# AASHTO T 209: Effect of Agitation Equipment Type on Theoretical Maximum Specific Gravity Values

## DETAILS

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# Research Results Digest 369

## AASHTO T 209: EFFECT OF AGITATION EQUIPMENT TYPE ON THEORETICAL MAXIMUM SPECIFIC GRAVITY VALUES

This digest summarizes key findings of research conducted in NCHRP Project 10-87(01), "Precision Statements for AASHTO Standard Methods of Test," by the AASHTO Asphalt Materials Reference Laboratory (AMRL) under the direction of the principal investigator, Dr. Haleh Azari. The digest is an abridgement of the full final report, which is available for download at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3049.

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## BACKGROUND

AASHTO T 209, *Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures,* describes a test method for determination of the theoretical maximum specific gravity ($G_{mm}$) and density of uncompacted hot mix asphalt (HMA).[1] The $G_{mm}$ and the density of HMA are fundamental properties whose values are influenced by the composition of the HMA mixtures in terms of types and amounts of aggregates and asphalt materials. $G_{mm}$ is used to calculate percent air voids in compacted HMA and to provide target values for the compaction of HMA. $G_{mm}$ also is essential when calculating the amount of asphalt binder absorbed by the internal porosity of the individual aggregate particles in HMA.

AASHTO T 209 requires application of a vacuum to a sample of HMA loose mix. The vacuum, combined with either manual or mechanical agitation, removes entrapped air in order to accurately determine the $G_{mm}$. The $G_{mm}$ is then used to determine both the air void content and the in-place density of the 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 that mechanical agitation provides less variation in test results when compared to manual agitation. However, several types of mechanical vibratory shakers are commonly used to apply agitation. It was not known if these different devices provide significantly different results when compared to one another. In addition, the effects on $G_{mm}$ values of changes in vibration intensity from various settings of the vibrating devices had not been explored.

## OBJECTIVES AND SCOPE

The goal of this research was to evaluate the effect of using various devices and methods on measured values of $G_{mm}$. The specific objectives were to (1) compare the $G_{mm}$ between manual and mechanical agitation; (2) investigate the relationship between the measured $G_{mm}$ and the vibratory

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[1] AASHTO T 209-10, Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA). In *Standard Specifications for Transportation Materials and Methods of Sampling and Testing,* 30th ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.

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parameters of the mechanical vibratory tables and determine an optimum vibration intensity of the vibrating devices; and (3) evaluate the effect on $G_{mm}$ measurements of several variables, such as the order of placing water and mixture and the period of vacuum and agitation. The research was conducted in ten major steps:

1. Survey the state highway agencies to determine what specific mechanical equipment and methods are currently being used for determining the $G_{mm}$ of asphalt mixtures.
2. Identify, based on the results of the survey, the most commonly used and the most unique equipment and methods used for measuring $G_{mm}$.
3. Select a variety of laboratory-prepared and plant-produced asphalt mixtures for the study, including (a) a fine-graded, low traffic volume (< 1 million ESALs) Superpave mix; (b) a coarse-graded, high traffic volume (> 30 million ESALs) Superpave mix; and (c) a gap-graded or SMA high traffic volume Superpave mix.
4. Measure $G_{mm}$ using manual agitation and at several settings of various mechanical agitators.
5. Evaluate the frequency, acceleration, and kinetic energy at various settings of the vibrating devices.
6. Evaluate the practical and statistical significance of the differences between $G_{mm}$ values obtained using (a) various settings of each vibratory device, (b) zero vibration, and (c) manual agitation, and use this information to determine the optimum setting of the various devices.
7. Evaluate the practical and statistical significance of the differences between the highest $G_{mm}$ values from various mechanical devices and manual agitation.
8. Examine the relationship between the vibration properties of the vibrating devices and the highest $G_{mm}$ value produced by the device.
9. Investigate the effect on $G_{mm}$ of the order in which mixture and water are placed in the vacuum flask or bowl.
10. Investigate the effect on $G_{mm}$ of changing the duration of the vacuum and agitation process.

## SURVEY OF STATE DOT LABORATORIES

The survey of the state DOTs included nine questions to identify the candidate devices for the study, how the devices are operated by each state, and whether any of the state's test methods deviate from those prescribed by AASHTO T 209. The 35 responses to the survey are organized and presented in Appendix A of the project final report, which can be accessed at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3049.

Based on the results of the survey, the most commonly used mechanical agitators were selected for the laboratory experiment so that the research findings would apply to the widest number of laboratories. Several unique setups also were selected to compare the application of non-typical methods to typical methods.

## EXPERIMENT DESIGN

A laboratory experiment was designed to measure $G_{mm}$ of various mixture types using different devices and a variety of agitation levels. The experiment also investigated the effects on $G_{mm}$ of factors such as the order in which water and mixture are placed in the pycnometer and the vacuum and agitation duration.

### Test Apparatus and Setup

Seven devices were selected for investigation, as follows:

1. Humboldt Vibrating Table (H-1756);
2. Gilson Vibro-Deaerator (SGA-5R);
3. Syntron Vibrating Table (VP-51 D1);
4. Orbital Shaker Table (SHKE 2000);
5. HMA Vibrating Table (VA-2000);
6. Aggregate Drum Washer (with vacuum lid); and
7. Corelok Vacuum Sealing Device.

Table 1 provides a brief description of each unit.

The Humboldt, Gilson, and HMA tables were selected because together they make up more than 80% of the devices used by the state laboratories. Despite being less common, the Orbital shaker (similar to the Barnstead shaker), Aggregate washer, and Corelok offered unique features and thus the opportunity to investigate differences between these devices and the more common setups. The Syntron shaker was selected because it is used with a unique setup by the Minnesota DOT.

**Table 1** Description of the devices selected for the refinement of AASHTO T 209 study.

| Device | Manufacturer | Agitation Type | Description |
|---|---|---|---|
| Humboldt Vibrating Table (H-1756) | Humboldt Mfg. Co. | Vibratory | The unit has a dial for adjusting the frequency and amplitude of vibration. Different intensities are indicated by numbers on the dial from 1 to 10. |
| Gilson Vibro-Deaerator (SGA-5R) | Gilson Co., Inc. | Vibratory | The unit has a dial for adjusting the frequency and amplitude of vibration. Different intensities are indicated by bars with different thicknesses. No number is associated with the bars. |
| Syntron Vibrating Table (VP-51 D1) | FMC Technologies, Inc. | Vibratory | The unit comes with a dial-rheostat for adjusting the amplitude of the vibration. The dial-rheostat is part of a separate control box, which allows for remote control if desired. |
| Orbital Shaker Table (SHKE 2000) | Thermofisher Scientific | Orbital | The unit has an adjustable knob that controls the speed of the shaker platform in an orbital pattern in the range of 0 to 350 rpm. |
| HMA Vibrating Table (VA-2000) | HMA Lab Supply | Vibratory | The unit has a fixed intensity. This table was the most frequently used by the state DOTs. |
| Aggregate Drum Washer (with vacuum lid) | Karol-Warner Co. | Rotary | The unit rotates slowly at the rate of 25 rpm and tumbles the loose mixture while the vacuum is applied. |
| Corelok (vacuum sealing device) | InstroTek, Inc. | No agitation (vacuum sealing method) | The unit vacuum-seals the loose asphalt mixture in a plastic bag. |

The setup used for measuring $G_{mm}$ 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 that conforms to the requirements of Sections 6.2 to 6.11 of AASHTO T 209.

Vibratory frequency and amplitude measurements were made using a triaxial accelerometer, a signal conditioner, and SignalView computer software. An accelerometer produces an electrical signal that is a function of mechanical vibration. A signal conditioner obtains the signal voltage and acts as an interface between the accelerometer and the computer, which processes and displays the signals.

The accelerometer was attached to the top of the vacuum container lid with 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. Looking down at the container from the top, the *x*-axis extended 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.

## Specimen Preparation

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 the laboratory. Dense-graded 9.5-mm and

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

| | Laboratory-Prepared Mixtures | | | | Plant-Produced Mixtures | |
|---|---|---|---|---|---|---|
| Sieve (mm) | 4.75-mm Percent Passing (%) | 12.5-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 |

19.0-mm NMAS mixtures were obtained from construction sites at the National Institute of Standards and Technology, Gaithersburg, Maryland, and gap-graded stone matrix asphalt (SMA) 9.5-mm, 19.0-mm, and 25.0-mm NMAS mixtures were obtained at construction sites in Richmond, Virginia. The mixture designs of the dense-graded laboratory-prepared and plant-produced mixtures are provided in Table 2; however, the mixture designs for the SMA mixtures were not available from the contractor.

Plant-produced samples were obtained in conformance to the requirements of AASHTO T 168 and stored in sealed boxes until the time of testing.[2] To prepare the plant mixtures for testing, they were first heated in their boxes at 135 ± 5°C (275 ± 9°F) for about 2 hours. The materials were then worked until a loose mixture condition was obtained. Mechanical splitter and quartering methods were used to split the mixtures to the appropriate size for testing in accordance with AASHTO R 47.[3] Mixtures were then dried in the oven at 105 ± 5°C (221 ± 9°F) to constant mass. HMA particles were further separated by hand so that the particles of the fine aggregate portion were no larger than 6.3 mm (¼ in.). The mixtures were then cooled to room temperature before weighing and testing.

The laboratory mixtures were designed according to the Superpave mix design procedure. Non-

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[2] AASHTO T 168-03, Sampling Bituminous Paving Mixtures. In *Standard Specifications for Transportation Materials and Methods of Sampling and Testing,* 30th Ed. (CD-ROM), American Association of State Highway and Transportation Officials, Washington, D.C., 2010.

[3] AASHTO R 47-08, Reducing Samples of Hot Mix Asphalt (HMA) to Testing Size. In *Standard Specifications for Transportation Materials and Methods of Sampling and Testing,* 30th ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.

absorptive limestone-dolomite aggregate and PG 64-22 asphalt were mixed at 157°C (315°F) and short-term conditioned for 2 hours at 145°C (293°F) according to AASHTO R 30.[4] The mixtures then were separated by hand so that the particles of the fine aggregate portion were not larger than 6.3 mm. Samples then were cooled to room temperature before weighing and testing.

