.0-mm compacted mixtures.

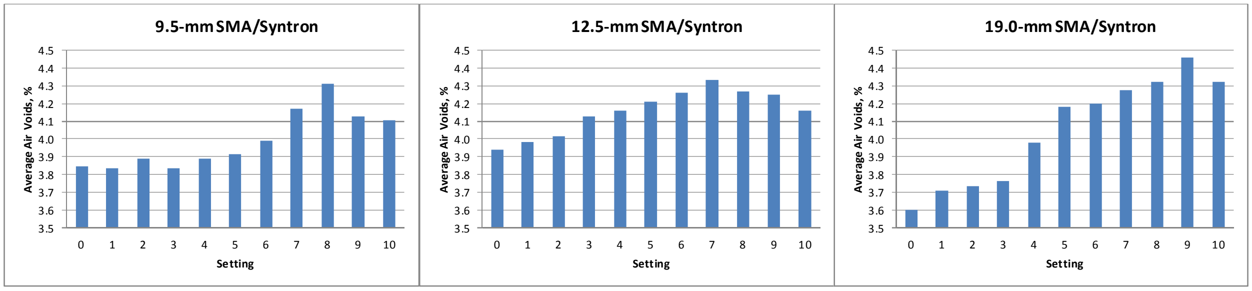

Figure 4-28- Air voids of SMA Mixtures at various settings of the Syntron device

Table 4-35- Gmm values using Syntron device at settings of specific importance (setting of highest Gmm and mid-range setting) and the differences in air voids resulted from those settings

Mixture Type	Setting of Maximum Gmm	Gmm, Highest	Gmm, Setting 5	Difference in Air Voids, Highest and Setting 5, %
9.5-mm	8	2.646	2.635	0.40
12.5-mm	7	2.464	2.461	0.15
19.0-mm	9	2.448	2.441	0.30

The results of statistical comparison are provided in Table 4-36 through Table 4-38. As indicated from Table 4-36, the highest Gmm of 9.5-mm mixture (from Setting 8) is significantly different from Gmm of Setting 0 through 5.

Table 4-37 shows that for the 12.5-mm mixture, the only differences that are significant are between the highest Gmm and those of Settings 0 and 1. For the 19.0 mm mixture (Table 4-38), the highest Gmm is significantly different from those of Setting 0 through 4 and not significantly different from the mid-range setting and higher. From the above information it is indicated that for the 9.5-mm and 19.0-mm mixtures, if Syntron table is operated at the mid-range setting, the resulted Gmm would be significantly lower than the highest Gmm.

Table 4-36- Computed F values for comparison of Gmm of 9.5-mm SMA mixture at various vibration settings of Syntron device; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8	9
1	0.002									
2	0.046	0.067								
3	0.002	0.000	0.067							
4	0.046	0.067	0.000	0.067						
5	0.101	0.132	0.011	0.132	0.011					
6	0.456	0.520	0.213	0.520	0.213	0.128				
7	2.366	2.508	1.753	2.508	1.753	1.489	0.744			
8	4.973	5.179	4.064	5.179	4.064	3.657	2.417	0.479		
9	1.780	1.903	1.254	1.903	1.254	1.033	0.434	0.042	0.803	
10	1.552	1.667	1.064	1.667	1.064	0.861	0.325	0.085	0.969	0.008

Table 4-37- Computed F values for comparison of Gmm of 12.5-mm SMA mixture at various vibration settings of Syntron device; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8	9
1	0.043									
2	0.148	0.032								
3	0.902	0.551	0.319							
4	1.230	0.814	0.524	0.025						
5	1.915	1.384	0.997	0.189	0.075					
6	2.574	1.952	1.487	0.429	0.245	0.049				
7	4.015	3.228	2.620	1.111	0.800	0.385	0.159			
8	2.771	2.124	1.638	0.511	0.309	0.079	0.004	0.115		
9	2.424	1.821	1.373	0.369	0.200	0.030	0.002	0.200	0.012	
10	1.221	0.806	0.518	0.024	0.000	0.078	0.250	0.808	0.313	0.204

Table 4-38- Computed F values for comparison of Gmm of 19.0-mm SMA field mixture at various vibration settings of Syntron device; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8	9
1	0.144									
2	0.214	0.007								
3	0.305	0.030	0.008							
4	1.802	0.928	0.774	0.624						
5	4.251	2.832	2.557	2.278	0.518					
6	4.577	3.099	2.812	2.518	0.635	0.006				
7	5.780	4.102	3.770	3.429	1.127	0.117	0.070			
8	6.702	4.884	4.521	4.147	1.554	0.278	0.202	0.034		
9	9.528	7.333	6.886	6.423	3.043	1.051	0.898	0.466	0.248	
10	6.643	4.834	4.473	4.100	1.525	0.266	0.192	0.030	0.000	0.259

The possibility of selecting one setting of the Syntron device for all three mixtures was explored. Table 4-39 shows the difference between the air voids from the highest Gmm and the Gmm from Setting 7, Setting 8, and Setting 9 at which the highest Gmm values were achieved. As shown in the table, the differences are the smallest between the air voids from the highest Gmm and from Gmm of Setting 8 (maximum of 0.14%). Therefore, Setting 8 can be operated for the SMA mixtures without significant decrease in the air voids. This is also supported by statistical analysis of the data, where F values for comparison of Gmm of Setting 8 with those of Setting 7 and 9 are lower than the critical F value.

Table 4-39- Gmm of the SMA field mixtures at the settings of Syntron device which resulted in the highest Gmm of one or more of the mixtures and the differences between the air voids resulted from the measurements

Mixture Type	Setting of Maximum Gmm	Gmm, Setting 7	Gmm, Setting 8	Gmm, Setting 9	Difference in Air Voids, Highest and Setting 7, %	Difference in Air Voids, Highest and Setting 8, %	Difference in Air Voids, Highest and Setting 9, %
9.5-mm	8	2.642	2.646	2.641	0.14	0.00	0.19
12.5-mm	7	2.464	2.462	2.462	0.00	0.07	0.09
19.0-mm	9	2.443	2.445	2.448	0.19	0.14	0.00

Based on the above observations, Setting 8 is recommended as the optimum operational setting of the Syntron device for measuring the Gmm of the SMA mixtures. At this setting, water was also not significantly cloudy. Setting 8 of Syntron table corresponds to the frequency, acceleration, and energy data found in Table 4-40.

Table 4-40- Frequency, acceleration, and kinetic energy of the Syntron device at Setting 8 for measuring Gmm of SMA mixtures

Vibration Properties	X	Y	Z	Total
Frequency, Hz	83.4	90.7	631.9	-
Acceleration, m/s^2	19.16	21.50	73.52	-
Energy (x 10^{-5}), Joule	21.8	26.5	299.3	347.6

4.2.3.3 Dense-Graded Laboratory Mixtures

Two of the four dense-graded laboratory mixtures were tested with the Syntron shaking table. The Gmm of the 4.75-mm and 12.5-mm mixtures were measured at Settings 1 through 10 of the Syntron concrete shaker and at zero agitation as well. As shown in Figure 4-29, the highest Gmm of 2.556 and 2.582 for the 4.75-mm and 12.5-mm mixtures were achieved at Setting 8 of the Syntron table. The visual observation of the water indicated that water remained clear through Setting 4. At Settings 5 through 7 and at Setting 10, water was slightly cloudy, and at Settings 8 and 9, water was significantly cloudy.

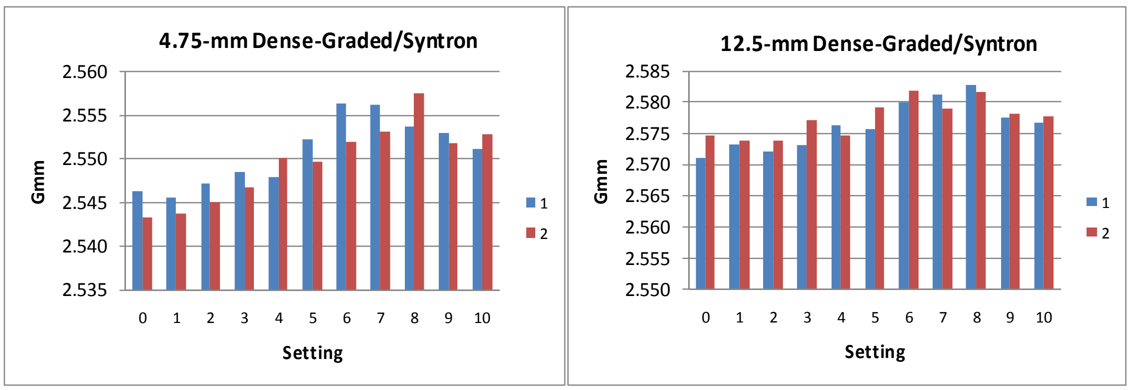

Figure 4-29- Gmm of dense-graded laboratory-prepared mixtures at various settings for the Syntron Device

Figure 4-30 shows the differences between the two replicate Gmm values at various settings of the Syntron device. As shown by the figure, there is no defined trend between the variability of measurement and the intensity of vibration. As also indicated by the figure, the difference between replicate measurements at any setting is smaller than 0.005, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

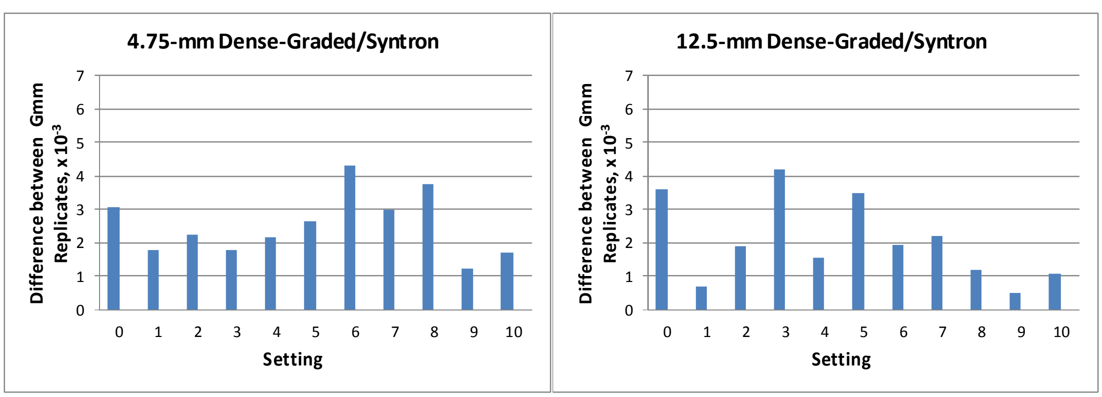

Figure 4-30- Difference between replicate Gmm of laboratory-prepared mixtures at various settings for the Syntron device

The practical significance of the difference between the highest Gmm and those from the settings of specific importance was examined by comparing the calculated air void values. Figure 4-31 provides the air voids calculated from Gmm values at various settings of the Syntron table. The bulk specific gravity values of 2.444 and 2.466 were assumed for calculating the air voids of the 4.75-mm and 12.5-mm mixtures, respectively. The differences between the air voids from the highest Gmm and those from Setting 5, which is commonly used by the state laboratories, are provided in Table 4-41. As shown in the table, the difference between the air voids using the highest Gmm and the Gmm from Setting 5 is 0.17% and 0.18% for the 4.75-mm and 12.5-mm mixtures, respectively. From practical point of view, these differences are not considered significant.

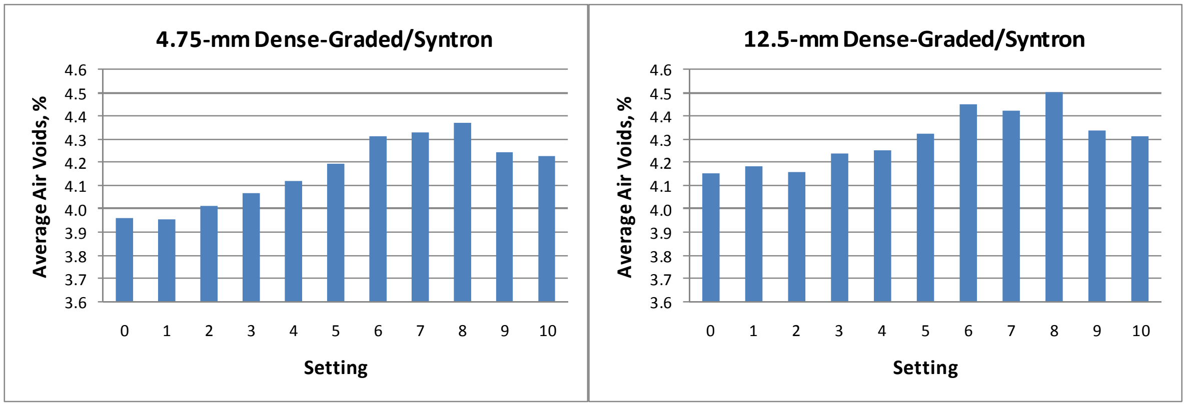

Figure 4-31- Air voids of the laboratory-prepared mixtures at various settings for the Syntron device

Table 4-41- Gmm using Syntron device at settings of specific importance (setting of highest Gmm and mid-range setting) and differences in air voids from the highest Gmm and Gmm resulted from mid-range setting of Syntron device

Mixture Type	Setting of Highest Gmm	Gmm, Highest	Gmm, Mid-Range Setting (Setting 5)	Gmm, Maximum Setting (Setting 10)	Difference in Air Voids between Highest and Setting 5, %	Difference in Air Voids between Highest and Setting 10, %
4.75-mm	8	2.556	2.551	2.552	0.17	0.14
12.5-mm	8	2.582	2.577	2.577	0.18	0.19

The significance of the difference between Gmm measurements from various settings of the Syntron table were also evaluated statistically. Table 4-42 and Table 4-43 provide the computed F values from the Scheffe test for comparison of Gmm values. As shown in the tables, the highest Gmm of the two dense-graded laboratory mixtures are not significantly different from those of Setting 5, which are commonly used by the state laboratories. The F-values also indicate that for measuring Gmm of the dense-graded laboratory mixtures any setting higher than Setting 3 would result in statistically the same Gmm values.

Since water became significantly cloudy at Setting 8, the use of a lower setting as the optimum setting was evaluated. The difference between the air voids from Setting 8 and Setting 7 are shown in Table 4-44. As indicated from the table, the differences are smaller than 0.1%, which is not practically significant. This is also supported by the results of statistical analysis in Table 4-43, where Setting 7 and 8 are shown to produce statistically the same Gmm values. Therefore, based on the clarity of the water and the small difference between the air voids from Setting 8 and Settings 7, Setting 7 is recommended as the optimum operational setting of the Syntron device for measuring the Gmm of the 4.75-mm and 12.5-mm dense graded field mixtures. The vibration properties of Syntron device at Setting 8 was previously provided in Table 4-40.

Table 4-42- Computed F values for comparison of Gmm of 4.75-mm dense-graded laboratory mixture at various vibration settings of Gilson device; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8	9
1	0.001									
2	0.046	0.063								
3	0.218	0.253	0.063							
4	0.485	0.537	0.232	0.053						
5	1.055	1.130	0.659	0.314	0.109					
6	2.416	2.530	1.794	1.183	0.736	0.278				
7	2.718	2.838	2.054	1.397	0.906	0.386	0.009			
8	3.267	3.399	2.535	1.798	1.234	0.609	0.064	0.025		
9	1.601	1.693	1.103	0.638	0.323	0.057	0.084	0.147	0.294	
10	1.420	1.507	0.954	0.526	0.245	0.027	0.132	0.209	0.379	0.005

Table 4-43- Computed F values for comparison of Gmm of 12.5-mm dense-graded field mixture at various vibration settings of Gilson device; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	1	2	3	4	5	6	7	8	9
1	0.018									
2	0.001	0.012								
3	0.187	0.090	0.168							
4	0.254	0.138	0.232	0.005						
5	0.772	0.556	0.733	0.199	0.140					
6	2.321	1.935	2.253	1.192	1.040	0.416				
7	1.906	1.558	1.844	0.900	0.768	0.252	0.020			
8	3.215	2.757	3.135	1.853	1.662	0.837	0.073	0.170		
9	0.900	0.666	0.857	0.267	0.198	0.005	0.331	0.187	0.713	
10	0.679	0.478	0.643	0.154	0.103	0.003	0.489	0.310	0.939	0.015

Table 4-44- Gmm of the laboratory prepared dense-graded mixtures using Syntron device at a setting lower than the setting of highest Gmm and the differences between the air voids of the two settings

Mixture Type	Gmm, Setting 7	Gmm, Setting 8 (Highest)	Difference in Air Voids, Highest and Setting 7, %
4.75-mm	2.555	2.556	0.04
12.5-mm	2.580	2.582	0.08

4.2.4 Orbital Shaker

The orbital shaker has a digital dial for the continuous increase of vibration in the range of 15 to 500 rpm. The measurement of Gmm of the dense-graded field mixtures was conducted at 9 vibration intensity levels in the range of 90 rpm through 330 rpm at 30 rpm intervals. The measurements were conducted at zero and manual agitations as well. Based on the survey of the state laboratories reported in Chapter 2, the vibration level of 270 rpm is the most commonly used setting.

4.2.4.1 Dense-Graded Field Mixtures

Figure 4-32 shows the Gmm values at various settings of the Orbital shaker. As shown in Figure 4-32, for 9.5-mm and 19.5-mm mixtures, the highest Gmm of 2.512 and 2.537 were obtained at 240 rpm and 210 rpm of the Orbital shaker, respectively. The Gmm values from manual agitation were equivalent to the Gmm values obtained at 150 rpm for the 9.5-mm mixture and 90 rpm for the 19.0-mm mixture. The visual observation of the water indicated that the water remained clear through 150 rpm. From 180 rpm through 240 rpm, the water became slightly cloudy. At 270 rpm and higher, the water became significantly cloudy.

