NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP)

Project 20-07/Task 391

Energy Criteria for Maintaining Fully Animated Particles of Loose Asphalt in AASHTO

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CHAPTER 1 Introduction

Problem Statement

The American Association of State Highway and Transportation Officials (AASHTO) T 209 test procedure is used to determine the theoretical maximum specific gravity (G_{mm}) and density of an uncompacted asphalt mix. The G_{mm} is required to calculate key properties used for mix design and construction quality control of asphalt mixtures. The basic process consists of determining the ratio of weight of a unit volume of a loose asphalt mix sample to the weight of an equal volume of water at the same temperature. G_{mm} is used to calculate the laboratory air voids in the mixture during mix design and production and is used to specify and control the compaction of asphalt mixture in the field. Both of these properties must be closely controlled to ensure production of a satisfactory asphalt mixture. The air voids criteria indirectly controls the amount of asphalt binder added to the mixture, which is necessary for producing a mixture with acceptable stability and durability. The in-place density criterion directly controls the in-place air voids and is essential for ensuring long term durability.

Research conducted in NCHRP Project 10-87(01), "Precision Statements for AASHTO Standard Methods of Test," found that the difference in calculated air voids when using G_{mm} values measured after manual and mechanical agitation was in the range of 0.2% to 0.4%. Since air voids are normally controlled within 3% to 5%, deviations of 0.2% to 0.4% can be significant and can affect decisions about the acceptability of a mixture. In addition, the study indicated that analysis of the AMRL Proficiency Sample Program demonstrated that mechanical agitation provides less variability in the test results than manual agitation; therefore, the use of manual agitation was not recommended. The latest version of the AASHTO T 209 standard includes different precision statements based on the agitation method (mechanical vs. manual).

AASHTO T 209, test Method A using mechanical agitation states "agitate the container and contents using the mechanical device during the vacuum period," but no other information is given regarding the mechanical device to be used for removing entrapped air from the asphalt mix. Project NCHRP 10-87 (01) evaluated the use of different mechanical shakers and vibratory parameters of the shakers to determine an optimum vibration intensity of the devices, but the study did not evaluate the level of agitation to set individual particles in motion for the duration of the test.

Original Project Objective

The original objective of this research was to establish criteria for sample mechanical shaking in AASHTO T 209 that assures measurement of true G_{mm} values. The criteria shall include: 1) the optimum amplitude and frequency required to obtain full animation of the mix sample particles for each unique mix sample, 2) adjustments to the amplitude and frequency required to prevent settling of the particles throughout the duration of the test, and 3) adjustments to the specified vacuum range to compensate for the added mechanical energy, if necessary.

Although some recommendations regarding optimum equipment setting are presented in this report, during the execution of this project, it was not possible to accomplish the original objectives using the current equipment available. Therefore, the remainder of the project focused on exploring solutions to make improvements to the test procedure related with the effect of changing the duration of the vacuum process on G_{mm} measurements.

CHAPTER 2 Background

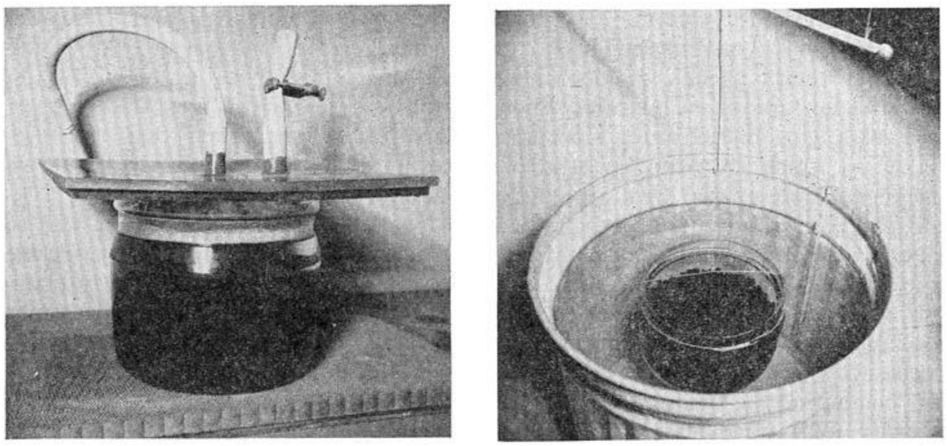
The theoretical maximum specific gravity (G_{mm}) of an uncompacted asphalt mix is required to calculate key properties used for mix design and construction quality control of asphalt mixtures. The basic process of measuring G_{mm} consists of determining the ratio of weight of a unit volume of a loose asphalt mix sample to the weight of an equal volume of water at the same temperature. G_{mm} is required to calculate the laboratory air voids in the mixture during mix design and production and to specify and control the compaction of asphalt mixture in the field. Both properties must be closely controlled to ensure production of satisfactory asphalt mixtures. The air voids criterion indirectly controls the amount of asphalt binder added to the mixture which is necessary for producing a mixture with acceptable stability and durability. The in-place density criterion directly controls the in-place air voids and is essential for ensuring long term durability of the pavement.

The Federal Highway Administration (FHWA) suggested that the effect of G_{mm} on air voids can be analyzed with the following approximate relationships using Equation 1 (FHWA, 2010). If the bulk specific gravity of a compacted asphalt mixture (G_{mb}) is kept constant, when G_{mm} changes by +0.01, air voids typically change by approximately +0.4%. Note that the exact difference will depend on the initial value of G_{mm}. Using this approximation, it is very likely that the current precision estimate for G_{mm} specified in AASHTO T 209 could allow a difference in air voids of +/0.4% or even higher. This is a significant error when the air voids are typically controlled between 3 and 5 percent.

$$V_a = \left(1 - \frac{G_{mb}}{G_{mm}}\right) * 100 \quad (1)$$

Development and Evolution of G_{mm} Test Procedure

The procedure of measuring the G_{mm} of an uncompacted asphalt mix was first developed by Rice in the 1950s and is widely referred to as the Rice method (Rice, 1956). The test procedure is briefly described as follows. A 1000g sample of loose asphalt mix is weighted, placed in a Pyrex bowl, and submerged under water containing a detergent or wetting agent, as shown in Figure 1(a). The bowl is then sealed with a cover equipped with a rubber gasket and hose connections. A vacuum is applied to the container to reduce the air pressure to 3 cm of mercury or less and is maintained for 10 to 30 minutes. During this period, the container is agitated using a mechanical shaker to facilitate the release of entrapped air in the loose mix. The procedure also allows for manual agitation of the container at intervals of about 2 min. Finally, the bowl and the mix are weighed in water at 77°F, as shown in Figure 1(b). The G_{mm} of the loose mix is calculated by dividing the dry weight of the mix by the difference between the weight in air and weight in water. In the same study, Rice also evaluated several variables that could affect the G_{mm} results, which included the container used for evacuating mix, evacuation time and pressure, time and temperature of water immersion, weight determinations, check tests, and correction for water absorption.



(a) (b)

Figure 1. Original G_{mm} Test Procedure; (a) Applying Vacuum to Remove Entrapped Air, (b) Weighing the Bowl and Mix in Water.

Although the Rice method was quick and sensitive, its repeatability and reproducibility had been questioned and was oftentimes considered unacceptable, especially when high absorptive aggregates were used in the mixture. The American Society for Testing and Materials (ASTM) standard method D2041-90, which was developed primarily based on the work by Rice (1956), specified a minimum vacuum level of 30 mm of Hg or less. However, such a high vacuum level increased the potential of aggregates to absorb water, which consequently resulted in inaccurate G_{mm} values. To overcome this deficiency, the ASTM procedure suggested the use of a supplemental procedure for testing asphalt mixtures containing high absorptive aggregates. However, this procedure was time-consuming, susceptible to testing errors, and lacking in repeatability and reproducibility criteria.

Due to the abovementioned issues, Kandhal and Khatri (1992) conducted a study with an overall objective of refining the Rice test method. The study tested two aggregates (one limestone with 0.38% water absorption and one granite with 1.68% water absorption) and one asphalt binder. The study consisted of two phases. Phase I was to determine the optimum levels of three factors in the main test procedure: temperature, residual pressure, and vacuuming time. Only the low absorptive limestone aggregate was tested in this phase to avoid the supplemental procedure of the Rice method. For each of three factors evaluated, three distinct levels were included, resulting in a total of 27 test combinations. An analysis of variance (ANOVA) was conducted on the test results and found that all three factors were statistically significant. The optimum level of each factor was identified as that that yielded the maximum G_{mm} value.

The focus of Phase II was to refine the supplementary test procedure using the high absorptive granite aggregate. Only two factors, residual pressure and vacuum time and their two-way interaction, were evaluated. A total of nine test combinations were tested that included three levels for the factor of residual pressure and three levels for the factor of vacuuming time. ANOVA analysis of the test results indicated that the factor of residual pressure and its two-way interaction with vacuuming time were statistically significant. The two criteria used to identify the optimum levels of factors in this phase were: (1) maximizing the G_{mm} values before running the supplementary procedure, and (2) minimizing the difference in G_{mm} values before and after running the supplementary procedure.

At the completion of the study, the following optimum levels of factors were selected: 77°F for temperature, 30 mm Hg for residual pressure, and 15 minutes for vacuuming time. In addition, several revisions and additions to the ASTM standard method D2041-90 were proposed accordingly. Finally, the study concluded that using these optimum levels could minimize the difference between the G_{mm} values obtained before and after the supplementary procedure and might even possibly eliminate the need of the supplementary procedure for absorptive aggregates.