The 4.75-mm and 9.5-mm mixtures were prepared in 1,500-g batches. The 12.5-mm mixtures were prepared in 2,000-g batches, and the 19-mm and 25-mm mixtures were prepared in 2,500-g batches. The 37.5-mm mixture also was prepared in 2,000-g batches given that the 4,000-g batch weight required by AASHTO T 209 for 37.5-mm and larger mixes could not fit in the flask or pycnometer. In this respect, four 2,000-g specimens of 37.5-mm mixture were tested, combined into two pairs, and the weight measurements from each of the two specimens per pair were added and served as values for one replicate.

## Measurement of Test Data

$G_{mm}$ 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 (77°F) distilled water then was added to cover the sample completely.

A deviation from the AASHTO T 209 test method was 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 deviation was to examine the effect on the release of air—and thus on the $G_{mm}$—of the order of placement of mixture and water. After adding 0.001% of wetting agent, the container or flask was sealed and subjected to vibration at 27.5 ± 2.5 mm Hg of vacuum for 15 minutes. For three of the mixtures, agitation-vacuum times of 10 minutes, 20 minutes, and 25 minutes also were used with the Gilson vibratory device to examine the effect on $G_{mm}$ of the duration of agitation.

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

$G_{mm}$ was measured using the Corelok vacuum sealing device according to ASTM D6857-09, "Standard Test Method for Maximum Specific Gravity and Density of Bituminous Paving Mixtures Using Automatic Vacuum Sealing Method."[5] The specified weight of loose asphalt mixture was placed in special plastic bags provided for the vacuum sealing device. The bags were sealed and subjected to a vacuum of 4 mm Hg. The weight of the dry sample in air, weight of the bag, and weight of the mixture and bag in water were used to calculate $G_{mm}$ of the mixture.

Table 3 presents the test factorial of the study. The effects of several variables on $G_{mm}$ were evaluated. The effect of vibration intensity on $G_{mm}$ was determined for four shaking devices with variable settings (Humboldt, Gilson, Syntron, and Orbital) and for all nine mixtures, yielding the 32 mixture–device test combinations designated as "a" in Table 3. The effect of measuring device on $G_{mm}$ was evaluated using four of the devices (Corelok, Aggregate Drum Washer, HMA, and Humboldt) with all nine mixtures, two of the devices (Gilson and Orbital) with eight mixtures, and one of the devices (Syntron) with seven mixtures. This evaluation yielded a total of 59 mixture-device test combinations, designated as "b" in Table 3. The comparison of manual and mechanical agitation was performed using four of the devices (Humboldt, Gilson, Orbital, and HMA) with all nine mixtures, yielding the 34 mixture device combinations designated as "c" in Table 3. The effect on $G_{mm}$ of the order of placement of water and mixture in the pycnometer was conducted using three devices with seven mixtures, yielding the 21 mixture-device combinations designated as "d" in Table 3. Finally, the effect of vacuum-agitation duration was deter-

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[4] AASHTO R 30-02, Mixture Conditioning of Hot Mix Asphalt (HMA). In *Standard Specifications for Transportation Materials and Methods of Sampling and Testing,* 30th Ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.

[5] ASTM D6857-09, Standard Test Method for Maximum Specific Gravity and Density of Bituminous Paving Mixtures Using Automatic Vacuum Sealing Method. In *Annual Book of ASTM Standards,* Vol. 4.03, ASTM International, West Conshohocken, PA, 2010.

**Table 3** Experimental plan for evaluation of the effects of various factors on $G_{mm}$ values.

| | Mixtures | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Plant-Produced Dense-Graded | | Plant-Produced Gap-Graded | | | Laboratory-Produced Dense-Graded | | | |
| Device | 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 (%) | 12.5-mm Percent Passing (%) | 25.0-mm Percent Passing (%) | 37.5-mm Percent Passing (%) |
| Humboldt Vibrating Table (H-1756) | 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 Vibrating Table (VP-51 D1) | a, b | a, b | a, b, d | a, b | a, b, d | a, b, d | a, b, d | — | — |
| Orbital Shaker Table (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 (vacuum sealing device) | b | b | b | b | b | b | b | b | b |

a = Change in vibration
b = Equipment evaluation
c = Manual versus mechanical
d = Order of placement (water and mixture)
e = Vacuum/agitation duration

mined using one device (Gilson) and three mixtures, yielding the three mixture-device combinations designated as "e" in Table 3.

## RESULTS AND ANALYSIS

The experimental results were analyzed to determine the effects of the variables discussed in the previous section on $G_{mm}$. The variables included vibration settings of mechanical agitators, agitation type (manual or mechanical), brand of mechanical agitators, order of placement of water and mixture in pycnometer, and the duration of the vacuum/agitation process. The relationship between the vibration properties of vibrating tables and the highest $G_{mm}$ measured by them also was examined.

The significance of the effects of these variables on $G_{mm}$ was evaluated statistically, physically, and from a practical point of view. The physical significance was evaluated by visually observing the change in water cloudiness during agitation. The practical significance was evaluated by estimating the change in air void values resulting from the observed change in $G_{mm}$. The statistical significance was evaluated using either a Scheffé test for multivariate comparisons or a paired *t*-test for two-variable comparisons.

### Vibration Measurements

Using an accelerometer, frequency and acceleration were measured in *x, y,* and *z* directions for the four vibratory devices (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, $KE = \frac{1}{2} mv^2$, where m is the mass of the object and v is the velocity of vibration. The velocity was calculated by integrating the acceleration data over the 10-second period. The energy values in the three directions were then summed to calculate the total kinetic energy. The total energy of vibration of the various shaking tables was compared to examine whether the same energy of vibration would yield the same $G_{mm}$ value.

For the Humboldt device, at each vibration setting, the frequency was the same in the *x, y,* and *z* directions. However, the acceleration and energy were not the same in all directions; they were the highest in the *z* direction and the lowest in the *y* direction. No noticeable change in vibration occurred until Setting 5. The frequency, acceleration, and energy started to increase 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 a maximum kinetic energy of 50 microjoules were achieved at Setting 8 and were maintained through Setting 10.

As with the Humboldt device, for the Gilson device the frequency was the same in the *x, y,* and *z* directions at each vibration setting. Also as with the Humboldt device, the acceleration and energy were most prominent in the *z* direction and least prominent in the *y* direction. The difference between the vibrations imparted by the Gilson and Humboldt devices was in the vibration trends. Although the Humboldt device did not provide any noticeable acceleration up to Setting 5, the acceleration of the 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 a maximum total kinetic energy of 90 microjoules were achieved at the highest setting (Setting 8).

Unlike the previous devices, the Syntron device showed substantial differences in the directional frequencies. At Setting 3 and lower, the *x* and *y* directions were fairly close in magnitude, and the magnitude in the *z* direction was about half of this value. However, from Setting 4 until the peak at Setting 8, the increase in magnitude in the *z* direction was far greater than that of the *x* and *y* magnitudes. Although the frequency 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 at Setting 9 were 76.3 m/s$^2$ and 4,307 microjoules, respectively.

The HMA device operates at a fixed setting. Although the vibration frequencies in the *x, y,* and *z* directions were the same, differences occurred in the directional accelerations and energies. The acceleration and energy in *y* and *z* directions were relatively close in magnitude, but the magnitude in the *x* direction was considerably less. The maximum acceleration and total energy for the HMA device were 26 m/s$^2$ and 1,400 microjoules, respectively.

As the above results show, the vibration properties of the four devices are very different. As shown from the comparison of the total energy from the

Syntron and Humboldt devices, the total energy from one device could be as much as 10 times greater than that from another device. The next sections discuss the effect on $G_{mm}$ of different vibration intensities.

## $G_{mm}$ Measurements at Various Settings of the Vibrating Tables

Four vibratory tables with variable settings were used to evaluate the effect of vibration intensity on $G_{mm}$: the Humboldt Vibrating Table, Gilson Vibro-Deaerator, Syntron Vibrating Table, and Orbital Shaker. Measurements of $G_{mm}$ were made at several settings of the vibrating devices, as well as at zero agitation and manual agitation. A comparison of $G_{mm}$ at various settings would indicate if there was a systematic change in $G_{mm}$ and its variability with change in vibration setting. Although measurements at zero agitation were performed with all four mechanical devices, the manual agitation was only performed with three of the device setups. The Minnesota DOT setup with the Syntron device was not used for manual agitation because it was not practical to strike or shake its bell-jar vacuum chamber.

To examine the physical significance of the vibration intensity, changes in the clarity of water in which the HMA sample was immersed were observed in conjunction with the changes in intensity of vibration. Substantially cloudy water would indicate the occurrence of asphalt stripping due to intensive vibration of the shaking tables.

The practical significance of the change in $G_{mm}$ was examined using the equation

$$V_a = \frac{G_{mm} - G_{mb}}{G_{mm}}$$

where

$V_a$ = air voids,
$G_{mm}$ = theoretical maximum specific gravity, and
$G_{mb}$ = bulk specific gravity.

For calculating the air voids, a $G_{mb}$ that would result in air voids equal to 4% ± 1% was assumed for each mixture. Although a change of more than ±0.5% in air voids is typically significant, in this study a change greater than 0.2% in air voids was considered practically significant, compensating for the potential variability in the measurement of $G_{mb}$, which here was assumed to be a constant for each mixture.

The statistical significance of the difference between values of $G_{mm}$ was examined using a Scheffé test.[6] Whenever multivariate analysis of variance (MANOVA) rejects the null hypothesis, the Scheffé test will find which comparison yielded the significant difference. A Scheffé test was conducted to compare the $G_{mm}$ values that resulted from various settings of each device. The comparison of the computed F from the Scheffé test with the critical F values would determine whether the difference between $G_{mm}$ of each pair of vibration settings was significant.

To determine the optimum vibration setting, the results of both the physical evaluation and the statistical analysis were taken into account. The setting that provided the highest $G_{mm}$ without substantially clouding the water was considered the optimum setting for a device. The statistical tests on $G_{mm}$ and the comparison of the computed air void values were used to select an optimum setting of a device that would result in a $G_{mm}$ that was not significantly different from the highest $G_{mm}$ of the several mixtures.

The significance of the difference between the $G_{mm}$ from manual agitation and the highest $G_{mm}$ obtained with a mechanical device also was evaluated statistically and from a practical standpoint. If this difference was significant, use of manual agitation would not be recommended for that particular mixture.

The following sections discuss the analysis of the results obtained from the four vibrating tables with variable settings.