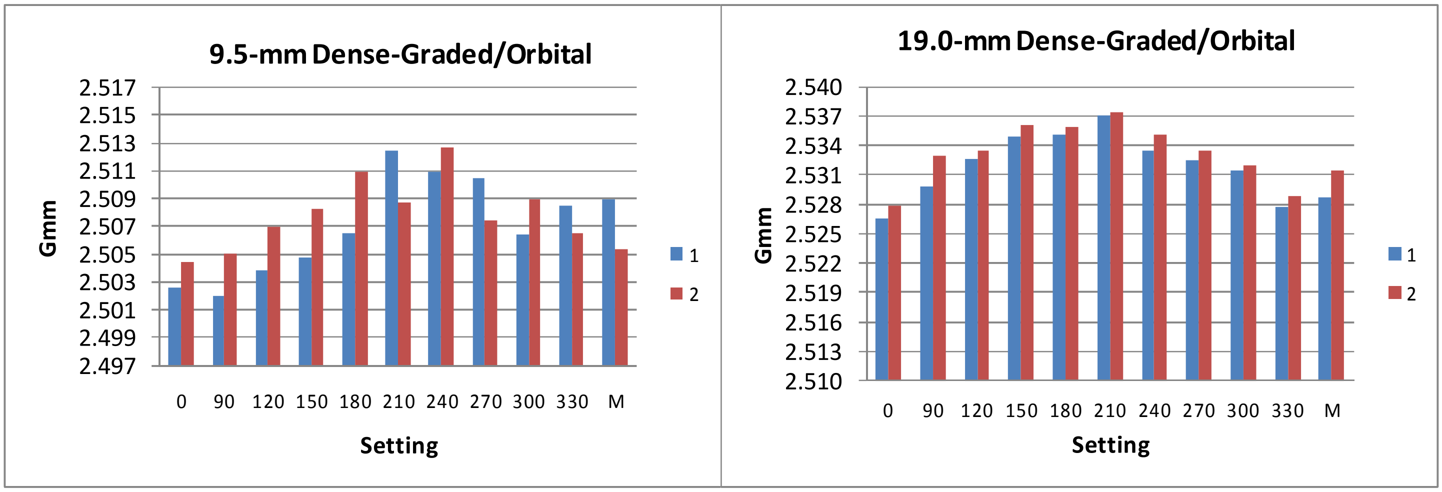

Figure 4-32- Gmm of dense-graded field mixtures at various settings of Orbital device

The differences between the two replicate Gmm values at various settings of the Orbital device are shown in Figure 4-33. As shown in the figure, there is no defined trend between the variability of measurement and the intensity of vibration for the 19.0-mm mixture. However, the difference between replicates of the 9.5-mm mixture seems to have been maximized at the Setting of 180 rpm. Nevertheless, for both mixtures, the difference at any setting was smaller than 0.005, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

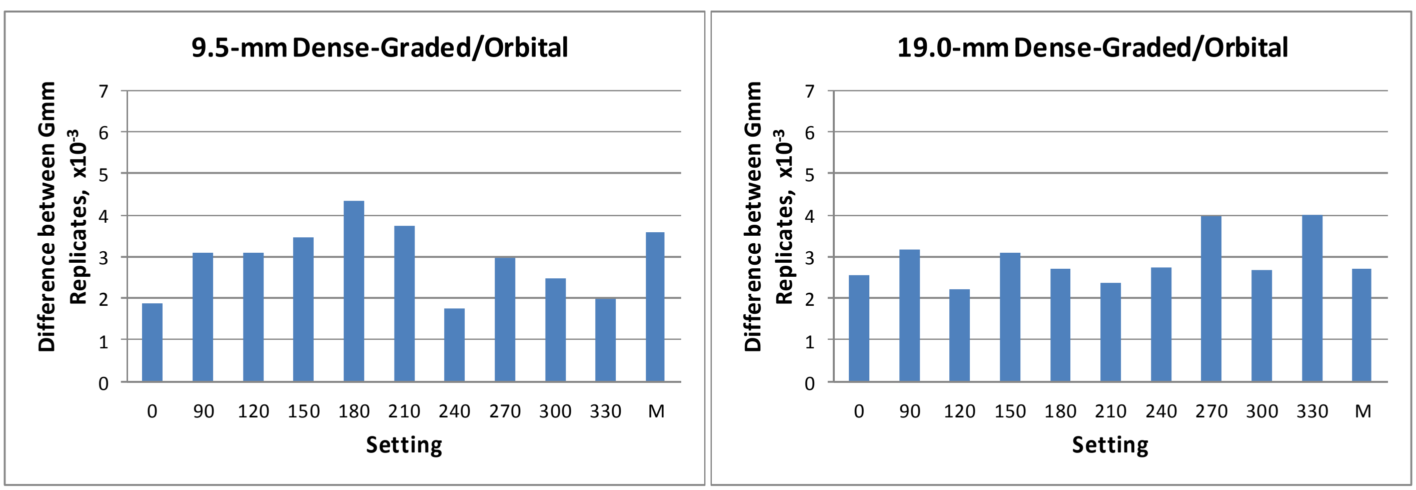

Figure 4-33- Difference between replicate Gmm of dense-graded mixtures at various settings for Orbital device

The practical significance of the difference between the highest Gmm and those from the settings of specific importance was examined by comparing the calculated air void values. Figure 4-34 shows the computed air voids using the measured Gmm values. Bulk specific gravity values of 2.404 and 2.422 were assumed for calculating the air voids of 9.5-mm and 19.0-mm mixtures, respectively. Table 4-45 provides the difference between the air voids from the highest Gmm and those from manual agitation and 270 rpm (commonly used by the state laboratories). As shown in the table, for the 9.5-mm mixture, the difference between the air voids from the highest Gmm and that from manual agitation is 0.18 % and for the19-mm mixture, the difference is 0.27 %. Considering variability of the bulk specific gravity measurements, use of manual agitation might result in significantly lower air voids of the 19.0-mm compacted mixtures.

The difference between the air voids from the highest Gmm and those from 270 rpm is also provided in Table 4-45. As shown in the table the difference is 0.11 % for the 9.5-mm mixture and 0.16 % for the 19.0-mm mixture. This indicates that for 9.5-mm and 19.0-mm mixtures, 270 rpm would produce air voids that are not significantly different from the highest air void values.

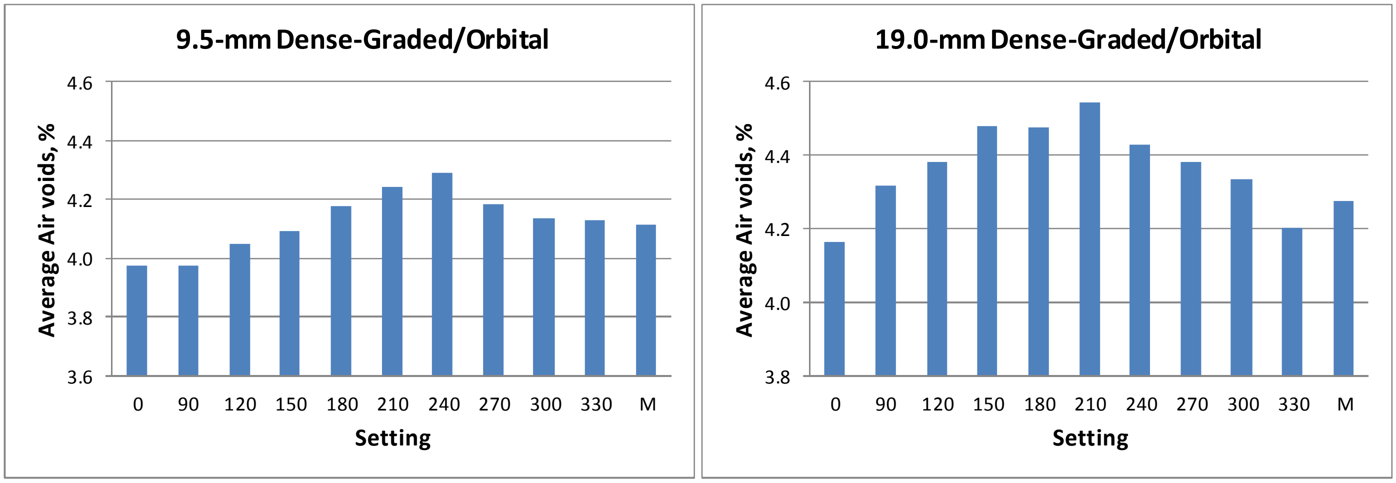

Figure 4-34- Air voids of dense-graded field mixtures at various settings of Orbital device

Table 4-45- Gmm values using Orbital shaker at settings of specific importance (setting of highest Gmm, manual agitation, 270 rpm) and the differences in air voids resulted from measurements at the various settings

Mixture Type	Setting of Maximum Gmm, rpm	Gmm, Highest	Gmm, Manual Agitation	Gmm, @ 270 rpm	Difference in Air Voids, Highest and Manual, %	Difference in Air Voids, Highest and @ 270 rpm, %	Difference in Air Voids, Setting 210 rpm and 240 rpm, %
9.5-mm	240	2.512	2.507	2.509	0.18	0.11	0.05
19.0-mm	210	2.537	2.530	2.533	0.27	0.16	0.11

The statistical significance of the difference between the Gmm from various settings of the Orbital device was evaluated using a Scheffe test. Table 4-46 and Table 4-47 provide the computed F values for comparison of all possible pairs of Gmm. As indicated from Table 4-46, the difference between the highest Gmm (Setting 240) and those of other settings, including manual agitation, are not significant. However, for the 19.0-mm mixture, the difference between the highest Gmm (Setting 210) and that from manual agitation is significant.

Table 4-46- Computed F values for comparison of Gmm of 9.5-mm dense-graded field mixture at various vibration settings of Orbital Shaker; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	90	120	150	180	210	240	270	300	330
90	0.000									
120	0.074	0.074								
150	0.198	0.198	0.030							
180	0.582	0.582	0.241	0.101						
210	1.054	1.054	0.569	0.339	0.070					
240	1.462	1.461	0.878	0.584	0.199	0.033				
270	0.624	0.624	0.268	0.119	0.001	0.056	0.176			
300	0.370	0.370	0.113	0.027	0.024	0.175	0.361	0.033		
330	0.348	0.348	0.101	0.021	0.030	0.191	0.383	0.040	0.000	
M	0.277	0.277	0.065	0.007	0.056	0.251	0.466	0.070	0.007	0.004

Table 4-47- Computed F values for comparison of Gmm of 19.0-mm dense-graded field mixture at various vibration settings of Orbital Shaker; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	90	120	150	180	210	240	270	300	330
90	1.389									
120	2.749	0.230								
150	5.728	1.476	0.540							
180	5.621	1.422	0.508	0.001						
210	8.264	2.877	1.480	0.232	0.254					
240	4.093	0.713	0.133	0.137	0.121	0.725				
270	2.704	0.217	0.000	0.561	0.528	1.514	0.144			
300	1.650	0.011	0.140	1.229	1.180	2.529	0.546	0.129		
330	0.094	0.760	1.827	4.355	4.261	6.596	2.947	1.790	0.957	
M	0.686	0.123	0.689	2.449	2.379	4.188	1.428	0.666	0.208	0.272

The possibility of selecting one setting of orbital shaker for both 9.5-mm and 19.0-mm mixtures were explored. As shown from Table 4-45, the differences between the air voids of Settings 210 rpm and 240 rpm are 0.05 % for the 9.5-mm and 0.11 % for the 19.0-mm mixtures, which are not considered significant. The results of statistical analysis in Table 4-46 and Table 4-47 also indicate that for both mixtures, the Gmm from Settings 210 and 240 are statistically the same. Therefore, either setting of 210 rpm or 240 rpm could be selected. Based on the slight level of cloudiness in the water at the setting of 240 rpm, it is recommended to use the higher setting of 240 rpm as the optimum setting of the orbital shaker for the dense-graded field mixtures.

4.2.4.2 SMA Field Mixtures

The three SMA mixtures of 9.5-mm, 12.5-mm, and 19.0-mm NMAS were tested with the orbital shaker. The measurements were conducted at 9 vibration intensity levels from 90 rpm through 330 rpm at 30 rpm intervals. The measurements were also conducted at zero and manual agitation. As shown in Figure 4-35, for the 9.5-mm mixture the highest Gmm of 2.649 was obtained at 270 rpm, for the 12.5-mm mixture the highest Gmm of 2.464 was obtained at 240 rpm, and for the 19.0-mm mixture the highest Gmm of 2.449 was obtained at 300 rpm for the Orbital shaker. For the three SMA mixtures, the manual agitation resulted in Gmm values that were equivalent to the values obtained in the range of 90 to 150 rpm. The visual observation of the water

indicated that the water remained clear through 150 rpm. From 180 rpm through 240 rpm water became slightly cloudy, and at 270 rpm and higher, the water became significantly cloudy.

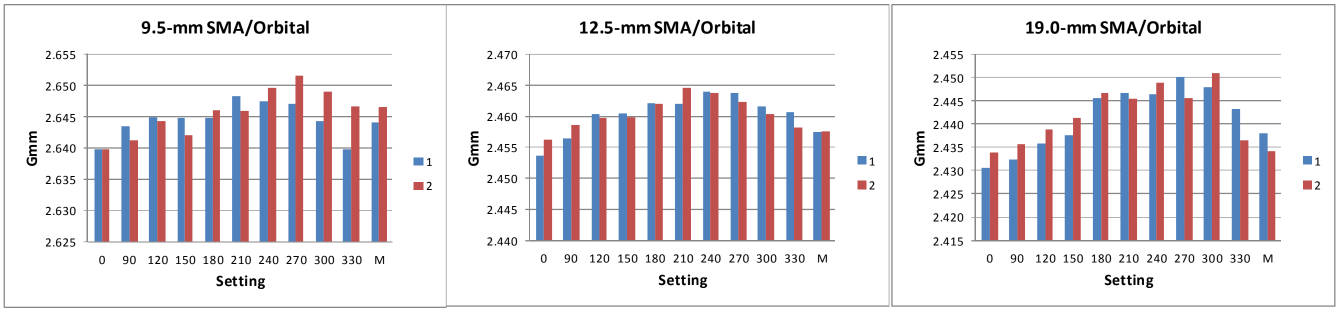

Figure 4-35-Gmm of SMA Mixtures at various settings of the Orbital device

The differences between the two replicate Gmm values at various settings of the orbital shaker in Figure 4-36 show that there is no defined trend between the variability of measurement and the intensity of vibration. Figure 4-36 also shows that the difference between replicates at any setting is smaller than 0.007, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

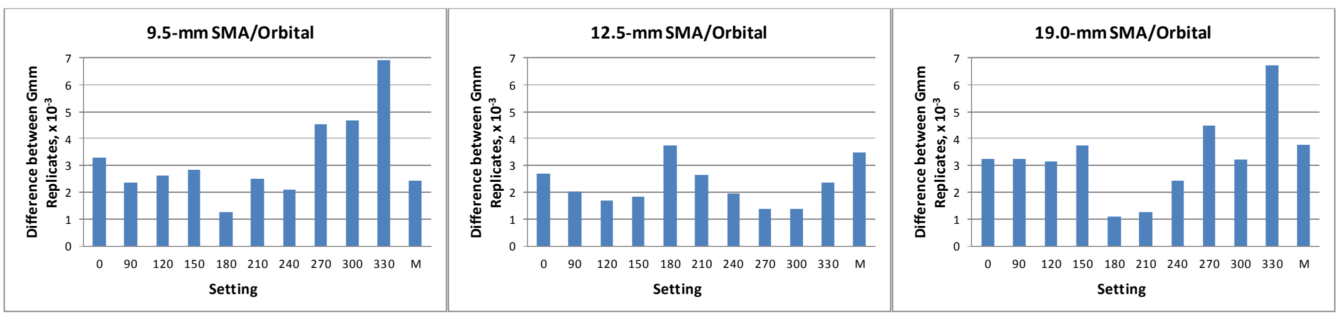

Figure 4-36-Difference between replicate Gmm of SMA Mixtures at various settings of the Orbital device

The practical significance of the difference between the highest Gmm and those from the settings of specific importance was examined by comparing the calculated air voids. The air void values from various settings of the orbital shaker are shown in Figure 4-37. The bulk specific gravity values of 2.532, 2.357, and 2.339 were assumed for calculating the air voids of 9.5-mm, 12.5-mm, and 19.0-mm mixtures, respectively. The differences in air voids resulted from settings of the most importance is provided in Table 4-48. As shown in the table, the difference between the air voids from the highest Gmm and that from manual agitation is 0.17%, 0.24%, and 0.53% for the 9.5-mm, 12.5-mm, and 19.0 mm mixtures, respectively. Considering other sources of variability in measuring air voids, using manual agitation would most probably provide significantly lower air voids than the actual air voids for the 12.5-mm and 19.0-mm mixtures.

Table 4-48 also provides the differences between the air voids resulted from the highest Gmm and those from Setting 270, which is commonly used by the states. As shown in the table, for the 19.0-mm mixture, the difference between air voids from highest Gmm and from Gmm of Setting 270 is 0.03% and for the 12.5-mm mixture, the difference is 0.07%. These differences in air voids are not practically significant.

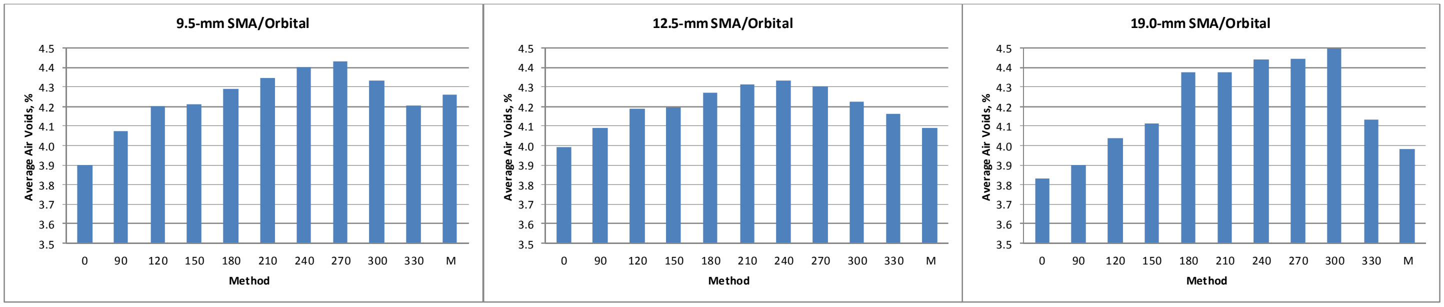

Figure 4-37- Air voids of SMA Mixtures at various settings of the Orbital device

Table 4-48- Gmm values using Orbital shaker at the settings of specific importance (manual agitation, 270 rpm, settings of highest Gmm) and the difference in air voids resulted from various Gmm measurements

Mixture Type	Setting of Maximum Gmm, rpm	Gmm, Highest	Gmm, Manual Agitation	Gmm, 270 rpm	Difference in Air Voids, Highest and Manual (%)	Difference in Air Voids, Highest and 270 rpm (%)
9.5-mm	270	2.649	2.645	2.649	0.17	0.00
12.5-mm	240	2.464	2.458	2.463	0.24	0.03
19.0-mm	300	2.449	2.436	2.448	0.53	0.07

The significance of the differences between Gmm values from various settings of the orbital shaker was also examined statistically. Table 4-49 through Table 4-51 provides the computed F values from a Scheffe test. As indicated from the tables, for the 9.5-mm mixture, the difference between Gmm of any pair of settings is not significant. For the 19.0-mm mixture, the difference between the highest Gmm from Setting 300 is only different from those of zero agitation and Setting 90 rpm. However, for the 12.5-mm mixtures, the highest Gmm of Setting 240 rpm is significantly different from those of zero agitation, Setting 90, and manual agitation. In summary, based on the differences between the air voids, manual agitation is not recommended for 12.5-mm and 19.0-mm SMA mixtures and based on statistical analysis manual agitation is not recommended for 12.5-mm mixture.

