TechBrief

The Asphalt Pavement Technology Program is an integrated, national effort to improve the long-term performance and cost effectiveness of asphalt pavements. Managed by the Federal Highway Administration through partnerships with State highway agencies, Industry and academia the program's primary goals are to reduce congestion, improve safety, and foster technology innovation. The program was established to develop and implement guidelines, methods, procedures and other tools for use in asphalt pavement materials selection, mixture design, testing, construction and quality control.

U.S. Department of Transportation
Federal Highway Administration

Office of Pavement Technology

FHWA-HIF-11-032

December 2010

SUPERPAVE GYRATORY COMPACTORS

This Technical Brief provides an overview of the gyratory issues that affects the performance of asphalt pavements.

Background

The Superpave mix design procedure features the Superpave gyratory compactor (SGC) for compacting specimens of hot mix asphalt. The primary operating parameters for the SGC include the pressure applied to the specimen during compaction; the speed of gyration/rotation; the number of gyrations applied to the specimen; and the angle of gyration. Values for these parameters were established during the development of the Superpave system under the Strategic Highway Research Program. It is correctly and commonly assumed that gyratory compactors in which the gyration angle, speed of gyration, and applied pressure are properly calibrated will produce hot mix asphalt specimens having similar volumetric properties.

In recent years, however, this basic assumption of the equivalency of properly calibrated compactors has been called into question. Reports of replicate specimens, compacted on different SGC units, exhibiting significantly varying volumetric properties focused scrutiny on the angle of gyration. Procedures for calibrating/validating the gyration pressure and speed may be considered relatively generic and universal; however, procedures for calibrating the angle of gyration were unique to specific models of gyratory compactor. In addition, the angle of gyration was measured "externally" (outside the specimen mold) and relative to the frame of the SGC. It was theorized that compliance of the SGC frame under load detrimentally affected the measurement of the gyration angle – thus, rendering the calibration of the SGC suspect.

The Federal Highway Administration (FHWA) led an effort to develop technology for a universal method for measuring the angle of gyration on all compactors from *inside* the specimen mold. Subsequently,

“internal angle” measurement devices were refined and marketed by private manufacturers. Associated research demonstrated that the use of the internal angle of gyration to calibrate SGC units could result in replicate specimens having more consistent volumetric properties.

However, there are numerous potential sources of variability related to the production of a laboratory-compacted hot mix asphalt specimen. It is important that practitioners recognize and minimize all such sources of variability – in addition to the use of internal angle of gyration to calibrate the SGC. The FHWA Expert Task Group on Mixtures and Aggregates (ETG) developed this document with two primary goals: (1) to help practitioners address all potential sources of variability in producing compacted hot mix asphalt specimens; and (2) provide a brief history of the development of the concepts, practices, and equipment for measuring the internal angle of gyration and the development of specifications for implementing the use of the internal angle into routine practice.

Sources of Variability in Determining the Bulk Specific Gravity (G_{mb}) of Hot Mix Asphalt (HMA)

It is important to recognize that variability in the bulk specific gravity (G_{mb}) of a compacted hot mix asphalt (HMA) specimen can stem from a number of sources. Prior to adjusting settings on the Superpave gyratory compactor (SGC), these “external” sources of variability should be investigated. If problems are discovered, these issues should be settled insofar as possible. A brief discussion of some potential sources of variability follows.

SGC Maintenance

Studies related to the angle of gyration applied to a hot mix asphalt specimen have indicated that the physical condition of a given SGC affects the resulting measured angle of gyration. At a minimum, recommended maintenance items listed in the User’s Manual for each SGC must be performed at the recommended task frequencies.

In addition to “routine” maintenance issues, users are cautioned that parts of SGC units subject to wear, i.e. bearings, rollers, etc., should be periodically checked for condition. SGC manufacturers can provide information related to specific parts and indications of excessive wear. SGC parts showing excessive wear should be replaced.

SGC Cleanliness

The SGC must be kept as clean as possible, including all surfaces, rollers, plates, and molds. Table 1 reports the results of a small study to demonstrate the effect of an 'intrusion' under the gyratory compactor mold base plate. In general, the data in Table 1 suggests that an intrusion under the base plate of 0.1 mm could decrease the effective internal angle of gyration by approximately 0.05 degrees; given current specifications related to the internal angle of gyration, such a change is significant.

Table 1. Effect of Intrusions Under SGC Base Plate on Internal Angle of Gyration

Mold[1]	Thickness of Intrusion[2] Under Base Plate[3] (mm)	Average Internal Angle[4] (deg)
A	0.0	1.145
A	0.19	1.002
A	0.45	0.860
A	0.62	0.850
B	0.0	1.155
B	0.18	1.048
B	0.39	0.915
B	0.61	0.885
C	0.0	1.153
C	0.21	1.043
C	0.45	0.892
C	0.61	0.875
D	0.0	1.150
D	0.19	1.030
D	0.37	0.883
D	0.58	0.875
[1] Four SGC Molds were used in the study; average internal mold diameters ranged from 149.81 mm to 149.96 mm		
[2] Intrusions were created by affixing successive 1" x 1" squares of duct tape to the bottom-center of the baseplate		
[3] One SGC Base Plate was used in the study; the average diameter of the base plate was 149.66 mm		
[4] The Average internal angle represents three replicate measurements performed with a RAM device		

Molds

The FHWA Expert Task Group for Mixtures and Aggregates (ETG) is continuing to study the issue of excessive mold wear, with the goal of recommending possible specification limits for SGC molds. Current mold diameter specifications included in AASHTO T312 lists the inside diameter specification as 149.90 to 150.00 mm; however, this measurement is made at the top and bottom edges of the mold – rather than in the area in which compaction occurs. It is unclear at what diameter greater than 150.00 mm (in the area of compaction) mold wear becomes 'excessive' and significantly affects the volumetric properties of the HMA specimen.

There is also a specification regarding the diameter of the bottom mold plate; however, the specification does not address the 'gap' between the bottom mold plate and the mold itself – in other words, the difference between the inside mold diameter and the bottom mold plate. There has been speculation that this gap, if excessive, could affect the internal angle measurement, and ultimately, the volumetric properties of compacted HMA specimens.

SGC molds should be checked for excessive wear by measuring the inside diameter in the area of the mold wall subject to compaction, i.e. 1 to 5 inches from the bottom. Figure 1 shows examples of inside diameter measurements. AASHTO T312 lists the inside diameter specification as 149.9 to 150.0 mm, measured at the top and bottom of the mold.

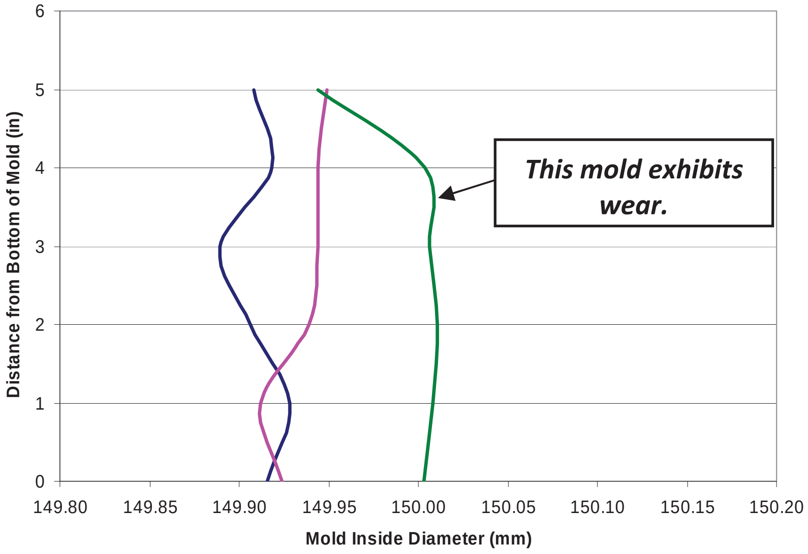


Figure 1. Example of SGC Mold Diameter Measurement

Figure 2 summarizes data collected in a study of the effect of the base plate / mold 'gap'. In this study, various combinations of mold and base plates were used with four models of gyratory compactor. Replicate measurements of internal angle were obtained using the Rapid Angle Measurement (RAM) device. As shown in Figure 2, for mold/plate 'gaps' ranging from 0.24 mm to 0.62 mm there was no consistent effect of the gap size on internal angle – although the data does suggest a potential decrease in internal angle with increasing gap size.

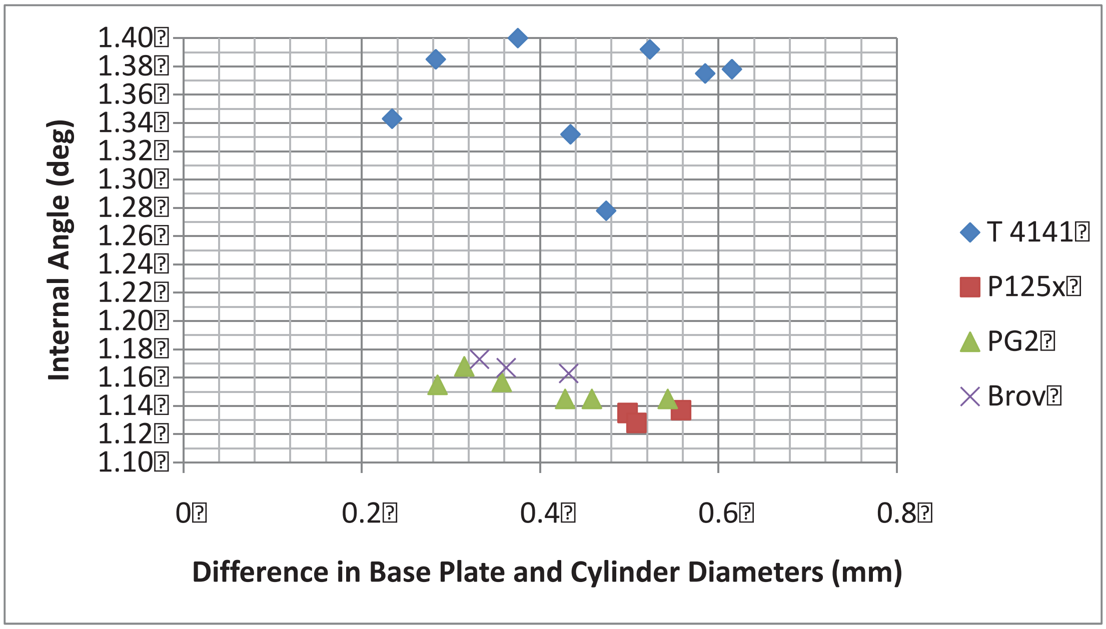


Figure 2. Effect of SGC Mold Internal Diameter / Base Plate 'Gap' on Internal Angle

A study was conducted at the University of Arkansas to investigate the relationship between internal mold diameter and bulk specific gravity of compacted HMA specimens. Four HMA mixes were used in the study: (1) 9.5 mm, PG 64-22 field mix compacted to 65 gyrations; (2) 12.5 mm, PG 76-22 field mix compacted to 50 gyrations; (3) 12.5 mm, PG70-22 laboratory mix compacted to 100 gyrations; and (4) 25 mm, PG 70-22 laboratory mix compacted to 100 gyrations. Three models of gyratory compactor – Troxler 4141, Pine 125x, and Pine G2 – were used to compact specimens. The internal diameter of the molds for each compactor were measured starting the bottom, and in 1-inch increments from the bottom to a total height above the bottom of 7 inches. Three replicate specimens of HMA were compacted in each mold used, for each mix in the study.