### *Humboldt Vibrating Table (H-1756)*

The Humboldt Vibrating Table has 11 discrete vibration settings marked 0 to 10. Based on the results of the state DOT survey, Setting 5 (mid-range) and Setting 10 (maximum) are commonly used with the Humboldt device. The $G_{mm}$ of field and laboratory mixtures was measured at various settings of the Humboldt device, and the highest $G_{mm}$ values were compared with the $G_{mm}$ from manual agitation and from the settings commonly used by the states.

*Dense-Graded Field Mixtures.* For the dense-graded 19.0-mm field mixture, measurements were conducted at all 11 settings of the device. For the dense-graded 9.5-mm field mixture, the measurements at Settings 1 through 4 were omitted from the

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[6] *NIST/SEMATECH e-Handbook of Statistical Methods,* available at http://www.itl.nist.gov/div898/handbook/.

analysis because the changes in $G_{mm}$ at these settings with respect to the zero setting were very small. The $G_{mm}$ of the mixtures increased with the increase in the device setting until $G_{mm}$ reached a maximum. Further increases in vibration intensity resulted in decreases of $G_{mm}$. For the 9.5-mm mixture, the highest $G_{mm}$ of 2.512 was achieved at Setting 8, and for the 19.0-mm mixture, the highest $G_{mm}$ of 2.536 was achieved at Setting 7 of the Humboldt device. For the 9.5-mm mixture, $G_{mm}$ from manual agitation (2.506) was equivalent to $G_{mm}$ at Setting 5; for the 19.0-mm mixture, $G_{mm}$ from manual agitation (2.525) was equivalent to $G_{mm}$ from Setting 4.

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

The differences in replicate $G_{mm}$ values at different settings would indicate if there is a relationship between vibration setting and measurement variability. 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.

Calculated air void values were compared to examine the practical significance of differences between the highest $G_{mm}$ and the $G_{mm}$ at settings indicated as important by the state DOT survey. $G_{mb}$ values of 2.404 and 2.422 were assumed for calculating the air voids of the 9.5-mm and 19.0-mm mixtures, respectively. The differences between the air voids from the highest $G_{mm}$ and from the $G_{mm}$ with manual agitation were 0.25% for 9.5-mm mixtures and 0.41% for 19.0-mm mixtures. The differences in air voids between the highest $G_{mm}$ and $G_{mm}$ at mid-range agitation (Setting 5) were 0.24% and 0.22% for 9.5-mm and 19.0-mm mixtures, respectively. Moreover, the differences between the air voids from the highest $G_{mm}$ and the $G_{mm}$ of the maximum setting (Setting 10) were 0.21% and 0.27% for 9.5-mm and 19.0-mm mixtures, respectively. Considering other possible sources 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.

The significance of the differences between $G_{mm}$ measurements from various settings also was evaluated statistically using the Scheffé test. For the 9.5-mm mixture, the comparison of the computed F and the critical F value for a 5% level of significance indicated that the highest $G_{mm}$ value from Setting 8 was significantly different from those of Settings 0 through 5, Setting 10, and manual agitation. The $G_{mm}$ of Setting 8 was not statistically different from those of Settings 6, 7, and 9. For the 19.0-mm mixture, comparison of the computed F with the critical F value indicated that the highest $G_{mm}$ from Setting 7 was significantly greater than those of Settings 0 through 2. The rest of the settings provided $G_{mm}$ that were statistically the same as that of Setting 7.

Based on the results of the statistical analysis and the air voids comparison, manual agitation and the mid-range (Setting 5) and maximum (Setting 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 $G_{mm}$ of Setting 7 was statistically the same as the $G_{mm}$ from manual agitation and the mid-range and maximum settings. This suggests that manual agitation and lower agitation settings would be adequate for measuring $G_{mm}$ of the coarser mixtures.

Given that the water became substantially cloudy at Settings 8, 9, and 10, the possibility of using Setting 7 for the 9.5-mm mixture was investigated. The F values from comparison of $G_{mm}$ at Settings 7 and 8 indicate that Settings 7 and 8 produced not significantly different values of $G_{mm}$ for the 9.5-mm mixture. The difference between the calculated air voids at Settings 7 and 8 is 0.07%, which is not considered practically significant. Based on the small difference in the $G_{mm}$ of the 9.5-mm mixture at Settings 7 and 8, Setting 7 of the Humboldt device is suggested as the optimum operational setting for measuring $G_{mm}$ of 9.5-mm and 19.0-mm dense-graded field mixtures.

*Gap-Graded (SMA) Field Mixtures.* The $G_{mm}$ of the three gap-graded (SMA) mixtures (9.5-mm, 12.5-mm, and 19.0-mm NMAS) were measured using the Humboldt device. Because 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 highest $G_{mm}$ of the 9.5-mm and 12.5-mm mixtures (2.647 and 2.466, respectively) were achieved at Setting 8 and the highest $G_{mm}$ of the 19.0-mm mixture (2.448) was achieved at Setting 9. The $G_{mm}$ of the 9.5-mm and 12.5-mm mixtures with manual agitation were equivalent to those from Setting 5 (2.641 and 2.459, respectively) and the $G_{mm}$ of the 19.0-mm mixture with manual agitation was equivalent to that of Setting 6 (2.439).

Visual observation of the water indicated that for all three mixtures the water remained clear up to Setting 6. At Settings 7 and 8, the water became slightly cloudy, and at Settings 9 and 10, the water became substantially cloudy.

The differences in replicate $G_{mm}$ values at different settings would indicate if there is a relationship between vibration setting and measurement variability. The differences in $G_{mm}$ of two replicates at various settings did not indicate a defined trend as a function of vibration setting. However, the differences between replicate measurements of the 19.0-mm mixture were larger than those of the 9.5-mm and 12.5-mm mixtures. Nevertheless, at every setting of the Humboldt device, the difference between replicate measurements of the three mixtures was less than 0.007, significantly smaller than the acceptable difference between two replicate measurements specified in AASHTO T 209.

The calculated air voids were compared to examine the practical significance of the differences between the highest $G_{mm}$ and $G_{mm}$ of the settings indicated as important by the state DOT survey. $G_{mb}$ 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 difference between air voids from the highest $G_{mm}$ and $G_{mm}$ from manual agitation was in the range of 0.23% to 0.30%; the difference between the air voids from the highest $G_{mm}$ and $G_{mm}$ of mid-range agitation was in the range of 0.23% to 0.45%; and the difference between the air voids from the highest $G_{mm}$ and $G_{mm}$ from the maximum setting (Setting 10) was in the range of 0.05% to 0.20%. Considering other possible sources of variability in determining air voids, using the mid-range settings or manual agitation would most likely provide significantly lower air voids. However, operating the Humboldt device at the maximum setting would produce $G_{mm}$ practically the same as the highest $G_{mm}$.

The significance of the differences between $G_{mm}$ measurements from various settings was evaluated statistically. For the 9.5-mm mixture, comparison of the computed F and the critical F value indicates that, for a 5% level of significance, the $G_{mm}$ values from manual agitation and those of various settings are statistically the same. For the 12.5-mm mixture, the highest $G_{mm}$ of a 12.5-mm mixture from Setting 8 is significantly greater than the $G_{mm}$ from Setting 0, Setting 5, and manual agitation. The rest of the settings provide statistically the same $G_{mm}$ values as that of Setting 8. For the 19.0-mm SMA mixture, the highest $G_{mm}$ of the 19.0-mm mixture from Setting 9 is only significantly greater than the $G_{mm}$ obtained with zero agitation.

Given that water became substantially 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 computed F values also show that the $G_{mm}$ values from Setting 8 and Setting 9 are statistically the same. Therefore, conducting the $G_{mm}$ measurement of the 19.0-mm mixture at Setting 8 is recommended.

Based on the highest achieved $G_{mm}$ of the 9.5-mm and 12.5-mm mixtures at Setting 8 and the small difference between the $G_{mm}$ from Settings 8 and 9 for the 19.0 mixtures, Setting 8 is suggested as the optimum operational setting of the Humboldt device for measuring $G_{mm}$ of the SMA mixtures.

*Dense-Graded Laboratory Mixtures.* The $G_{mm}$ of 4.75-mm, 12.5-mm, 25.0-mm, and 37.5-mm dense-graded laboratory mixtures were measured at Settings 4 through 10 of the Humboldt device. The highest $G_{mm}$ of the 4.75-mm mixture (2.557) was achieved at the maximum setting (Setting 10); the highest $G_{mm}$ of the 12.5-mm mixture (2.580) was obtained at Setting 8; and the highest $G_{mm}$ of the 25.0-mm and 37.5-mm mixtures (2.617 and 2.629, respectively) were achieved at Setting 9 of the Humboldt device. For the 4.75-mm and 12.5-mm mixtures, the $G_{mm}$ from manual agitation (2.548 and 2.572, respectively) are equivalent to the $G_{mm}$ from Setting 5, and for the 25.0-mm and 37.5-mm mixtures, the $G_{mm}$ from manual agitation (2.610 and 2.625, respectively) are equivalent to the $G_{mm}$ from Setting 6. This finding suggests that, for coarser mixtures, manual agitation produces $G_{mm}$ equivalent to those from higher agitation levels than are found for finer mixtures.

The change in water clarity was monitored to examine the physical effect of vibration on the mixtures. The water did not become substantially cloudy at any of the settings. For the four mixtures, water was slightly cloudy at the settings of the highest $G_{mm}$ (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).

The differences in replicate $G_{mm}$ values at different settings would indicate if there is a relationship between vibration setting and measurement variability. For these mixtures, the difference in $G_{mm}$ of two replicates at various settings did not follow a defined trend as a function of vibration setting. At every setting of the device, the difference between replicate measurements was less than 0.005, which is significantly smaller than the acceptable difference between two replicate measurements specified in AASHTO T 209.

The practical significance of the difference between the highest $G_{mm}$ and the $G_{mm}$ of the settings indicated as important by the state DOT survey was examined by evaluating the differences between their corresponding air voids. $G_{mb}$ of 2.444, 2.466, 2.502, and 2.515 were assumed for calculating the air voids of the 4.75-mm, 12.5-mm, 25.0-mm, and 37.5-mm mixtures, respectively. The difference between the air voids that resulted from the highest $G_{mm}$ and those that resulted from manual agitation was 0.30% for the 4.75-mm and 12.5-mm mixtures and 0.24% and 0.15% for the 25.0-mm and 37.5-mm mixtures, respectively. Considering other possible sources of variability in measuring the air voids, these differences could be significant. Therefore, from a practical viewpoint, for obtaining the highest $G_{mm}$ of mixtures, use of manual agitation is not recommended for these dense-graded laboratory mixtures.