The AASHTO standard method T 209-12 is the most updated test procedure for measuring the G_{mm} and density of a hot asphalt mix (HMA). To conduct the test, a dry mass of a loose mix sample is placed in a container, its weight is determined, water is added to completely cover the sample, and a vacuum is applied gradually until the pressure reads 3.7 ± 0.3 kPa. The vacuum is maintained for 15 ± 2 minutes while the container is agitated either manually or mechanically to remove entrapped air. The mass of the sample can then be determined in water or in air and the theoretical specific gravity can be calculated. If there is air in the sample when weighed, the G_{mm} results will not be accurate. Hence, it is essential that best procedures are used to remove the air from the sample during vacuum and agitation.

Table 1 presents the AASHTO precision estimates for G_{mm} measurements, which include separate single-operator and multi-laboratory precision values for both mechanical and manual agitation methods. As shown, the mechanical agitation method is more consistent (i.e., less variable) than the manual agitation method, as indicated by lower standard deviation (1s) and acceptance range of two test results (d2s) values.

Table 1. AASHTO T 209-12 Precision Estimate for G_{mm} Measurements.

Method	Standard Deviation (1s)		Acceptable Range of Two Test Results (d2s)	
	Single-operator	Multi-laboratory	Single-operator	Multi-laboratory
Mechanical Agitation	0.0051	0.0084	0.014	0.024
Manual Agitation	0.0064	0.0103	0.018	0.029

State Agency Methods of Measuring G_{mm}

As part of the National Cooperative Highway Research Program (NCHRP) Project 10-87, a survey of state highway agencies was conducted to identify the most commonly used test devices and methods for measuring G_{mm} of HMA. Among the 35 survey respondents, 24 states (including FHWA) used AASHTO T 209 or a modified version of it, and 11 states (including one Canadian province) used state test methods (Figure 2). Table 2 provides a summary of modifications to the AASHTO procedure made by selected state highway agencies.

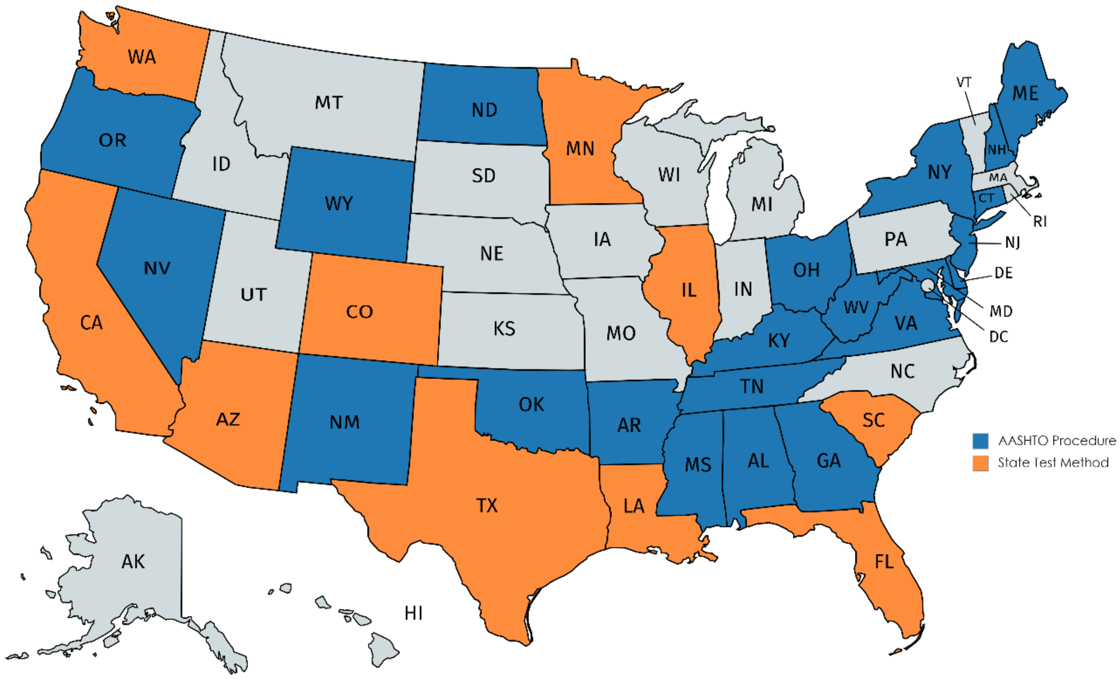


Figure 2. State Agency Methods of Measuring G_{mm}.

Table 2. Modifications to AASHTO T 209 Procedure for Measuring G_{mm}.

Arizona	• Vacuum with a minimum of 20 mm Hg • Manually agitate the container only three to four times during the vacuum period • Weigh the sample immediately after the agitation period is complete
Florida	• Vacuum with 30 ± 2 mm Hg • Use an orbital shaker table to provide agitation
Idaho	• Measure dry mass of the sample by taking the difference in weights of flask and cover with and without the sample • Require the use of petroleum gel to seal the container and the lid
Illinois	• Vacuum with 30 ± 2.5 mm Hg
Indiana	• Allow both mechanical and manual agitation methods
Minnesota	• Require the use of a cylindrical screen and a vacuum desiccator within the container • Dry field sample to a constant weight at 110 ± 5°C • Measure dry mass of the sample by taking the difference in weights of container and screen with and without the sample • Require the use of a wetting agent before and after the agitation and for determining the calibrated weight of the container
New Mexico	• Require simultaneous manual (using a rubber mallet) and mechanical agitation
North Dakota	• Agitate the container for 15 minutes ± 30 seconds • Submerge the container in water for 10 minutes ± 30 seconds • Use an orbital shaker to provide agitation
Ontario (CA)	• Vacuum with 30 ± 1 mm Hg
Washington	• Require simultaneous manual (using a mallet) and mechanical agitation

29 out of the 35 states that responded to the survey used mechanical agitation during the vacuum period and the rest used manual agitation. However, the brand and model of agitators used

for mechanical agitation varied significantly among the laboratories. The two most common devices were the Humboldt and Gilson. Even for laboratories that used the same brand and model of agitators, the frequency setting also varied. Some laboratories used the middle level while others set the frequency level of the agitators at the maximum or minimum. Overall, there was no established guidance on the selection of frequency level for mechanical agitation.

Summary of NCHRP Project 10-87

NCHRP Project 10-87 was a comprehensive study that was undertaken to evaluate the effect of using various test devices and methods on G_{mm} measurements (Azari, 2010). Specific objectives of the project were to: (1) compare the G_{mm} from manual and mechanical devices, (2) investigate the relationship between the measured G_{mm} and the vibration properties of the mechanical vibratory tables and determine an optimum vibration intensity of the vibrating devices, and (3) evaluate the effect of several variables on G_{mm} measurements, such as the order of placing water and mixture and the period of vacuum and agitation.

The project included seven test devices based on the survey responses of state highway agencies mentioned above, including Gilson SGA-5R, Humboldt H-1782, Syntron Shaking Table, HMA Lab Supply VA-2000, Orbital Shaker Table (SHKE 2000 table), Aggregate Drum Washer, and the Corelok Vacuum Sealing Device. The mechanism used in most of these devices is a vibratory action, which is usually specified in terms of speed of vibrations per minute (VPM) and frequency of the power motor in Hertz (Hz). The vibratory action used in these devices is achieved with the use of an eccentric rotating mass motor. These motors have a small eccentric weight attached to the shaft that produces a centrifugal force when they rotate. This force causes displacement of the motor and attached frame at high speed, resulting in vibrations. The force of vibration in these motors is given by Equation 2.

$$F = m * e * w^2 \qquad (2)$$

Where: *F* is the force, *m* is the mass of the eccentric mass on the motor, *e* is the eccentricity of the eccentric mass, and *w* is the speed of the motor.

The vibration frequency and amplitude are dependent upon the speed of the motor; therefore, one cannot vary vibration frequency and amplitude independently. From this equation it can be observed that a bigger offset from the shaft or a larger eccentric mass will produce more force, and hence, more vibration amplitude.

It is important to consider that the vibration force of the motor doesn’t take the target mass (vacuum container and loose asphalt mix) into consideration and the effect of the system, motor, plus mechanical shaker device on the actual vibration of the target mass must be evaluated. A heavier target mass will require more force to generate the same acceleration when compared to a smaller mass; therefore, a vibrating device under specific vibration settings may keep one sample of asphalt mixture fully animated during testing but may not keep a larger sample fully animated.

Each test device was set up in compliance with the testing arrangement specified in AASHTO T 209, which is graphically illustrated in Figure 3. A total of nine asphalt mixtures were tested, with four prepared in the laboratory and five sampled from the field. Three out of the nine mixtures were gap-graded stone matrix asphalt (SMA) mixes, and the rest were dense-graded mixes. The nominal maximum aggregate size (NMAS) of the mixtures ranged from 4.75 mm to 37.5 mm.

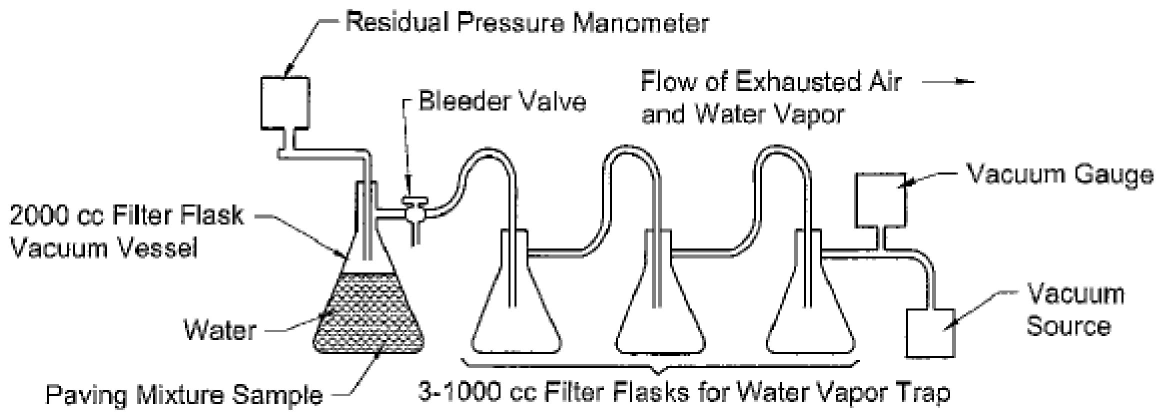


Figure 3. Example of G_{mm} Testing Arrangement as Illustrated in AASHTO T 209.