Figures 3-5 show the relationship between the maximum measured internal diameter of the SGC mold and the average bulk specific gravity of the replicate specimens compacted in the mold, for the Troxler

4141, Pine 125x, and Pine G2, respectively. While the data shown in Figures 3-5 hint at a general trend of increasing bulk specific gravity with increasing internal mold diameter, there is not a significant difference in bulk gravity values. It is reasonable to conclude that, for the diameters measured in this study, values slightly exceeding the maximum specified value of 150.00 mm do not appear to significantly affect the bulk specific gravity of compacted HMA specimens.

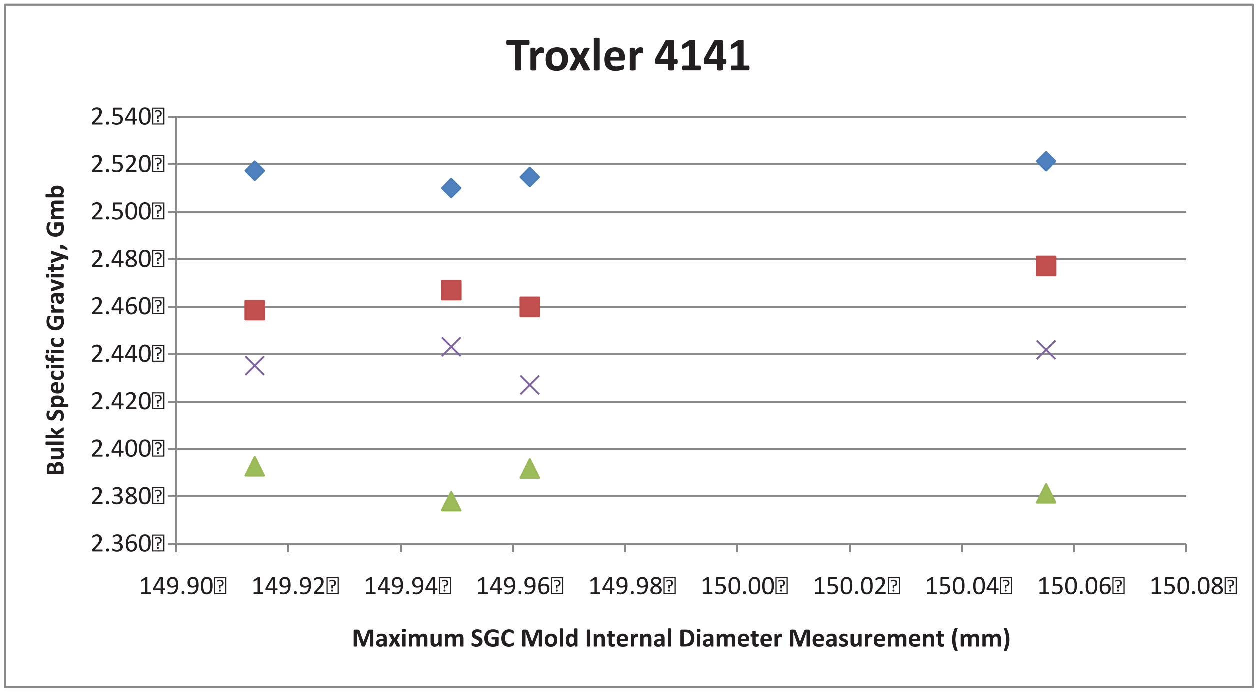


Figure 3. Relationship Between Specimen Density and SGC Mold Diameter, Troxler 4141

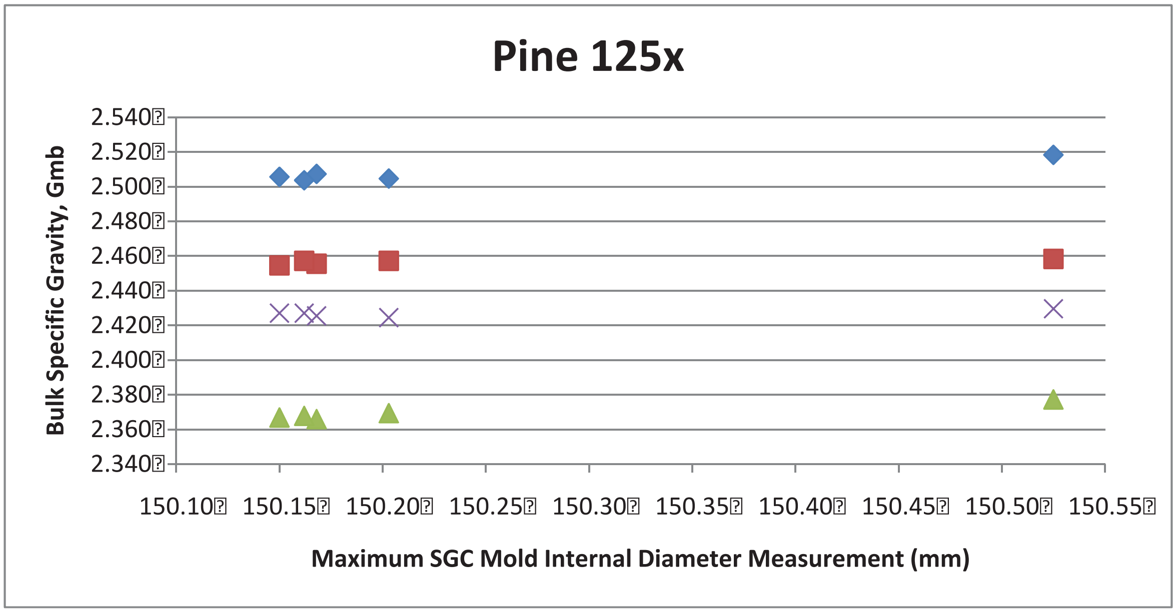


Figure 4. Relationship Between Specimen Density and SGC Mold Diameter, Pine 125x

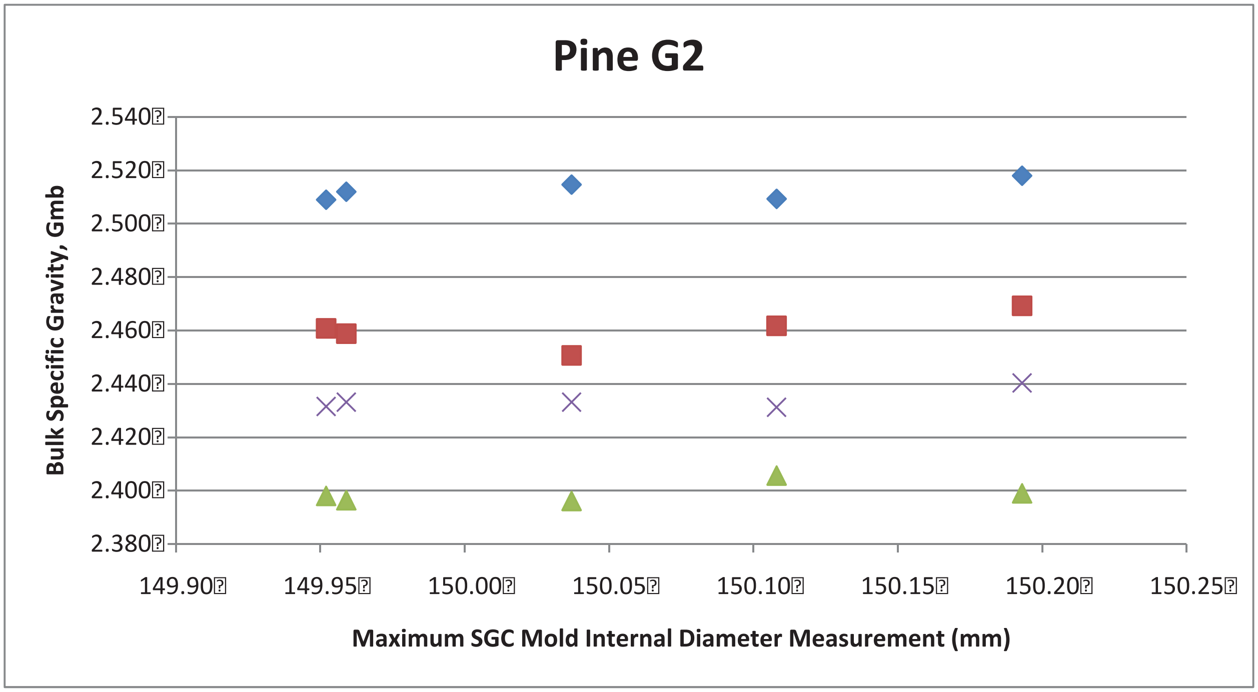


Figure 5. Relationship Between Specimen Density and SGC Mold Diameter, Pine G2

Sampling and Testing

A potentially significant source of variability in G_{mb} of compacted HMA relates to sampling and testing. In many cases, relatively coarse-graded HMA, such as Superpave and Stone-Matrix Asphalt (SMA) may increase the potential for segregation during sampling and subsequent sample handling/preparation (i.e. splitting, SGC mold loading). Industry groups such as the National Asphalt Pavement Association (NAPA) and the Asphalt Institute (AI) provide information relating to “best practices” associated with sampling and handling. Steps must be taken to ensure that all persons involved in HMA sampling and preparations adhere to best practices.

It should be recognized that any material test contains inherent variability. This is the case with the determination of bulk specific gravity (G_{mb}). AASHTO and ASTM material test methods typically contain statements concerning the precision of the method. One key piece of information in the “precision and bias” statement regards the D2s – the acceptable range of two test results. For example, two persons should be able to determine the G_{mb} of the same HMA specimen so that the difference in the two test results is less than the stated D2s limits for the test method. If this consistently proves not to be the case, a thorough examination should be conducted of all steps included in the test method to ensure that each person performing the test is indeed performing the test according to the test method.

Addressing all the potential sources of variability previously discussed should be the first step(s) taken by a laboratory that experiences difficulties in obtaining consistent, verifiable G_{mb} values for compacted hot mix asphalt specimens.