For the 4.75-mm, 25.0-mm, and 37.5-mm mixtures, the difference between the highest air voids and those from the mid-range setting (Setting 5) averaged 0.30%, which could be significant. The differences between the highest air voids and those from the maximum setting (Setting 10) averaged 0.03%, which was not practically significant. These numbers suggest that operation of the Humboldt device at its higher settings will achieve the highest $G_{mm}$ for these dense-graded laboratory mixtures.

The significance of the differences between $G_{mm}$ measurements obtained from various settings also was evaluated statistically. Based on a comparison of the computed and critical F values, the differences between the highest $G_{mm}$ and the $G_{mm}$ from manual agitation, Setting 5, and Setting 10 were not statistically significant. However, use of manual agitation and mid-range settings are not suggested for the dense-graded laboratory mixtures because of the potential significance of the differences in air voids.

The possibility of using one vibration setting for all four dense-graded laboratory mixtures also was explored. The highest $G_{mm}$ of each mixture was compared with $G_{mm}$ at the settings that produced the highest $G_{mm}$ of other mixtures. The differences between the air voids of the mixtures resulting from the settings that yielded the highest $G_{mm}$ were below 0.1%, which is considered not significant. Comparison of $G_{mm}$ from Settings 8, 9, and 10 confirmed this finding statistically by providing F values that were smaller than the critical F value.

Based on the highest achieved $G_{mm}$ of the four laboratory mixtures at Settings 8, 9, and 10 and the similarity of the air voids from Settings 8, 9, and 10, Setting 8 is suggested as the optimum operational setting for the Humboldt device for measuring the $G_{mm}$ of the dense-graded laboratory mixtures. At Setting 8, the water was only slightly cloudy.

### *Gilson Vibro-Deaerator (SGA-5R)*

The Gilson device has an adjustable dial that permits a continuous increase of the vibration level. Eight marks, labeled 1 through 8, were made at approximately equal intervals on the dial to represent eight discrete levels of vibration. Based on the results of the state DOT survey, in the state laboratories the Gilson device is commonly operated in its middle to maximum range. The $G_{mm}$ of field and laboratory mixtures were measured at various settings of the Gilson device, and the resulting highest $G_{mm}$ values were compared with the $G_{mm}$ from manual agitation and from the settings commonly used by the states.

*Dense-Graded Field Mixtures.* The $G_{mm}$ of the 9.5-mm and 19.0-mm dense-graded field mixtures were measured at Settings 1 through 8 of the Gilson device, as well as at zero agitation and using manual agitation. The highest $G_{mm}$ (2.515 for the 9.5-mm mixture and 2.536 for the 19.0-mm mixture) were achieved at Settings 6 and 7, respectively. The $G_{mm}$ values from manual agitation were equivalent to $G_{mm}$ values from Setting 3 for both mixtures (2.507 for the 9.5-mm mixture and 2.527 for the 19.0-mm mixture).

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

The differences between two replicate $G_{mm}$ values at various settings of the Gilson device were examined. No defined trend existed between the variability of measurements and the intensity of vibration; however, higher variability was observed at high $G_{mm}$ values for the 19.5-mm mixture. Nevertheless, the difference between replicates at any setting was less than 0.005, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

The practical significance of the difference between the highest $G_{mm}$ and the $G_{mm}$ values obtained from the settings of importance identified in the state DOT survey was examined by comparing the calculated air voids. $G_{mb}$ of 2.404 and 2.422 were assumed for calculating the air voids of the 9.5-mm and 19.0-mm mixtures, respectively. The difference between air voids of the highest $G_{mm}$ and the $G_{mm}$ from manual agitation was 0.31% for the 9.5-mm mixture and 0.35% for the 19.0-mm mixture. Considering other possible 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.

The difference between air voids from the highest $G_{mm}$ and that of mid-range agitation (Setting 4) was 0.23% for the 9.5-mm mixture and 0.11% for the 19.0-mm mixture. This finding suggests that use of the 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 air voids similar to Setting 7.

The results also showed that the difference between air voids from the highest $G_{mm}$ and those from the maximum setting (Setting 8) is 0.07% for the 9.5-mm mixture and 0.24% for the 19.0-mm mixture. This suggests that for finer mixtures, the Gilson device can be operated at maximum setting to achieve air voids similar to those achieved 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.

The significance of the difference between $G_{mm}$ measurements from various settings of the Gilson device also was evaluated statistically. The highest $G_{mm}$ of the 9.5 mm mixture from Setting 6 is significantly different from the $G_{mm}$ at zero agitation and using manual agitation, and significantly different from the $G_{mm}$ yielded by Settings 1 through 4, but it is statistically the same as the $G_{mm}$ from Settings 5 through 8. For the 19.0-mm mixture, the highest $G_{mm}$ from Setting 7 is only significantly different from the $G_{mm}$ yielded by zero agitation and Setting 1. The rest of the settings provide statistically the same $G_{mm}$ as that of Setting 7. This agrees with previous observations that manual and lower vibration levels might provide adequately high $G_{mm}$ values for coarser mixtures.

Given that water was substantially cloudy at Setting 7 and higher, the possibility of using Setting 6 for the 19.0-mm mixture was investigated. It was observed from both air voids values and from statistical results that for measuring the 19.0-mm mixture, lower settings (up to Setting 4) would result in $G_{mm}$ not significantly different from the highest $G_{mm}$. Therefore, Setting 6 can be used for accurate measurement of $G_{mm}$ for both the 9.5-mm and 19.0-mm dense-graded field mixtures.

*Gap-Graded (SMA) Field Mixtures.* The three SMA mixtures of 9.5-mm, 12.5-mm, and 19.0-mm NMAS were tested using the Gilson device. The $G_{mm}$ of the mixtures were measured at Settings 1 through 8. For all mixtures, measurements also were made at zero agitation and using manual agitation. The highest $G_{mm}$ values (2.649, 2.463, and 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 $G_{mm}$ values from manual agitation were equivalent to the $G_{mm}$ values in the range of Settings 3 through 5. Change in water clarity was monitored to examine the physical effect of vibration on the mixtures. 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 substantially cloudy.

The differences between two replicate $G_{mm}$ values at various settings of the Gilson device were examined. No defined trend was found between the variability of measurement and the intensity of vibration; however, the differences between replicates were larger for the 19.0-mm mixtures. Nevertheless, the difference between replicates 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.

The practical significance of the difference between the highest $G_{mm}$ and the $G_{mm}$ from settings of importance identified in the state DOT survey was examined by comparing the calculated air voids. $G_{mb}$

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 difference between the air voids from the highest $G_{mm}$ and the $G_{mm}$ at the maximum setting (Setting 8) is in the range of 0.08 to 0.10, which is not practically significant. At 0.25% for the 9.5-mm mixture and 0.28% for the 19.0-mm mixtures, the differences between air voids from the highest $G_{mm}$ and the $G_{mm}$ from manual agitation could be significant. At 0.39% for the 19.0-mm mixture, the difference between using the highest $G_{mm}$ and using the $G_{mm}$ from mid-range agitation (Setting 4) also could be significant.

The significance of the differences between $G_{mm}$ measurements from various settings of the Gilson device also were evaluated statistically. Based on the computed F values, the highest $G_{mm}$ of the SMA mixtures from Setting 7 was statistically the same as those from manual agitation, from the mid-range setting (Setting 4), and from maximum agitation (Setting 8). Thus, manual agitation, mid-range, and maximum settings would provide statistically the same $G_{mm}$ as that from Setting 7. However, from a practical point of view, the differences between air voids from Setting 7 and those from the mid-range setting and from manual agitation could become significant if the variability of the $G_{mb}$ measurements is considered.

Given that the highest $G_{mm}$ was produced at Setting 7 and water was only slightly cloudy at this setting, Setting 7 of the Gilson device is suggested as the optimum operational setting for the SMA mixtures.

*Dense-Graded Laboratory Mixtures.* The $G_{mm}$ of the 4.75-mm, 12.5-mm, and 37.5-mm dense-graded laboratory mixtures were measured at Settings 1 through 8, at zero agitation, and using manual agitation. The highest $G_{mm}$ of 2.555, 2.580, and 2.631 of the 4.75-mm, 12.5-mm, and 37.5-mm mixtures were achieved at Settings 7, 6, and 6 of the Gilson device, respectively. For all three dense-graded laboratory mixtures, manual agitation resulted in $G_{mm}$ values that were equivalent to or less than the $G_{mm}$ values from Setting 2. 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.

The differences between the two replicate $G_{mm}$ values at various settings of the Gilson device were examined. Although no defined trend was found between the variability of measurement and the intensity of vibration, a smaller variability at the settings of higher $G_{mm}$ was observed for the 12.5-mm mixture. The variability of the 37.5-mm mixture was less than those of the 4.75-mm and 12.5-mm mixtures, which might be attributed to the better release of air from coarser mixtures. Nevertheless, the difference between replicates at any setting was less than 0.005, significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

The practical significance of the difference between the highest $G_{mm}$ and the $G_{mm}$ from settings of importance identified in the state DOT survey was examined by comparing the calculated air voids. $G_{mb}$ 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 $G_{mm}$ and the air voids from mid-range agitation (Setting 4) was in the range of 0.12% to 0.18%. The difference between the air voids from the highest $G_{mm}$ and the air voids from the maximum setting (Setting 8) was in the range of 0.10% to 0.15%. The difference between the air voids from the highest $G_{mm}$ and the air voids from manual agitation was in the range of 0.20% to 0.37%. Therefore, from a practical point of view, the use of $G_{mm}$ from manual agitation could result in significantly lower air voids for compacted mixtures.

The statistical significance of the difference between $G_{mm}$ from various device settings was evaluated using a Scheffé test. A comparison of the computed and critical F values showed that the difference between the highest $G_{mm}$ and the $G_{mm}$ from manual agitation was significant for the 12.5-mm and 37.5-mm mixtures but not significant for the 4.75-mm mixture. Comparison of the highest $G_{mm}$ with the $G_{mm}$ of Settings 4 and 8 revealed that the highest $G_{mm}$ values were 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 suggested.