To accomplish the objectives of the project, five separate experiments were conducted. The first experiment was on the effect of vibration intensity on G_{mm}. It included four test devices and nine asphalt mixtures, resulting in a total of 36 test combinations. The second experiment was on the effect of measuring device on G_{mm} and included 56 mixture-device test combinations. The third experiment was on the comparison of manual and mechanical agitation and used the same 36 test combinations as the first experiment. The fourth experiment was on the effect of the order of placing water and mixture in pycnometer on G_{mm} measurements. It included three test devices and seven asphalt mixtures, resulting in a total of 21 test combinations. Finally, the fifth experiment was on the effect of vacuum/agitation period using three mixture-device test combinations. Test results and key conclusions of each experiment are briefly discussed in the following subsections.

Experiment 1 on Vibration Intensity

In this experiment, G_{mm} measurements were conducted using four test devices with various vibration intensities. In order to determine the optimum setting for each unit, the acceleration and frequency in the x, y, and z axes of the vibrating tables were measured using a triaxial accelerometer, a data acquisition system, and analysis software. The accelerometer was attached to the top of the vacuum container lid to measure frequency and acceleration of the vibration. The frequency and acceleration data were collected for 10 seconds at 5 minutes into the 15-minute agitation period. Using the acceleration measurements, the kinetic energy of the vibration was computed using Equation 3. The total kinetic energy was calculated as the sum of the energy values in the three directions.

$$KE = 1/2 \times m \times v^2 \quad (3)$$

Where: *m* is the mass of the object, and *v* is the velocity of vibration.

Test results were analyzed to determine if there was a systematic change of G_{mm} and its variability with change in vibration setting. During the test, the clarity of water in the pycnometer was closely monitored to assess asphalt stripping due to excessively intensive vibration. Figure 4 presents an example of the G_{mm} results of a 9.5mm NMAS dense-graded mixture measured using the Humboldt device. As shown, the G_{mm} value generally increased with an increase in the vibration setting until reaching a maximum value. After that, the G_{mm} value decreased as the vibration setting increased. It was speculated that this occurrence may be caused by stripping of the asphalt binder from the aggregate. In this example, the maximum G_{mm} value occurred at the vibration setting of 8. A similar trend was observed for the majority of mixture-device combinations, although the vibration setting with the maximum G_{mm} value varied from mixture to mixture and from device to device.

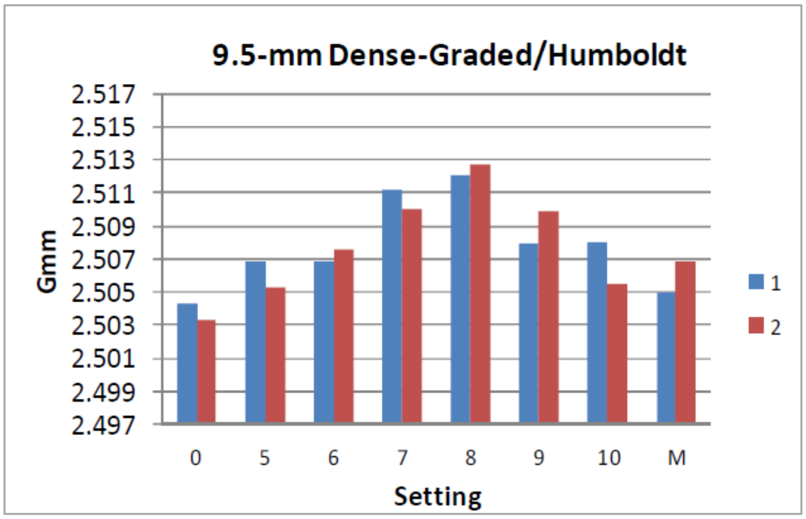


Figure 4. Example of G_{mm} Results of a 9.5mm NMAS Dense-Graded Mixture using Humboldt Device (Azari, 2010).

The researchers indicated that at every setting of the vibratory devices, the difference between replicates was smaller than 0.005 for most cases, which is significantly smaller than the acceptable difference between replicate results as specified in AASHTO T 209. Nonetheless, when the practical significance of the difference between the highest and lowest measured G_{mm} values were compared, based on its effect on air voids, the difference was as high as 0.4% as presented in Figure 5.

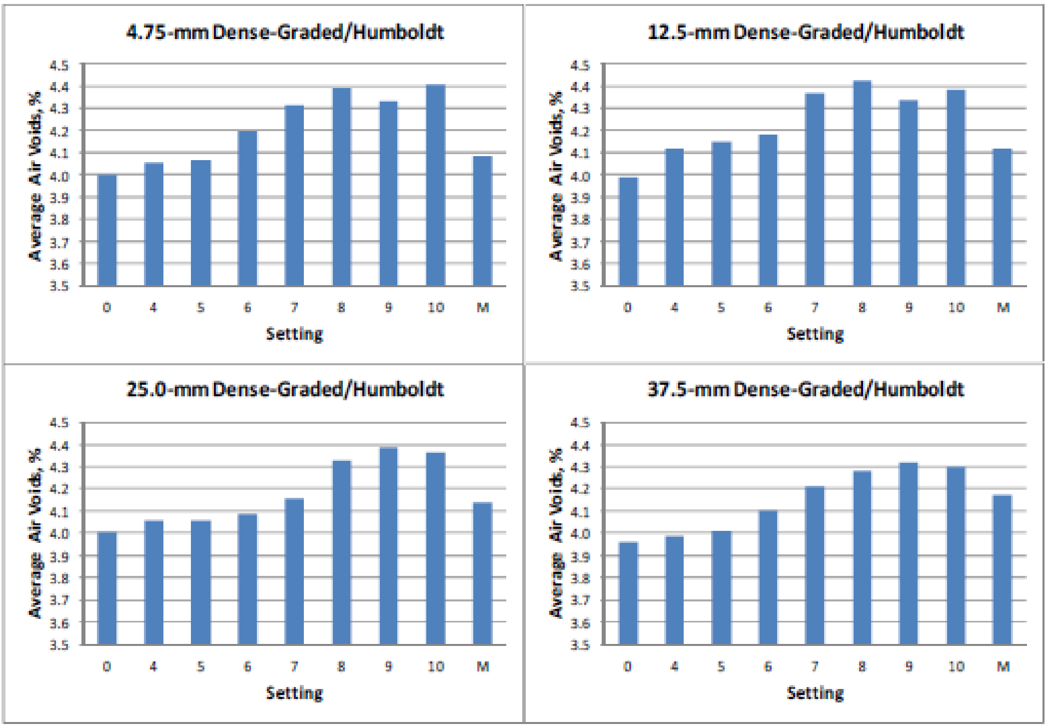


Figure 5. Air Voids of Dense-Graded Laboratory Mixtures at Various Settings for the Humboldt Device (Azari, 2010).

It was also suggested that despite the fact that the highest measured G_{mm} values for different devices were very similar, the vibration properties of the devices, such as the kinetic energy measurements, were very different. This indicates that a wide range of devices should be acceptable for use in measuring $G_{mm.}$ It was speculated by Azari that the amount of energy produced by a device is not the same as the amount of energy transferred to the mixture.

For each test device, the optimum vibration setting was identified based on the statistical comparison of the G_{mm} results and the physical evaluation of the clarity of water during the test. Specifically, the vibration setting that yielded the highest G_{mm} without significantly muddling the water in the pycnometer was considered the optimum. Table 3 presents a summary of the test results. The recommended optimum vibration settings for the four test devices evaluated in the experiment were selected as follows: 7 for Humboldt, 5 for Gilson, 7 for Syntron, and 240 rpm for Orbital.

Table 3. Setting Yielding the Highest G_{mm} of the Mechanical Shakers with Variable Setting (Azari, 2010).

Device	Mixtures								
	Plant-Produced Dense Graded		Plant-Produced Gap- Graded			Laboratory-Produced Dense-Graded			
	9.5 mm Percent Passing	19 mm Percent Passing	9.5 mm Percent Passing	12.5 mm Percent Passing	19 mm Percent Passing	4.75 mm Percent Passing	12.5 mm Percent Passing	25 mm Percent Passing	37.5 mm Percent Passing
Humboldt (H-1756)	8	7	8	8	9	10	8	9	9
Suggested for Humboldt	7 (cloudy at 8)					8 (No significant cloudiness)			
Gilson (SGA-5R)	6	7	7	7	7	7	6	-	6
Suggested for Gilson	7 (cloudy at 8)		7 (cloudy at 8)			5 (cloudy at 8, 7, and 6, respectively)			
Syntron (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 (SHKE 2000) (rpm)	240	210	270	240	300	270	240	300	-
Suggested for Orbital (rpm)	240 (cloudy at 270)								

Measurements of frequency and acceleration at the optimum setting are presented in Table 4. Although the study recommended optimum setting by device type, no recommendation was provided in terms of actual vibration parameters such as amplitude and frequency.

Table 4 Suggested Setting and Parameters of the Mechanical Shakers with Variable Settings (Azari, 2010).