Determination of SGC Bias

For laboratories that experience difficulties in producing consistent G_{mb} values that verify among two or more gyratory compactors (and have investigated and addressed those sources of variability listed in the previous Section), a second step in defining the potential problem is to determine whether a bias exists among compactors. To do this, one or more comparison studies may be performed. A brief outline of those steps necessary for a successful comparison study follows. It is assumed in the discussions that all SGCs are properly calibrated using current manufacturer's recommendations and/or applicable specifications.

Hot Mix Asphalt (HMA) – to compare two or more compactors, a consistent mixture is vital. Ideally, a plant-produced mixture is sampled at the hot mix plant and split into specimen sizes (generally 4500 to 5000 g) "on site" – without reheating the mix. If laboratory-prepared HMA is used, extreme caution must be used to ensure that each separate batch is prepared – aggregate blending, mixing, aging/heating – as consistently as possible.

Number of Specimens/Mixes – comparison studies related to gyratory compactors may be performed for a particular HMA mixture, or for a variety of mixtures. A higher number of mixtures included in a comparison study provides a more complete picture of the relationship between two or more compactors. In addition, mixture variety – various nominal maximum aggregate sizes, number of gyrations, and binder grade – adds to the completeness of the comparison. It is noted that AASHTO PP 35 (the original specification used to validate a gyratory compactor) recommends a minimum of four mixtures for the SGC validation process. A minimum of six (6) HMA specimens should be compacted in each SGC for each mixture used.

Compaction and Testing – it is apparent that the number of specimens involved in a comparison study ranges from a minimum of 12 to a potentially very large value. Great care must be taken to ensure that each HMA specimen is treated as "equally" as possible. Some issues related to this consideration follow.

Randomness: specimens should be selected for compaction and testing using a “blind” random process. That is, each individual specimen is chosen from the “pool” of specimens using a random process and assigned to a particular compactor. It is also recommended that compaction and testing be performed randomly – that is, avoid compacting all of the specimens for a particular compactor at one time, before moving to the next compactor. This recommendation holds for the testing sequence – all of the specimens produced by one compactor should not be tested as a group prior to the specimens from a subsequent compactor.

Operator: insofar as possible, the same operator should perform all compaction and testing activities. This is particularly important for testing, to avoid or limit inherent operator-related variability in test results.

Data Analysis: two numbers related to G_{mb} test results are used to compare compactors. Brief comments related to the comparison follow.

a. Mean: the mean G_{mb} of specimens compacted on subject SGC units is the “bottom line” of the comparison effort. Two analyses should be performed:

   (1) *statistical* comparison, in which mean values are compared using statistical tests such as the Student’s t-test or an analysis of variance, or F-test. For comparisons of mean values, the “t” test is typically used. These analysis tools will indicate whether a *statistical* difference exists between the data sets.

   (2) *practical* comparison, in which the mean values are examined to estimate the *practical* effect a difference in mean values will have on determining mixture properties such as air voids, VMA, etc. In some cases, test results displaying a *statistically significant* difference may be judged to be “close enough” to avoid having a *practical* effect on mixture properties.

b. Standard Deviation: the standard deviation of G_{mb} may be used to judge the variability of HMA specimen density exhibited by a compactor. However, persons conducting comparison studies are strongly cautioned to use standard deviation results with care – the standard deviation of test results contains the variability of the G_{mb} test method itself. An Analysis of Variance (ANOVA) may be used to compare standard deviation values.

Based on the comparison of mean G_{mb} values, a quantifiable bias among two or more SGC units may be identified. That bias may be taken into account in future mixture verification activities, or further investigations into reducing or eliminating the bias may be pursued.

Establishing the existence of a quantifiable bias among compactors may be a desirable second step taken by a laboratory that experiences difficulties in obtaining consistent, verifiable G_{mb} values for compacted hot mix asphalt specimens.

Using the Dynamic Internal Angle (DIA) to Calibrate the SGC

Once all potential sources of variability have been addressed and a bias has been demonstrated between two or more compactors, an additional procedure might be performed by a laboratory/agency to reduce or eliminate differences in G_{mb} produced by various gyratory compactors. The discussion that follows highlights a method for calibrating SGC units using an *internal* angle of gyration.

Background on Variability

As early as 2000-2001, growing evidence showed that an HMA mixture compacted with different Superpave Gyratory Compactors (SGCs) could result in significantly different densities and air voids *(1,2,3,4)*. Carefully controlled experiments showed that the air voids can differ as much as 1.0 percent when the same technician molds a set of specimens in two different, but properly calibrated SGCs *(1)*. Furthermore, data from the AASHTO Materials Reference Laboratory indicated that the multilab precision of SGC compacted specimens by accredited laboratories was so poor that the acceptable range of air voids between two labs may be as much as 1.8 percent *(2)*. This difference impeded HMA mix design processes, created disputes between contractor QC results and agency QA results, and caused confusion about the appropriate compactive effort to use for selecting design asphalt contents.

It is important to note that no particular brand of SGC was labeled as being correct or incorrect, right or wrong. However, it is necessary to recognize that the machines react differently to asphalt mixture shear resistance during compaction, and that these reaction differences may result in different properties of the compacted HMA samples. Figure 6 illustrates the differences obtained from two “brands” of SGCs. This data was provided from research performed at the National Center for Asphalt Technology (NCAT) on validation of the Superpave N_{design} table *(4)*. The X and Y axes are the number of gyrations to achieve the initial in-place density from a wide spectrum of projects. The fact that all the data lie above the “Line of Equality” clearly shows that fewer gyrations are required for Brand 1 compactor to achieve the same density as Brand 2 compactor.

It was theorized that then-current requirements for calibrating SGCs in AASHTO T 312 using the ‘external’ angle of gyration did not sufficiently limit the parallelness of the top and bottom plates during the gyratory compaction process. A confounding factor is that each SGC manufacturer utilized a different approach to measuring the angle of gyration of the mold (external). Therefore, it was not been possible to independently verify the critical parameters of the compaction process for each type of machine with a single calibration technique. Differences in frame compliance of each SGC, and differences in calibration technique, led to biases in properties of compacted HMA samples from machine to machine.

A New Approach: The Dynamic Internal Angle

Starting in 1998, FHWA's Tuner-Fairbank Highway Research Center developed a device to measure the angle of gyration from inside the mold. The device was initially referred to as the AVK (Angle Validation Kit) and is now know as the Dynamic Angle Validator or DAV.

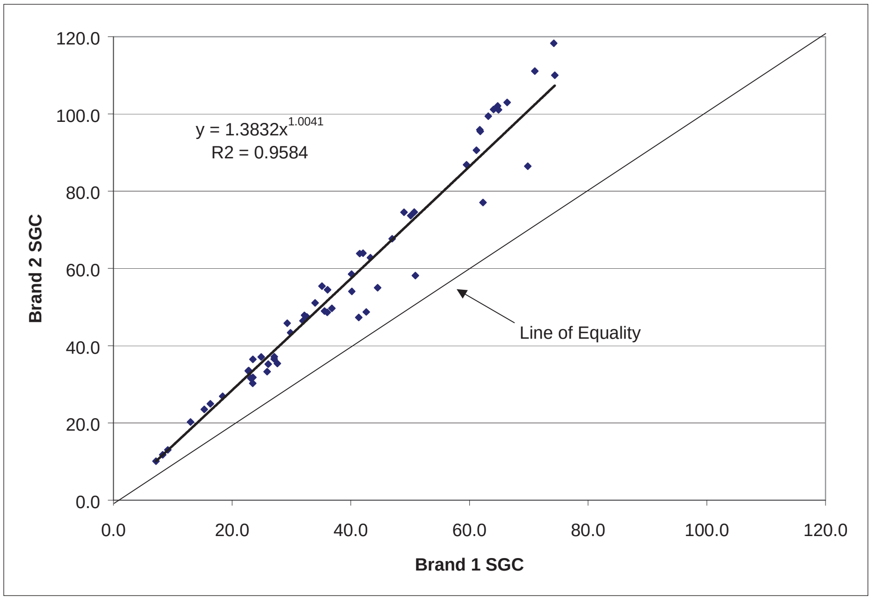


Figure 6. Illustration of Bias Among SGC Brands(4)

Figure 7 is an example of the output from the original AVK (now DAV), with the instrument positioned at the bottom of the mold. The upper line shows the angle measured at each gyration. Typically the data between 10 and about 90 gyrations were averaged to determine the angle at each position. The bottom line shows the temperature recorded inside the DAV that was used to ensure that the electronic components were not damaged.

FHWA used the DAV to determine the effective internal angle of the original "first article" SGCs made by Pine Instrument Co. and Troxler Electronics Labs *(5)*. These machines have served as the "standards" to which other makes and models have been evaluated. Their measurements showed that the original Pine SGC had an internal angle of 1.18° when set to an external angle of 1.25° as required by AASHTO T 312. Likewise, the original Troxler SGC had an internal angle of 1.14° when set up to an external angle of 1.25°. The target for the effective internal angle was thus set as 1.16°, the average of those two machines.

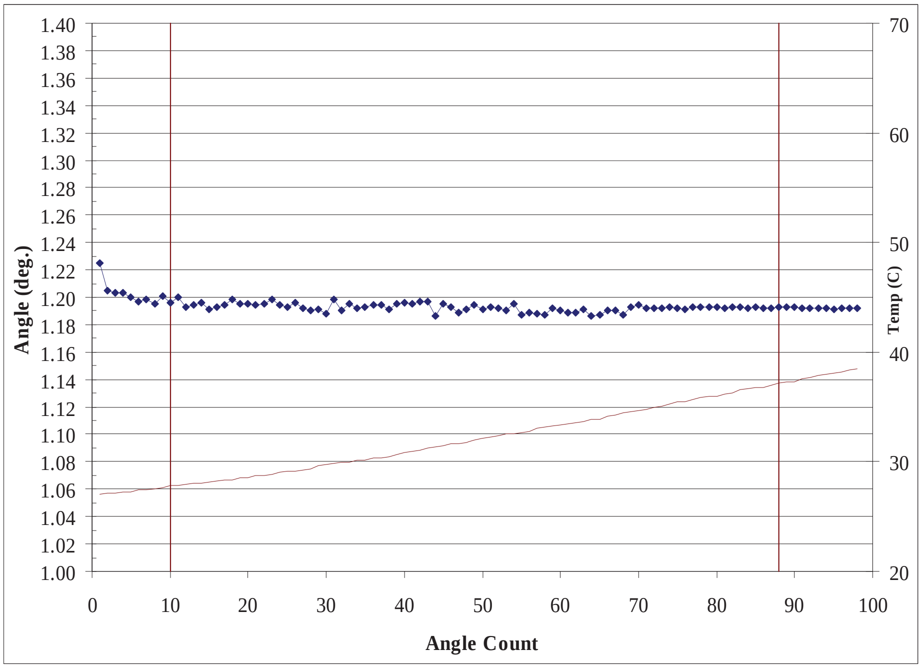


Figure 7. Example Output from Angle Validation Kit (AVK)

FHWA initially established a tolerance of the effective internal angle at ± 0.02°. This range was calculated to limit the effect of the angle on selecting asphalt content within 0.1 percent *(5)*. Tolerance for the effective internal angle was consistent with the angle standard based on external mold measurements, was shown to be an appropriate range in the 1996 SGC ruggedness study *(6)*.