Table 4-49- Computed F values for comparison of Gmm of 9.5-mm SMA field mixture at various vibration settings of Orbital device; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	90	120	150	180	210	240	270	300	330
90	0.120									
120	0.418	0.091								
150	0.243	0.022	0.024							
180	0.595	0.181	0.015	0.077						
210	0.982	0.416	0.119	0.248	0.048					
240	1.399	0.701	0.288	0.476	0.170	0.037				
270	1.660	0.889	0.412	0.633	0.268	0.089	0.011			
300	0.861	0.339	0.079	0.189	0.025	0.004	0.065	0.130		
330	0.216	0.014	0.033	0.001	0.094	0.277	0.516	0.678	0.215	
M	0.550	0.157	0.009	0.062	0.001	0.062	0.195	0.299	0.035	0.077

Table 4-50- Computed F values for comparison of Gmm of 12.5-mm SMA field mixture at various vibration settings of Orbital device; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	90	120	150	180	210	240	270	300	330
90	0.477									
120	1.975	0.511								
150	2.126	0.588	0.003							
180	3.900	1.648	0.324	0.267						
210	5.343	2.626	0.821	0.728	0.113					
240	6.017	3.105	1.097	0.990	0.229	0.020				
270	5.026	2.405	0.700	0.615	0.071	0.005	0.045			
300	2.784	0.956	0.069	0.044	0.094	0.413	0.615	0.329		
330	1.527	0.297	0.029	0.049	0.546	1.157	1.481	1.012	0.187	
M	0.502	0.000	0.486	0.562	1.604	2.570	3.044	2.352	0.922	0.278

Table 4-51- Computed F values for comparison of Gmm of 19.0-mm SMA field mixture at various vibration settings of Orbital device; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	90	120	150	180	210	240	270	300	330
90	0.047									
120	0.402	0.173								
150	0.790	0.451	0.065							
180	2.937	2.239	1.166	0.681						
210	2.937	2.239	1.166	0.681	0.000					
240	3.649	2.866	1.629	1.044	0.039	0.039				
270	3.714	2.923	1.673	1.078	0.046	0.046	0.000			
300	4.569	3.686	2.261	1.560	0.180	0.180	0.052	0.044		
330	0.884	0.523	0.094	0.003	0.598	0.598	0.941	0.974	1.433	
M	0.218	0.062	0.028	0.178	1.554	1.554	2.083	2.132	2.790	0.224

Since water was significantly cloudy at Setting 270 and above, the possibility of using Setting 240 for the three SMA mixtures was explored. Table 4-52 provides the differences between the air voids from Setting 240 rpm and those of Settings 270 rpm and 300 rpm. As indicated from the table, the differences are 0.00% for the 9.5-mm mixture and 0.01% for the 19.0-mm mixture, which are not practically significant. This is also confirmed by the results of statistical analysis in Table 4-49 through Table 4-51, where for the 9.5-mm and 19.0-mm mixtures, the F values from comparison of Gmm of Setting 240 with those of Settings 270 and 300, are smaller than the critical F values. Therefore, the setting of 240 rpm can be operated for the SMA mixtures without a significant decrease in Gmm.

Table 4-52- Gmm of the SMA field mixtures using Orbital shaker at the settings of highest Gmm and the differences between the air voids resulted from those settings

Mixture Type	Setting of Maximum Gmm	Gmm, Setting 240	Gmm, Setting 270	Gmm, Setting 300	Difference in Air Voids, Highest and Setting 240, %
9.5-mm	270	2.649	2.649	2.647	0.00
12.5-mm	240	2.464	2.464	2.461	0.00
19.0-mm	300	2.448	2.448	2.449	0.01

4.2.4.3 Dense-Graded Laboratory Mixtures

Three out of four dense-graded laboratory mixtures were tested using the orbital shaker. The Gmm of the 4.75-mm, 12.5-mm, and 25.0-mm dense-graded laboratory mixtures were measured at 9 vibration intensity levels in the range of 90 rpm through 330 rpm, at 30 rpm intervals. The measurements were also conducted at zero and manual agitations. As shown in Figure 4-38, for the 4.75-mm, 12.5-mm, and 25.0-mm mixtures, the highest Gmm of 2.556, 2.580, and 2.616 were obtained at the 270, 240, and 300 rpm settings of the Orbital shaker, respectively. The visual observation of the water indicated that the water remained clear through 150 rpm setting. From 180 rpm through 240 rpm, the water became slightly cloudy, and at 270 rpm and above, the water became significantly cloudy.

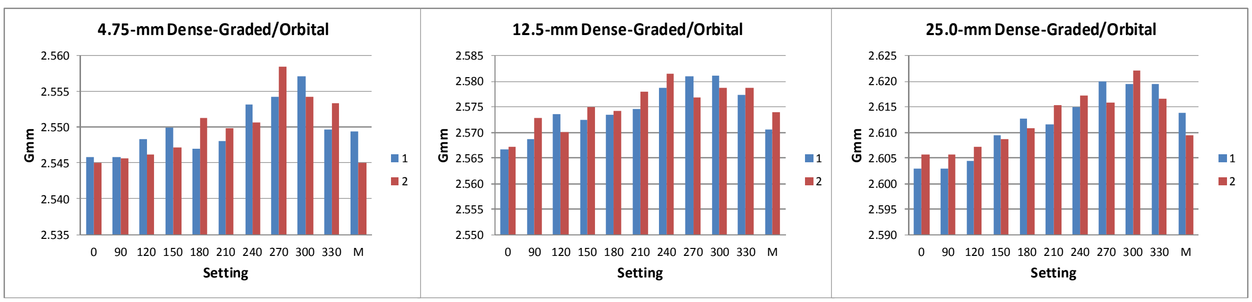

Figure 4-38- Gmm of dense-graded laboratory-prepared mixtures at various settings of the Orbital device

The differences between the two replicate Gmm values at various settings of orbital shaker are shown in Figure 4-39. As indicated from the figures, there is no defined trend between the variability of measurements and the intensity of vibration. Also indicated from the figure, the difference between replicate measurements at any setting is smaller than 0.005, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

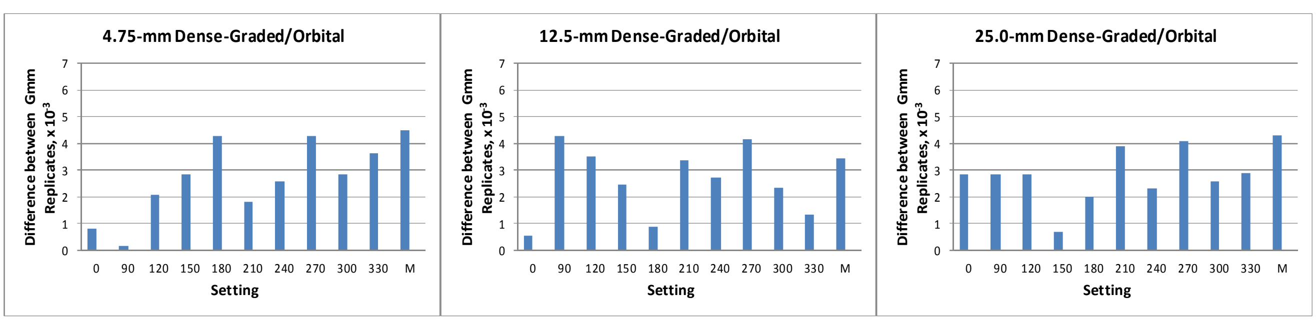

Figure 4-39- Difference between Gmm replicates of laboratory-prepared mixtures at various settings of the Orbital device

The practical significance of the difference between the highest Gmm and those from the settings of specific importance was examined by comparing the calculated air voids. Figure 4-40 provides the air voids calculated from the Gmm values at various settings of the orbital shaker. The bulk specific gravity values of 2.444, 2.466, and 2.502 were assumed for calculating the air voids of the 4.75-mm, 12.5-mm, and 25.0-mm mixtures, respectively. The differences between the air voids from the highest Gmm and those from manual agitation and 270 rpm, which is commonly used by the states, are provided in Table 4-53. As shown in the table, the differences between the air voids from manual and highest Gmm are in the range of 0.28% to 0.34%. This would indicate that manual agitation of the orbital shaker flasks could result in significantly lower air voids than the actual air voids of the compacted mixtures. Also shown in Table 4-53, the differences between the air voids from the highest Gmm and the Gmm of 270 rpm are 0.04% and 0.10% for the 12.5-mm and 25.0-mm mixture, respectively. These differences are not considered practically significant.

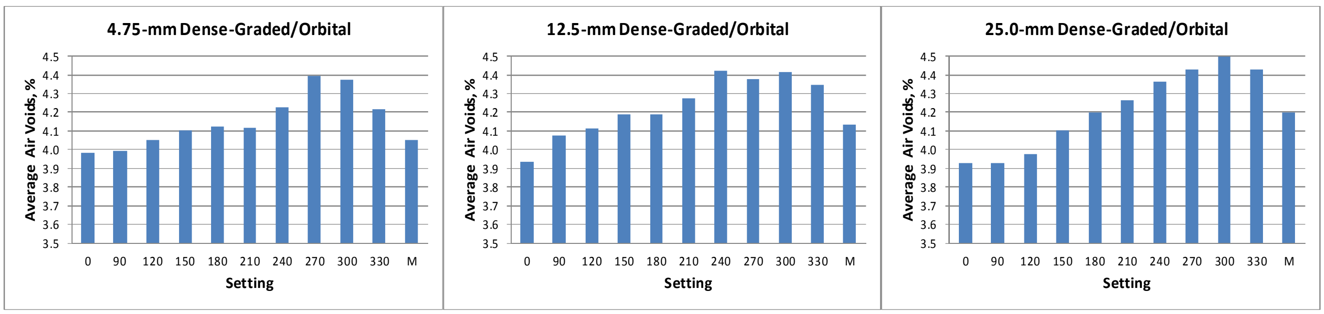

Figure 4-40- Air voids of the laboratory-prepared mixtures at various settings for the Orbital device

Table 4-53- Gmm values using Orbital shaker at settings of specific importance (setting of highest Gmm, manual agitation, 240 rpm, 270 rpm) and the difference in air voids resulted from various Gmm measurements

Mixture Type	Setting of Highest Gmm	Gmm, Highest	Gmm, manual	Gmm, @ 270 rpm	Difference in Air Voids between Highest and Manual, %	Difference in Air Voids between Highest and Setting 270, %	Difference in Air Voids between Highest and Setting 240, %
4.75-mm	270	2.556	2.547	2.556	0.34	0.00	0.17
12.5-mm	240	2.580	2.572	2.572	0.28	0.04	0.00
25.0-mm	300	2.621	2.612	2.618	0.33	0.10	0.17

The differences between the Gmm of the dense-graded laboratory mixtures from various settings of orbital shaker were also examined statistically. The computed F values from a Scheffe test are provided in Table 4-54 through Table 4-56. As shown in the tables, for the 4.75-mm mixture, the highest Gmm from Setting 270 rpm is statistically the same as the Gmm from every other setting. For the 12.5-mm mixture, the highest Gmm from Settings 240 rpm is only different from the Gmm of zero agitation. For the 25.0-mm mixture, the highest Gmm from Setting 300 rpm is significantly different from those of zero through 150 rpm. For none of the three mixtures, the manual agitation produced significantly different Gmm from the mechanical settings. This disagrees with the decision from practical point of view on the significance of the difference between mechanical and manual agitation.

Table 4-54- Computed F values for comparison of Gmm of 4.75-mm dense-graded laboratory mixture at various vibration settings of Orbital device; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	90	120	150	180	210	240	270	300	330
90	0.002									
120	0.082	0.057								
150	0.229	0.186	0.037							
180	0.314	0.263	0.075	0.007						
210	0.284	0.235	0.061	0.003	0.001					
240	0.939	0.849	0.467	0.241	0.167	0.190				
270	2.662	2.509	1.811	1.330	1.148	1.208	0.439			
300	2.345	2.202	1.552	1.109	0.943	0.997	0.316	0.010		
330	0.837	0.753	0.396	0.191	0.126	0.146	0.003	0.513	0.380	
M	0.075	0.051	0.000	0.042	0.082	0.067	0.483	1.843	1.581	0.411

Table 4-55- Computed F values for comparison of Gmm of 12.5-mm dense-graded laboratory mixture at various vibration settings of Orbital device; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	90	120	150	180	210	240	270	300	330
90	0.360									
120	0.560	0.022								
150	1.120	0.210	0.096							
180	1.131	0.214	0.099	0.000						
210	2.037	0.684	0.461	0.136	0.132					
240	4.149	2.064	1.661	0.958	0.948	0.372				
270	3.434	1.570	1.221	0.632	0.624	0.182	0.034			
300	4.030	1.981	1.586	0.901	0.892	0.337	0.001	0.024		
330	2.908	1.221	0.916	0.419	0.412	0.077	0.110	0.022	0.091	
M	0.693	0.054	0.007	0.051	0.053	0.353	1.450	1.041	1.380	0.761

Table 4-56- Computed F values for comparison of Gmm of 25.0-mm dense-graded laboratory mixture at various vibration settings of Orbital device; Critical F value=2.854 and DOF= (10, 11) for 5% level of significance

Setting	0	90	120	150	180	210	240	270	300	330
90	0.000									
120	0.040	0.040								
150	0.492	0.492	0.251							
180	1.217	1.217	0.815	0.162						
210	1.843	1.843	1.340	0.431	0.065					
240	3.064	3.064	2.403	1.101	0.419	0.154				
270	4.089	4.089	3.320	1.745	0.845	0.442	0.074			
300	6.019	6.019	5.077	3.070	1.823	1.200	0.494	0.186		
330	4.137	4.137	3.363	1.777	0.867	0.457	0.081	0.000	0.176	
M	1.200	1.200	0.802	0.156	0.000	0.069	0.429	0.858	1.843	0.881

Since water was significantly cloudy at settings of 270 and above, the possibility of using Setting 240 for the dense-graded laboratory mixtures were explored. Table 4-53 provides the difference between air voids from the highest Gmm and the Gmm at 240 rpm. As shown in the table, the difference in air voids is 0.17% for both the 4.75-mm and 25.0-mm mixtures. These differences are considered not significant. The results of the statistical analysis in Table 4-54 through Table 4-56 also confirms that there is no significant difference between the Gmm from Setting 240 and those from Setting 210 and 300 rpm for the 4.75-mm and 25.0-mm mixture respectively. Based on the above observation, the setting of 240 rpm is recommended as the optimum setting of the orbital shaker for the dense-graded laboratory mixtures.

4.2.5 Selecting Optimum Settings of Devices

In the previous sections, the optimum settings of the devices for each of the three categories of mixture types were selected. A summary of the settings that resulted in the highest Gmm and the recommended settings for each mixture type is provided Table 4-57. The recommended settings were selected based on the evaluation of change in air voids, statistical significance of change in Gmm, and significant change in water clarity. Here the possibility of choosing one setting of each device for all mixture types is explored.

As shown in Table 4-57, for the Humboldt device, the highest Gmm of the nine mixtures were produced at a range of Settings 7 to Setting 10. However, based on the concern with water clarity at Settings 8 and 9, Setting 7 was recommended for the dense-graded field mixtures and Setting 8 was recommended for the SMA and dense-graded laboratory mixtures. The possibility of using Setting 7 of Humboldt device for all mixture types is evaluated by examining the computed F values from comparison of Gmm from setting 7 and 8. As indicated from the tables of computed F values in Section 4.2.1, the difference between Gmm from Setting 7 and 8 is not significant for any of the mixtures. Therefore, the recommended setting for Humboldt device is Setting 7.

For the Gilson device, Table 4-57 shows that Settings 6 and 7 provided the highest Gmm of the mixtures. However, based on the increased cloudiness of the water at Settings 6 through 8, Settings 5, 6, and 7 were recommended for dense-graded laboratory, dense-graded field, and SMA mixtures, respectively. To explore if Setting 5 can be recommended for all three mixture categories, the results of statistical Scheffe test for comparison of the Gmm values from Settings 5, 6, and 7 were examined. The tables of computed F values in Section 4.2.2 indicate that the computed F-values for comparison of Gmm from Settings 5, 6, and 7 are all smaller than the critical F values. Therefore, Setting 5 of Gilson can be recommended for all mixture types.

For the Syntron device, Table 4-57 indicates that Settings 7, 8, and 9 provided the highest Gmm of the three mixture types. However, based on the significant water cloudiness at Settings 8 and 9, Settings 7 was recommended for dense-graded field and laboratory mixtures and Setting 8 was recommended for the SMA mixtures. To explore the possibility of using Setting 7 for all mixture types, the computed F-values for the comparison of Gmm from Setting 7 and 8 were examined. The table of computed F-values in Section 4.2.3 indicates that the differences between Gmm from Setting 7 and 8 are not significant for any of the mixtures. Therefore, Setting 7 of Syntron is recommended for measuring Gmm of any mixture type.

For the Orbital device, Table 4-57 indicates that the highest Gmm of the mixtures were obtained at the settings in a range of 210 rpm to 300 rpm. However based on the significant level of water cloudiness at Setting 270 rpm and above, Setting 240 was selected for each mixture category.

Table 4-58 provides a summary of the recommended settings for the four devices that have adjustable settings. The table also provides the vibration properties of the vibrating devices at the recommended settings. The manufactures of the devices can adjust the vibration settings of their devices to the recommended settings

to minimize the between-laboratory variability that could result from the differences in vibration intensity of the Gmm measuring devices.