Device	Optimum Setting	Frequency, Hz			Acceleration, m/s^2			Energy, microjoules			
		x	y	z	x	y	z	x	y	z	Total
Humboldt (H-1756)	7	48.7	48.7	48.7	3.79	1.35	4.68	14.3	1.7	24.9	40.9
Gilson (SGA-5R)	5	44.3	44.3	44.3	3.95	2.71	6.05	16.1	7.5	38.8	62.4
Syntron (VP-51 D1)	7	83.8	91.4	612.2	19.13	21.67	72.32	217	268	2899	3384
Orbital (SHKE 2000)	240	-	-	-	-	-	-	-	-	-	

Experiment 2 on Test Device

No statistically significant difference was found among the G_{mm} results measured using the four test devices evaluated in the experiment. Therefore, all test devices should provide comparable G_{mm} results when operated at their optimum vibration settings. Nevertheless, for three out of nine mixtures, the difference in the calculated air voids using the G_{mm} results of at least two devices were more than 0.2%, which was considered practically significant for the acceptance of a project. Therefore, it was recommended that contractors and agencies should use the same test device and setting to measure G_{mm} during mix design and quality control and quality assurance throughout a project.

Experiment 3 on Agitation Method

The comparison on agitation method indicated that in most cases the G_{mm} results from manual agitation were lower than those from mechanical agitation at the optimum vibration setting. For four out of nine mixtures evaluated in the experiment, the difference in G_{mm} from the two agitation methods was found statistically significant. In addition, the difference in the calculated air voids using the G_{mm} results from manual and mechanical agitation was in the range of 0.2% to 0.4%, which was considered practically significant. Therefore, the use of manual agitation for measuring G_{mm} was not recommended.

Experiment 4 on Order of Placing Water and Mixture

The order of placing water and mixture in the vacuum container was found to have a significant effect on the G_{mm} results. Specifically, adding the mixture to water always yielded practically higher G_{mm} and calculated air voids results than adding water to the mixture. However, the cause of the difference was not fully understood. One possible explanation was that the release of air was facilitated by adding the mixture to water.

Experiment 5 on Vacuum and Agitation Period

For all three SMA mixtures evaluated in the experiment, the G_{mm} results generally increased as the vacuum and agitation period increased up to 20 minutes and then decreased afterwards. Statistical analysis of the results found that the difference in G_{mm} results measured between 15 and 20 minutes of vacuum and agitation was insignificant. Therefore, it was recommended to maintain the current vacuum and agitation period of 15 minutes in the AASHTO procedure.

CHAPTER 3 Experimental Plan and Results

Original Experimental Plan

As presented in the Problem Statement, Project NCHRP 10-87 (01) evaluated the use of different mechanical shakers and vibratory parameters of the shakers to determine an optimum vibration intensity of the devices, but it did not determine the optimum mechanically derived G_{mm}. It was believed that since the researchers used a single amplitude and frequency setting throughout the test, there was no guarantee that an accurate measurement of G_{mm} could take place. The sample could become animated, settle, and begin to rotate as a single mass, making it more difficult for any additional air to be released once the particles interlocked. Therefore, in this research it was desired to develop a criteria to ensure that samples maintain full animation through the test period with the assumption that a more accurate measurement of G_{mm} would take place.

The experimental plan that was proposed for this project was as follows.

Test Equipment

A vibro-deairator, Gilson SGA-5R/SGA-5RT as shown in Figure 6, was selected to conduct measurements of G_{mm} of asphalt samples. This unit was selected because it allows adjustment to the intensity of vibration, and the evaluation of different speed settings would yield different amplitudes. In addition, this unit was selected because adjustments to the rotating weights of the motor can be made to indirectly change the amplitude. Figure 7 illustrates how the rotating weights can be adjusted, which would allow assessing a wider range of combinations than just the ones that could be obtained without any modifications to the mechanical shaker.

Figure 6. Gilson SGA-5R/SGA-5RT with Pycnometer.

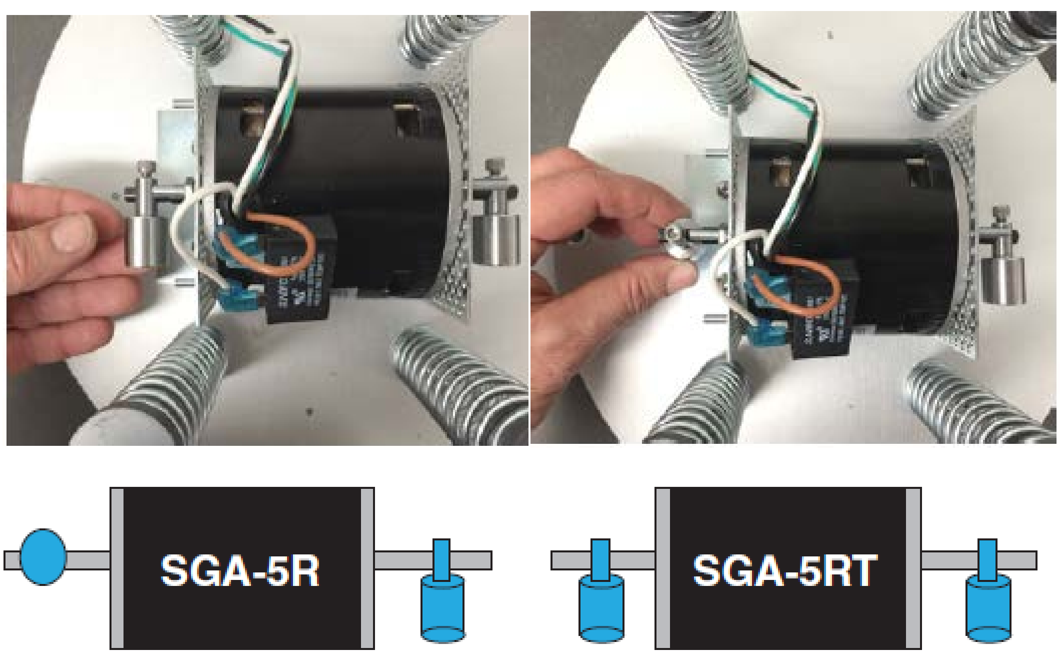


Figure 7. Adjustment of the Mechanical Shaker Rotating Weights (Gilson, 2016).

Inertial Measurement Unit (IMU)

In order to characterize the energy of the system for the vibratory shaker under evaluation, it was necessary to identify a device capable of capturing the six degrees of freedom of the unit since the container can rotate as well as translate. There are three axes of potential linear acceleration and three axes of potential rotation. Therefore, three-axis accelerometer along with a three-axis gyroscope could capture and characterize the full motion of the container. Although this can be accomplished using two three-axis accelerometers with an offset in each axis (to capture rotation), the simplest and best approach is to use a single six-degree of freedom device called an Inertial Measurement Unit (IMU). An IMU contains a three-axis accelerometer and a three-axis gyroscope. The accelerometer measures linear acceleration and the gyroscope measures rate of rotation about each axis. The sensor selected for this project was a Vectornav VN-100 rugged miniature high performance IMU.

Energy would be calculated as follows: the total kinetic energy of the container is the sum of the three axes of translational kinetic energy and the three axes of rotational kinetic energy. If total energy proves to be the governing parameter, it would be the kinetic energy per unit mass since this would be the measured kinetic energy intensity experienced by any particle in the system. The translational kinetic energy per unit mass for each axis is calculated as:

$$KE\ (translational) = 1/2*V_{max}^2 \tag{4}$$

The quantity V_{max} is calculated as:

$$V_{max} = A_{max}/(2*\pi*f) \tag{5}$$

Where: Vmax is the maximum speed, A_{max} is the acceleration measured by the accelerometer, and f is the frequency (Hz) of the vibration. Note that this expression of V_{max} assumes sinusoidal vibrating motion, which would be expected with the eccentric mass driver. The translational kinetic energy for each axis would be summed to obtain the total translational kinetic energy.

The rotational kinetic energy for each axis is calculated as:

$$KE\ (rotational) = 1/2*I*w^2 \tag{6}$$

Where: w is the maximum rate of rotation in radians per second as measured by the axis gyroscope, and I is the mass moment of inertia about that axis. The rotational kinetic energy per unit mass would then be obtained for each axis and the total rotational kinetic energy per unit mass is calculated by summing the rotational kinetic energy per unit mass for each of the three axes.

Finally, the total kinetic energy per unit mass is calculated as the sum of the total translational kinetic energy per unit mass and the total rotational kinetic energy per unit mass.

It is important to emphasize that the location of the IMU is critical. Because of the yawing motion of the container induced by the eccentric mass, the acceleration is expected to be a strong function of location. Consistent location of the accelerometer is needed to produce consistent and comparable results. Careful attention was given to clearly specify how the accelerometers were located and used and how this data affects the animation of the asphalt mixture during the test.

Materials and Test Samples

A total of four laboratory produced dense-graded mixes were originally selected to be included in the experimental plan based on their nominal maximum aggregate size (fine to coarse) and one asphalt binder PG 67-22. The minimum sample sizes by nominal maximum aggregate size (NMAS) per AASHTO T 209 are presented in Table 5. Two replicates per mix at variable settings were anticipated. The mix design information for the mixes is summarized in Table 6. As it will be presented later in this chapter, the 37.5mm NMAS mix was not included in the final evaluation.

Table 5. Minimum Sample Sizes.

NMAS (mm)	Minimum Sample Size (g)
37.5 or greater	4000
19 to 25	2500
12.5 or smaller	1500

Table 6. Mix Designs under Evaluation.