Early Experimental Results Using Internal Angle of Gyration

Proof was needed that changing to an effective internal angle calibration procedure would remove or significantly reduce the bias between results from different SGCs. Eight laboratories participated in an experiment to assess the effectiveness of proposed procedure. This volunteer cooperative effort included most of the SGC models used throughout the USA and a wide range of mixture types. Table 2 presents the general scope of the cooperative research.

Table 2. Research Scope of Initial Internal Angle Cooperative Study

Laboratory	Mix Sizes	Superpave Gyratory Compactors Evaluated
Asphalt Institute	12.5mm, 25.0mm	Pine AFGC125X, Trolxer 4140
APAC, Inc.	9.5mm	Interlaken, Pine AFGC125X, Pine AFG1, Troxler 4140, Troxler 4141
NCAT	4.75mm	Pine AFGC125X, Troxler 4140, Troxler 4141
FHWA	9.5 mm, 12.5 mm, 19.0 mm	Troxler 4140, TestQuip Brovold
Florida DOT	12.5mm	Pine AFGC125X, Trolxer 4140
Pine Instrument Co.	9.5mm, 12.5mm, 19.0mm, 25.0mm	Pine AFGC125X, Pine AFG1, Pine AFGB
Troxler Electronic Labs	9.5mm, 19.0mm	Troxler 4140, Troxler 4141
University of Arkansas	12.5mm	Pine AFGC125X, Trolxer 4140

The primary objective of this research effort was to calibrate SGCs to an effective internal angle of 1.16± 0.02° with the DAV, and then make comparisons of specimens compacted with the different SGCs. Comparisons were made on the basis of air void contents. An example of a plot used to make comparisons among the results from different SGCs is shown in Figure 8.

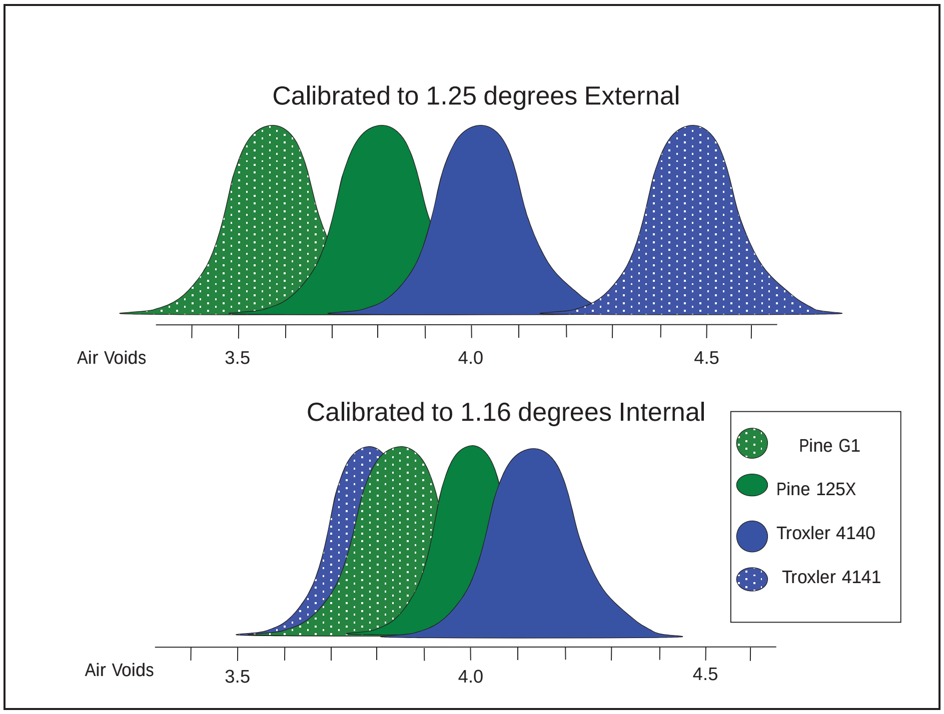


Figure 8. Example Results from Initial Internal Angle Cooperative Study

The results from the cooperative study generally indicated that the DAV calibration procedure removed some of the bias between the SGCs. In particular, comparisons of data from Pine and Troxler compactors were improved 20 to 100 percent. The average reduction in the bias between these two manufacturers was about 50 percent. As expected, results from models of the same manufacturer (Troxler to Troxler, Pine to Pine) continued to match well when using the DAV procedure.

Initial Implementation of the Dynamic Internal Angle Calibration Procedure

The initial procedure for using the Dynamic Angle Validator (DAV) was developed as AASHTO PP 48. This procedure required the DAV to be inserted into a compaction mold with hot mix asphalt, to provide a measure of the dynamic internal angle while the compactor was 'under load'. In addition, the procedure required internal angle measurements to be conducted with the DAV unit "under" the mix (for the "bottom" internal angle) and with the DAV unit "above" the mix (for the "top" internal angle). Procedures for calibrating SGCs via the internal angle of gyration using hot mix asphalt presented a number of potentially significant issues. The discussion that follows here was adapted from information provided by the DAV Task Group sponsored by the Mixtures and Aggregates ETG and ASTM subcommittee D04.25.

Time Required for Angle Determination

Measurements of the internal angle were required at multiple positions in the molds. Replicate measurements at each position were also necessary to assure greater accuracy of the data. The overall time to complete the measurements and analysis for an engineer or lab technician experienced with the procedure was typically four to eight hours. Notably, a second-generation DAV device (the "DAV 2") was introduced in the summer of 2004. The time required for SGC calibration using hot mix asphalt was subsequently reduced; however, a full calibration continued to require a number of hours to complete.

Extrapolation and Full-Height Methods

Some Superpave gyratory compactor molds are not tall enough to accommodate the DAV and the volume of loose mixture for a standard 115 mm HMA specimen. To solve this problem, a method was developed in which the internal angle measurements were made using specimens at two smaller heights. The data from the internal measurements at the two smaller heights were used to extrapolate to the internal angle for a full-sized specimen. Figure 9 illustrates the concept. Independent measurements made on replicate specimens compacted to heights of approximately 30 mm and 70 mm are used to linearly extrapolate to the angle for a full size (115 mm) specimen. This process was required for both “top” and “bottom” internal angles. The extrapolated top and bottom angles were then averaged to determine the effective internal angle of gyration.

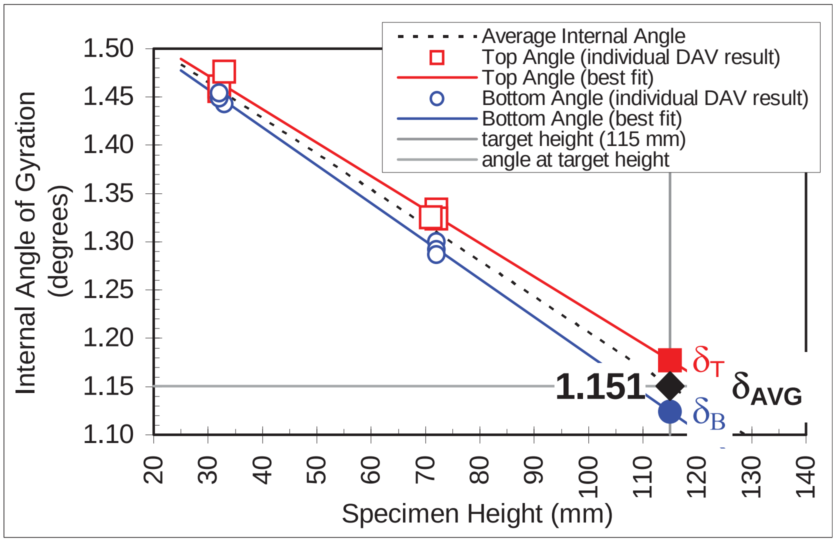


Figure 9. Extrapolation Method for Determining Dynamic Internal Angle

Data collected from several laboratories initially indicated the extrapolation method yielded an internal angle comparable to that obtained using full-height specimens. Figure 10 shows such data. The difference in internal angles derived using both methods is not statistically significant at the 0.05 level. This plot also shows a ±0.02° “band” around the line of equality. In all cases but one, the internal angle from extrapolation falls within this range compared to the full-height angle. It is noted that the uncertainty of an angle measurement using the DAV is also approximately 0.02°. Thus, differences in internal angles as shown in the plot fall within the projected “accuracy” of the DAV device. It was concluded that either angle measurement method, full-height or extrapolation, yielded the same average internal angle of the gyratory compactor.

However, additional data were generated and presented to the Mixtures and Aggregates ETG in September 2006 which refuted the conclusion that a linear extrapolation procedure would yield an internal angle of gyration equivalent to that value measured using a full-height specimen (*8)*.

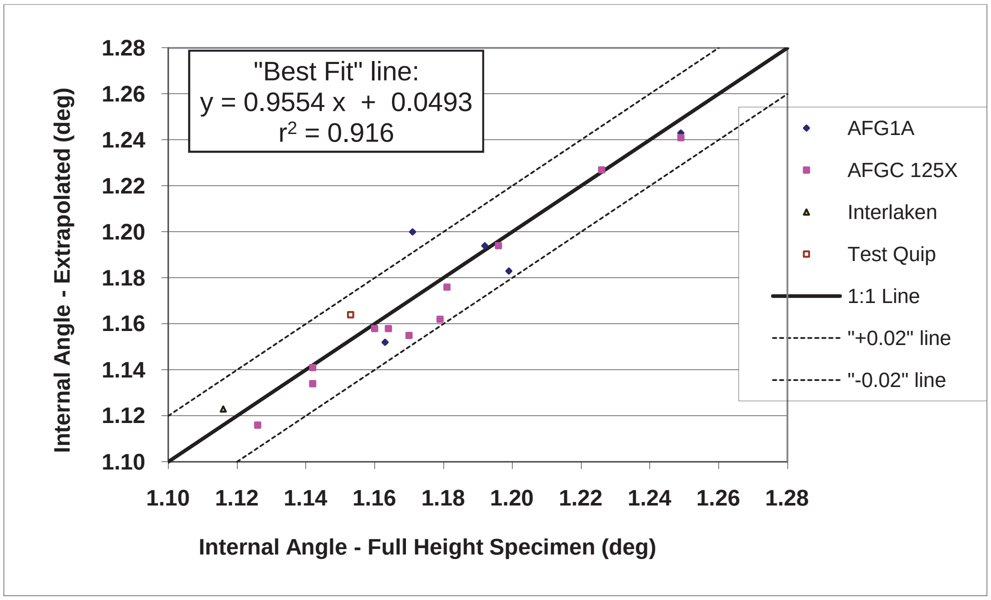


Figure 10. Comparison of Internal Angle Values Using Full-Height Specimens and the Extrapolation Procedure

HMA Mix for SGC Calibration

Research indicated that the stiffness of the mixture used during the internal angle measurements had an effect on the resulting angle. In general, stiffer mixtures develop more resistance to compaction and cause more strain within the frame of the SGC, which may result in a lower effective internal angle. Therefore, calibrating two or more SGC units using a *particular* HMA mixture will not necessarily ensure that those units will produce specimens having similar G_{mb} values for *all* HMA mixtures.