Table 4-57 Summary of the Settings of the highest Gmm of the vibrating devices with variable settings

Devices	Mixtures								
	Plant-Produced Dense-Graded		Plant-Produced Gap-Graded			Laboratory-Produced Dense-Graded			
	9.5-mm Percent Passing (%)	19.0-mm Percent Passing (%)	9.5-mm Percent Passing (%)	12.5-mm Percent Passing (%)	19.0-mm Percent Passing (%)	4.75-mm Percent Passing (%)	12.0-mm Percent Passing (%)	25.0-mm Percent Passing (%)	37.5-mm Percent Passing (%)
Humboldt	8	7	8	8	9	10	8	9	9
Suggested for Humboldt	7 (Cloudy at 8)		8 (Cloudy at 9)			8 (No significant cloudiness)			
Gilson	6	7	7	7	7	7	6	-	6
Suggested for Gilson	6 (Cloudy at 7)		7 (Cloudy at 8)			5 (Cloudy at 8, 7, 6, respectively)			
Syntron	7	7	8	7	9	8	8	-	-
Suggested for Syntron	7 (Cloudy at 9)		8 (Cloudy at 9)			7 (Cloudy at 8)			
Orbital	240	210	270	240	300	270	240	300	-
Suggested for Orbital	240 (Cloudy at 270)		240 (Cloudy at 270)			240 (Cloudy at 270)			

Table 4-58- The suggested settings and the vibration properties at the suggested settings of the four vibrating devices with variable settings

Device Type	Optimum Setting	Frequency, Hz			Acceleration, m/s^2			Energy, microJoules			
		x	y	z	x	y	z	x	y	z	Total
Humboldt	7	48.7	48.7	48.7	3.79	1.35	4.68	14.3	1.7	24.9	40.9
Gilson	5	44.3	44.3	44.3	3.95	2.71	6.05	16.1	7.5	38.8	62.4
Syntron	7	83.8	91.4	612.2	19.13	21.67	72.32	217	268	2899	3384
Orbital	240 rpm	-	-	-	-	-	-	-	-	-	-

4.3 Comparison of Devices and Methods

The Gmm measuring devices/ methods are compared in terms of the highest measured Gmm and based on the variability of measurements. The highest Gmm of the mixtures from the devices/methods are compared statistically and from practical point of view. The variability of each device is represented by the pooled standard deviations of the Gmm measurements from various settings of the device. The variability of manual agitation is represented by the pooled standard deviations from manual agitations using different setups. The results of comparison are discussed as follows:

4.3.1.1 Dense-Graded Field Mixtures

Figure 4-41 shows the Gmm of the two dense-graded field mixtures measured using the eight devices/methods. For the 9.5-mm mixture, the largest difference between Gmm from mechanical devices is 0.003, which is between the Gmm of Orbital and Gilson. This difference corresponds to 0.13% difference in air voids. For the 19.0-mm dense graded field mixture, the largest difference of 0.006 is between the Gmm of

Corelok and Orbital. This difference in Gmm corresponds to 0.24% difference in air voids. Considering the variability due to bulk specific gravity measurements, the difference between air voids of 19.0-mm mixture using Corelok and Orbital might become significant.

Figure 4-41 also shows the comparison of Gmm of mechanical devices and manual agitation. As shown in the figure, for both mixtures the manual agitation provides the lowest Gmm of the mixtures. For the 9.5-mm mixture, the largest difference of 0.008 is with the Gmm of Gilson, which corresponds to 0.29% difference in air voids. For the 19.0-mm dense graded field mixture, the largest difference of 0.010 is with the Gmm of Orbital, which corresponds to 0.38% difference in air voids. Considering the variability due to bulk specific gravity measurements, the differences between air voids of mechanical devices and manual agitation could become significant.

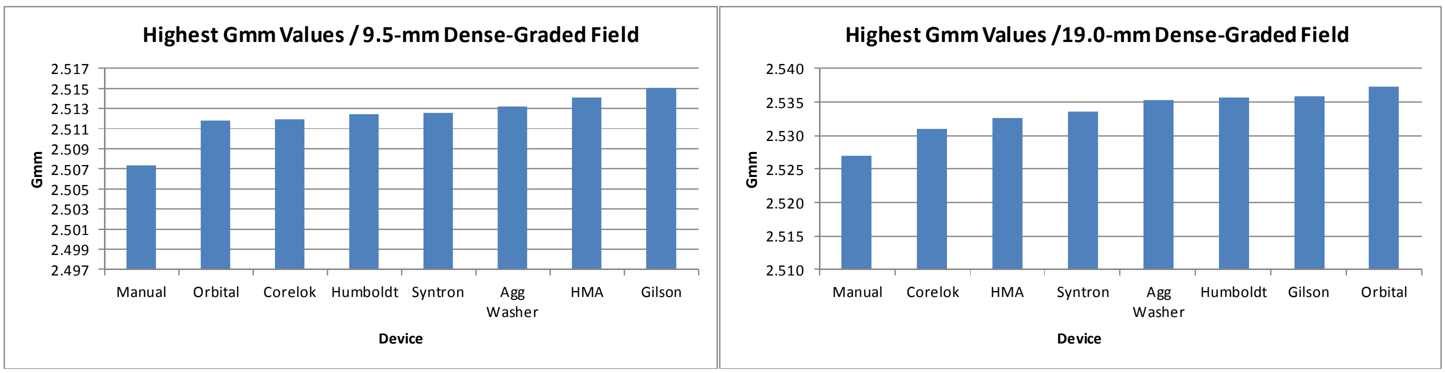

Figure 4-41- Ranked highest Gmm of dense-graded field mixtures from various devices/methods

Table 4-59 and Table 4-60 provide the F values from the Scheffe test for comparison of the highest Gmm of the 9.5-mm and 19.0-mm dense-graded field mixtures using the eight devices/methods. As indicated from the tables, the differences between Gmm values from various mechanical devices are not statistically significant. However, the shaded cells indicate that the differences between Gmm from manual agitation and mechanical devices are significant in five out of seven comparisons for the 9.5-mm mixture and in one out of seven comparisons for the 19.0-mm mixture. Therefore, based on the comparison of the air voids and the results of statistical analysis, it might be concluded that mechanical devices produce the same Gmm if they are operated at their optimum settings; however, manual agitation produce statistically lower Gmm than the mechanical devices.

Table 4-59- Computed F values for comparison of the highest Gmm of 9.5-mm dense-graded field mixture by various devices/methods; Critical F value=3.500 for 5% Level of significance and DOF of (7, 8)

Device	Aggregate Washer	Corelok	Gilson	HMA	Humboldt	Orbital	Syntron
Corelok	0.250						
Gilson	0.520	1.490					
HMA	0.124	0.725	0.136				
Humboldt	0.092	0.038	1.050	0.430			
Orbital	0.298	0.002	1.605	0.806	0.059		
Syntron	0.057	0.068	0.921	0.349	0.004	0.094	
Manual	4.947	2.973	8.673	6.635	3.687	2.816	3.942

Table 4-60- Computed F values for comparison of highest Gmm of 19.0-mm dense-graded field mixture by various devices/methods; Critical F value=3.500 for 5% Level of significance and DOF of (7, 8)

Device	Agg. Washer	Corelok	Gilson	HMA	Humboldt	Orbital	Syntron
Corelok	0.694						
Gilson	0.014	0.907					
HMA	0.242	0.117	0.373				
Humboldt	0.011	0.881	0.000	0.357			
Orbital	0.174	1.561	0.088	0.825	0.097		
Syntron	0.097	0.273	0.185	0.033	0.173	0.529	
Manual	2.649	0.631	3.052	1.291	3.004	4.179	1.734

Figure 4-42 shows the standard deviation of the Gmm measurements of the 9.5-mm and 19.0-mm dense-graded field mixtures using the eight devices/methods. As indicated from the figure, for the 9.5-mm and 19.0-mm mixtures, the highest Gmm standard deviations of the devices are 0.002 and 0.003, which are even smaller than the acceptable 1s repeatability standard deviation for single-operator test condition described in AASHTO T209. The manual agitation provided either equivalent or smaller standard deviations than the majority of the devices. As also indicated from Figure 4-42, among the two mixtures, none of the devices/ methods is consistently more variable than the others.

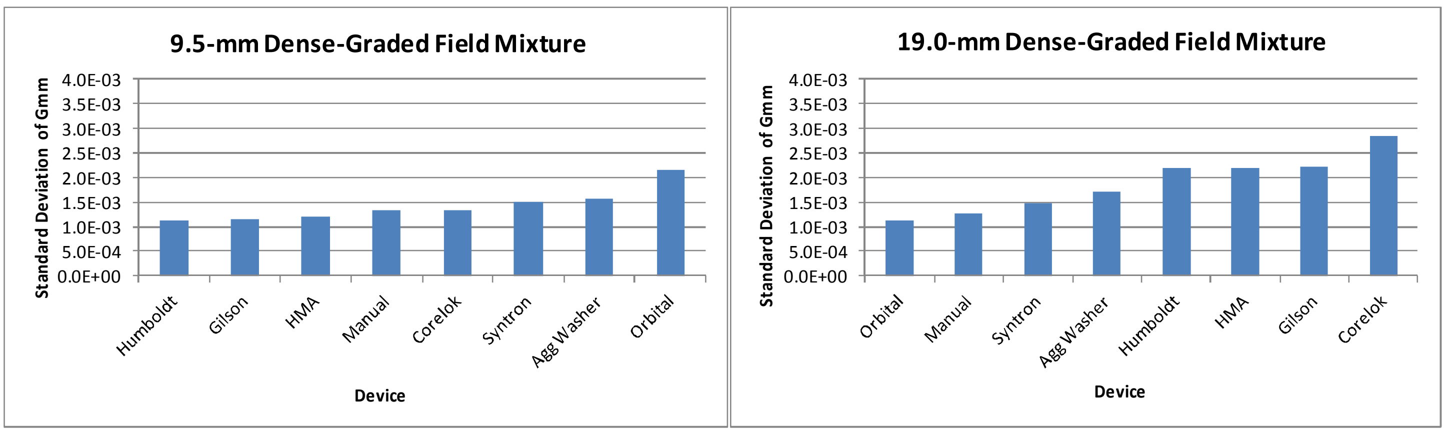

Figure 4-42- Ranked standard deviations of Gmm of dense-graded field mixtures from various devices/methods

4.3.1.2 SMA Field Mixtures

Figure 4-43 shows the ranked highest Gmm values of the three SMA mixtures measured using the eight methods/devices. For the 9.5-mm, 12.5-mm, and 19.0-mm SMA mixtures, the largest differences between the highest Gmm values of various mechanical devices are 0.005, 0.003, and 0.003, respectively. These differences correspond to differences of 0.17%, 0.10%, and 0.12% between the air voids, which are not considered practically significant.

Figure 4-43 also shows the comparison of Gmm from mechanical and manual agitation. As shown in the figure, the manual agitation provides the lowest Gmm of the mixtures. For the 9.5-mm mixture, the largest difference is 0.007, which corresponds to 0.26% difference in air voids. For the 12.5-mm SMA mixture, the largest difference of 0.008 corresponds to 0.27% difference in air voids. For the 19.0-mm SMA mixture, the largest difference of 0.011 corresponds to 0.43% difference in air voids. Considering the variability due to bulk specific gravity measurements, the differences between Gmm of manual and mechanical agitations could become practically significant.

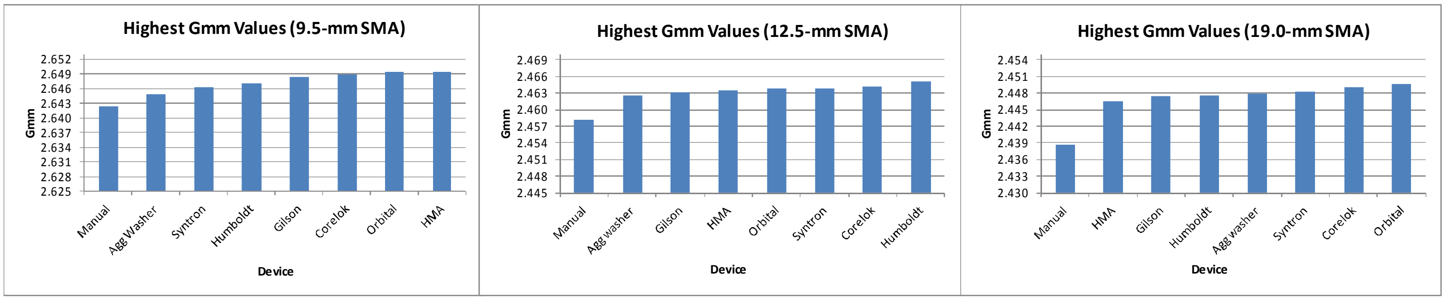

Figure 4-43- Ranked Highest Gmm of SMA mixtures from various devices

Table 4-61 through Table 4-63 provide the F values from the Scheffe test for comparison of the highest Gmm of the 9.5-mm, 12.5-mm, and 19.0-mm SMA mixtures using the eight devices/methods. As indicated from the tables, the computed F-values for comparison of the Gmm of mechanical devices are all smaller than the critical F-value of 3.500 for 5% level of significance; therefore, the differences between Gmm from various devices are not statistically significant. The comparison of the manual agitation and mechanical devices indicates that the differences between manual and mechanical Gmm are also not significant. Although the statistical results do not support the significance of the difference between the air voids from manual and mechanical methods, the use of manual agitation is not recommended for measuring the Gmm of SMA mixtures.

Table 4-61- Computed F values for comparison of highest Gmm of 9.5-mm dense-graded field mixture by various devices; Critical F value=3.500 and DOF = (7, 8) for 5% Level of significance

Device	Aggregate Washer	Corelok	Gilson	HMA	Humboldt	Orbital	Syntron
Corelok	0.873						
Gilson	0.615	0.023					
HMA	1.050	0.008	0.058				
Humboldt	0.267	0.175	0.072	0.259			
Orbital	1.005	0.005	0.048	0.001	0.236		
Syntron	0.101	0.381	0.218	0.501	0.040	0.469	
Manual	0.287	2.160	1.742	2.434	1.106	2.365	0.727

Table 4-62- Computed F values for comparison of highest Gmm of 12.5-mm SMA mixture by various devices; Critical F value=3.500 and DOF= (7, 8) for 5% Level of significance

Device	Aggregate washer	Corelok	Gilson	HMA	Humboldt	Orbital	Syntron
Corelok	0.184						
Gilson	0.017	0.089					
HMA	0.069	0.028	0.017				
Humboldt	0.489	0.073	0.323	0.190			
Orbital	0.115	0.008	0.043	0.006	0.130		
Syntron	0.118	0.007	0.045	0.006	0.127	0.000	
Manual	1.342	2.520	1.663	2.021	3.452	2.241	2.254

Table 4-63- Computed F values for comparison of highest Gmm of 19.0-mm SMA mixture by various devices; Critical F value=3.500 for 5% Level of significance and DOF of (7, 8)

Device	Aggregate washer	Corelok	Gilson	HMA	Humboldt	Orbital	Syntron
Corelok	0.025						
Gilson	0.011	0.068					
HMA	0.054	0.151	0.016				
Humboldt	0.004	0.047	0.002	0.029			
Orbital	0.054	0.006	0.114	0.216	0.086		
Syntron	0.001	0.015	0.020	0.072	0.009	0.039	
Manual	2.157	2.643	1.862	1.530	1.984	2.895	2.265

Figure 4-44 shows the standard deviations of the Gmm measurements of the SMA mixtures using the eight devices/methods. As indicated from the figure, the aggregate washer and Gilson provided the lowest standard deviations for two out of three SMA mixtures and Corelok provided the largest standard deviations of the three SMA mixtures. Nevertheless, the standard deviations from Corelok were all less than 0.003, which is even smaller than the acceptable 1s repeatability standard deviation for single-operator test condition described in AASHTO T209. The standard deviations from manual agitation were in the middle of the range of standard deviations from mechanical devices.

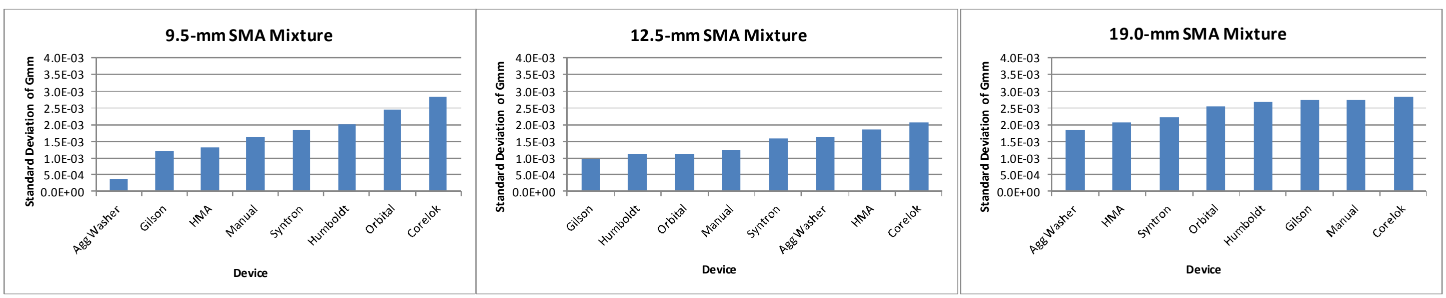

Figure 4-44- Ranked standard deviation of Gmm of SMA mixtures from various devices/methods

4.3.1.3 Dense-Graded Laboratory Mixtures

Figure 4-45 shows the Gmm of the four dense-graded laboratory mixtures. The Gmm of 4.75-mm and 12.5-mm mixtures were measured using all seven devices and the Gmm of 25.0-mm and 37.5-mm mixtures were each measured using five devices. The largest difference between the highest Gmm produced by the devices for 4.75-mm, 12.5-mm, 25.0-mm, and 37.5-mm mixture is 0.005, 0.006, 0.008, and 0.005 respectively. These differences translate into 0.18%, 0.23%, 0.30%, and 0.20% differences in air voids. While the Gmm of the 4.75-mm and 37.5-mm mixtures from various devices are not considered different, for the 12.5-mm and 25.0-mm mixtures, the difference between the Gmm of at least two devices could become practically significant.

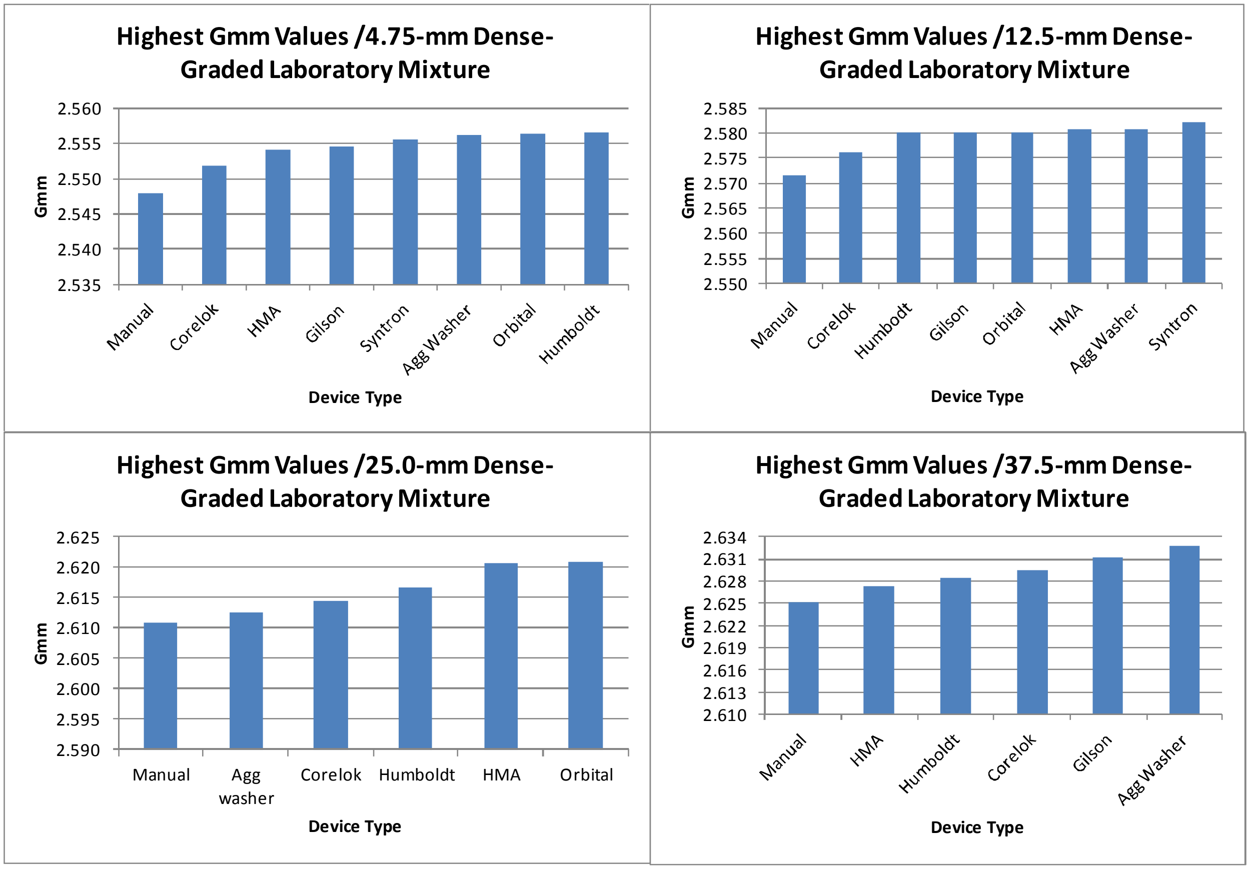

Figure 4-45- Ranked highest Gmm of the dense-graded laboratory mixtures using various devices

Table 4-64 through Table 4-67 provide the computed F-values from the Scheffe test for statistical comparison of the highest Gmm of the four dense-graded laboratory mixtures produced by various devices/methods. As indicated from the tables, the computed F-values for comparison of mechanical devices are all smaller than the critical F-values; therefore, it might be concluded that if the Gmm measuring devices operate at their optimum setting they would provide the same Gmm values.