Sieve Size (mm)	4.75mm NMAS	12.5mm NMAS	19.0mm NMAS	37.5mm NMAS
	% Passing			
50.0	100.0	100.0	100.0	100.0
37.5	100.0	100.0	100.0	99.3
25.0	100.0	100.0	100.0	71.4
19.0	100.0	100.0	96.3	65.7
12.5	100.0	97.0	84.2	59.3
9.5	100.0	86.0	63.5	49.7
4.75	90.3	60.3	49.8	43.0
2.36	70.1	46.5	45.0	39.6
1.18	52.4	36.3	35.5	31.4
0.6	34.4	23.7	23.1	20.0
0.3	20.6	13.1	12.6	10.4
0.15	13.2	7.7	7.5	6.0
0.075	9.6	5.0	4.8	3.9
Mix Volumetrics				
Ndes, gyrations	100	100	100	100
Optimum AC, %	6.0	5.4	4.5	4.1
VMA, %	16.3	15.4	14.0	12.9
VFA, %	75.4	74.1	71.7	69.0
D/B	1.81	1.01	1.15	1.04
Gmm @ Ndes	2.457	2.454	2.560	2.527
Gmb @ Ndes	2.359	2.355	2.457	2.425
Gsa	2.700	2.674	2.758	2.696
Gse	2.696	2.663	2.754	2.693
Gsb	2.648	2.633	2.731	2.670
Pba, %	0.69	0.43	0.32	0.34
Pbe, %	5.34	4.95	4.22	3.75
Aggregate Sources				
Opelika Limestone 57s			13	
Opelika Limestone 78s			39	20
Calera Limestone 820s	30			
Loachapoka Granite M10s	20	20	22	16
LaGrange Granite 78's		32		
Columbus Granite 89's	20	22		
Shorter Sand	29	25	25	25
Stockbridge Granite #4 Stone				38
Baghouse Fines	1	1	1	1
Agg Majority	Limestone	Granite	Limestone	Granite
Minimum Sample Size, g	1500	1500	2500	4000

Initial Assessment to Achieve Full Animation of Particles

The research team considered that firstly, it was necessary to investigate if it was possible to achieve full animation of the system by evaluating alternatives that included using different unit settings, and adjustments to the mechanical shaker (rotation of weights) before any other measurement took place.

In order to monitor if sample particles were in motion for the duration of the test, a clear container was used to conduct the tests so that the sample could be visually observed and verified that full animation was occurring or not. The measured responses were compared to the observed mixture animation to help determine optimum settings for vibration. A video camera was used to capture the agitation process during testing. A video provided by one the panel members showing full animation was used as a reference of what should be considered the expected "full animation of the particles.

The results of this effort are summarized as follows:

- Several trial tests with mixes with different NMAS mixes were conducted to achieve full animation of the particles.
- Firstly, tests were conducted using 19 mm and 12.5 mm NMAS mixes. Different settings of the unit were tried, starting from low setting to high setting, but no full animation was achieved. Since no animation was achieved for the 19 mm mix, the research team decided that full animation of samples of the 37.5 mm NMAS mix would not be possible.
- Tests were then conducted using a 4.75 mm NMAS mix, the smallest NMAS mix. Full animation was achieved for few minutes; after that, the particles didn't seem to be animated and started to settle. G_{mm} tests were conducted at different settings to evaluate the effect on G_{mm} values. Table 7 summarizes the results at low, medium, and high settings. These results correspond to one replicate only.
- From this evaluation, it was concluded that with the Gilson SGA-5R, full animation for a short period of time can only be achieved for mixes with small particle size.

Table 7. G_{mm} Test Results for 4.75 mm NMAS Mix at Different Settings.

Dial Setting, %	G_{mm}	Notes
100 (high)	2.466	Full animation
50 (medium)	2.460	Full animation
25 (low)	2.463	Full animation

- Additional tests were conducted adjusting the mechanical shaker rotating weights as shown in Figure 7. Tests were conducted with the 4.75mm and 12.5 mm NMAS mixes. Full animation was temporarily achieved on low, medium, and high settings for the 4.75 mm NMAS mix and only on medium and high settings for the 12.5mm mix. For the medium and high settings, the water started to get cloudy after a few minutes of testing. Therefore, even when full animation was achieved, when adjustments were made to the rotating weights, the excessive agitation apparently had a negative effect on the clarity of the water. The research team had concerns that excessive agitation may affect the integrity of the mix. No animation was achieved for the 19 mm NMAS mix using a high setting and water also got very cloudy.

- As presented in a previous chapter, research conducted as part of NCHRP 10-87(01) indicated that G_{mm} of the mixes increases with the increase in the intensity of vibration until the highest G_{mm} of the mixture is reached. From that point, additional increase in vibration intensity results in a decrease in G_{mm}. This phenomenon was speculated to be caused by stripping of the asphalt and significant cloudiness of the water.

Characterization of the Energy of the System

Since full animation was only achieved for smaller NMAS mixes with the standard Gilson unit configuration (SGA-5R), and adjustment to the mechanical shaker rotating weights yielded issues with the clarity of the water, it was decided to characterize the energy of the system running G_{mm} tests on the 4.75mm and 12.5 mm NMAS mixes using the standard unit configuration. This would allow assessing if the energy of the system for different unit settings correlates with G_{mm} results, and also, how critical the full animation of the particles is to obtain the optimum G_{mm} values.

To obtain the energy of the system at each setting, the initial approach was to place the IMU along the centerline of a principal axis of the container and analyze the data generated during the tests. To accomplish this, the IMU was mounted to the rubber stopper on top of the vacuum flask as shown in Figure 8.

Figure 8. IMU Mounted on Top of Vacuum Flask.

Tests were conducted using the 4.75mm NMAS and 12.5mm NMAS mixes. To analyze the information obtained from the IMU, the energy at different times during the test was calculated. The procedure is as follows:

- The data captured from the IMU sensor includes acceleration in three dimensions and angular velocity in three dimensions.

- The kinetic energy at the top of given flask is calculated using Equations 4-6. The mass of each sample is assumed equal (~1,500 grams), and hence, kinetic energy would be directly proportional to the square of velocity.

The energy was calculated at different times during each test. Several trials were conducted, but no consistent results were obtained for the duration of the test. It was believed that placing the IMU on a rubber stopper was not able to provide a stable surface and was causing a significant amount of variability in the test results. Due to this, it was decided to change the location of the IMU by placing it at the bottom of the flask as shown in Figure 9. In this location, the IMU is also closer to the center of gravity of the system, which was expected to provide more accurate results.

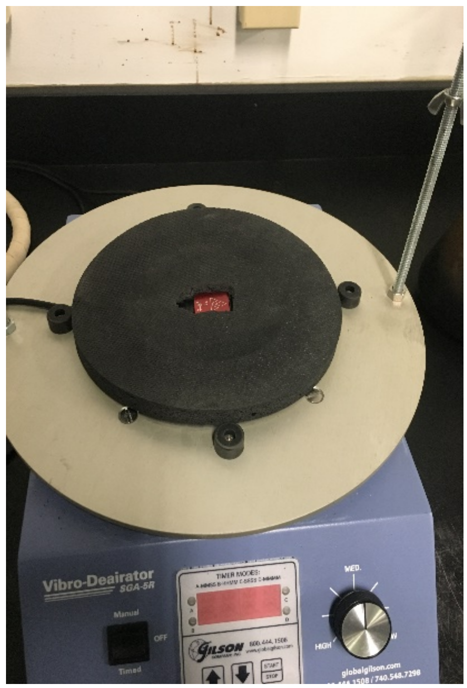


Figure 9. IMU Mounted at the Bottom of the Flask

The results of these tests are summarized in Table 8. They correspond to the results of the 4.75 mm NMAS and 12.5 mm NMAs mix, respectively. These tables also include G_{mm} values for each of the two replicates tested at each setting (low, medium, and high). As it can be observed from the test results, the energy of the system obtained at different times during each test is relatively consistent. Higher variability was observed for the readings taken on the low setting.

Table 8. Energy and G_{mm} for 4.75mm and 12.5 NMAS Mixes at Different Settings

Setting	Time (min)	4.75 mm			12.5 mm		
		Sample ID	Energy $(m/sec)^2$	G_{mm}	Sample ID	Energy $(m/sec)^2$	G_{mm}
Low	2	414	8.62E-006	2.443	512	1.83E-007	2.446
	8		2.60E-005			1.62E-007	
	13		1.95E-005			4.41E-007	
	Average		**1.80E-005**			**2.62E-007**	
Low	2	411	9.84E-003	2.449	513	4.33E-005	2.445
	8		1.01E-002			1.58E-005	
	13		1.03E-002			2.10E-005	
	Average		**1.01E-002**			**2.67E-005**	
Medium	2	415	2.30E-002	2.456	514	9.27E-003	2.46
	8		2.35E-002			9.31E-003	
	13		2.26E-002			9.15E-003	
	Average		**2.30E-002**			**9.24E-003**	
Medium	2	416	1.45E-002	2.455	515	7.05E-003	2.463
	8		1.43E-002			7.14E-003	
	13		1.44E-002			7.95E-003	
	Average		**1.44E-002**			**7.38E-003**	
High	2	417	2.63E-002	2.459	516	1.81E-002	2.456
	8		2.30E-002			1.88E-002	
	13		1.92E-002			1.86E-002	
	Average		**2.28E-002**			**1.85E-002**	
High	2	418	1.14E-002	2.459	517	6.01E-003	2.458
	8		1.11E-002			6.51E-003	
	13		1.04E-002			6.42E-003	
	Average		**1.10E-002**			**6.32E-003**	

Figures 10 and 11 compare the G_{mm} and energy results for the 4.75 mm mix for each setting. An ANOVA ($\alpha = 0.05$) with Tukey-Kramer grouping was used to statistically compare the results. This information is presented in Table 9. In this table, means that do not share a letter are significantly different. This table shows that similar statistical groupings were found for the G_{mm} test results at the medium and high setting, but the results for the low setting indicate that they are statistically significant. On the other hand, the energy results show the same statistical grouping for all settings. This may be due to the variability of the test results and limited number of replicates available. In addition, G_{mm} and energy values seem to show a consistent trend with higher G_{mm} values for higher energy.