MEASUREMENT OF THE DYNAMIC INTERNAL ANGLE USING SIMULATED LOADING

A number of advancements concerning the measurement of effective internal angle occurred from 2003-2006. The original internal angle device and procedure (the AVK, later DAV) was formalized with the approval of AASHTO PP 48, and was included as an option in AASHTO T312-03, the specification for gyratory compaction. However, a number of significant issues were identified during the implementation of the original procedure, as detailed earlier. In response to concerns regarding the use of hot mix asphalt for determining the dynamic internal angle, two devices have been developed that will induce a load in a Superpave gyratory compactor similar to that induced by HMA during compaction.

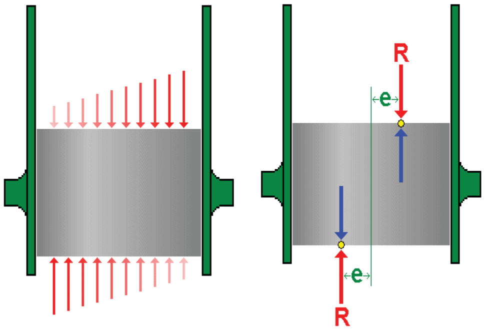
The theory behind the loading placed on a gyratory compactor by HMA has been described by Bahia *(9)*. Procedures developed for mechanically simulating the load placed on the SGC are based on this work. The two simulated load devices include the Rapid Angle Measurement (RAM) and the Hot mix Simulator (HMS). The HMS is used in conjunction with the Dynamic Angle Validator (DAV).

Rapid Angle Measurement (RAM) Device.

Dalton *(10)* provides an excellent synopsis of the gyratory load theory suggested by Bahia. A synopsis of the concept used by the RAM (shown in Figure 11) to simulate gyratory loading is presented here.

Figure 11. Rapid Angle Measurement (RAM) Device.

In general, the forces acting within the SGC mold during compaction produce a load gradient across the face of the HMA specimen *(11)*. This gradient may be represented by a single point load acting at a distance away from the center axis of the mold. This "offset" distance may be termed the *eccentricity*, as illustrated in Figure 12. The RAM simulates the eccentric-point-load approach through the use of two raised contact rings of specified diameter affixed to the top and bottom faces of the device. The diameter (or radius) of these rings provides a known eccentricity for a rotating point load.



SGC Load Gradient **Representation of Load Gradient by Point Load**

Figure 12. Eccentric-Point-Load Concept Used by the RAM to Simulate Gyratory Load

Figure 13 shows a production-model RAM with additional contact rings; the rings are affixed to the device beneath the wearing plate (shown on the upper surface of the device). Figure 14 is a schematic illustrating how the raised ring ensures a single, rotating point of contact between the load platens of an SGC and the RAM unit. Traces of two different diameter contact rings are visible on the surface of the wearing plate in Figure13.

Figure 13. Production model Rapid Angle Measurement (RAM) with Contact Rings.

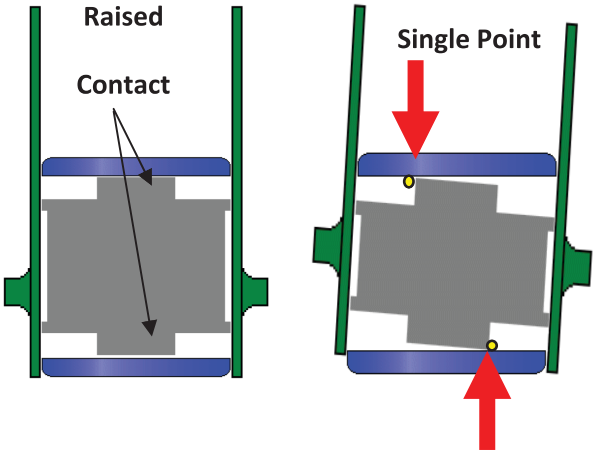


Figure 14. RAM Simulation of Single Eccentric Point Load

Hall and Easley developed an initial estimate of the precision of the angle measurement provided the RAM in 2004 *(12)*. Table 3 summarizes the mean, repeatability standard deviation (s_r), reproducibility standard deviation (s_R), and the estimate of the 95 percent repeatability and reproducibility limits for the RAM device when used on the compactor models featured in the study. As shown in Table 3, the repeatability of the RAM met or exceeded the value assumed (0.02) for the original DAV device for most major brands of Superpave gyratory compactor.

Table 3. Initial Estimate of the Precision of the Dynamic Internal Angle Measurement Using the Rapid Angle Measurement (RAM)(12)

Superpave Gyratory Compactor	**x**	s_r	s_R	**r**	**R**
Pine AFG1A	1.168	0.0034	0.0122	0.0094	0.0342
Pine AFGC125X	1.147	0.0047	0.0126	0.0131	0.0353
Pine AFGB1A	1.149	0.0017	0.0102	0.0049	0.0285
Troxler 4140	1.054	0.0095	0.0127	0.0267	0.0355
Troxler 4141	1.100	0.0029	0.0108	0.0081	0.0304

where:

x	average of study data
s_r	repeatability standard deviation
s_R	reproducibility standard deviation
r	repeatability acceptable range of two test results (d2s: 95% limit)
R	reproducibility acceptable range of two test results (d2s: 95% limit)

Hot Mix Simulator (HMS)

The Hot Mix Simulator (HMS) was introduced in the Spring of 2004. The HMS is a fixture that is used in conjunction with the Dynamic Angle Validator (DAV) which simulates the loading placed on the Superpave gyratory compactor by hot mix asphalt. Figure 15 shows the HMS. Brovold *(13)* provides general guidance relating to the theory behind the method of simulating shear resistance used by the Hot mix Simulator (HMS); a schematic of the basic mechanical relationships is shown in Figure 16.

Gyratory force is transmitted through a point of contact between the surface of an upper dome (of the HMS) and the inside of a cone-shaped depression machined into the HMS upper plate (shown in Figure 15). A shear force is created by the wedge angle, δ. This shear force forms one moment couple acting on the DAV/HMS unit. Another moment couple is created through the gyratory force (F) acting at a distance away from the center of the mold (recall that the point of force contact is on the outside of the dome structure).

Resolution of forces (and resulting moments) leads to an expression for the eccentricity, shown as

Equation 1. $e = \tan \delta * 115 / 2$ Eq. 1

where: e = eccentricity (mm) δ = angle of depression in upper HMS plate (rad)

Figure 15. The Hot mix Simulator (HMS) Attachment to the Dynamic Angle Validator (DAV)

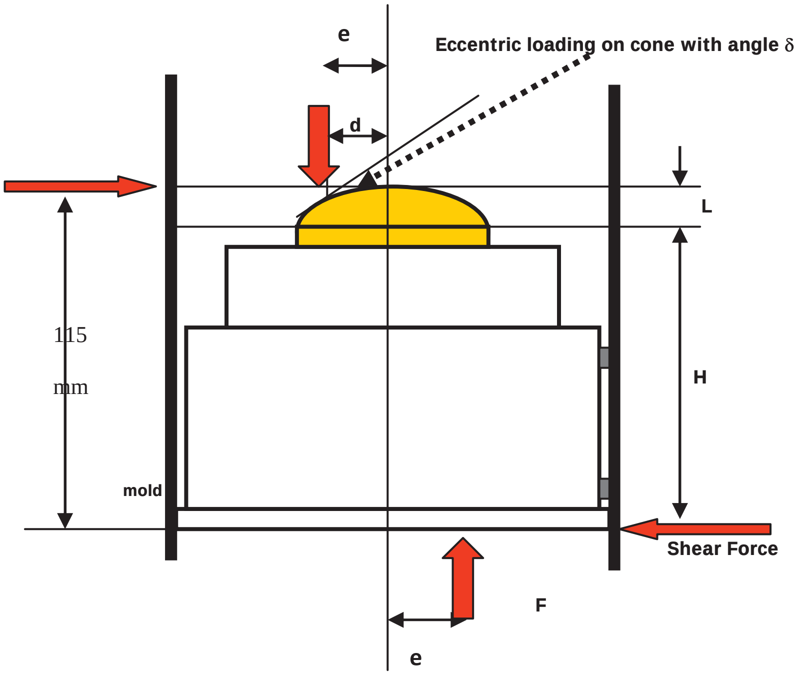


Figure 16. Operational schematic of the Hot mix Simulator (HMS)

Hall and Easley developed an initial estimate of the precision of the angle measurement provided by the DAV2/HMS combination in 2006 *(14)*. Table 4 summarizes the mean, repeatability standard deviation (s_r), reproducibility standard deviation (s_R), and the estimate of the 95 percent repeatability and reproducibility limits for the DAV2 device when used on the compactor models featured in the study. As shown in Table 4, the repeatability of the DAV2 meets or exceeds the value assumed (0.02) for the original DAV device for most major brands of Superpave gyratory compactor.

Table 4. Initial Estimate of the Precision of the Dynamic Internal Angle Measurement Using the Dynamic Angle Validator (DAV2) with the Hot mix Simulator(14)

Superpave Gyratory Compactor	x	s_r	s_R	r	R
Pine AFG1A	1.179	0.0044	0.0062	0.0123	0.0174
Pine AFGC125X	1.153	0.0026	0.0042	0.0072	0.0117
Pine AFGB1A	1.134	0.0031	0.0078	0.0087	0.0219
Troxler 4140	0.982	0.0049	0.0080	0.0138	0.0225
Troxler 4141	1.137	0.0120	0.0144	0.0336	0.0404

where:	x	average of study data
	s_r	repeatability standard deviation
	s_R	reproducibility standard deviation
	r	repeatability acceptable range of two test results (d2s: 95% limit)
	R	reproducibility acceptable range of two test results (d2s: 95% limit)

ADDITIONAL CONSIDERATIONS FOR THE DYNAMIC INTERNAL ANGLE

Gyratory Frame Stiffness Concepts

As mentioned previously, the measured value of the internal angle of gyration appears to be related to the stiffness of the HMA mix (real or simulated) used in the determination. The most likely major contributing factor to this phenomenon is the stiffness of the frame of the SGC. Simulated loading devices such as the RAM and HMS allow the control of load eccentricity (simulating the shear resistance offered by HMA mixes of varying stiffness) to create a known tilting moment coupling on the device inside the SGC mold. A plot of the applied tilting moment versus the measured internal angle provides a representation of the "frame stiffness" for a given SGC. The general relationship between tilting moment and eccentricity is shown in Equation 4.

$$\text{Moment (N-m)} = \text{eccentricity (mm)} * \text{SGC Force (N)} / 1000 \qquad \text{Eq. 4}$$

A typical value for SGC Force (at 600 kPa pressure) is approximately 10,602 N.