The possibility of selecting one optimum setting of the Gilson device for the dense-graded laboratory mixtures was investigated. As indicated earlier, for the 37.5-mm mixture, the water was substantially cloudy at Setting 6, so the possibility of using Setting 5 for the three mixtures was examined. The difference between the air voids from Settings 5, 6, and

7 for the three mixtures was less than 0.11%, which is not considered practically significant. This finding is reinforced by the results of the statistical analysis, where the computed F values from comparison of $G_{mm}$ of Settings 5, 6, and 7 were smaller than the critical F value. Considering the small difference between the air voids yielded from Setting 5 and those from Settings 6 and 7, Setting 5 is suggested for the 4.75-mm, 12.5-mm, and 25.0-mm mixtures.

*Syntron Vibrating Table (VP-51 D1)*

The Syntron device can be operated at ten discrete settings (Settings 1 through 10). Based on the results of the state DOT survey, the Syntron device is commonly operated at Setting 5 in state laboratories. During this study, the device was used following the setup used by the Minnesota DOT. Measurements at zero agitation were performed along other settings, but manual agitation was not performed with this device as it is impractical to strike or shake the bell-jar vacuum chamber given this setup. The following results are based on $G_{mm}$ measurements.

*Dense-Graded Field Mixtures.* The highest $G_{mm}$ (2.513 and 2.534 for the 9.5-mm and 19.0-mm mixtures, respectively) were achieved at Setting 7 of the Syntron device. Visual observation indicated that the water remained clear through Setting 4. At Settings 5 through 8 and at Setting 10, the water was slightly cloudy. At Setting 9, the water was substantially cloudy.

Examination of differences between two replicate $G_{mm}$ values at various settings of the Syntron device yielded no defined trends between the variability of measurements and the intensity of vibration. The difference between replicate measurements at any setting was smaller than 0.004, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

The practical significance of the difference between the highest $G_{mm}$ and the $G_{mm}$ from the settings of importance indicated by the state DOT survey was examined by comparing calculated air voids. $G_{mb}$ values of 2.404 and 2.422 were assumed for calculating the air voids of the 9.5-mm and 19.0-mm mixtures, respectively. Air voids resulting from the highest $G_{mm}$ (at Setting 7) were compared with air voids resulting from Setting 5, which is commonly used by the state laboratories. The difference was 0.07% for the 9.5-mm mixture and 0.08% for the 19.0-mm mixture; neither of these differences is considered practically significant.

The significance of the difference between $G_{mm}$ values from various settings also was examined statistically using a Scheffé test. For the 9.5-mm mixture, the differences between $G_{mm}$ values from various settings were not significant. For the 19.0-mm mixture, only the differences between the highest $G_{mm}$ and the $G_{mm}$ from Setting 10 and zero agitation are statistically significant.

Based on achieving the highest $G_{mm}$ and water clarity, Setting 7 is suggested as the optimum operational setting of the Syntron device for measuring $G_{mm}$ of the 9.5-mm and 19.0-mm dense-graded field mixtures.

*Gap-Graded (SMA) Field Mixtures.* The $G_{mm}$ of the 9.5-mm, 12.5-mm, and 19.0-mm SMA mixtures were measured at Settings 1 through 10 of the Syntron device. Measurements also were conducted at zero agitation. The highest $G_{mm}$ 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, respectively. The water appeared clear through Setting 5. At Settings 6 through 8 and at Setting 10, the water became slightly cloudy. At Setting 9, the water was substantially cloudy.

The differences between two replicate $G_{mm}$ values at various settings of the Syntron device yielded no defined trend between the variability of measurement and the intensity of vibration. However, the differences between replicates of the 19.0-mm mixtures were larger than those of the other mixtures. Nevertheless, the difference between replicates at any setting was less than 0.007, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

The practical significance of the differences between the highest $G_{mm}$ and the $G_{mm}$ from the settings of importance indicated in the state DOT survey was examined by comparing calculated air voids. $G_{mb}$ 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 yielded from the mid-range (Setting 5) and the highest $G_{mm}$ were 0.40%, 0.15%, and 0.30% for the 9.5-mm, 12.5-mm, and 19.0-mm mixtures, respectively. Considering other possible sources of variability in measuring air voids, using Setting 5 would likely result in significantly lower air voids than the actual air voids of the 9.5-mm and 19.0-mm compacted mixtures.

The statistical comparison indicated that the highest $G_{mm}$ of the 9.5-mm mixture (from Setting 8) is significantly different from the $G_{mm}$ of Settings 0 through 5. For the 12.5-mm mixture, the only significant differences were found between the highest $G_{mm}$ and the $G_{mm}$ of Settings 0 and 1. For the 19.0-mm mixture, the highest $G_{mm}$ differed significantly from the $G_{mm}$ at Settings 0 through 4, but not significantly from the $G_{mm}$ at Setting 5 and higher. These results suggest that for the 9.5-mm and 19.0-mm mixtures, if the Syntron device is operated at the mid-range setting, the resulting $G_{mm}$ would likely be significantly lower than the highest $G_{mm}$.

The possibility of selecting one setting of the Syntron device for all three mixtures was explored. Comparing the air voids from the highest $G_{mm}$ and the $G_{mm}$ from Settings 7, 8, and 9, the smallest differences occurred between the air voids from the highest $G_{mm}$ and from the $G_{mm}$ of Setting 8 (a maximum of 0.14%). Therefore, Setting 8 can be used for the SMA mixtures without a significant decrease in air voids. This finding is supported by the statistical analysis of the data. F values for comparison of $G_{mm}$ from Setting 8 with $G_{mm}$ from Settings 7 and 9 were lower than the critical F value. Based on these observations, Setting 8 is suggested as the optimum operational setting of the Syntron device for measuring the $G_{mm}$ of the SMA mixtures.

*Dense-Graded Laboratory Mixtures.* Two of the four dense-graded laboratory mixtures were tested with the Syntron device. The $G_{mm}$ of the 4.75-mm and 12.5-mm mixtures were measured at Settings 1 through 10 and at zero agitation. The highest $G_{mm}$ (2.556 and 2.582, for the 4.75-mm and 12.5-mm mixtures, respectively) were achieved at Setting 8. Visual observation indicated that the water remained clear through Setting 4. At Settings 5 through 7 and at Setting 10, the water was slightly cloudy. At Settings 8 and 9, the water was substantially cloudy.

Comparison of the differences between two replicate $G_{mm}$ values at various settings of the Syntron device yielded no defined trend between the variability of measurement and the intensity of vibration. The difference between replicate measurements at any setting was less than 0.005, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

The practical significance of the differences between the highest $G_{mm}$ and the $G_{mm}$ from the settings of importance indicated by the state DOT survey was examined by comparing the calculated air voids. $G_{mb}$ 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 $G_{mm}$ and the air voids from Setting 5, which is commonly used by the state laboratories, were 0.17% for the 4.75-mm mixture and 0.18% for the 12.5-mm mixture. From a practical point of view, these differences are not considered significant.

The significance of the difference between $G_{mm}$ measurements from various settings of the Syntron table also was evaluated statistically. The highest $G_{mm}$ of the two dense-graded laboratory mixtures were not significantly different from the $G_{mm}$ from Setting 5, which is commonly used by the state laboratories. Computed F values also indicated that, for measuring $G_{mm}$ of the dense-graded laboratory mixtures, any setting higher than Setting 3 would yield $G_{mm}$ values that were not statistically different.

Because water became substantially cloudy at Setting 8, the use of a lower setting as the optimum setting was evaluated. Comparing the air voids from Settings 7 and 8 yielded differences smaller than 0.1%, which is not practically significant. This finding also was supported by statistical analysis: Settings 7 and 8 were found to produce statistically the same $G_{mm}$ values. Therefore, based on the clarity of the water and the non-significant differences between the air voids from Settings 7 and 8, Setting 7 is suggested as the optimum operational setting of the Syntron device for measuring the $G_{mm}$ of the 4.75-mm and 12.5-mm dense-graded laboratory mixtures.

### *Orbital Shaker (SHKE 2000)*

The Orbital Shaker has a digital dial for the continuous increase of vibration in the range of 15 to 500 rpm. The measurement of $G_{mm}$ of the dense-graded field mixtures was conducted at nine vibration intensity levels at 30-rpm intervals between 90 and 330 rpm. Measurements also were conducted at zero agitation and using manual agitation. Based on the survey of the state laboratories, 270 rpm is the most commonly used vibration level.

*Dense-Graded Field Mixtures.* For the dense-graded field mixtures, the highest $G_{mm}$ (2.512 and 2.537, for 9.5-mm and 19.0-mm mixtures, respectively) were obtained at vibration levels of 240 rpm and 210 rpm of the Orbital device. The $G_{mm}$ values from manual agitation were equivalent to the $G_{mm}$ values obtained at 150 rpm for the 9.5-mm mixture and at 90 rpm for the 19.0-mm mixture. Visual observation 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 substantially cloudy.

Examination of the differences between two replicate $G_{mm}$ values at various settings of the Orbital device showed no defined trend between the variability of measurement and the intensity of vibration for the 19.0-mm mixture. The difference between replicate values of the 9.5-mm mixture reached a maximum at 180 rpm; nevertheless, for both mixtures, the difference at any setting was less than 0.005, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

The practical significance of the difference between the highest $G_{mm}$ and those from the settings of importance indicated from the state DOT survey was examined by comparing the calculated air voids. $G_{mb}$ values of 2.404 and 2.422 were assumed for calculating the air voids of the 9.5-mm and 19.0-mm mixtures, respectively. Differences between the air voids from the highest $G_{mm}$ and the air voids from manual agitation and at 270 rpm (the level commonly used by the state laboratories) were examined. For the 9.5-mm mixture, the difference between the air voids from the highest $G_{mm}$ and the air voids from manual agitation was 0.18%. For the 19-mm mixture, the difference was 0.27%. Considering the possible variability of the $G_{mb}$ measurements, use of manual agitation might result in significantly lower air voids for the 19.0-mm compacted mixtures.

The differences between the air voids from the highest $G_{mm}$ and the air voids at a vibration level of 270 rpm is 0.11% for the 9.5-mm mixture and 0.16% for the 19.0-mm mixture. For 9.5-mm and 19.0-mm mixtures, vibration at 270 rpm produced air voids that were not significantly different from the highest air void values.

The statistical significance of the difference between the $G_{mm}$ from various settings of the Orbital device was evaluated using a Scheffé test. The differences between the highest $G_{mm}$ (from a vibration level of 240 rpm) and the $G_{mm}$ from other vibration levels or from manual agitation were not significant for the 9.5-mm mixture. For the 19.0-mm mixture, however, the difference between the highest $G_{mm}$ (from a vibration level of 210 rpm) and the $G_{mm}$ from manual agitation was significant.