Figures 10 and 11 also compare the G_{mm} and energy results for the 12.5 mm mix for each setting. Similar analyses to the ones conducted for the 4.75 mm NMAS mix were conducted for this mix. Table 10 shows the Tukey-Kramer grouping results. This table shows that the means for G_{mm} at different settings are different. Similar to the result for the 4.75 mm NMAS mix, the energy results show the same statistical grouping for all of the unit settings. G_{mm} and energy values seem to show a consistent trend with the exception of G_{mm} at the high setting, which indicates a decrease when compared to G_{mm} at the medium setting.

It is important to mention that when tests at the high setting were conducted, problems with the cloudiness of the water were observed for the two different mixes even with the standard unit configuration. It was also observed that even when no full animation was achieved for the 12.5 mm NMAS mix, there was an increase in the G_{mm} values at the medium setting when compared to the low setting.

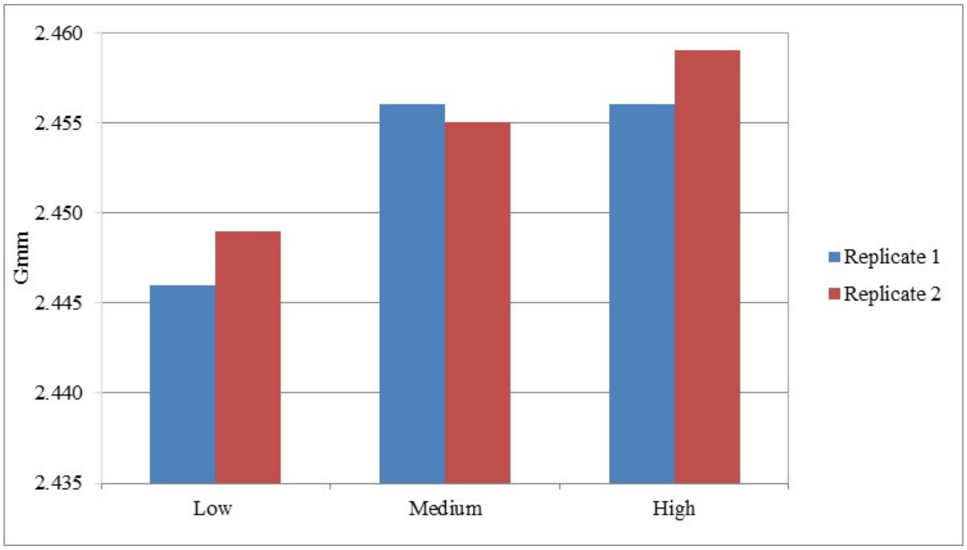


Figure 10. G_{mm} of 4.75 mm NMAS Mix at Different Settings (Low, Medium, High).

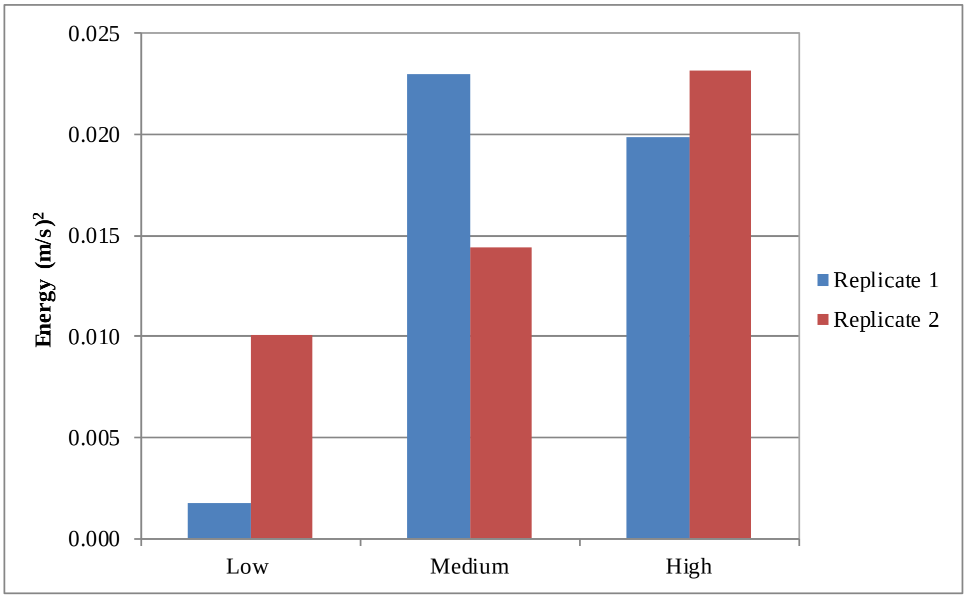


Figure 11. Energy of 4.75 mm NMAS Mix at Different Settings (Low, Medium, High).

Table 9. Summary of Tukey Statistical Groupings for G_{mm} and Energy Results 4.75 mm NMAS.

G_{mm}		
Setting	**Average**	**Grouping**
High	2.458	A
Medium	2.455	A
Low	2.448	B
Energy		
Setting	**Average**	**Grouping**
High	0.0215	A
Medium	0.0187	A
Low	0.006	A

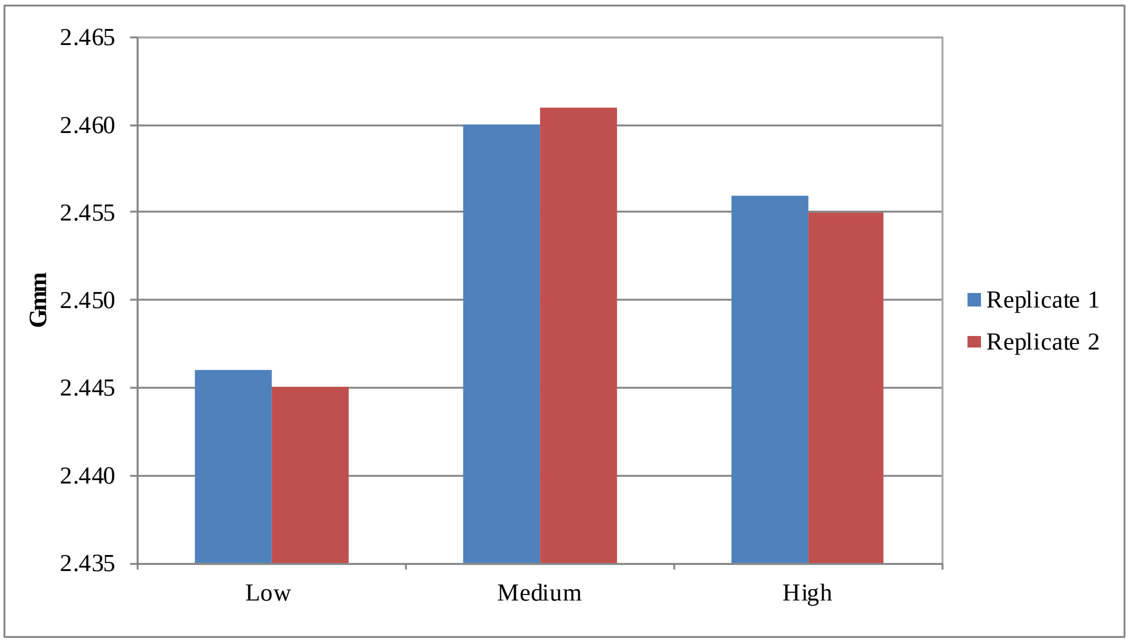


Figure 12. G_{mm} of 4.75 mm NMAS Mix at Different Settings (Low, Medium, High).

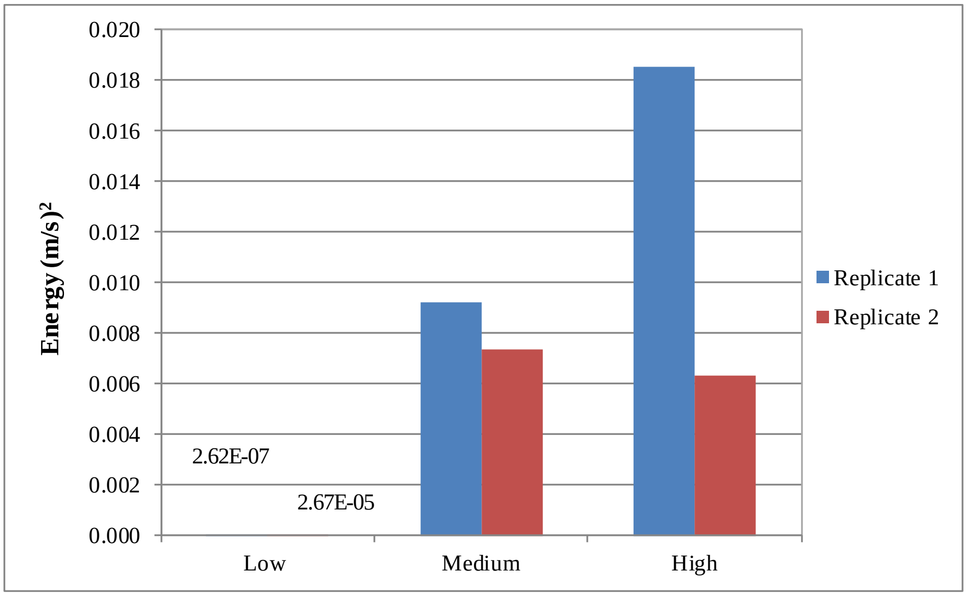


Figure 13. Energy of 12.5 mm NMAS Mix at Different Settings (Low, Medium, High).