Table 4-64 through Table 4-67 also provide the F-values for the comparison of the Gmm using mechanical devices with the Gmm from manual agitation. For the 4.75-mm and 12.5-mm mixtures, the computed F-values are all smaller than the critical F-values; therefore, the differences between Gmm of various mechanical devices with the Gmm from manual agitation are not statistically significant. However, for the 25.0-mm mixture, the difference between the Gmm from manual agitation is significantly different from Gmm using HMA and orbital devices and for the 37.5 –mm mixture the difference between the Gmm from manual agitation is significantly different from Gmm from Aggregate Washer. Based on practical significance of the difference between air voids and statistical significance of the differences between Gmm of manual agitation and Gmm of several mechanical devices, the use of manual agitation is not recommended for measuring the Gmm of dense-graded laboratory mixtures.

Table 4-64- Computed F values for comparison of highest Gmm of 4.75-mm SMA mixture by various devices; Critical F value=3.500 and DOF= (7, 8) for 5% Level of significance

Device	Aggregate Washer	Corelok	Gilson	HMA	Humboldt	Orbital	Syntron
Corelok	0.497						
Gilson	0.068	0.198					
HMA	0.127	0.121	0.009				
Humboldt	0.004	0.595	0.107	0.179			
Orbital	0.001	0.548	0.087	0.153	0.001		
Syntron	0.008	0.377	0.029	0.071	0.025	0.016	
Manual	1.848	0.428	1.208	1.005	2.033	1.944	1.610

Table 4-65- Computed F values for comparison of highest Gmm of 12.5-mm SMA mixture by various devices; Critical F value=3.500 and DOF= (7, 8) for 5% Level of significance

Device	Aggregate Washer	Corelok	Gilson	HMA	Humbodt	Orbital	Syntron
Corelok	0.672						
Gilson	0.017	0.478					
HMA	0.000	0.671	0.016				
Humboldt	0.018	0.472	0.000	0.018			
Orbital	0.015	0.486	0.000	0.015	0.000		
Syntron	0.057	1.120	0.135	0.057	0.138	0.130	
Manual	2.524	0.591	2.132	2.522	2.119	2.150	3.338

Table 4-66- Computed F values for comparison of highest Gmm of 25.0-mm SMA mixture by various devices; Critical F value=4.387 and DOF= (5, 6) for 5% Level of significance

Device	Aggregate washer	Corelok	HMA	Humboldt	Orbital
Corelok	0.234				
HMA	3.738	2.103			
Humboldt	0.988	0.261	0.882		
Orbital	3.898	2.223	0.002	0.961	
Manual	0.140	0.736	5.327	1.873	5.518

Table 4-67- Computed F values for comparison of highest Gmm of 37.5-mm SMA mixture by various devices; Critical F value=4.387 and DOF = (5, 6) for 5% Level of significance

Device	Aggregate Washer	Corelok	Gilson	HMA	Humboldt
Corelok	0.963				
Gilson	0.203	0.281			
HMA	2.420	0.330	1.221		
Humboldt	1.474	0.054	0.583	0.117	
Manual	4.892	1.514	3.101	0.431	0.995

Figure 4-46 shows the standard deviations of the Gmm measurements of the dense-graded laboratory mixtures using various devices/methods. As indicated from the figure, the largest standard deviations from the devices is less than 0.004, which is even smaller than the acceptable 1s repeatability standard deviation for single-operator test condition described in AASHTO T209. Also shown from the figure, there is no one device that is consistently producing the highest or the lowest standard deviation.

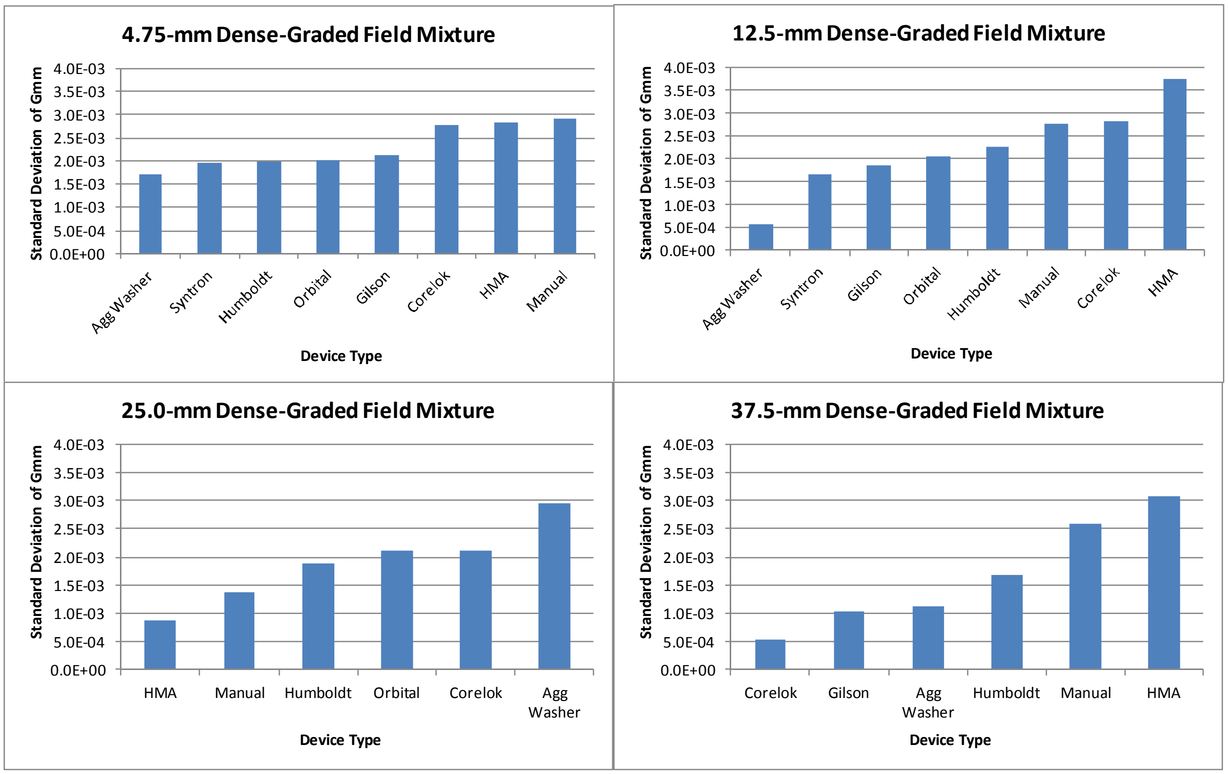

Figure 4-46- Ranked Standard deviations of the dense-graded laboratory mixtures using various devices

4.4 Relationship between vibration Properties of the Devices and Highest Gmm

In previous sections, the Gmm measuring devices were compared in terms of the highest Gmm they produce and in terms of the variability of their measurements. It was shown that different mechanical devices produce statistically the same Gmm values at their optimum settings. In this section the vibration properties of the devices at their optimum setting are compared to examine if the same vibration properties resulted in the same highest Gmm values. Table 4-68 through Table 4-70 provide the highest Gmm values and where applicable, the vibration properties (frequency, acceleration, and energy) of the devices at the setting of the highest Gmm.

As shown in the tables, while the highest Gmm values from various devices/ methods are very similar (Column 3) at the setting of the highest Gmm (Column 2), the vibration properties of the devices at those settings are very different (Columns 5 to 14). For example, the highest Gmm of the 19.0-mm dense-graded field mixture measured by the four vibratory devices of Humboldt, Gilson, Syntron, and HMA are in the range of 2.533 to 2.536; however, the total kinetic energy of the devices are in a range of 38.3 to 2854 MicroJoules. This might indicate that the energy that is produced by a device is not necessarily the same as the energy that is transferred to the mixture.

Table 4-68- Highest Gmm of dense-graded field mixtures and the vibration properties at the settings of the highest Gmm

Device Type	Optimum Setting	Highest Gmm		Frequency, Hz			Acceleration, m/s^2			Energy, Joules (x 10^{-5})			
		9.5-mm	19.0-mm	x	y	z	x	y	z	x	y	z	Total
Aggregate Washer	-	2.513	2.535	-	-	-	-	-	-	-	-	-	-
Corelok	-	2.512	2.531	-	-	-	-	-	-	-	-	-	-
Gilson	6	2.515	2.536	48.7	48.7	48.7	4.60	3.26	7.01	2.11	0.95	4.90	7.96
HMA	-	2.514	2.533	55.9	55.9	55.9	14.48	26.11	23.30	20.42	72.24	54.15	146.81
Humboldt	7	2.512	2.536	48.7	48.7	48.7	3.66	1.35	4.59	1.34	0.161	2.33	3.831
Orbital	240	2.512	2.537	-	-	-	-	-	-	-	-	-	-
Syntron	7	2.513	2.534	73.8	103.4	630.6	25.3	22.5	72.7	16.3	25.0	244.1	285.4
Manual	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 4-69- Highest Gmm of SMA mixtures and the vibration properties at the settings of the highest Gmm

Device Type	Optimum Setting	Highest Gmm			Frequency, Hz			Acceleration, m/s^2			Energy, Joules (x 10^{-5})			
		9.5-mm	12.5-mm	19.0-mm	x	y	z	x	y	z	x	y	z	Total
Aggregate Washer	-	2.645	2.463	2.448	-	-	-	-	-	-	-	-	-	
Corelok	-	2.649	2.464	2.449	-	-	-	-	-	-	-	-	-	
Gilson	7	2.648	2.463	2.447	49.0	49.0	49.0	4.57	3.33	6.96	2.11	0.91	4.70	7.72
HMA	-	2.649	2.464	2.447	55.9	55.9	55.9	14.48	26.11	23.30	20.42	72.24	54.15	146.81
Humboldt	8	2.647	2.465	2.448	52.8	52.8	52.8	4.29	1.84	5.04	1.82	0.31	2.71	4.84
Orbital	240 rpm	2.649	2.464	2.449	3.5	-	-	-	-	-	-	-	-	
Syntron	8	2.646	2.464	2.448	83.4	90.7	631.9	19.16	21.50	73.52	21.79	26.52	299.27	347.6
Manual	-	-	-	-	-	-	-	-	-	-	-	-	-	

Table 4-70- Highest Gmm of dense-graded laboratory mixtures and the vibration properties at the settings of the highest Gmm

Device Type	Optimum Setting	Highest Gmm				Frequency, Hz			Acceleration, m/s^2			Energy, Joules (x 10^{-5})			
		4.75-mm	12.5-mm	25.0-mm	37.5-mm	x	y	z	x	y	z	x	y	z	Total
Aggregate Washer	-	2.556	2.581	2.612	2.633	-	-	-	-	-	-	-	-	-	
Corelok	-	2.552	2.576	2.615	2.629	-	-	-	-	-	-	-	-	-	
Gilson	5	2.555	2.580		2.631	45.8	45.8	45.8	4.14	2.89	6.53	1.74	0.84	4.50	7.10
HMA	-	2.554	2.581	2.621	2.627	55.9	55.9	55.9	14.5	26.1	23.3	20.42	72.24	54.15	146.8
Humboldt	8	2.557	2.580	2.617	2.629	52.8	52.8	52.8	4.33	1.84	5.03	1.86	0.31	2.67	4.84
Orbital	240 rpm	2.556	2.580	2.621	-	-	-	-	-	-	-	-	-	-	
Syntron	7	2.556	2.582		-	73.8	103.4	630.6	25.3	22.5	72.7	16.3	25.0	244.1	285.4
Manual	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

4.5 Change in Gmm from Changing the Order of Placing Water and Mixture

The effect of the order of placing the mixture and water in vacuum container on Gmm measurements was examined. Seven of the mixtures were each tested with three of the devices twice: once by placing the water first (Water First) and then by placing the mixture first (Sample First) in the vacuum container. The significance of the difference between the Gmm values from the two procedures was evaluated by comparison of the resulted air voids and by conducting statistical t-test.

4.5.1.1 Dense-Graded Field Mixtures

The Gmm values measured by three devices and the resulted air voids of the dense-graded laboratory mixtures are shown in Figure 4-47 and Figure 4-48. The Gmm measurements in Figure 4-47 were conducted at the settings that provided the highest Gmm values. The air voids in Figure 4-48 were calculated using the measured Gmm values and assumed bulk specific gravity values of 2.404 and 2.422 for the 9.5-mm and 12.5-mm mixtures, respectively. It is readily observed from Figure 4-47 that by placing the water prior to adding the mixture, consistently higher Gmm values were measured. Figure 4-48 shows that the difference in air voids that resulted from the difference in Gmm could be as high as 0.23% , as shown for the 19.0-mm mixture tested by HMA or the Humboldt device, or as low as 0.11% as shown for the 9.5-mm mixture tested by the Orbital or Humboldt device.

A paired t-Test was conducted to evaluate if the mean Gmm from the Sample First and Water First procedures are the same. For the 9.5-mm and 19.0-mm dense-graded field mixtures, the computed t-values from the comparison of the Gmm values of the Sample First and Water First methods are 8.07 and 4.786, respectively. The comparison of the computed t values with the critical t value of 2.571 for 5% level of significance and degrees of freedom of 5 (6 measurements) indicates that the Water First method produces significantly higher Gmm values than the Sample First method.

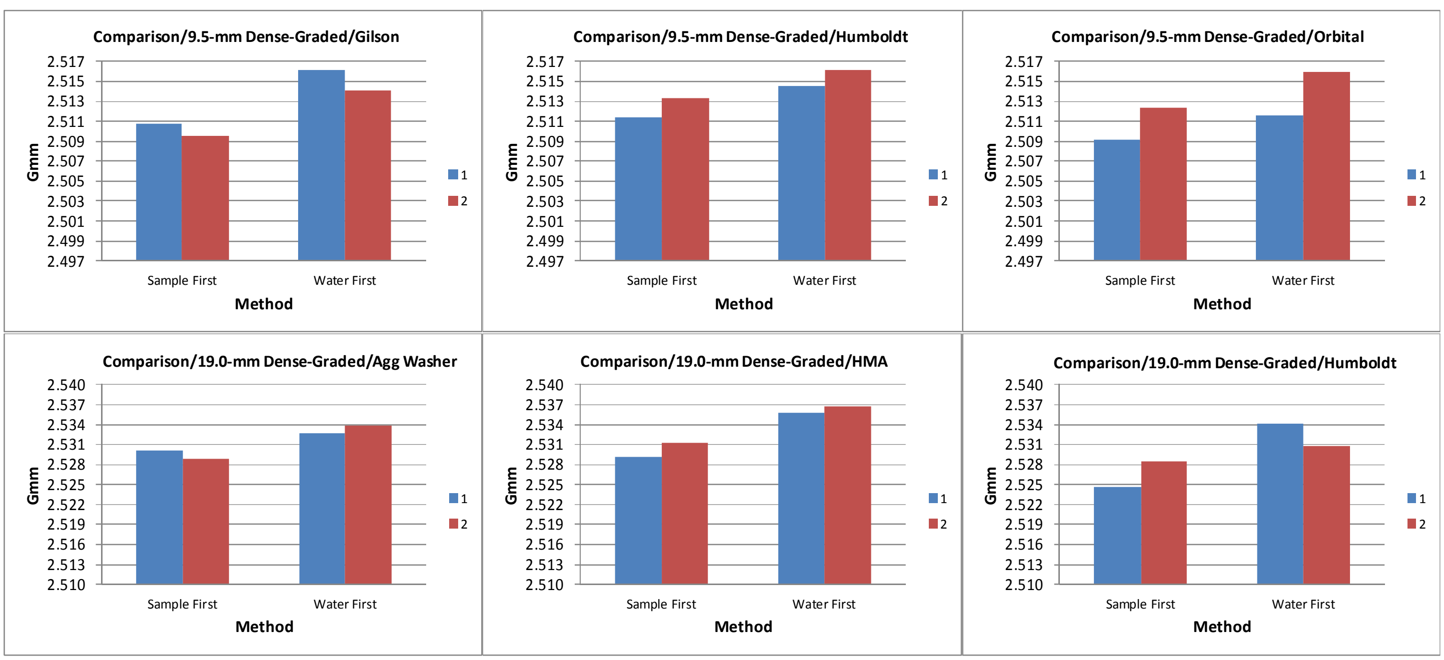

Figure 4-47- Effect of the order of placing mixture and water in pycnometer on Gmm of dense-graded field mixtures