The possibility of selecting one setting for the Orbital device for both the 9.5-mm and 19.0-mm mixtures was explored. The differences between the air voids at vibration levels of 210 rpm and 240 rpm were 0.05% and 0.11% for the 9.5-mm and 19.0-mm mixtures, respectively. These differences are not considered significant. Statistical analysis also indicated that, for both mixtures, the $G_{mm}$ from vibration levels of 210 rpm and 240 rpm are statistically the same. Therefore, a setting of either 210 rpm or 240 rpm could be selected. Based on observation of a slight level of cloudiness in the water at 240 rpm, use of the higher setting of 240 rpm is suggested as the optimum vibration level at which to set the Orbital device for dense-graded field mixtures.

*Gap-Graded (SMA) Field Mixtures.* The three SMA mixtures (9.5-mm, 12.5-mm, and 19.0-mm NMAS) were tested with the Orbital shaker. Measurements were conducted at nine vibration intensity levels at 30-rpm intervals between 90 rpm and 330 rpm. Measurements also were conducted at zero agitation and using manual agitation. For the 9.5-mm mixture, the highest $G_{mm}$ (2.649) was obtained at a vibration level of 270 rpm; for the 12.5-mm mixture, the highest $G_{mm}$ (2.464) was obtained at 240 rpm; and for the 19.0-mm mixture, the highest $G_{mm}$ (2.449) was obtained at 300 rpm. Manual agitation resulted in $G_{mm}$ values that were equivalent to the values obtained at vibration levels in the range of 90 rpm to 150 rpm. Visual observation indicated that the water remained clear at vibration levels through 150 rpm. From 180 rpm through 240 rpm, water became slightly cloudy, and at 270 rpm and higher, the water became substantially cloudy.

The differences between two replicate $G_{mm}$ values at various settings of the Orbital device showed no defined trend between the variability of measurement and the intensity of vibration. Differences between replicate values at any vibration level were less than 0.007, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

The practical significance of the difference between the highest $G_{mm}$ and the $G_{mm}$ from the settings of importance identified in the state DOT survey was examined by comparing calculated air voids. $G_{mb}$ 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 difference in air voids between the highest $G_{mm}$ and the $G_{mm}$ from manual agitation was 0.17%, 0.24%, and 0.53% for the 9.5-mm, 12.5-mm, and 19.0 mm mixtures, respectively. Considering other possible sources of variability in measuring air voids, using manual agitation would probably provide significantly lower air voids than the actual air voids for the 12.5-mm and 19.0-mm compacted mixtures.

For the 19.0-mm mixture, the difference in air voids between the highest $G_{mm}$ and the $G_{mm}$ at a vibration level of 270 rpm, which is the level commonly used by the states, was 0.03%. For the 12.5-mm mixture, the difference was 0.07%. These differences in air voids are not practically significant.

The significance of the differences between $G_{mm}$ values from various settings of the Orbital device also was examined statistically using F values from a Scheffé test. For the 9.5-mm mixture, the difference between the $G_{mm}$ of any pair of vibration levels was not significant. For the 19.0-mm mixture, the highest $G_{mm}$ from a vibration level of 300 rpm was only significantly different from the $G_{mm}$ from zero agitation and from a vibration level of 90 rpm. For the 12.5-mm mixtures, however, the highest $G_{mm}$ from a vibration level of 240 rpm was significantly different from the $G_{mm}$ from zero agitation, at 90 rpm, and using manual agitation. In summary, based on differences between the air voids, manual agitation is not suggested for the 12.5-mm and 19.0-mm SMA mixtures.

Water was observed to be substantially cloudy at vibration levels of 270 rpm and above. Therefore, the possibility of using a level of 240 rpm for the three SMA mixtures was examined on the basis of differences in air voids between vibration levels at 240 rpm, 270 rpm, and 300 rpm. The differences (0.00% for the 9.5-mm mixture and 0.01% for the 19.0-mm mixture) were not practically significant. This finding was confirmed by the results of statistical analysis. For the 9.5-mm and 19.0-mm mixtures, F values from comparisons of $G_{mm}$ from vibration levels of 240 rpm, 270 rpm, and 300 rpm were smaller than the critical F values. This indicates that a vibration level of 240 rpm can be used for the SMA mixtures without a significant decrease in $G_{mm}$.

*Dense-Graded Laboratory Mixtures.* Three out of four dense-graded laboratory mixtures were tested using the Orbital device. The $G_{mm}$ of the 4.75-mm, 12.5-mm, and 25.0-mm dense-graded laboratory mixtures were measured at nine vibration intensity levels at 30-rpm intervals between 90 rpm and 330 rpm. Measurements also were conducted at zero agitation and using manual agitation. For the 4.75-mm, 12.5-mm, and 25.0-mm mixtures, the highest $G_{mm}$ of 2.556, 2.580, and 2.616 were obtained at the 270, 240, and 300 rpm settings of the Orbital device, respectively. Visual observation indicated that the water remained clear through a vibration level of 150 rpm. From 180 rpm through 240 rpm, the water became slightly cloudy, and at levels of 270 rpm and above, the water became substantially cloudy.

The differences between two replicate $G_{mm}$ values at various settings of the Orbital device showed no defined trend between the variability of measurements and the intensity of vibration. Also, the difference between replicate measurements at any setting was less than 0.005, which is significantly smaller than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

The practical significance of the difference between the highest $G_{mm}$ and the $G_{mm}$ from the vibration levels identified as important from the state survey was examined by comparing calculated air voids. $G_{mb}$ 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 in air voids between manual agitation and the highest $G_{mm}$ were in the range of 0.28% to 0.34%. Such differences suggest that manual agitation of the Orbital shaker flasks could result in significantly lower air voids than the actual air voids of compacted mixtures. The differences in air voids between the highest $G_{mm}$ and the $G_{mm}$ at a vibration level of 270 rpm are 0.04% and 0.10% for the 12.5-mm and 25.0-mm mixtures, respectively. These differences are not considered practically significant.

The differences in $G_{mm}$ of the dense-graded laboratory mixtures using various vibration levels of the Orbital device also were examined statistically using F values from a Scheffé test. For the 4.75-mm mixture, the highest $G_{mm}$ at 270 rpm is statistically the same as the $G_{mm}$ at every other setting. For the 12.5-mm mixture, the highest $G_{mm}$ at 240 rpm differs only from the $G_{mm}$ at zero agitation. For the 25.0-mm mixture, the highest $G_{mm}$ at 300 rpm is significantly different from the $G_{mm}$ at zero agitation through 150 rpm. For the three mixtures, manual agitation produced $G_{mm}$ that were not significantly different from $G_{mm}$ using the mechanical settings. This finding regarding manual agitation disagrees with that based on the calculated air voids discussed in the previous paragraph.

Given that water was substantially cloudy at vibration levels of 270 rpm and above, the possibility of using 240 rpm for the dense-graded laboratory mixtures was explored through an examination of the difference in air voids. Between the highest $G_{mm}$ and the $G_{mm}$ at 240 rpm, the difference in air voids was 0.17% for both the 4.75-mm and 25.0-mm mixtures, which is considered not significant. Statistical analysis also confirmed no significant differences between the $G_{mm}$ at 240 rpm and the $G_{mm}$ at 210 rpm for the 4.75-mm mixture and at 300 rpm for the 25.0-mm mixture. Based on the above observations, a vibration level of 240 rpm is suggested as the optimum setting of the Orbital device for the dense-graded laboratory mixtures.

## Selecting Optimum Device Settings

Previously, the optimum setting of each agitation device was selected for each of the three mixture types. A summary of the settings that resulted in the highest $G_{mm}$ and the device settings suggested for each mixture type are provided in Table 4. The suggested settings were selected based on the evaluation of change in air voids, statistical significance of differences in $G_{mm}$, and observed substantial changes in water clarity. This section explores the possibility of choosing one setting of each device for all mixture types.

As shown in Table 4, using the Humboldt device, the highest values of $G_{mm}$ for the nine mixtures were produced over a range from Setting 7 to Setting 10. Based on the concern with water clarity at Settings 8 and 9, however, 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 the Humboldt device for all mixture types was evaluated by examining the computed F values for the comparison of $G_{mm}$ from Settings 7 and 8. This difference was not significant for any of the mixtures. Therefore, Setting 7 of the Humboldt device can be suggested for all three mixture types.

For the Gilson device, Settings 6 and 7 provided the highest $G_{mm}$ for the three mixture types. Based on the increased cloudiness of the water at Settings 6 through 8, however, 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 types, the results of the Scheffé test comparing the $G_{mm}$ values from Settings 5, 6, and 7 were examined. This analysis indicated that the computed F values for the comparisons of $G_{mm}$ for Settings 5, 6, and 7 were all less than the critical F values. Therefore, Setting 5 of the Gilson device can be recommended for all three mixture types.

For the Syntron device, Settings 7, 8, and 9 provided the highest $G_{mm}$ for the three mixture types. Based on the substantial water cloudiness at Settings 8 and 9, however, Setting 7 was suggested for dense-graded field and laboratory mixtures and Setting 8 was suggested for the SMA mixtures. To explore the possibility of using Setting 7 for all mixture types, the computed F values for the comparison of $G_{mm}$ from Settings 7 and 8 were examined. These differences were not significant for any of the mixtures. Therefore, Setting 7 of the Syntron device is suggested for measuring $G_{mm}$ of all three mixture types.

For the Orbital device, the highest $G_{mm}$ values of the mixtures were obtained using vibration levels in the range of 210 rpm to 300 rpm. Based on the substantial level of water cloudiness at vibration levels of 270 rpm and above, however, a vibration level of 240 rpm was selected for each mixture category.

Table 5 summarizes the suggested settings for the four vibrating devices that have adjustable settings. The table also provides the vibration parameters of the vibrating devices at the suggested settings. The manufacturers can adjust the vibration settings of their devices to these suggested settings to minimize the between-laboratory variability that could result from differences in vibration intensity of the $G_{mm}$ measuring devices.