Table 10. Summary of Tukey Statistical Groupings for G_{mm} and Energy Results 12.5 mm NMAS.

G_{mm}		
Setting	**Average**	**Grouping**
High	2.462	A
Medium	2.455	B
Low	2.446	C
Energy		
Setting	**Average**	**Grouping**
High	0.01241	A
Medium	0.0083	A
Low	0.0000013	A

Although the original objective of this project was to establish a criterion to ensure full animation of mix sample particles, the following findings based on the work conducted for this study present the complexity of accomplishing this objective with the current equipment available:

- Achieving full animation for mixes with NMAS higher than 12.5 mm can't be accomplished with the unit under evaluation even with adjustments to the eccentric masses.
- When full animation was achieved using the high unit setting, problems with the cloudiness of the water were observed. Although the consequences of this cloudiness were not investigated in this study, it appears that the more intense vibration may have an effect on mix integrity.
- It appears that the low setting provides significantly lower G_{mm} values. This indicates that this setting may not be recommended.
- Although the relative energy values may roughly correlate to G_{mm} values for individual mixes (as it was found for the 4.75 mm NMAS mix), it doesn't seem feasible to recommend an energy range to provide the level of agitation to set individual particles in motion that

would ensure the complete removal of air from the sample. Each mix type at the same setting (low, medium, high) yielded different values, which indicates that each mix will have its own energy requirements.

- The location of the IMU is critical to obtain somewhat consistent results. Changing the location of the IMU would yield different results for the same setting and mix combination. This suggests that it would be difficult to specify a procedure to measure the energy that could be replicated at different labs using different units and different vacuum containers (e.g. metal bowls vs. pycnometers).

From the results obtained, the research team suggested modification to the original project as follows: with the current equipment available, the full animation and energy of the system approaches to obtain the "true G_{mm}" value do not seem feasible. In addition, no indication was found that achieving full animation would yield more accurate G_{mm} results. Therefore, for the remainder of the project, the research team suggested to focus on the following items:

- Further investigate the causes of the cloudiness of the water and the potential effect on the G_{mm} values. Since metal bowls are very common, it is possible that this issue is actually currently happening, but has not been addressed because the cloudiness is more difficult to identify with this type of container.
- Further investigate the use of different vacuum containers and their effect on the G_{mm} results.
- Further investigate the possibility of reducing the testing time required. In this project, it was observed that after several minutes, the samples did not appear to be releasing any more air, so it may be worth it to revisit the test duration recommended in the AASHTO procedure.

As a result, the following new tasks were recommended and conducted.

Changes to Original Project Objectives

The original objective of this project was to establish a criterion to ensure complete removal of entrapped air from an asphalt mix during the vacuum period required in AASHTO T 209. This was anticipated to be possible if full animation of the particles was achieved for the duration of the test. Findings from Phase I of this project identified the complexity of accomplishing this objective with the equipment currently available. Therefore, the research team recommended conducting additional tasks with the remaining budget to find possible ways to improve the AASHTO T 209 test procedure. The following tasks were proposed:

- Task 1: Investigate the cause(s) of cloudiness of the water.
- Task 2: Investigate the use of different vacuum container sizes and their effect on the G_{mm} results.
- Task 3: Investigate the effect of test duration on G_{mm}.
- Task 4: Prepare a Final Report to summarize the results of the study.

Task 1: Investigate the cause(s) of cloudiness of the water.

G_{mm} tests on the medium and high setting were conducted on mixes with different NMAS (4.75 mm, 12.5 mm, and 19 mm). Since cloudiness could potentially be caused by asphalt stripping and dissolving in water, the dry back supplemental procedure included in AASHTO T 209 was conducted on the G_{mm} samples to determine if, in fact, the aggregate after stripping absorbs water. If the pores of the aggregates are not sealed by an asphalt film, they may absorb water during the vacuuming procedure and affect the measurements. The differences in test results before and after the dry back procedure need to be evaluated to determine the level of significance. If significant, recommendations will be made regarding agitation level and cloudiness effect on G_{mm} test results.

Task 2: Investigate the use of different vacuum container sizes and their effect on the G_{mm} results.

Tests conducted during this research showed that the size of vacuum container (pycnometer) may affect the agitation process for mixes with different NMAS since the minimum sample size to conduct the test per AASHTO standard is selected based on the NMAS of the mix. Figure 14 shows examples of two test samples conducted using a 2L flask; the one on the left contains a 4.75 mm NMAS mix with a sample size of 1500 grams, and the one on the right contains a 19 mm NMAS mix with a sample size of 4000 grams. As it can be observed, the level of the mix in the container for the 19 mm NMAS is higher and could potentially affect the removal of entrapped air, and therefore, the G_{mm} results.

To assess the effect of vacuum container size, a 4L pycnometer was used to conduct tests on the 19 mm NMAS mix. The results were compared to the ones obtained with the 2L flask and guidance regarding vacuum container size and NMAS of the mixes was provided.

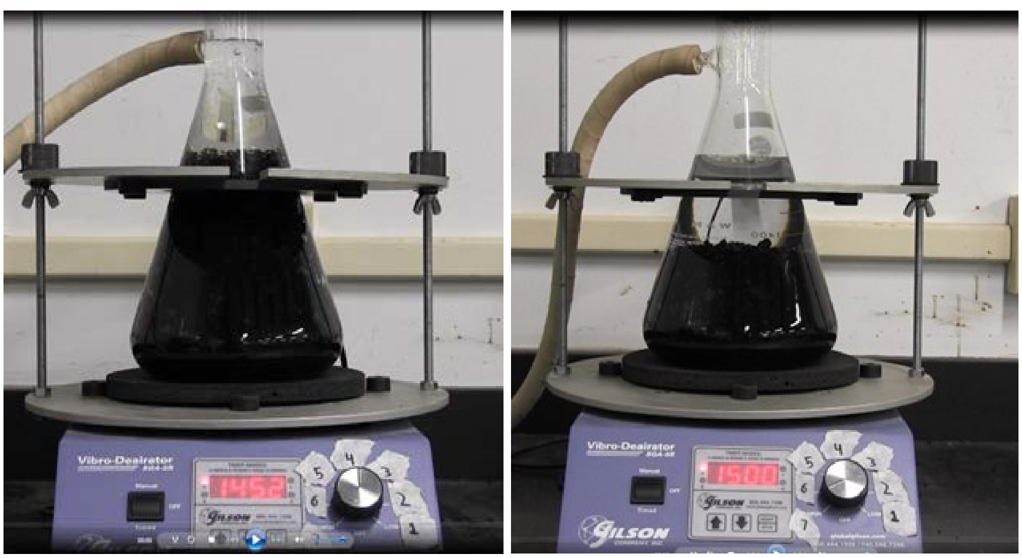


Figure 14. G_{mm} Samples on 2L Pycnometer, 4.75mm Mix (left), and 19 mm Mix (right).

Task 3: Investigate the effect of Vacuuming Time on G_{mm}

In this project, it was observed that after several minutes running G_{mm} tests, the samples did not appear to be releasing any more air, so it may be of value to revisit the vacuuming time recommended in the AASHTO procedure. In addition, the original recommendation of using a vacuuming time of 15 minutes was based on a study conducted by Kandhal and Khatri in 1992 using only two mixes, a 9.5mm and 12.5 mm NMAS. In their study, three factors were investigated, temperature, residual pressure, and vacuuming time. Each factor was evaluated at three different levels as presented in Table 11. The cumulative average of 27 observations for all the factors are presented in this table. Table 12 shows the results that the researchers obtained when considering the only interaction that was found to be significant, temperature vs. vacuuming time. Based on these results, the levels of the factors that yielded the highest G_{mm} values were considered the optimal levels. The selected levels were: temperature at 77°F, residual pressure at 30 mm hg, and a vacuuming time of 15 min.

As it can be observed from the results in Table 11 and Table 12, there is not much variation in G_{mm} at different vacuuming times. Therefore, these results also support the recommendation to reevaluate vacuuming time, which could potentially reduce the time required to run the test and could also be beneficial during quality control of asphalt mixes.

Table 11. Cumulative Averages G_{mm} for All Factors under Evaluation (Kandhal, 1992).

Level	**G_{mm} Cumulative Average**
Temperature (°F)	
69	2.497
77	2.495
85	2.496
Residual pressure (mm Hg)	
16	2.495
23	2.496
30	2.497
Vacuuming time (min)	
5	2.495
10	2.496
15	2.498

Table 12. Average G_{mm} Considering Significant Interaction Vacuuming Time x Temperature (1).

Temperature (°F)	**Vacuuming Time (min)**		
	5	10	15
69	2.497	2.497	2.498
77	2.493	2.494	2.498
85	2.494	2.496	2.497

Laboratory Test Results Phase II

Task 1. Investigate the cause(s) of cloudiness of the water.

G_{mm} tests on medium and high setting were conducted on mixes with different NMAS (4.75 mm, 12.5 mm, and 19 mm). Table 13 summarizes the G_{mm} results before and after the dry back procedure. Based on these results, no significant differences were observed, which suggests that the particles did not absorb water, and therefore, cloudiness may not be attributed to the absorption of water as a result of stripping.

As part of this task, a chemical analysis was conducted on the water residue (cloudy water) after G_{mm} testing to investigate if any asphalt components could be identified. For this analysis, attenuated total reflectance (ATR) fourier-transform infrared (FTIR) spectroscopy was used. A total of eight samples were tested: tap water only, asphalt binder, and water residue after G_{mm} for 4.75 mm medium and high, 12.5mm-medium and high, and 19 mm medium and high (medium and high refer to the vibration condition used for G_{mm} testing). The results are summarized in Figure 15, and clearly show that the spectrum of tap water is exactly the same as the spectrum of the water residue, indicating that no asphalt was present in any of the samples.