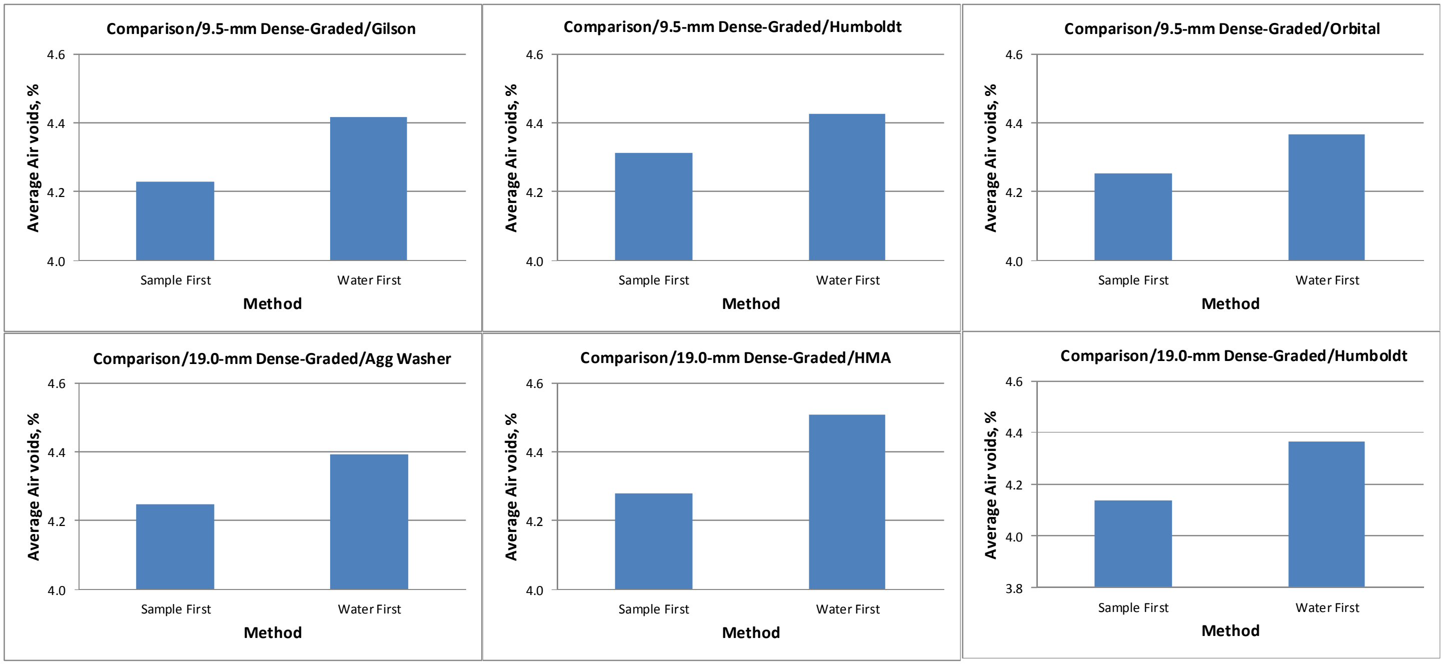

Figure 4-48- Effect of the order of placing mixture and water on air-voids of dense-graded field mixtures

4.5.1.2 SMA Field Mixtures

The Gmm values of the SMA mixtures measured by three of the vibrating devices are shown in Figure 4-49 and the resulted air voids are shown in Figure 4-50. The measurements in Figure 4-49 were conducted at the settings that provided the highest Gmm values. The air voids in Figure 4-50 were calculated using the measured Gmm values and assumed bulk specific gravity values of 2.532, 2.357, and 2.339 for the 9.5-mm, 12.5-mm, and 19.0-mm mixtures, respectively. It is readily observed from Figure 4-49 that by placing the water prior to placing the mixture in the vacuum container, consistently higher Gmm values were measured. Figure 4-50 shows that on average, the difference in the air voids resulted from the difference in Gmm is about 0.2%; however, the difference could be as high as 0.35% as shown for the 19.0-mm SMA tested by the Syntron table.

A paired t-Test was conducted to evaluate if the mean Gmm from the Sample First and Water First procedures are the same. For the 9.5-mm, 12.5-mm, and 19.0-mm SMA mixtures, the computed t-value from the comparison of the Gmm values of the Sample First and Water First methods are 3.636, 4.782, and 4.880, respectively. The comparison of the computed t values with the critical t value of 2.571 for 5% level of significance and degrees of freedom of 5 (6 measurements) indicates that the Water First method produces significantly higher Gmm values than the Sample First method.

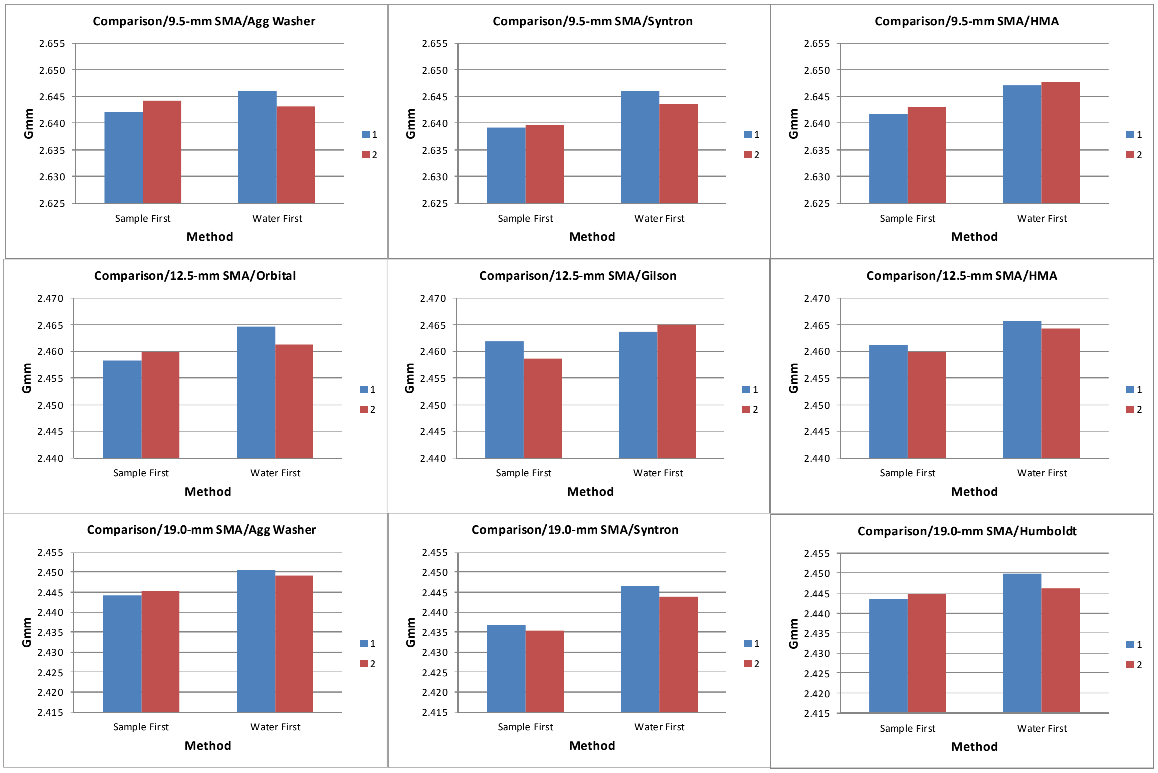

Figure 4-49- Effect of the order of placing mixture and water in pycnometer on Gmm of SMA mixtures

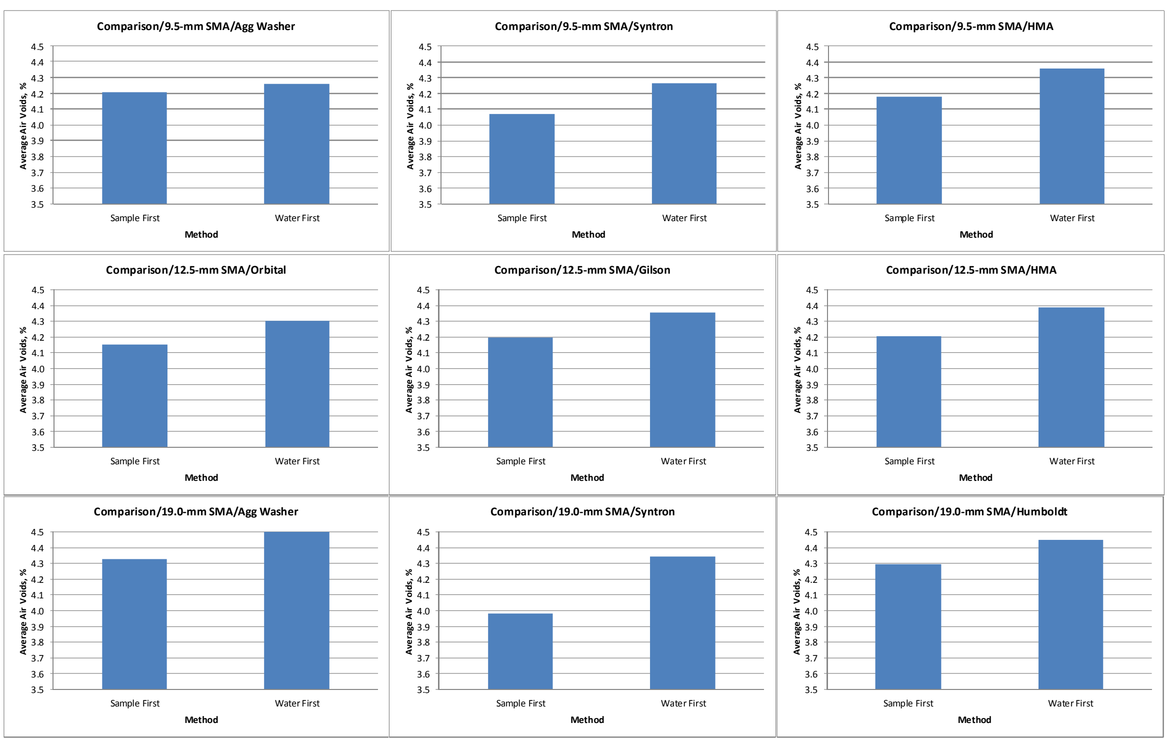

Figure 4-50- Effect of the order of placing mixture and water in pycnometer on air-voids of SMA mixtures

4.5.1.3 Dense-Graded Laboratory Mixtures

The Gmm values of the 4.75-mm and 12.5-mm dense-graded laboratory mixtures measured by three devices are shown in Figure 4-51 and the resulted air voids are shown in Figure 4-52. The measurements in Figure 4-51 were conducted at the settings that provided the highest Gmm values. The air voids in Figure 4-52 were calculated using the measured Gmm values and assumed bulk specific gravity values of 2.444, 2.466 for the 4.75-mm, 12.5-mm mixtures, respectively. It is readily observed from Figure 4-51 that by placing the water in the pycnometer prior to adding the mixture, consistently higher Gmm values were measured. Figure 4-52 shows that on average the difference in air voids resulted from the difference in Gmm is about 0.1%; however, the difference could be as high as 0.2% as shown for the 12.5-mm mixture tested by the Syntron table.

A paired t-Test was conducted to evaluate if the mean Gmm from the Sample First and Water First procedures are the same. For the 4.75-mm and 12.5-mm dense-graded laboratory mixtures, the computed t-value from the comparison of the Gmm values of the Sample First and Water First methods are 7.073 and 3.037, respectively. The comparison of the computed t values with the critical t value of 2.571 for 5% level of significance and degrees of freedom of 5 (6 measurements) indicates that the Water First method produces significantly higher Gmm values than the Sample First method.

It was observed from the above that the change in Gmm as a result of the change in the order of placing the mixture and water in the vacuum container was statistically and practically significant. Therefore, to facilitate the release of air from the mixture and to achieve the highest Gmm of the mixture, it is recommended to add the water to the vacuum container before placing the mixture.

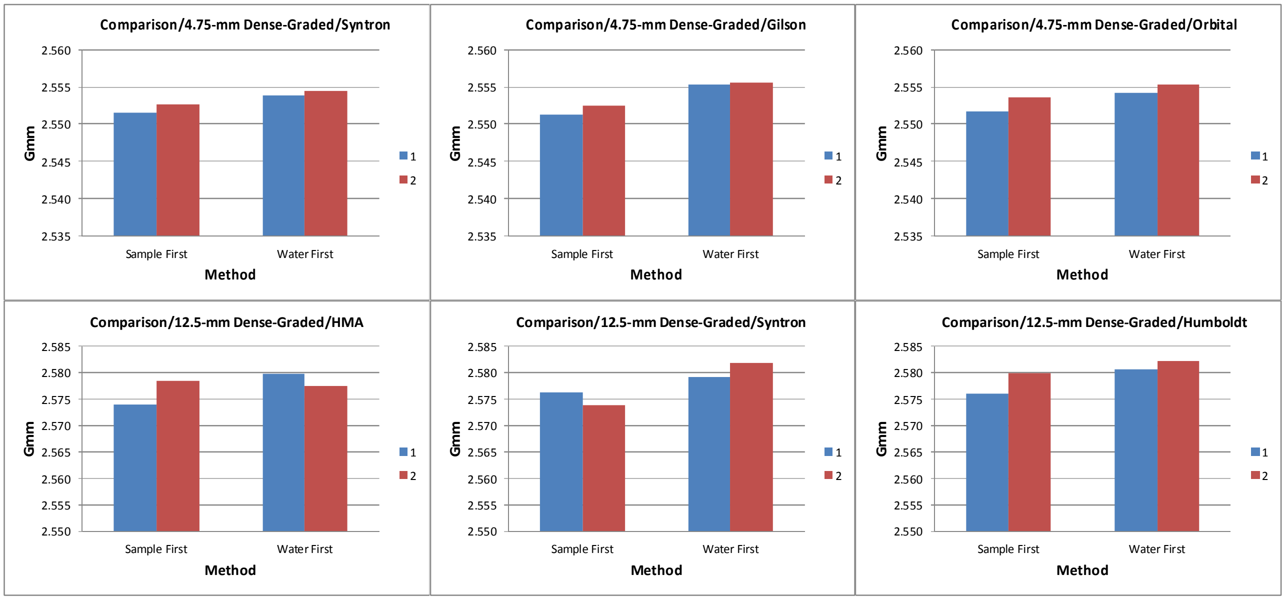

Figure 4-51- Effect of the order of placing mixture and water in pycnometer on Gmm of 4.75-mm and 12.5-mm dense-graded laboratory mixtures

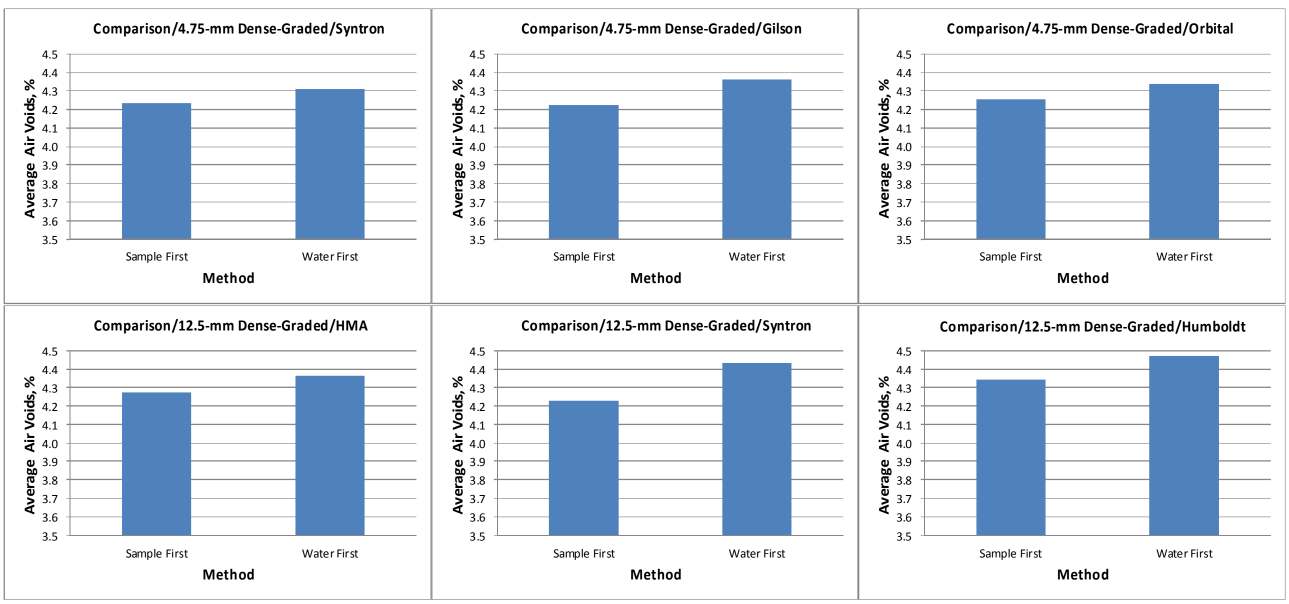

Figure 4-52- Effect of the order of placing mixture and water in pycnometer on air-voids of 4.75-mm and 12.5-mm dense-graded laboratory mixture

4.6 Effect of Vacuum Duration on Gmm Measurement

For the purpose of improving accuracy and precision of Gmm measurements, the effect of vacuum duration on the Gmm and its variability was investigated. The three SMA mixtures were used for this evaluation. Two replicates of each mixture were tested at Setting 6 of the Gilson device for five vacuum/agitation durations of 5 min, 10 min, 15 min, 20 min, and 25 min. The Gmm measurements are shown in Figure 4-53. As shown in the figure, the Gmm of the mixture increases with the increase in the vacuum/agitation time until it reaches a maximum after 20 min. An increase of vacuum/agitation time to 25 min has resulted in decrease in the Gmm. The visual observation of the water indicated that the water was slightly cloudy after 20 min of vacuum/agitation and became significantly cloudy after 25 min of vacuum/agitation. The variability of the Gmm measurements for the five agitation durations is shown in Figure 4-54. As shown in the figure, while higher variability of Gmm is usually observed at higher agitation durations, there is no specific trend of increase or decrease in Gmm variability with the increase in agitation time.