Figures 17 and 18 are plots of tilting moment versus measured internal angle for five models of Superpave gyratory compactor, from ongoing studies being performed by the University of Arkansas using "production model" RAM and DAV2/HMS units. Relative frame stiffness is assessed by comparing the slope of the lines shown on the graph. For ease of comparison, the slope for each data set (in deg/N-m) is shown in the legend of the figure. It is apparent that real differences occur in the measured internal angle, for the same compactor, when using different simulated loads. These differences in internal angle can be significant, considering the original internal angle specification for compaction is 1.16±0.02 degrees (AASHTO T312).

Table 5 summarizes the "frame stiffness" (slope of the internal angle-versus-tilting moment line) as evaluated by the RAM and DAV2/HMS for the five SGC units in the University of Arkansas study. It is noted that the single point shown for each angle in Figures 17 and 18 represents the average of three angle measurements.

The frame stiffness phenomenon complicates the comparison of dynamic internal angle values measured using simulated loading devices with those measured using hot mix asphalt. For a direct comparison, an "equivalent eccentricity" must be determined for the hot mix asphalt used in the measurement. Research to characterize hot mix asphalt mixtures in terms of equivalent eccentricity (to allow such comparisons) has not successfully identified any such relationships suitable for implementation into routine practice *(15)*.

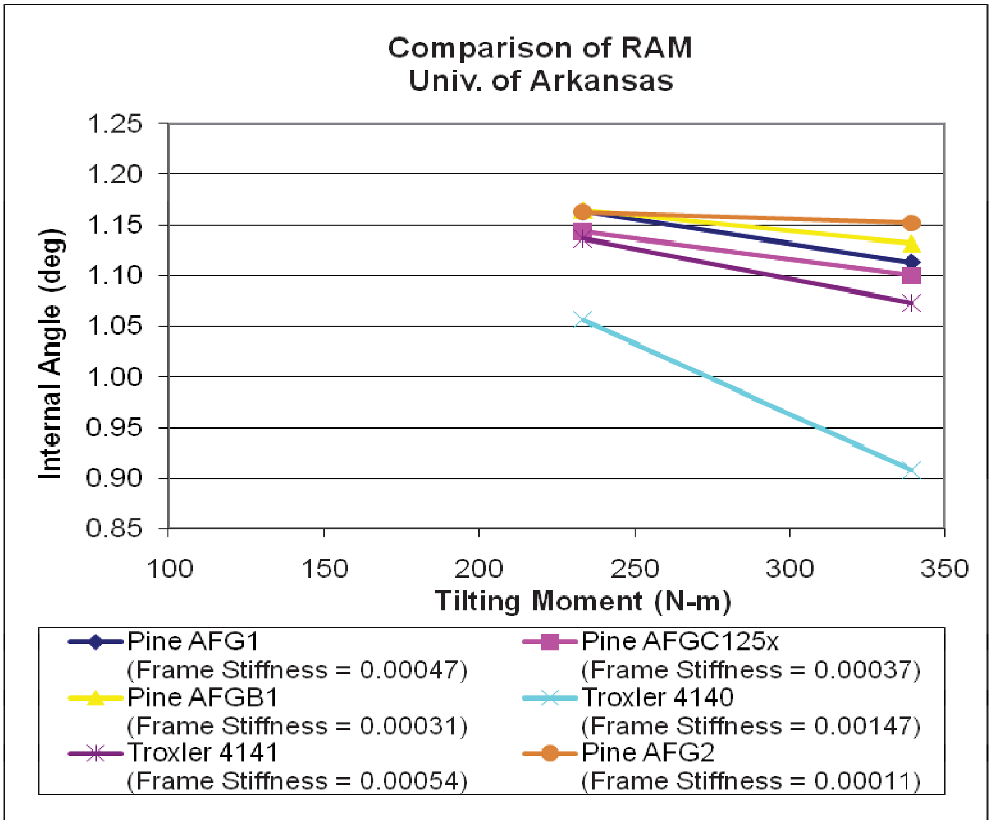


Figure 17. Comparison of SGC frame stiffness using the Rapid Angle Measurement Device (RAM).

Table 5. Comparison of SGC Frame Stiffness Values – RAM and DAV2/HMS

SGC Frame Stiffness (deg / N-m)					
Internal Angle Device	**Superpave Gyratory Compactor**				
	Pine AFGC125	**Pine AFG1**	**Pine AFGB1**	**Troxler 4141**	**Troxler 4140**
RAM	0.00041	0.00047	0.00031	0.00060	0.00140
DAV2/HMS	0.00030	0.00043	0.00028	0.00052	0.00184

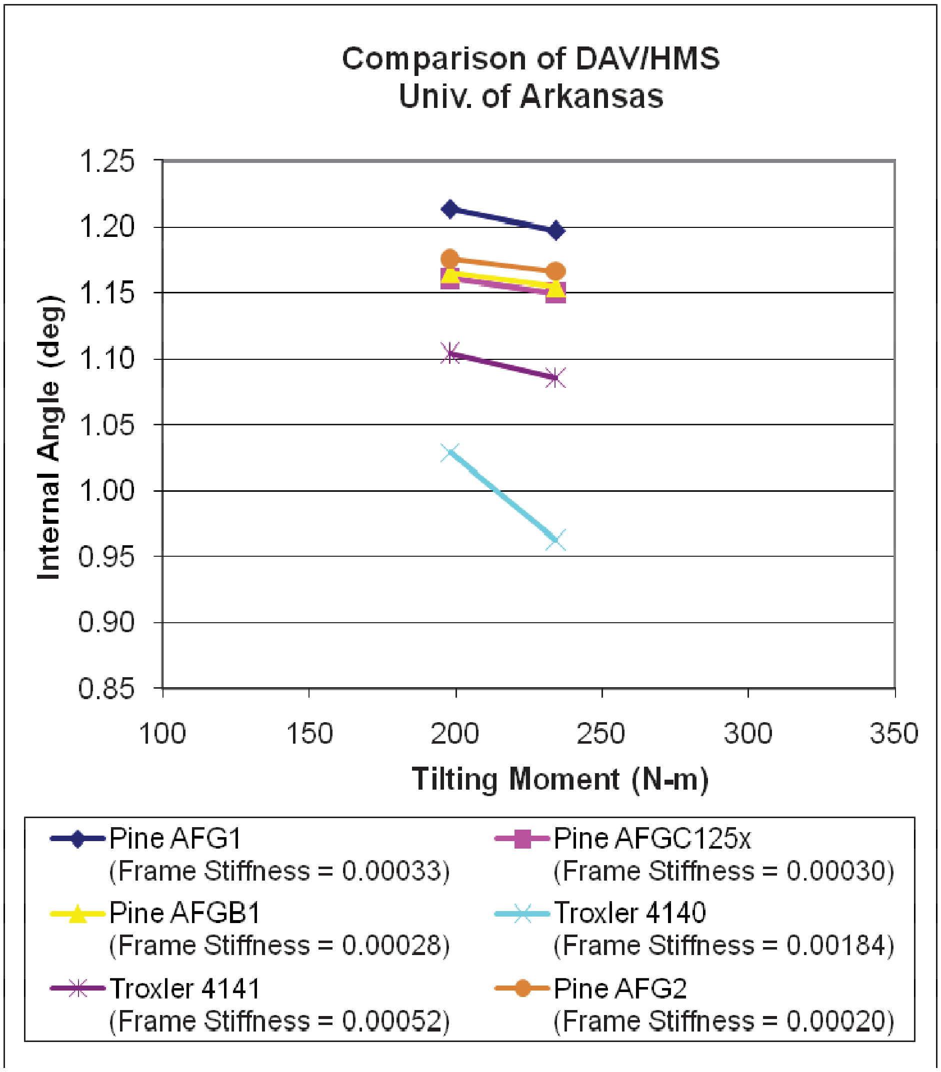


Figure 18. Comparison of SGC frame stiffness using the Hot mix Simulator (HMS).

Temperature Issues

One issue that arose during research studies and specification subcommittee meetings regarding the measurement of internal angle relates to the temperature of the SGC mold used during angle measurements. Obviously, the most expedient method for measuring internal angle is to use SGC molds at room temperature; however, it is recognized that during compaction, all surfaces will be heated. Thus the question of the suitability of using room temperature molds is valid.

Figure 19 shows a comparison of internal angles measured on various SGC models using both "hot" and room temperature molds, conducted by the Florida DOT using a RAM with 44 mm diameter contact ring. A "paired-t" test conducted on the data indicates that the differences between internal angles measured "hot" and "cold" are not significant at a significance level of five percent (⍰=0.05).

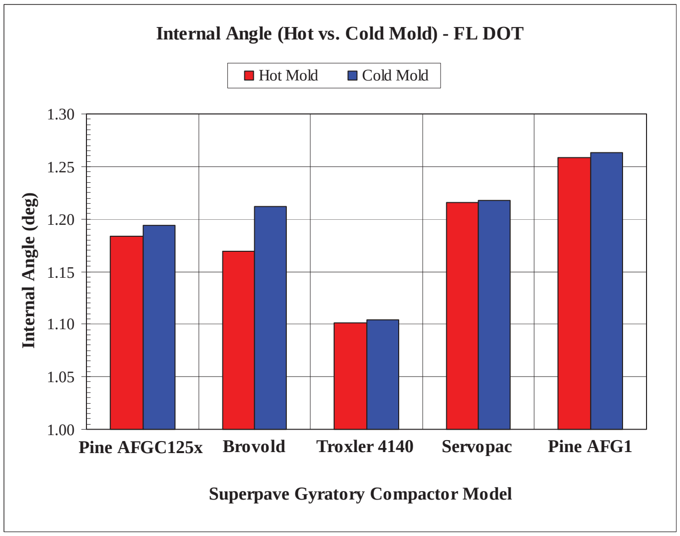


Figure 19. Comparisons of Internal Angle Values using Hot and Room-Temperature SGC Molds.
(Data courtesy of Florida Department. of Transportation)

A "hot versus cold" study using the RAM device conducted at the University of Arkansas is summarized in Table 6. Differences in internal angle for this study generally agree with the Florida DOT study, except that the relatively large effect of temperature on the AFGB1 (Brovold) compactor noted in the Florida DOT study (see Figure 19) is not reflected in the Arkansas study. In Table 6, differences between "hot" and "cold" internal angle values are not consistent across RAM contact ring sizes, nor is there an apparent pattern associated with ring size. It is also noted that, while the majority of comparisons show the "hot mold" angle to be less than the associated "cold mold" angle, some measurements showing the cold mold to be the lesser angle were recorded. These results suggest that a consistent, quantifiable difference does not exist between angle measurements taken with hot and cold compaction molds. A statistical "paired t-test" performed on the Arkansas data indicates differences in cold-versus-hot angles are not significant (t_{stat} = 1.181, compared to $t_{critical}$ = 2.145).