Table 13. G_{mm} Test Results Before and After Dryback Procedure

NMAS	Vibration Setting	G_{mm} Before Dryback			G_{mm} after Dryback			Average Difference
		Sample 1	Sample 2	Average	Sample 1	Sample 2	Average	
4.75	Medium	2.458	2.466	2.462	2.458	2.463	2.461	0.001
	High	2.463	2.465	2.464	2.460	2.463	2.462	0.002
12.5	Medium	2.477	2.481	2.479	2.475	2.482	2.478	0.001
	High	2.479	2.478	2.478	2.478	2.476	2.477	0.001
19	Medium	2.571	2.560	2.565	2.567	2.560	2.564	0.002
	High	2.565	2.564	2.565	2.566	2.565	2.565	0.000

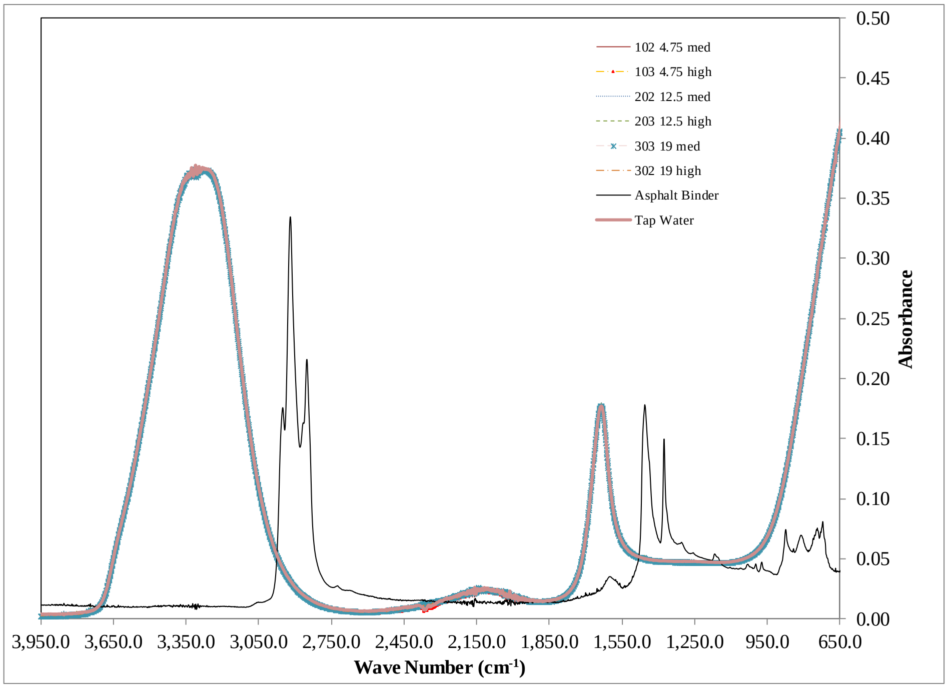


Figure 15. FTIR-ATR Results

Task 2. Investigate the use of different vacuum container sizes and their effect on the Gmm results.

Table 14 shows the G_{mm} results for 19 mm NMAs mix samples using a 2 L flask and 4 L flask; medium and high vibration frequencies were tested. The goal was to assess the effect of vacuum container on the test results. From these results, vacuum size does not seem to influence the results, since very consistent numbers G_{mm} were found for the mix under evaluation.

Table 14. Task 2 Test Results

NMAS	Flask Size	Vibration Setting	G_{mm}		
			Sample 1	Sample 2	Average
19	2 L	Medium	2.567	2.568	2.568
	2 L	High	2.568	2.563	2.566
	4 L	Medium	2.560	2.571	2.565
	4 L	High	2.565	2.564	2.565

Task 3. Investigate the effect of Vacuuming Time on G_{mm}

Table 15 summarizes the G_{mm} results for samples using vacuuming times of 5, 10, and 15 minutes. The goal was to assess if it is really required to apply vacuum and shake the samples for 15 minutes, or if this test time could be reduced. Tests were conducted on 4.75 mm, 12.5 mm, and 19 mm NMAS samples. Based on these results, no significant differences were found for the 4.75 mm and 12.5 mm NMAS samples at all testing times. For the 19 mm samples, tests run for 5 and 10 minutes show a difference of 0.011, but no significant difference was observed between tests run for 10 and 15 minutes. Although the results of this evaluation are limited, there is a strong indication that the testing time could potentially be reduced to a maximum of 10 minutes without significantly affecting the G_{mm} test results.

Table 15. Task 3 Test Results

NMAS	Vibration Time (min)	G_{mm}		
		Sample 1	Sample 2	Average
4.75	5	2.465	2.466	2.465
	10	2.463	2.464	2.464
	15	2.458	2.466	2.462
12.5	5	2.478	2.476	2.477
	10	2.479	2.470	2.474
	15	2.481	2.477	2.479
19	5	2.558	2.559	2.558
	10	2.571	2.568	2.569
	15	2.560	2.571	2.565

CHAPTER 4 Summary, Discussion, and Recommendations

This report documents the results of a study to assess possible refinements of the AASHTO T 209 test method to determine the theoretical maximum specific gravity (G_{mm}) of asphalt mixtures. Since the intent of the test procedure is to remove all of the air from a loose asphalt mix to establish the G_{mm}, if any air remains in the sample at the end of the test, the results may not be accurate. Concerns exist that if the level of agitation is not enough to maintain full animation of the particles during the test, air will remain in the sample; therefore, true G_{mm} values can't be obtained. It was anticipated that the refinement would provide the optimum amplitude and frequency to provide the energy required to achieve full animation of the particles.

The results of this work present the complexity of accomplishing the original objective with the current equipment available and emphasizes the difficulties of achieving full animation through the duration of the test without causing excessive cloudiness of the water, which could potentially indicate problems with the integrity of the mix.

In this study, a Gilson SGA-5R/SGA-5RT unit was selected to conduct measurements of G_{mm} because it allows adjustment to the intensity of vibration. In addition, adjustments to the rotating weight of the unit can be made to modify the amplitude and frequency for each setting. To characterize the energy of the system, a Vectornav VN-100 rugged miniature high performance inertial measurement unit (IMU) was selected because it contains a three-axis accelerometer and a three-axis gyroscope required to capture the six degrees of freedom of the unit since the container can rotate as well as translate during the test. Three laboratory produced dense-graded mixes (4.75 mm, 12.5 mm and 19.0 mm NMAS) were selected to conduct G_{mm} measurements.

The results of this study are summarized as follows:

- When the mechanical shaker rotating weights were adjusted, full animation was temporarily achieved on low, medium, and high settings for the 4.75 mm NMAS mix and on medium and high settings only for the 12.5 mm mix. After a few minutes (typically less than two minutes), the particles settled.
- Achieving full animation for mixes with NMAS higher than 12.5 mm was not possible with the unit under evaluation even with adjustments to the shaker's rotating weights.
- When full animation was achieved using the high unit setting, problems with the cloudiness of the water were observed. Although the consequences of this cloudiness were not fully investigated in this study, it appears that the more intense vibration may have an effect on the integrity of the mix.
- For the mixes under evaluation (4.74 mm and 12.5 mm NMAS), the low setting provides significantly lower G_{mm} values. This indicates that this setting may not be recommended.
- Although the relative energy values measured with the IMU seemed to roughly correlate to G_{mm} values for individual mixes, it is not feasible to recommend an energy range to provide the level of agitation to set individual particles in motion that will ensure the

complete removal of air from the sample. Each mix type at the same setting yielded different values, which indicates that each mix will have its own energy requirements.

- The location of the IMU is critical to obtain somewhat consistent results. Changing the location of the IMU would yield different results for the same setting and mix combination. This would make it difficult to specify a procedure to measure the energy that could be replicated at different labs using different units and different vacuum containers.

Since the original objective of this project could not be accomplished, the remaining work focused on the following evaluations: investigate the cause(s) of cloudiness of the water, investigate the use of different vacuum container sizes and their effect on the G_{mm} results, and investigate the effect of test duration on G_{mm} results.

Since cloudiness of the water could potentially be caused by asphalt stripping and dissolving in water, the dry back supplemental procedure included in AASHTO T 209 was conducted on the G_{mm} samples to determine if, in fact, the aggregate absorbed water after stripping. G_{mm} tests were conducted on mixes with different NMAS, 4.75 mm, 12.5 mm, and 19 mm. The results show no significant differences in the G_{mm} values before and after the dry back procedure. In addition, FTIR test results conducted on water residue indicated that there was no asphalt present that could explain the cloudiness of the water.

A limited investigation was conducted to assess the effect of vacuum container size in the G_{mm} measurement. Results for 19 mm NMAs mix samples using a 2 L flask and 4 L flask indicated that vacuum size does not seem to influence the results, since very consistent G_{mm} values were found for the mix under evaluation.

A final evaluation was conducted to assess if the vacuum time recommended in the test procedure could be reduced. In this project, it was observed that after several minutes of running the test, the samples did not seem to be releasing any more air. Tests were conducted on 4.75 mm, 12.5 mm, and 19 mm NMAS samples. The results of this evaluation showed no significant differences in G_{mm} after 10 and 15 minutes. Although the results of this evaluation are limited, there is a strong indication that the testing time could potentially be reduced to a maximum of 10 minutes without significantly affecting the G_{mm} test results.

Although this research did not accomplish the envisioned objective, some lessons learned were presented regarding the feasibility and significance of achieving full animation to determine an accurate G_{mm} value. In addition, this study showed that establishing a criteria for sample mechanical shaking in AASHTO T 209 based on an optimum amplitude and frequency is not feasible.

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