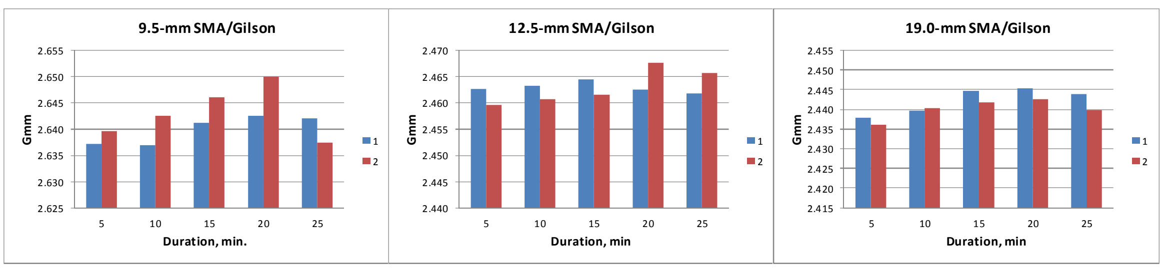

Figure 4-53- Effect of the agitation and vacuum duration on Gmm measurement of SMA mixtures

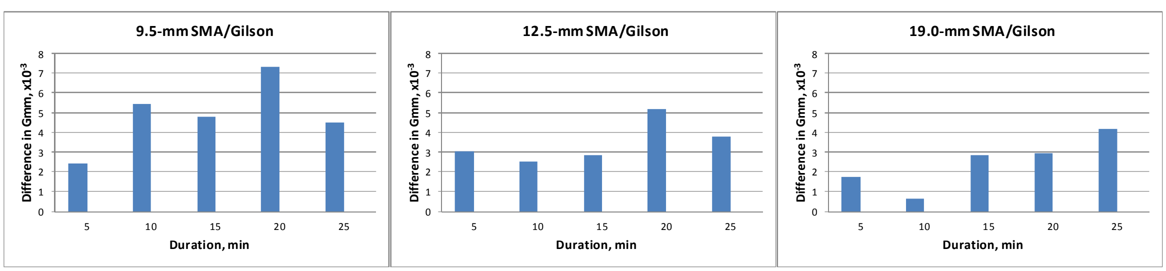

Figure 4-54- Difference in replicate Gmm measurements of SMA mixtures resulted from different vacuum durations

The significance of the difference between Gmm of various agitation/vacuum durations would indicate if higher vacuum duration is necessary to produce more accurate Gmm measurement. From practical point of view, the significance of the difference between the Gmm values is evaluated by evaluating the difference in air voids. Figure 4-55 shows the air void values computed using the measured Gmm values. A bulk specific gravity of 2.532, 2.357, and 2.339 were assumed for the 9.5-mm, 12.5-mm, and 19.0-mm SMA mixtures. As indicated from the figure, the difference between the air voids from 15 min of agitation, which is specified in AASHTO T 209, and from 20 min of agitation, which produced the highest Gmm is less than 0.1%. This difference is not considered practically significant.

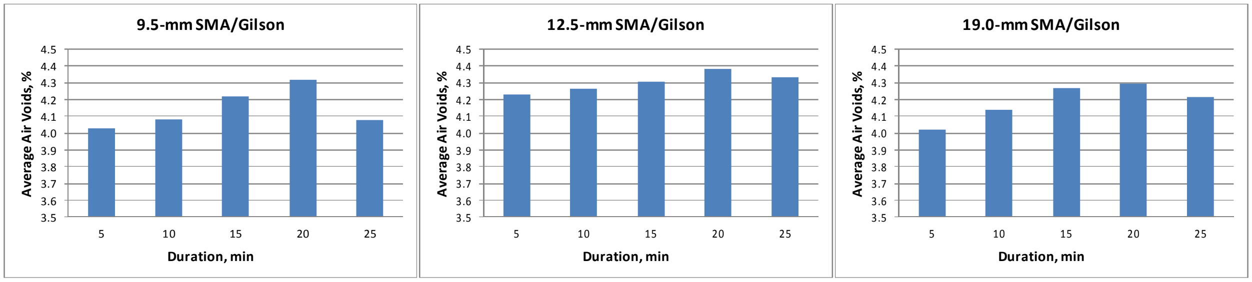

Figure 4-55- Average Air voids of the SMA mixtures at various vacuum duration of Gilson device

The statistical comparison of Gmm values for various vacuum/agitation durations was conducted using a Scheffe test. Table 4-71 through Table 4-73 provides the computed F values for comparison of Gmm of all combinations of vacuum/agitation periods. As indicated from the tables, none of the computed F values are greater than the critical F value of 5.192 for 5% level of significance. Therefore, vacuum/agitation period does not significantly affect Gmm. Based on the above observations, the agitation period of 15 min is found to be appropriate for the Gmm measurement. Although a higher Gmm value was measured at 20 min agitation, the difference in Gmm between 15 min and 20 min agitations was not practically and statistically significant.

Table 4-71- Computed F values for comparison of Gmm of 9.5-mm SMA mixture for various durations; Critical F value=5.192 and DOF= (4, 5) for 5% level of significance

Duration, min	5	10	15	20
10	0.035			
15	0.525	0.288		
20	1.176	0.803	0.130	
25	0.035	0.000	0.289	0.806

Table 4-72- Computed F values for comparison of Gmm of 12.5-mm SMA mixture for various durations; Critical F value=5.192 and DOF= (4, 5) for 5% level of significance

Duration, min	5	10	15	20
10	0.032			
15	0.145	0.040		
20	0.626	0.374	0.168	
25	0.286	0.126	0.024	0.066

Table 4-73- Computed F values for comparison of Gmm of 19.0-mm SMA mixture for various durations; Critical F value=5.192 and DOF= (4, 5) for 5% level of significance

Duration, min	5	10	15	20
10	0.533			
15	2.560	0.756		
20	3.210	1.127	0.037	
25	1.539	0.260	0.129	0.304

CHAPTER 5. CONCLUSIONS

This report presents the results of a study to evaluate the effect of various variables on measurement of maximum specific gravity measurement (Gmm) of asphalt mixtures for possible refinement of the AASHTO T209 test method. The variables examined include agitation and device type, vibration intensity of mechanical shaking tables, order of placing water and mixture in vacuum container, and duration of the vacuum/agitation process.

5.1 Summary

To conduct the study, nine laboratory-prepared and plant-produced dense-graded and SMA mixtures, ranging from 4.75-mm to 37.5-mm NMAS, were prepared into replicates test specimens. Seven Gmm measuring devices including a Humboldt vibrating table, a Gilson vibrating table, a Syntron concrete shaker, an HMA table, a Rotary Aggregate Washer, an Orbital shaker, and a Corelok vacuum sealing device were utilized. The devices were selected based on the responses from the State Departments of Transportation to a survey that was conducted on Gmm measuring methods and devices. The selected devices were either the most commonly used brands of agitators, pertinent to the widest number of laboratories, or they were non-traditional setups with the most unique features.

The effect of the device type/Method on Gmm measurement was examined using all seven selected mechanical devices. The significance of the change in Gmm from the change in the device type was examined from statistical and practical stand point.

The measurements using manual agitation were performed with the same setup as used with the mechanical agitation unless it was not possible to perform manual agitation. This was the case for the Syntron table where striking or shaking the bell jar vacuum chamber of the Minnesota setup used with the Syntron table was not practical. The significance of the difference between Gmm from manual and mechanical agitation was examined from statistical and practical stand point.

The effect of change in intensity of vibration of the mechanical agitators on Gmm measurements was investigated using four vibratory devices of Humboldt, Gilson, Syntron, and Orbital shaker. Along the Gmm measurement, the frequency and acceleration of vibration at each setting of the vibrating devices were measured. From the acceleration measurements, the kinetic energy of vibration was calculated to examine the relationship between the energy of vibrations and the highest Gmm values produced by the devices.

The change in water clarity was monitored to examine the physical effect of vibration on the mixtures. Significant cloudiness of the water at higher intensity of vibration was an indication of asphalt stripping and dissolving in water. Therefore, the level of discoloration of water was considered as a factor in determining the optimum vibration setting of the devices.

An optimum setting for accurate measurement of Gmm was determined for each vibratory device. This was determined based on the highest Gmm values measured, the level of

cloudiness of the water, and the significance of difference between Gmm from various vibration settings. If considerable cloudiness of water was observed at the setting of the highest Gmm, the results of statistical Scheffe test was used to select a lower setting that produces Gmm that is not significantly different from the highest Gmm and at which the water was not significantly cloudy.

As a potential improvement of the Gmm measuring process, the effect of the order of placing the water and mixture in a vacuum container on the Gmm measurements was investigated. This study involved seven mixtures each tested with three different devices. The significance of the change in Gmm from the change in the order of placing the mixture and water in vacuum containers was examined statistically.

Another investigation for possible enhancement of Gmm measurement was on the effect of the vacuum/agitation duration on the Gmm measurement. This evaluation was conducted using one device and three SMA mixtures. The Gmm of the mixtures were measured after five durations of 5 min to 25 min in 5-min intervals and the significance of the difference in the measured Gmm values were examined from statistical and practical point of view.

The practical significance of the change in Gmm was examined by examining the changes in air voids of compacted mixtures. The air voids were computed using the measured Gmm values and assumed bulk specific gravity (Gmb) values. Although a change in air voids of up to ±0.5% is not typically significant, in this study the criterion for a significant change in air voids was set as ±0.2%. This was in consideration of the additional variability from measuring Gmb, which is not included in the calculations of air voids when Gmb is assumed. In this respect, any change in air voids of more than 0.2 % was considered practically significant in this study.

The statistical significance of the change in Gmm was examined using a Scheffe test or paired t-test. A Scheffe test was used for multivariate comparisons. The Gmm values from various vibration levels, various devices/methods, and various duration levels were compared using a Scheffe test. A paired t-test was used for two-sample comparison. The Gmm from changing the order of placing water and mixture in vacuum container were compared using a paired t-test.

5.2 Conclusions and Recommendations

The following provides the observations and conclusions from the study:

The change in Gmm values from changing the order of placing water and mixture in vacuum container indicated that by adding the mixture to water, higher Gmm values are measured. The results of statistical analysis of Gmm values and evaluation of the computed air voids confirmed the significance of the increase in Gmm as a result of placing the water first. It is speculated that the release of air is facilitated by adding the mixture to water as opposed to adding water to the mixture. Therefore, it is recommended to refine AASHTO T 209 to specify placing the water in the vacuum container prior to adding the mixture.

The effect of the vacuum/agitation duration on the Gmm measurement on the three SMA mixtures indicated that Gmm increased by increasing the vacuum/agitation time until the highest Gmm was achieved after 20-min vacuum/agitation period. Further increase of the agitation time resulted in a decrease of Gmm. Although the highest Gmm was obtained after the 20-min agitation/vacuum period, the statistical analysis of Gmm values and evaluation of the air voids indicated that the difference in Gmm and air voids between the 15-min and 20-min agitation periods was not significant. In addition, the variability of measurements was slightly larger after 20-min than after 15-min of vacuum/agitation. Therefore, it is recommended that the 15-min vacuum/agitation time specified in T 209 be maintained.

The Gmm measurements at various settings of the devices indicated that for each vibratory device, Gmm of the mixture increases with the increase in intensity of vibration until the highest Gmm of the mixture is reached. From that point on, a further increase in vibration intensity was resulting in a decrease in Gmm. This phenomenon is speculated to be caused by stripping of the asphalt.

The Gmm values from manual agitation were always smaller than the highest Gmm values from mechanical devices. In most cases, manual agitation produced Gmm values that were equivalent to Gmm produced by the mid-range intensity setting of mechanical devices. The results of statistical analysis indicated that for four out of nine mixtures, measurements from manual agitation were significantly different from those of at least one mechanical device. In addition, the difference between air voids from manual agitation and mechanical devices were in a range of 0.2% to 0.4%, which could be practically significant. Therefore, use of manual agitation for the measurement of Gmm is not recommended.

Investigation of the change in Gmm from the change in the device type indicated that statistically, the differences between the Gmm values of the nine mixtures measured by various devices were not significant. Therefore, based on statistical results, it could be concluded that if vibrating devices are operated at their optimum settings, they could produce statistically the same Gmm values. Even devices with constant setting (HMA, Aggregate Washer, Corelok) could produce statistically the same Gmm values as those produced by the optimum setting of the vibrating devices with variable settings.

The evaluation of the air voids from various devices indicated that for three out of nine mixtures, the differences between the air voids from at least two devices were more than 0.2%, which could be practically significant. This implies that the difference between the air voids measured by a state and contractors using different devices could have an impact on the acceptance of a project. Therefore, it is recommended that the same method/apparatus that was used for measuring Gmm for a mix design be used during testing of the same mix during production for Quality Control and Quality Acceptance.

The relationship between the energy of vibration and the highest Gmm produced by a device indicated that although the highest Gmm values from various vibrating devices were very similar, the vibration properties of the mechanical devices were very different. An example of this is the Gmm values measured by Syntron and Humboldt devices, which are very comparable; however, the kinetic energy of the Syntron table is two orders of magnitude larger than that of

the Humboldt device. It is speculated that the amount of energy produced by a device is not the same as the amount of energy transferred to the mixture.

In the selection of the optimum setting of the devices, it was found that the variability of the Gmm was not a defining factor. The reason is that there was no specified trend between the variability of the data and the vibration settings. For all Gmm measurements, the difference between the replicate measurements at any setting was smaller than 0.007, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

Based on the data gathered in the study, the following recommendations regarding the optimum settings of the devices are made. Table 5-1 provides the suggested settings and their corresponding vibration properties. For the Humboldt device, the optimum range of operation is Settings 7. Although, the highest Gmm of the nine mixtures were produced at a range of Settings 7 to Setting 10, based on the concern with water clarity at Settings 8 through 10 and lack of significant difference between Gmm from those settings and Setting 7, Setting 7 was selected as the optimum setting of Humboldt device. For the Gilson device, the optimum setting of operation is Setting 5. Although, the majority of the highest Gmm readings did occur at Setting 6 and 7, one case of significant cloudiness at Setting 6 resulted in selecting Setting 5 as the optimum setting of the Gilson device. For the Syntron device, the optimum range of operation is at Setting 7. A few optimum readings did occur at Setting 8. However, based on the issues with water cloudiness at higher settings, and a lack of significant differences in Gmm between Setting 7 and Setting 8, the recommended setting is Setting 7. For the Orbital device, the optimum setting is 240 rpm. The highest Gmm were obtained in the span from 210 rpm to 300 rpm. However, based on increasing water cloudiness at higher settings, the recommended setting is a Setting 240 rpm. The laboratories are advised to adjust their vibrating tables to the recommended settings to ensure accurate measurement of the maximum specific gravity of their asphalt mixtures.

Table 5-1- The optimum settings and the vibration properties at the optimum setting of the four vibrating devices with variable settings

Device Type	Optimum Setting	Frequency, Hz			Acceleration, m/s^2			Energy, Joules (x 10^{-5})			
		x	y	z	x	y	z	x	y	z	Total
Humboldt	7	48.7	48.7	48.7	3.79	1.35	4.68	14.3	1.7	24.9	40.9
Gilson	5	44.3	44.3	44.3	3.95	2.71	6.05	16.1	7.5	38.8	62.4
Syntron	7	83.8	91.4	612.2	19.13	21.67	72.32	217	268	2899	3384
Orbital	240 rpm	-	-	-	-	-	-	-	-	-	-

It is important to note that any changes to the current test procedures due to the recommendations from this study may result in increased Gmm values that will affect air voids for laboratory and field compacted specimens. Agencies should consider the effect of this change on acceptance and pay criteria in their specifications.

REFERENCES

1- AASHTO, Designation T 209, “Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA)” Standard Method of Test for Transportation Materials and Methods of Sampling and Testing, 30th Edition, AASHTO, Washington, DC, 2010, CD-ROM

2- Arizona DOT test method (ARIZ 417b): **http://www.azdot.gov/Highways/Materials/QA/QA_Manuals/Materials_Testing/Series400/PDF/Ariz417b.pdf**

3- Florida State DOT test method (FM 1-T 209): **http://www.dot.state.fl.us/statematerialsoffice/administration/resources/library/publications/fstm/methods/fm1-t209.pdf**

4- Idaho State DOT test method (T209_short): **http://itd.idaho.gov/manuals/Online_Manuals/Current_Manuals/QA%20Manual/July_08/FOPs/T209_short_07.pdf**

5- Illinois State DOT test method (Ill-mod AASHTO T 209-05 #4):

6- Indiana State SOT modified test procedure (T209 INDOT): **http://www.in.gov/indot/files/209(1).pdf**

7- Minnesota DOT test method (MNDOT 1807.0): **http://www.dot.state.mn.us/materials/manuals/laboratory/1807.pdf**

8- New Mexico DOT test method (T-209 NM): **http://www.nmshtd.state.nm.us/upload/images/State_Material_Bureau/HMA-Asphalt/T-209.pdf**

9- North Dakota DOT test method (AASHTO T 209 NDDOT modified): **http://www.dot.nd.gov/manuals/materials/testingmanual/t209.pdf**

10- Ontario Ministry of Transportation test method (LS-264 R19):

11- Washington State DOT test method (WSDOT FOP for AASHTO T 209): **http://www.wsdot.wa.gov/publications/manuals/fulltext/M46-01/Materials.pdf**

12- AASHTO, Designation AASHTO T 168-03, “Sampling Bituminous Paving Mixtures” Standard Method of Test for Transportation Materials and Methods of Sampling and Testing, 30th Edition, AASHTO, Washington, DC, 2010, CD-ROM

13- AASHTO, Designation AASHTO R47-08, “Reducing Samples of Hot Mix Asphalt (HMA) to Testing Size” Standard Practice for Transportation Materials and Methods of Sampling and Testing, 30th Edition, AASHTO, Washington, DC, 2010, CD-ROM

14- AASHTO, Designation AASHTO R30-02, “Mixture Conditioning of Hot Mix Asphalt (HMA)” Standard Practice for Transportation Materials and Methods of Sampling and Testing, 30th Edition, AASHTO, Washington, DC, 2010, CD-ROM

15- ASTM, Designation ASTM D6857 - 09, “Standard Test Method for Maximum Specific Gravity and Density of Bituminous Paving Mixtures Using Automatic

Vacuum Sealing Method" Annual Book of ASTM Standards, Volume 4.03, ASTM, West Conshohocken, PA, 2010

16- NIST SEMATECH Engineering Statistics Handbook; **http://www.6sigma.us/handbook/index1.html**

APPENDIX A- RESULTS OF THE SURVEY OF STATES' LABORATORIES

Results of Survey: Question 1

What method of test do you follow for measuring G_{mm}?

- T 209
- ASTM 2041
- State test method

	State	Answer
1	Alabama	AASHTO T-209
2	Arizona	State test method
3	Arkansas	AASHTO T-209
4	California	State test method (CTM309
5	Colorado	State test method
6	Connecticut	AASHTO T-209
7	Delaware	AASHTO T-209
8	Florida	State test method (FM1-T209)
9	Georgia	AASHTO T-209
10	Illinois	State test method
11	Kentucky	AASHTO T209
12	Louisiana	State test method
13	Maine	AASHTO T209
14	Maryland	AASHTO T209
15	Minnesota	State test method
16	Mississippi	AASHTO T209
17	Nevada	AASHTO T209
18	New Hampshire	AASHTO T209
19	New Jersey	AASHTO T209
20	New Mexico	AASHTO T209
21	New York	AASHTO T209
22	New York DOT Region-09	AASHTO T209
23	North Dakota	AASHTO T209
24	Ohio	AASHTO T209
25	Oklahoma	AASHTO T209
26	Oregon	AASHTO T209
27	South Carolina	State method (SC-T-83)
28	Tennessee	AASHTO T209
29	Texas	State method (Tex-227-F, Part II)
30	Virginia	AASHTO T209

	Washington	
31	FHWA	AASHTO T209
32	DOT	State method
33	West Virginia	AASHTO T209
34	Wyoming	AASHTO T209
35	Canada, Ontario	State method

Results of Survey: Question 2

What type of agitation do you apply for measuring maximum gravity of asphalt mixtures?