The data presented here may suggest that temperature effects are not identical for different SGC models. However, the variability / uncertainty associated with the measurement of the internal angle using the RAM must also be considered. The differences shown in internal angle measurements between hot and cold molds are, in almost all cases, within the repeatability limits for the RAM (Table 3). Thus, the differences in angle shown cannot be solely assigned to effects of temperature. It must be noted, however, that recent anecdotal reports have surfaced which purport to demonstrate significant differences in measured internal angle attributable to test temperature.

Table 6. Effect of Mold Temperature on Measured Internal Angle (University of Arkansas).

SGC Model	Contact Ring Diameter (mm)	Internal Angle (deg)		
		Cold Mold	Hot[a] Mold	Difference (Cold-Hot)
Pine AFGC125x	35	1.187	1.181	0.006
	44	1.155	1.151	0.004
	60	1.128	1.116	0.012
Pine AFGC1	35	1.185	1.185	0.000
	44	1.156	1.170	-0.014
	60	1.140	1.136	0.004
Brovold (Pine AFGB1)	35	1.176	1.164	0.012
	44	1.157	1.147	0.010
	60	1.136	1.130	0.006
Troxler 4140	35	1.193	1.189	0.004
	44	1.099	1.086	0.013
	60	1.042	1.056	-0.014
Troxler 4141	35	1.208	1.199	0.009
	44	1.150	1.132	0.018
	60	1.063	1.083	-0.020
[a]Hot refers to a mold temperature of approximately 300F				

Comparison of Internal Angle Measurement Systems

Currently, there are three primary methods for determining the internal angle of gyration – DAV with mix, DAV with the HMS, and the RAM. Two questions, then, arise: (1) how do the methods compare? and (2) are the methods interchangeable? A direct comparison of angle measurements taken using hot mix asphalt with DAV and measurements taken using either simulated-loading method is difficult due to the uncertainty of establishing the tilting moment applied to the SGC by the hot mix asphalt. Research recently completed by the Asphalt Institute and the University of Arkansas, among others, concluded that a definitive relationship between the stiffness of a given HMA mixture to a particular equivalent eccentricity applied using the RAM or the HMS did not exist for the mixtures studied *(15).*

Comparisons between the two simulated-loading systems, the RAM and the DAV/HMS, are possible when made on the basis of applied tilting moment. Table 7 shows a comparison of internal angles measured using a production model RAM (with 44 mm contact ring) and an early production/prototype DAV/HMS system (with a 21-deg HMS cone). The tilting moment for each system is calculated using equation 4. For purposes of comparison, the applied SGC force for each system is taken as the nominal 10,602 N. The calculated tilting moments for the RAM is shown as Equation 5. The calculation for the eccentricity of the DAV/HMS (with a 21-deg cone) is shown in Equation 6; the DAV/HMS tilting moment calculation is shown as Equation 7 (taken from Equation 3).

RAM Moment (N-m) = 22 mm * 10,602 N / 1000 = 233.2 N-m (Equation 5)

DAV/HMS eccentricity = tan((radians) 21 deg) * 115 / 2 = 22.07 mm (Equation 6)

DAV/HMS Moment (N-m) = 22.07 mm * 10,602 N / 1000 = 234.0 N-m (Equation 7)

Thus, the best direct comparison of the internal angle values generated by the RAM and DAV/HMS uses the 44 mm RAM contact ring and the 21 deg HMS cone.

The data shown in Table 7 represent the average of three replicate tests on each compactor using each device. The two simulated loading devices do not appear to provide the same value for internal angle at a similar applied tilting moment. Single-factor analysis of variance (ANOVA) tests performed on the data indicate the differences in average internal angle are significant for the Pine G1 and Pine 125x compactors. However, an examination of the *actual* differences in average internal angle values between the two simulated load devices suggests that, in practical terms, the differences noted may not be significant.

ASTM Comparison Study and Current AASHTO/ASTM Specifications

In 2007, Dukatz headed a comprehensive study focused on establishing the precision and bias of the internal angle measurement using simulated load, sponsored by the American Society for Testing and Materials (ASTM) as Interlaboratory Study (ILS) 151 *(16)*. This study also provided a comprehensive comparison of internal angle results generated by the two simulated load devices. The study, which included 28 SGCs representing the major models currently in service, 9 laboratories/agencies, and 12 internal angle instruments (6 RAM devices and 6 DAV/HMS devices), has been generally acknowledged as likely more representative of routine field conditions than previous efforts by Hall and others.

Table 7. Comparison of RAM (44 mm contact ring) and DAV/HMS (21 deg cone)

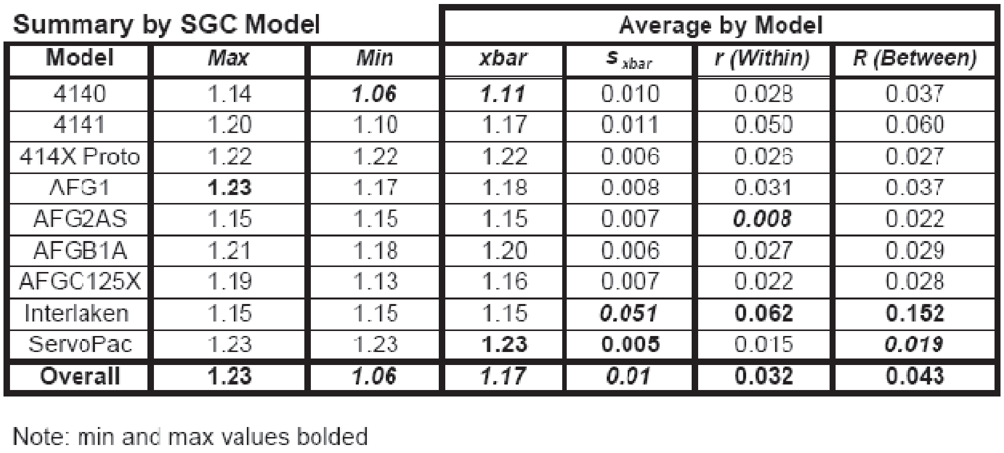
	Average Internal Angle, deg		
	Std. Deviation, 3 replicates		**Difference**
Compactor	**RAM**	**DAV/HMS**	**Significant?[a]**
Pine G1	1.177	1.193	Yes
	0.0076	*0.0025*	
Pine 125x	1.143	1.157	Yes
	0.0029	*0.0020*	
Brovold	1.165	1.160	No
	0.0087	*0.0021*	
Troxler 4140	1.057	1.051	No
	0.0029	*0.0026*	
Troxler 4141	1.137	1.155	No
	0.0161	*0.0096*	
[a]ANOVA (F-test) with level of significance $\alpha = 0.05$			

The major findings of the ILS 151 study, as reported by Dukatz, are summarized:

- The acceptable range of two internal angle measurements (d2s) for single operators is 0.03 degrees;
- The acceptable range of two internal angle measurements (d2s) for multiple operators is 0.04 degrees;
- There is no consistent, significant difference in angle measurements generated by the RAM and DAV/HMS instruments, across the major SGC brands/models typically in service in the U.S.

Table 8 reproduces the summary precision statistics from the ILS 151 study.

Table 8. Summary Statistics from the ASTM ILS 151 Study(16)



Summary by SGC Model			Average by Model			
Model	*Max*	*Min*	*xbar*	s_{xbar}	*r (Within)*	*R (Between)*
4140	1.14	***1.06***	***1.11***	0.010	0.028	0.037
4141	1.20	1.10	1.17	0.011	0.050	0.060
414X Proto	1.22	1.22	1.22	0.006	0.026	0.027
AFG1	**1.23**	1.17	1.18	0.008	0.031	0.037
AFG2AS	1.15	1.15	1.15	0.007	***0.008***	0.022
AFGB1A	1.21	1.18	1.20	0.006	0.027	0.029
AFGC125X	1.19	1.13	1.16	0.007	0.022	0.028
Interlaken	1.15	1.15	1.15	***0.051***	**0.062**	**0.152**
ServoPac	1.23	1.23	**1.23**	**0.005**	0.015	***0.019***
Overall	**1.23**	***1.06***	***1.17***	***0.01***	**0.032**	**0.043**

Note: min and max values bolded

The complete text of the full precision statement from the ILS 151 study follows:

> 13.1 The precision is based on an Interlaboratory Study (ILS #151) that was conducted in 2007 using ASTM E691 Practice for Conducting an Inter-laboratory Study to Determine the Precision of a Test Method and ASTM Practice C 670 for Preparing Precision Statements for Test Methods for Construction Materials. ILS #151 involved 27 laboratories, which featured 5 Troxler (DAVII-HMS) and 6 Pine Instruments AFLS1 (RAM) internal angle instruments and the following SGC models: Troxler Electronics 4140, 4141, and 414x; Pine Instruments AFG1, AFG2, AFGB1, AFGC125X; IPC ServoPac; and Interlaken. Within the study the internal angle measurements ranged from 1.014 to 1.290 degrees.
>
> Single-Instrument Precision — the single operator standard deviation of a single test result has been found to be 0.011 degrees. Therefore, results of two properly conducted measurements by the same operator with the same instrument in the same SGC should not differ by more than 0.03 degrees[3.]
>
> Multi-Instrument Precision — the multi-instrument standard deviation of a single test result has been found to be 0.015 degrees. Therefore, the results of properly conducted measurements by different operators using different instruments in the same SGC should not differ by more than 0.04 degrees[3].

[3] These numbers represent, respectively, the (1s) and (d2s) limits as described in ASTM Practice C 670 for Preparing Precision Statements for Test Methods for Construction Materials.

13.2 Bias — Since there is no accepted reference device suitable for determining the bias in this method, no statement of bias is made.

Current gyratory compaction specifications related to the calibration of the SGC – including AASHTO T312, and AASHTO PP58/ASTM D7115 (governing the measurement of internal angle using simulated loading) draw heavily on the studies previously described, including the precision and bias data reported by Dukatz.