## Comparison of Devices and Methods

The seven devices and methods listed in Table 1, along with manual agitation, were compared in terms of the highest measured $G_{mm}$ and the variability of the measurements. The highest $G_{mm}$ values of the mixtures were compared statistically and from a practical point of view. The variability of each device was represented by the pooled standard deviations of the $G_{mm}$ measurements from various settings of the device. The variability of manual agitation was represented

**Table 4** Settings yielding the highest $G_{mm}$ of the vibrating devices with variable settings.

| Device | 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 (%) | 12.5-mm Percent Passing (%) | 25.0-mm Percent Passing (%) | 37.5-mm Percent Passing (%) |
| Humboldt Vibrating Table (H-1756) | 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 Vibro-Deaerator (SGA-5R) | 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 Vibrating Table (VP-51 D1) | 7 | 7 | 8 | 7 | 9 | 8 | 8 | — | — |
| Suggested for Syntron | 7 (Cloudy at 9) | | 8 (Cloudy at 9) | | | 7 (Cloudy at 8) | | | |
| Orbital Shaker Table (SHKE 2000) | 240 | 210 | 270 | 240 | 300 | 270 | 240 | 300 | — |
| Suggested for Orbital | 240 (Cloudy at 270) | | 240 (Cloudy at 270) | | | 240 (Cloudy at 270) | | | |

**Table 5** Suggested settings and associated vibration parameters of the four vibrating devices with variable settings.

| Device | Optimum Setting | Frequency, Hz | | | Acceleration, m/s² | | | Energy, microjoules | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *x* | *y* | *z* | *x* | *y* | *z* | *x* | *y* | *z* | Total |
| Humboldt Vibrating Table (H-1756) | 7 | 48.7 | 48.7 | 48.7 | 3.79 | 1.35 | 4.68 | 14.3 | 1.7 | 24.9 | 40.9 |
| Gilson Vibro-Deaerator (SGA-5R) | 5 | 44.3 | 44.3 | 44.3 | 3.95 | 2.71 | 6.05 | 16.1 | 7.5 | 38.8 | 62.4 |
| Syntron Vibrating Table (VP-51 D1) | 7 | 83.8 | 91.4 | 612.2 | 19.13 | 21.67 | 72.32 | 217 | 268 | 2899 | 3384 |
| Orbital Shaker Table (SHKE 2000) | 240 rpm | — | — | — | — | — | — | — | — | — | — |

by the pooled standard deviations from manual agitations using different setups. The results of these comparisons are discussed below.

### *Dense-Graded Field Mixtures*

For the 9.5-mm mixture, the largest difference between $G_{mm}$ from the mechanical devices was 0.003 (between the Orbital and Gilson devices). This difference corresponds to a 0.13% difference in air voids. For the 19.0-mm dense graded field mixture, the largest difference was 0.006, between the Corelok and Orbital devices. This difference in $G_{mm}$ corresponds to a 0.24% difference in air voids. Considering the potential variability due to measurement of $G_{mb}$, the difference between air voids for the 19.0-mm mixture could become significant.

For both dense-graded field mixtures, manual agitation provided the lowest $G_{mm}$. For the 9.5-mm mixture, the largest difference was 0.008 with the Gilson device, which corresponds to a 0.29% difference in air voids. For the 19.0-mm mixture, the largest difference was 0.010 with the Orbital device, which corresponds to a 0.38% difference in air voids. Considering the potential variability due to measurement of $G_{mb}$, these differences between air voids of mechanical devices and manual agitation could become significant.

The F values from the Scheffé test were used to compare the highest $G_{mm}$ of the 9.5-mm and 19.0-mm dense-graded field mixtures obtained from the various devices and methods. The differences between the $G_{mm}$ values from the mechanical devices were not statistically significant. However, the differences in $G_{mm}$ between manual agitation and the mechanical devices were 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, the comparison of air voids and the results of statistical analysis suggest that the mechanical devices produce the same $G_{mm}$ if they are operated at their optimum settings, but that manual agitation produces statistically lower $G_{mm}$ values than the mechanical devices.

An analysis of the standard deviation of the $G_{mm}$ measurements for the 9.5-mm and 19.0-mm dense-graded field mixtures using the various devices and methods found that the highest $G_{mm}$ standard deviations of the mechanical devices were 0.002 and 0.003, which are below the acceptable 1s repeatability standard deviation for a single-operator test condition described in AASHTO T 209. Manual agitation provided either equivalent or smaller standard deviations than the majority of the devices. Between the two mixtures, none of the devices or methods was consistently more variable than the others.

### *Gap-Graded (SMA) Field Mixtures*

For the 9.5-mm, 12.5-mm, and 19.0-mm SMA mixtures, the largest differences in the highest $G_{mm}$ values of the various mechanical devices were 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.

A comparison of the $G_{mm}$ from mechanical and manual agitation shows that manual agitation provides the lowest $G_{mm}$ for the SMA mixtures. For the 9.5-mm mixture, the largest difference was 0.007, which corresponds to a 0.26% difference in air voids. For the 12.5-mm SMA mixture, the largest difference was 0.008, which corresponds to a 0.27% difference in air voids. For the 19.0-mm SMA mixture, the largest difference was 0.011, which corresponds to a 0.43% difference in air voids. Considering the potential variability due to measurement of $G_{mb}$, the differences in $G_{mm}$ between manual and mechanical agitation could be practically significant.

The F values from the Scheffé test were used to compare the highest $G_{mm}$ of the 9.5-mm, 12.5-mm, and 19.0-mm SMA mixtures for the various devices and methods, including manual agitation. The computed F values for comparison of the $G_{mm}$ of the mechanical devices were all below the critical F-value; therefore, the differences between values of $G_{mm}$ for the seven devices and methods listed in Table 1 were not statistically significant. A comparison of manual agitation with the mechanical devices indicates that the differences between manual and mechanical $G_{mm}$ also were 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 for measuring the $G_{mm}$ of SMA mixtures is not suggested.

### *Dense-Graded Laboratory Mixes*

The $G_{mm}$ of the 4.75-mm and 12.5-mm mixtures were measured using all seven Table 1 devices; the $G_{mm}$ of 25.0-mm and 37.5-mm mixtures were measured using five devices. The largest difference in the highest $G_{mm}$ produced by the devices for the 4.75-mm, 12.5-mm, 25.0-mm, and 37.5-mm mixtures was 0.005, 0.006, 0.008, and 0.005, respectively. These differences translate into air voids differences of 0.18%, 0.23%, 0.30%, and 0.20%. Although the $G_{mm}$ of the 4.75-mm and 37.5-mm mixtures from the various devices are not significantly different, for the 12.5-mm and 25.0-mm mixtures, the difference in $G_{mm}$ between at least two devices could become practically significant.

The F values from the Scheffé test were used to statistically compare the highest $G_{mm}$ of the four dense-graded laboratory mixtures as produced by various devices and methods. These F values were all less than the critical F values, suggesting that if the $G_{mm}$ measuring devices are operated at their optimum setting, they should all provide the same $G_{mm}$ value.

The F values for the comparisons of the values of $G_{mm}$ between the seven mechanical devices and manual agitation were all less than the critical F values for the 4.75-mm and 12.5-mm mixtures, indicating that the differences are not statistically significant. For the 25.0-mm mixture, however, the differences between the $G_{mm}$ from manual agitation and that from the HMA Vibrating Table and Orbital Shaker Table are significantly different; for the 37.5-mm mixture, the difference between the $G_{mm}$ from manual agitation and the $G_{mm}$ from the Aggregate Drum Washer is significantly different. In light of the practical significance of the difference in air voids and the statistical significance of the differences between $G_{mm}$ of manual agitation and the $G_{mm}$ of the several mechanical devices, the use of manual agitation for measuring the $G_{mm}$ of dense-graded laboratory mixtures is not suggested.

An analysis of the standard deviations of the $G_{mm}$ measurements of the dense-graded laboratory mixtures using various devices and methods found that the largest standard deviation from the devices is less than 0.004, which is less than the acceptable 1s repeatability standard deviation for single-operator test condition described in AASHTO T 209. No one device consistently produced the highest or the lowest standard deviation.

## Relationship Between Vibration Properties of the Devices and Highest $G_{mm}$

In previous sections, the agitation devices were compared in terms of the highest $G_{mm}$ they produce and the variability of their measurements. It was shown that different mechanical devices produce statistically the same $G_{mm}$ values at their optimum settings. The vibration properties of the devices at their optimum setting also were compared to determine if the same vibration properties produce the same highest $G_{mm}$.

This analysis showed that even though the highest $G_{mm}$ values from various devices and methods are very similar at the setting of the highest $G_{mm}$, the vibration properties of the devices at those settings are very different. For example, the highest $G_{mm}$ of the 19.0-mm dense-graded field mixture measured by four vibratory devices (Humboldt, Gilson, Syntron, and HMA) are in the range of 2.533 to 2.536, while the total kinetic energy of the devices is in a range of 38.3 to 2,854 microjoules. This finding suggests that the energy produced by a device is not necessarily equivalent to the energy transferred to the mixture.

## Relationship Between $G_{mm}$ and Order of Placement of Water and Mixture

The effect on $G_{mm}$ of the order of placement of the mixture and water in the vacuum container was examined. Seven mixtures were each tested twice with three of the devices: once by placing the water first (Water First) and once by placing the mixture first (Sample First). The significance of the difference between the $G_{mm}$ values from the two orders of placement was evaluated by a comparison of the resulting air voids and by the use of the statistical *t*-test.

### *Dense-Graded Field Mixtures*

$G_{mm}$ values were measured for two dense-graded field mixtures using three devices at the settings found to provide the highest $G_{mm}$ values. The resulting air voids were computed using these measured $G_{mm}$ values and assumed $G_{mb}$ values of 2.404 for the 9.5-mm mixture and 2.422 for the 19.0-mm mixture. It was found that placing the water prior to adding the mixture consistently produced higher $G_{mm}$ values. The difference in air voids that resulted from the difference in $G_{mm}$ was as high as 0.23%, as found for the 19.0-mm mixture tested using the HMA or the Humboldt device, or as low as 0.11%, as found for the 9.5-mm mixture tested using the Orbital or Humboldt device.

A paired *t*-test was conducted to evaluate if the mean $G_{mm}$ from the Water First and Sample First procedures were the same. For the 9.5-mm and 19.0-mm dense-graded field mixtures, the computed *t* values from the comparison of the $G_{mm}$ values of the Water First and Sample First methods were 8.07 and 4.786, respectively. Comparing these computed *t* values with the critical *t* value of 2.571 (for a 5% level of significance and 5 degrees of freedom, given 6 measurements) indicates that the Water First method produces significantly higher $G_{mm}$ values than the Sample First method.