- Manual agitation
- Mechanical agitation

	State	Answer
1	Alabama	Mechanical agitation
2	Arizona	Manual agitation
3	Arkansas	Mechanical agitation
4	California	Mechanical agitation
5	Colorado	Mechanical agitation
6	Connecticut	Mechanical agitation
7	Delaware	Mechanical agitation
8	Florida	Mechanical agitation. Use an orbital shaker with an orbit of ¾", equipped with a platform that accommodates four 2000 ml flasks.
9	Georgia	Mechanical agitation and tap vessel at 1-min. intervals
10	Illinois	Both Manual agitation and Mechanical agitation are allowed. However, very few labs (State and Contractor) use Mechanical agitation. The Central Materials Lab uses Manual agitation. Approximately every two minutes the pycnometer top is held down (to stabilize the pycnometer and to prevent water from entering the vacuum lines) and the side of the pycnometer is "hit" three times by using the side of the fist. This helps to release the air bubbles from the sample and to knock the air bubbles from the side of the pycnometer so the air bubbles rise to the surface and are "removed".
11	Kentucky	Mechanical agitation
12	Louisiana	Mechanical agitation
13	Maine	Mechanical agitation
14	Maryland	Mechanical agitation
15	Minnesota	Mechanical agitation
16	Mississippi	Mechanical agitation
17	Nevada	Manual agitation
18	New Hampshire	Manual agitation
19	New Jersey	Mechanical
20	New Mexico	Manual agitation
21	New York	Mechanical agitation
22	New York DOT Region-09	Mechanical agitation

23	North Dakota	Mechanical agitation
24	Ohio	Mechanical agitation
25	Oklahoma	Mechanical agitation
26	Oregon	Mechanical agitation
27	South Carolina	Mechanical agitation
28	Tennessee	Mechanical agitation
29	Texas	Mechanical agitation
30	Virginia	Mechanical agitation
	Washington	
31	FHWA	Mechanical agitation; strike the bowl with a rubber mallet at least a couple of times during the test)
32	DOT	Mechanical agitation
33	West Virginia	Mechanical agitation
34	Wyoming	Manual agitation
35	Canada, Ontario	Mechanical agitation

Results of Survey: Question 3

If using mechanical agitation, what setup do you have?

- Typical setup explained in AASHTO T 209
- Unique setup

Please explain if you are using a unique setup, if possible, please provide a picture of it as well.

State	Answer
Alabama	Typical setup
Arizona	Typical setup
Arkansas	Typical setup
California	Typical setup
Colorado	Typical setup
Connecticut	Unique setup – *see Figure 1*
Delaware	Typical setup
Florida	Unique setup: – *see Figure 2*
Georgia	Typical setup
Illinois	Typical setup
Kentucky	Typical setup
Louisiana	Typical setup
Maine	Typical setup
Maryland	Typical setup
Minnesota	Typical setup
Mississippi	Typical setup
Nevada	Typical setup
New Hampshire	Typical setup
New Jersey	Typical setup– *see Figure 3*
New Mexico	Typical setup
New York	Typical setup
New York DOT Region-09	Typical setup
North Dakota	Typical setup
Ohio	Typical setup
Oklahoma	Typical setup– *see Figure 4*
Oregon	Typical setup
South Carolina	Typical setup– *see Figure 5*
Tennessee	Typical setup
Texas	Typical setup
Virginia	Typical setup
Washington	
FHWA	Typical setup
DOT	Typical setup

West Virginia	Typical setup
Wyoming	Typical setup
Canada, Ontario	Unique setup: – *see Figure 6*

Results of Survey: Question 4

What brand vibrator/ agitator are you using (Humboldt, Gilson, Others)? Please provide the brand and the model #.

	State	Answer
1	Alabama	Gilson Vibro-Deairator SGA-5R
2	Arizona	N/A
3	Arkansas	Humboldt H-1756
4	California	Humboldt
5	Colorado	Gilson Vibro-Deairator SGA-5R
6	Connecticut	Other: Our unit is improvised using an 120V, 1/3 HP electric motor and a pulley mounted to the center shaft. A small weight was added to one spot of the pulley which cause a vibration that we have determined to be adequate for the purposes intended.
7	Delaware	ELE International
8	Florida	Barnstead/Lab-Line shaker, Model No. SHKE2000
9	Georgia	Humboldt H-1756
10	Illinois	N/A
11	Kentucky	Humboldt Model No. H-1755 (Type E); Gilson (model unknown)
12	Louisiana	Fasco M 7121-6088, Q/C Resource Model 90-1755-00
13	Maine	Gilson Vibro-De-airator
14	Maryland	Gilson # SGA-5R
15	Minnesota	We use a concrete vibrating table found at both Humboldt and Gilson. Similar to Humboldt's model H-3755
16	Mississippi	Humboldt H-1782 (rotating agitator table); Humboldt H-1756A (vibrating table)
17	Nevada	N/A
18	New Hampshire	N/A
19	New Jersey	The smaller vibrating table is a Soiltest sourced CT-164/Syntron VP5101 (FMC VP-51) purchased and placed in service in 1987. The larger vibrating table was placed in service in 1992. It also appears to be a Soiltest sourced (FMC VP-181) unit although we can't read the model number as the information tags are on the side of the table facing the wall behind it. The tables were manufactured by FMC Technologies.
20	New Mexico	N/A
21	New York	Humboldt H-1756
22	New York DOT	Humboldt H-1756

	Region-09	
23	North Dakota	Thermolyne M49125
24	Ohio	HMA Lab Supply VA 2000
25	Oklahoma	ELE model AP-910A
26	Oregon	Gilson Vibro-Deairator, Model SGA-5R
27	South Carolina	Syntron Vib-table- Model #VVPSLNKL Serial #754196; Fasco Electric Motor Vibrating Table
28	Tennessee	Humboldt H-1756A
29	Texas	Gilson model #SGA-5R
30	Virginia	HMA Lab Supply
	Washington	
31	FHWA	Humboldt H-1756A
32	DOT	Humboldt model # H 1756 & H 1756A
33	West Virginia	VA Lab Supply Model # VA-2000
34	Wyoming	N/A
35	Canada, Ontario	Endecotts E.V.S.1.

Results of Survey: Question 5

Can you adjust the frequency/ amplitude of vibrator/ agitator on you system?

	State	Answer
1	Alabama	Yes
2	Arizona	N/A
3	Arkansas	No
4	California	Yes
5	Colorado	Yes
6	Connecticut	No
7	Delaware	No
8	Florida	Yes
9	Georgia	No
10	Illinois	N/A
11	Kentucky	No for Humboldt H 1755; No for Gilson (model unknown)
12	Louisiana	No
13	Maine	Yes
14	Maryland	Yes
15	Minnesota	Yes
16	Mississippi	Yes for Humboldt H 1782; Yes for Humboldt H 1756A
17	Nevada	N/A
18	New Hampshire	N/A
19	New Jersey	Yes for FMC VP-51; Yes for FMC VP-181
20	New Mexico	N/A
21	New York	No
22	New York DOT Region-09	No
23	North Dakota	Yes
24	Ohio	No
25	Oklahoma	No
26	Oregon	Yes
27	South Carolina	Yes for Syntron Vib-table No for Fasco Electric Motor Vibrating Table
28	Tennessee	Yes
29	Texas	Yes
30	Virginia	No
31	Washington	
31	FHWA	Yes
32	DOT	No for Humboldt H 1756; Yes for Humboldt H 1756A
33	West Virginia	No
34	Wyoming	N/A

35	Canada, Ontario	Yes

Results of Survey: Question 6

How many levels can the vibrator/agitator dial be adjusted to?

	State	Answer
1	Alabama	22
2	Arizona	N/A
3	Arkansas	N/A
4	California	Unlimited
5	Colorado	No level indicated. Just a range of minimum to maximum.
6	Connecticut	N/A
7	Delaware	N/A
8	Florida	Since ours is a digital model, you can set it to virtually any rpm within the range of the shaker's capabilities.
9	Georgia	N/A
10	Illinois	N/A
11	Kentucky	Humboldt H 1755: N/A; Gilson (model unknown): N/A
12	Louisiana	N/A
13	Maine	Gilson Vibro De-airator does not have discrete adjustment settings, rather it has a reostat-type knob with continuous adjustment.
14	Maryland	Variable (Potentiometer)
15	Minnesota	The electromagnetic vibrator is controlled by a rheostat which has 10 levels, but it can be set anywhere between 0-10.
16	Mississippi	Humboldt H-1782: 0-240 rpm; Humboldt H-1756A: 0-2400 vpm
17	Nevada	N/A
18	New Hampshire	N/A
19	New Jersey	FMC VP-51: infinite 0-10; FMC VP-181: infinite 0-100
20	New Mexico	N/A
21	New York	N/A
22	New York DOT Region-09	N/A
23	North Dakota	0-500 rpm
24	Ohio	N/A
25	Oklahoma	N/A
26	Oregon	The Gilson device has a full range from low to high and utilizes a rheostat to regulate the frequency via a dial.
27	South Carolina	A. 0-10 for Syntron B. N/A for HMA supply vibratory table
28	Tennessee	10
29	Texas	Free-turning dial that can be adjusted to any level within it's turning range.
30	Virginia	N/A

	Washington	
31	FHWA	0-10
32	DOT	Humboldt H 1756A: 0 to 10 with 0.2 rotary dial increments; Humboldt H 1756: N/A
33	West Virginia	N/A
34	Wyoming	N/A
35	Canada, Ontario	0-100

Results of Survey: Question 7

What levels of vibration do you usually set your vibrator/agitator table?

State	Answer
Alabama	11-15
Arizona	N/A
Arkansas	N/A
California	Maximum
Colorado	Approximately at the midpoint.
Connecticut	N/A
Delaware	N/A
Florida	All G_{mm} testing in Florida is performed with the orbital shaker operating at 270 rpm.
Georgia	N/A
Illinois	N/A
Kentucky	Humboldt H 1755: N/A; Gilson (model unknown): N/A
Louisiana	N/A
Maine	We always use the setting with the maximum frequency/amplitude.
Maryland	Max
Minnesota	A setting of 3-4 is typical. The tables are old, but we think that the maximum vibration is 3600 vpm.
Mississippi	Humboldt H-1782: 120-130 rpm; Humboldt H-1756A: 1500-1700 vpm
Nevada	N/A
New Hampshire	N/A
New Jersey	FMC VP-51: 6/10; FMC VP-181: 22/100
New Mexico	N/A
New York	N/A
New York DOT Region-09	N/A
North Dakota	225 rpm
Ohio	N/A
Oklahoma	N/A
Oregon	High Range
South Carolina	A. 3.5 out of 10 B. N/A
Tennessee	5
Texas	Maximum
Virginia	N/A
Washington	
FHWA	10
DOT	Humboldt H 1756A: To match the vibration speed of the H 1756;

	Humboldt H 1756: N/A
West Virginia	N/A
Wyoming	N/A
Canada, Ontario	Approx. 40

Results of Survey: Question 8

What is the basis of the selected levels of vibration (gradation, asphalt content, others)? Please explain.

State	Answer
Alabama	Gradation, because the finer mixes seem to require higher levels of vibrating in order to free entrapped air.
Arizona	N/A
Arkansas	Vibration is not adjustable; the system is set-up based on AASHTO T-209
California	We use the same level for all
Colorado	Set vibration level by feel. Do not want to high or too low.
Connecticut	N/A
Delaware	N/A
Florida	N/A
Georgia	N/A
Illinois	N/A
Kentucky	N/A
Louisiana	N/A
Maine	We use the maximum setting because it seems to be the most effective a removing air from the sample.
Maryland	Maximum Deairation
Minnesota	There really is no basis other than it's been our standard for years. Excessive vibration tends to cause other testing issues. Main idea is to evacuate all the entrapped air.
Mississippi	The settings selected have been found to slightly disturb the sample providing for release of trapped air.
Nevada	N/A
New Hampshire	N/A
New Jersey	The control dial on both tables is set at a level that we feel gives us adequate agitation without causing the HMA material to move around in the bowl. Also, this level of agitation does not cause the bowls to move around or create an uncomfortable noise level. Although this may seem very subjective, our PSP results are generally excellent which leads us to believe the settings are satisfactory.
New Mexico	N/A
New York	N/A
New York DOT Region-09	N/A
North Dakota	Comparison tests between Contractor and State are very accurate.

	Obtain good numbers between flasks. Mix is not over shaken causing water to enter the vacuum system. Mix is vigorously shaken but not slammed against the side of the glass flasks.
Ohio	My understanding is that when mechanical agitators were developed in the 1990s they sought to mimic results of hand agitation so that was the benchmark for vibration achieved.
Oklahoma	N/A
Oregon	Odot uses the highest frequency range in an effort to remove all the entrapped air. We really don't have a specific reasoning behind the selection, just want to ensure the highest degree of accuracy in regards to the measured Gmm value and its associated properties. Many states have indicated the mix tends to consolidate under the high frequency range and actually trap air, but we haven't experienced this problem with our HMAC mixtures.
South Carolina	A. same for all mixtures B. same for all mixtures
Tennessee	We do not have any specification designating level of agitation.
Texas	This level of agitation has produced repeatable and accurate test results as per AMRL and TxDOT proficiency programs. It also removes any bias in regards to agitation from the technicians performing the test.
Virginia	N/A
Washington	
FHWA	The level of agitation needs to be sufficient to remove all entrapped air. Even at the highest level of agitation air bubbles can remain. Thus we require that the side of the bowl be struck with a rubber mallet during the agitation period to assure that all bubbles are removed.
DOT	N/A
West Virginia	N/A
Wyoming	N/A
Canada, Ontario	None, except that technicians are comfortable with the gentle but effective action resulting from this setting.

Results of Survey: Question 9

If you are using a unique setup, are you willing to donate, loan a unit, or to help AMRL to put a similar unit together.

State	Answer
Alabama	N/A
Arizona	N/A
Arkansas	N/A
California	N/A
Colorado	N/A
Connecticut	Yes
Delaware	N/A
Florida	I wouldn't call out setup unique. We may have some equipment that others do not have (cold trap, two vacuum pumps, etc.), but the basic configuration is the same.
Georgia	N/A
Illinois	N/A
Kentucky	N/A
Louisiana	No. No spare.
Maine	N/A
Maryland	N/A
Minnesota	Yes
Mississippi	N/A
Nevada	N/A
New Hampshire	N/A
New Jersey	See attached Pictures
New Mexico	N/A
New York	N/A
New York DOT Region-09	N/A
North Dakota	N/A
Ohio	I am sure HMA Lab Supply would be willing to do this. They are in Virginia and are pretty involved in development work.
Oklahoma	We don't consider our setup unique. A photo of our setup is attached. We are considering Instrotek's pumpsaver to replace our filtering system. **http://instrotek.com/pumpsaver.php** Our vacuum pump is a 1/2 hp Welch model 1406B-01. We have used this setup since 2004. From 1990 to 2004, we used an Eberbach reciprocating shaker with 1.5: stroke and 180.280 osc/min. Before 1990, we vibrated by hand.

Oregon	N/A
South Carolina	N/A Misc. Note: We generally do not have any issues with MSG using a table that has a variable amplitude-frequency setting as long as it is not set excessively high. We do have some issues with possibly stripping or a metallic discolor (grey) in the non adjustment models that are designed to hold one pot at a time. These tables (picture attached) seem to break the asphalt materials or polish the insides of the MSG bowls during the vacuum process (not sure of the cause). This causes the water to be discolored in the MSG sample; and later causes the water baths to get very cloudy after running only a few tests, even after OT solution is added as necessary.
Tennessee	N/A
Texas	Not a unique setup, can be purchased from Gilson
Virginia	N/A
Washington	
FHWA	N/A
DOT	N/A
West Virginia	N/A
Wyoming	N/A
Canada, Ontario	We will gladly provide any information to help you put a similar unit together.

Pictures of the Setups

Figure 1- Connecticut

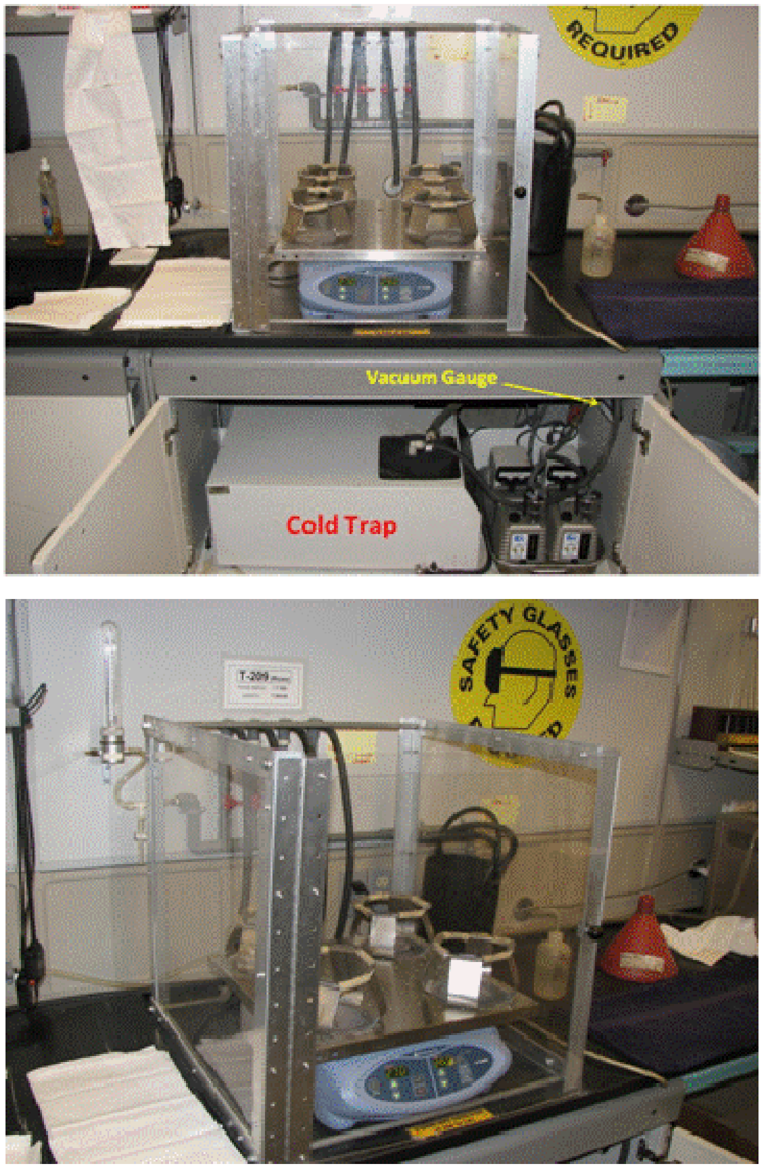

Figure 2- Florida

Figure 3- New Jersey

Figure 4- Oklahoma

Figure 5- South Carolina

Figure 6- Canada