Relationship Between Internal Angle and Air Voids for Compacted HMA

As stated previously, current specifications related to the measurement and use of the internal angle of gyration, e.g. ASTM D7115 AASHTO T312, and AASHTO PP58, require that the internal angle of gyration be set at 20.2±0.35 mrad (1.16±0.02 degrees). However, based on precision data generated by Dukatz *(16)* and Hall *(12,14)*, the suitability of the angle tolerance was questioned. The Federal Highway Administration (FHWA) Expert Task Group on Mixtures and Construction (ETG) commissioned a study to determine the relationship between internal angle and air voids for compacted hot mix asphalt specimens. The study was completed by the FHWA Mobile Asphalt Laboratory and the University of Arkansas in 2008. Complete details of the study are provided by Hall *(17).*

Two hot mix asphalt (HMA) mixtures were used in the investigation, including a fine-graded, 9.5 mm nominal maximum aggregate size mix with an unmodified PG 64-22 binder, and a coarse graded, 12.5 mm nominal maximum aggregate size mix with a polymer-modified PG 76-22 binder. Five internal angles were selected for testing: 15.0 mrad (0.86 deg); 18.5 mrad (1.06 deg); 20.2 mrad (1.16 deg); 22 mrad (1.26 deg); and 25.5 mrad (1.46 deg).

Figures 20 and 21 illustrate the relationship between the internal angle of compaction and the associated air voids of compacted specimens. Figure 1 shows the results from the FHWA Mobile Asphalt Laboratory, using the ServoPac compactor. Figure 2 shows the results from the University of Arkansas laboratory, using the Pine AFG2 compactor. It is apparent from the data presented in Figures 20 and 21, that the results are similar and consistent between the two laboratories/compactors. The Pine AFG2 compactor produced specimens with slightly lower air voids than the values exhibited by the specimens compacted with the ServoPac compactor. Figures 20 and 21 also include regression statistics for linear 'best fit' relationships between internal angle and air voids.

Of particular interest for this project is the slope of the angle-versus-voids relationship. This slope quantifies the effect of changes in the angle of gyration on the air voids of compacted specimens. Table 9 summarizes the slope values recorded in this study.

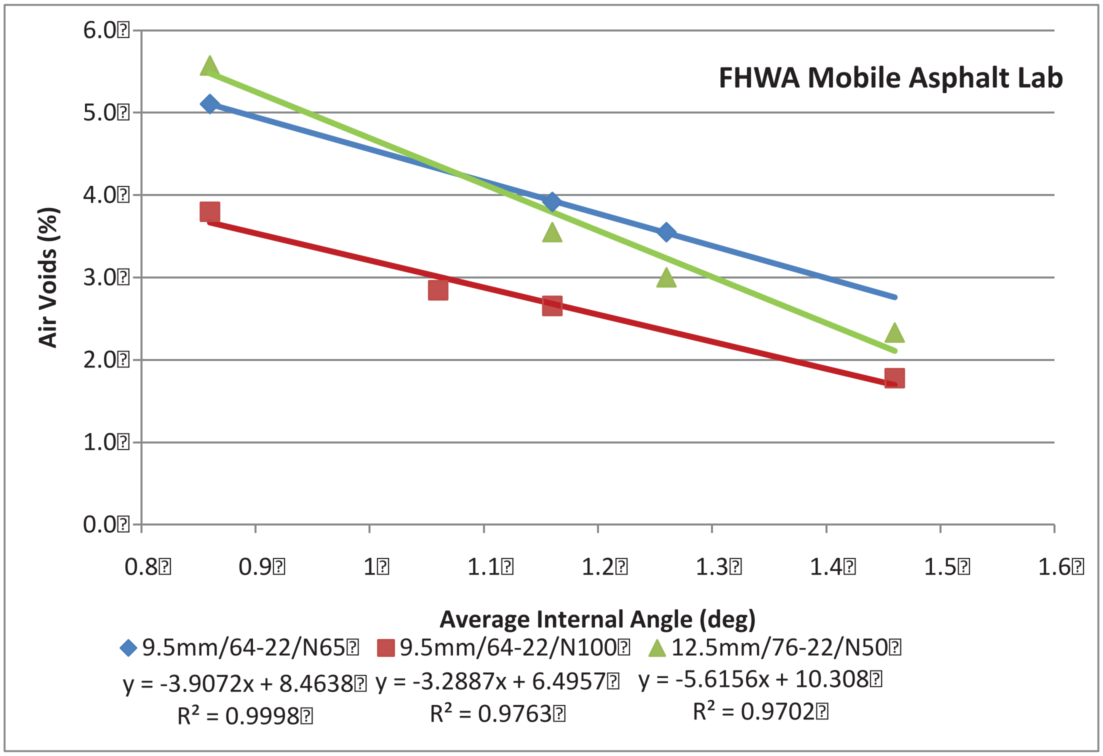


Figure 20. Relationship Between Internal Angle and Air Voids – FHWA/ServoPac Compactor

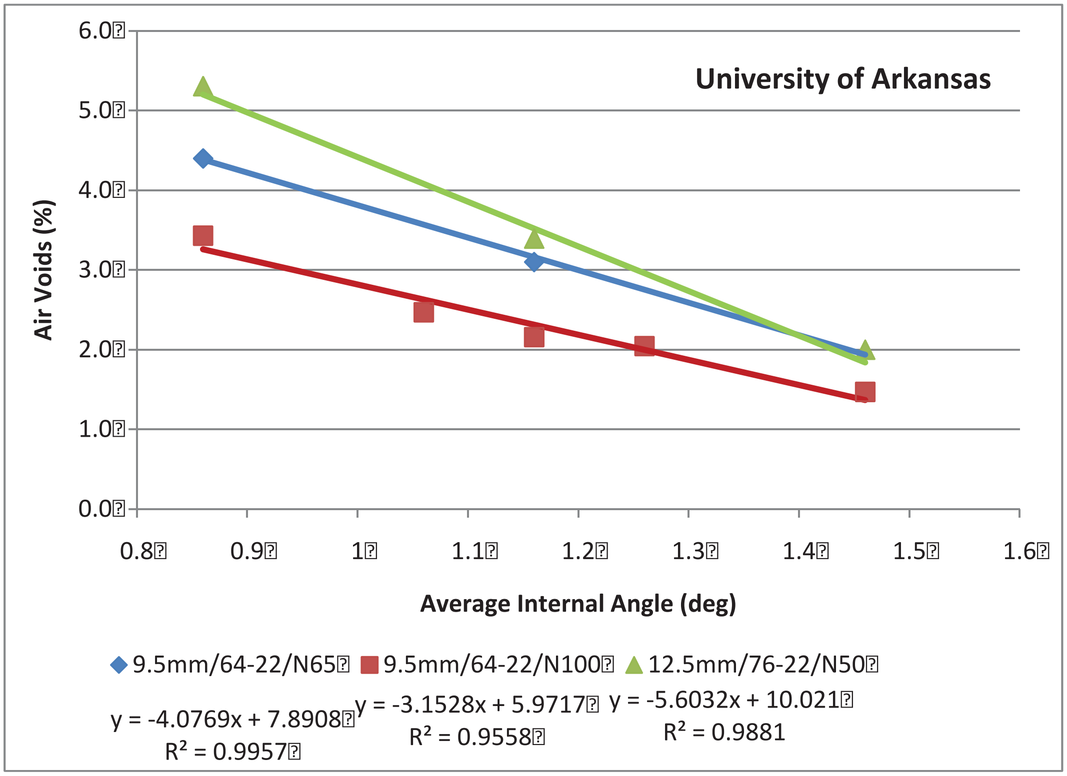


Figure 21. Relationship Between Internal Angle and Air Voids – U. of Arkansas/Pine AFG2 Compactor

Table 9. Slope of Internal Angle versus Air Voids

Slope of Internal Angle - versus - Air Voids		
	FHWA (ServoPac)	U of A (Pine AFG2)
9.5 mm PG 64-22 N100	-3.288	-3.152
9.5 mm PG 64-22 N65	-3.907	-4.076
12.5 mm PG 76-22 N50	-5.615	-5.603

The results from the 9.5 mm mix compacted using 100 gyrations may not be as representative as results from the other specimen sets, due to the relatively low air void levels. Focusing, then, on those results from the 9.5 mm mix at 65 gyrations and the 12.5 mm mix at 50 gyrations, the slopes shown in Table 9 range from -3.907 to -5.615, with an average value of -4.800. Thus, on average, an increase in internal angle of 0.01 degrees would result in a decrease of 0.048 percent air voids. In more general terms, it is reasonable to express the relationship as: *a change in internal angle of 0.01 degrees results in an* average *change in air voids of 0.05 percent.* However, the *exact* relationship between internal angle and air voids may be mixture specific.

Summary and Recommendations

In many states, hot mix asphalt (HMA) specimens compacted using different Superpave Gyratory Compactors (SGCs) exhibit different densities (or air voids). A number of factors might contribute to such differences. A recommended approach to identifying and minimizing cause(s) of air void differences among compactors is summarized as follows:

1. Ensure that each SGC is properly maintained in good working order. **At a minimum**, all maintenance activities recommended by the SGC manufacturer should be performed at the specified time interval. In addition to "routine" scheduled maintenance items, each SGC should be thoroughly inspected for mechanical wear by a qualified service technician at least once per year (or more often if the unit experiences heavy usage).

2. Ensure that each SGC is clean. Build-up of binder and mix on the working surfaces and internal mechanisms of a compactor may lead to variations in the compaction effort supplied by the unit to the hot mix specimen.

3. Periodically inspect each compaction mold for each SGC unit for physical defects, pits, etc. Measure the internal diameter of each mold in the region where mix is compacted (approximately 2 to 6 inches from the bottom). Consider removing any molds used for preparing specimens for acceptance testing that show an internal diameter greater than 150.0 mm. Ensure that SGC molds are cleaned. Build-up of binder and/or hot mix asphalt inside a compaction mold may lead to variations in the density of HMA specimens.

4. If a "bias" between two SGC units is suspected (and all recommendations in items 1 through 3 above have been completed), perform a comparison study as described in this document.

5. When all recommendations in items 1 through 4 (above) have been completed and a demonstrated bias exists between two or more SGC units, differences in air voids among HMA specimens may be reduced by calibrating each SGC using the internal angle of gyration. Current AASHTO and ASTM test methods require the calibration be performed using simulated load techniques.

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Acknowledgements

This **TechBrief** is the result of an FHWA Mixtures Expert Task Group activity to provide the latest information on the use of the Superpave Gyratory Compactor. Members included Kevin Hall (University of Arkansas), Erv Dukatz (Mathy Construction Company), Todd Lynn (Old Castle Company), Roger Pyle (Pine Instruments), Tom Brovold (TestQuip), Ken Brown (Troxler Laboratories) and Randy West (National Center for Asphalt Technology).

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This **TechBrief** was developed by the Office of Pavement Technology as part of the Federal Highway Administration's (FHWA's) Asphalt Pavement Technology Program.

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