### *Gap-Graded (SMA) Field Mixtures*

The $G_{mm}$ of the three SMA field mixtures were measured using three devices at the settings found to provide the highest $G_{mm}$ values. The resulting air voids were computed using these measured $G_{mm}$ values and assumed $G_{mb}$ values of 2.532, 2.357, and 2.339 for the 9.5-mm, 12.5-mm, and 19.0-mm mixtures, respectively. It was found that placing the water prior to adding the mixture consistently produced higher $G_{mm}$ values. On average, the difference in air voids that resulted from the difference in $G_{mm}$ was about 0.2%; however, the difference could be as high as 0.35%, as found for the 19.0-mm SMA field mixture tested using the Syntron device.

A paired *t*-test was conducted to evaluate whether the mean $G_{mm}$ values from the Water First and Sample First procedures were the same. For the 9.5-mm, 12.5-mm, and 19.0-mm SMA mixtures, the computed *t* values of the $G_{mm}$ from the Water First and Sample First methods were 3.636, 4.782, and 4.880, respectively. Comparing these computed *t* values with the critical *t* value of 2.571 (for a 5% level of significance and 5 degrees of freedom, given 6 measurements) indicates that the Water First method produces significantly higher $G_{mm}$ values than the Sample First method.

### *Dense-Graded Laboratory Mixtures*

The $G_{mm}$ of the 4.75-mm and 12.5-mm dense-graded laboratory mixtures were measured using three devices at the settings found to provide the highest $G_{mm}$ values. The resulting air voids were computed using the measured $G_{mm}$ values and assumed $G_{mb}$ values of 2.444 for the 4.75-mm mixture and 2.466 for the 12.5-mm mixture. It was found that placing the water prior to adding the mixture consistently produced higher $G_{mm}$ values. On average, the difference in air voids that resulted from the difference in $G_{mm}$ was about 0.1%; however, the difference was as high as 0.2% for the 12.5-mm mixture tested using the Syntron device.

A paired *t*-test was conducted to evaluate whether the mean $G_{mm}$ from the Water First and Sample First procedures were the same. For the 4.75-mm and 12.5-mm dense-graded laboratory mixtures, the computed *t* values from the Water First and Sample First methods were 7.073 and 3.037, respectively. Comparing these computed *t* values with the critical *t* value of 2.571 (for a 5% level of significance and 5 degrees of freedom, given 6 measurements) indicates that the Water First method produces significantly higher $G_{mm}$ values than the Sample First method.

In summary, this experiment established that the change in $G_{mm}$ as a result of the change in the order of placement of the mixture and water in the vacuum container of the various devices was statistically and practically significant. Therefore, to facilitate the release of air from the mixture and achieve the highest $G_{mm}$, adding water to the vacuum container before placing the mixture is suggested.

## Effect of Vacuum Duration on $G_{mm}$ Measurement

For the purpose of improving accuracy and precision of $G_{mm}$ measurements, the effect of vacuum duration on $G_{mm}$ and its variability was investigated. The three SMA field mixtures were used for this evaluation. Two replicates of each mixture were tested at Setting 6 of the Gilson device for vacuum/agitation durations of 5, 10, 15, 20, and 25 minutes. It was found that $G_{mm}$ increased with the increase in the vacuum/agitation time until a maximum was reached at or about 20 minutes. Increasing the vacuum/agitation time to 25 minutes resulted in a decrease in $G_{mm}$. Visual observation indicated that the water was slightly cloudy after 20 minutes of vacuum/agitation and became substantially cloudy after 25 minutes. Analysis of the variability of the $G_{mm}$ measurements for the five agitation durations indicates that higher variability is usually observed at higher vacuum/agitation durations, but that there was no specific trend of increase or decrease in variability with increasing time.

The significance of the difference between the $G_{mm}$ obtained at various durations of vacuum/agitation should indicate if a higher duration is necessary to produce a more accurate measurement of $G_{mm}$. From a practical point of view, the significance of the difference between the $G_{mm}$ is derived from an evaluation of the difference in air voids. Air voids were calculated using assumed $G_{mb}$ values of 2.532, 2.357, and 2.339 for the 9.5-mm, 12.5-mm, and 19.0-mm SMA mixtures, respectively. The difference between the air voids from 15 minutes of agitation, which is specified in AASHTO T 209, and the air voids from 20 minutes of agitation, which produced the highest $G_{mm}$, was less than 0.1%. This difference is not considered practically significant.

The statistical comparison of $G_{mm}$ values for various vacuum/agitation durations was conducted using a Scheffé test. F values were computed for comparisons of $G_{mm}$ of all combinations of vacuum/agitation durations. Of the computed F values, none was greater than the critical F value of 5.192 (for a 5% level of significance). Therefore, the vacuum/agitation duration does not significantly affect $G_{mm}$.

Based on the above findings, a vacuum/agitation period of 15 minutes appears appropriate for $G_{mm}$ measurement. Although a higher $G_{mm}$ value was measured at 20 minutes of agitation, there was no practical or statistical difference in $G_{mm}$ between 15- and 20-minute durations of vacuum/agitation.

## FINDINGS AND CONCLUSIONS

This report presents the results of research to evaluate the effects of key equipment and methodological variables on the measurement of the theoretical maximum specific gravity ($G_{mm}$) of asphalt mixtures for possible refinement of the AASHTO T 209 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. This section summarizes the findings and conclusions of the research.

The $G_{mm}$ measurements at various settings of the devices evaluated in the research indicated that for each vibratory device, $G_{mm}$ of the mixture increases with the increase in intensity of vibration until the highest $G_{mm}$ of the mixture is reached. From that point on, a further increase in vibration intensity resulted in a decrease in $G_{mm}$. This phenomenon may be related to stripping of the asphalt.

$G_{mm}$ values from manual agitation were always smaller than the highest $G_{mm}$ values from mechanical agitation devices. In most cases, manual agitation produced $G_{mm}$ values that were equivalent to $G_{mm}$ produced by the mid-range intensity settings of the mechanical devices. The results of the statistical analysis indicated that for four out of nine mixtures tested in the research, 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 from mechanical devices ranged from 0.2% to 0.4%, which could be practically significant. Therefore, use of manual agitation for the measurement of $G_{mm}$ is not suggested.

Investigation of the change in $G_{mm}$ resulting from change in the device type indicated that, statistically, the differences between the $G_{mm}$ of the nine mixtures measured using 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 should produce $G_{mm}$ values that are statistically the same. Even devices with a single, constant setting (HMA Vibrating Table, Aggregate Drum Washer, and Corelok) would produce $G_{mm}$ values that are statistically the same as the $G_{mm}$ values produced by the optimum settings of vibrating devices with variable settings.

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 greater than 0.2%, which could be practically significant. Differences between the air voids measured by a state DOT and by a contractor using a different vibrating device could impact the acceptance of a project. Therefore, it is proposed that the same method and apparatus used for measuring $G_{mm}$ for a mix design be used for quality assurance testing of that mix during production.

The relationship between the energy of vibration and the highest $G_{mm}$ produced by a device indicated that, although the highest $G_{mm}$ values from various vibrating devices were very similar, the vibration properties of the mechanical devices were very different. For example, the $G_{mm}$ values measured using Syntron and Humboldt devices are comparable, but the kinetic energy of the Syntron table is two orders of magnitude greater than that of the Humboldt device. It is speculated that the amount of energy produced by a device is not necessarily the same as the amount of energy transferred to the mixture.

In selecting the optimum setting for each device, it was found that the variability of $G_{mm}$ was not a defining factor as there was no correlation between measured $G_{mm}$ and the vibration settings. For all $G_{mm}$ measurements, the difference between replicate measurements at any setting was smaller than 0.007, which is much less than the acceptable difference between two replicate measurements as specified in AASHTO T 209.

The change in $G_{mm}$ values arising from changing the order of placement of water and mixture in the vacuum container indicated that adding the mixture to water produced higher $G_{mm}$ values. Statistical analysis of $G_{mm}$ values and evaluation of the computed air voids confirmed the significance of the increase in $G_{mm}$ 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 proposed that AASHTO T 209 be revised to specify placing the water in the vacuum container prior to adding the mixture.

The effect on $G_{mm}$ of duration of vacuum/agitation of the three SMA mixtures indicated that $G_{mm}$ increased with increasing the vacuum/agitation time until the highest $G_{mm}$ was achieved, after a 20-minute vacuum/agitation period. Further increase of the vacuum/agitation duration resulted in a decrease of $G_{mm}$. Although the highest $G_{mm}$ was obtained after the 20-minute vacuum/agitation period, statistical analysis of $G_{mm}$ values and evaluation of the air voids indicated that the difference in $G_{mm}$ and air voids between the 15-minute and 20-minute agitation periods was not significant. In addition, the variability of measurements was slightly greater after 20 minutes than after 15 minutes of vacuum/agitation. Therefore, it is suggested that the 15-minute vacuum/agitation time specified in T 209 be maintained.

Based on the data gathered in the study, several proposals are made related to the optimum settings of four vibration devices. Table 5 provides the proposed settings and their corresponding vibration properties.

For the Humboldt device, the highest $G_{mm}$ of the nine mixtures were produced over the range of Settings 7 to 10. Based on the concern with water clarity at Settings 8 through 10, however, and given the lack of significant difference between the $G_{mm}$ from those settings and Setting 7, Setting 7 was selected as the optimum setting of Humboldt device.

For the Gilson device, the majority of the highest $G_{mm}$ measurements occurred at Settings 6 and 7; however, the occurrence of substantial cloudiness at Settings 6 and above resulted in selecting Setting 5 as the optimum setting.

For the Syntron device, a few optimum readings occurred at Setting 8; however, based on issues with water cloudiness at higher settings and given a lack of significant differences in $G_{mm}$ between Setting 7 and Setting 8, Setting 7 was selected as optimum.

For the Orbital device, the highest $G_{mm}$ were obtained at vibration levels in the range from 210 rpm to 300 rpm. Based on increasing water cloudiness at higher settings, however, a vibration level of 240 rpm was selected as optimum for the Orbital device.

Laboratories are advised to adjust their vibration devices to the settings recommended in Table 5 to ensure accurate measurement of the $G_{mm}$ of their asphalt mixtures. Finally, agencies should note that any proposed changes to the current test procedures resulting from this research may result in increased $G_{mm}$ values that can or will affect air voids of laboratory- and field-compacted specimens. Agencies should consider the effect of such changes on acceptance criteria and pay factors in their specifications.

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