Evaluation of Simulated Load Techniques for Determining the Internal Angle of Gyration for the Superpave Gyratory Compactor

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ABSTRACT: Recently concerns have arisen regarding the inability of different Superpave gyratory compactors (SGC) to produce hot-mix asphalt (HMA) specimens with similar density. One proposed solution led to the development of the Dynamic Angle Validation (DAV) kit which measures the angle of gyration internally to the mold. DAV requires the use of HMA for the angle determination; logistical concerns and other issues led to the introduction of devices to mechanically simulate the load placed on the SGC by the mix being compacted. Two such devices – the Rapid Angle Measurement (RAM), which uses invelop load simulation (ILS) technology, and the Hot-Mix Simulator (HMS) – are described. Both simulation systems appear sound and applicable. Outstanding issues include SGC frame stiffness, the use of “cold” versus “hot” molds, comparisons of measurement systems, and the precision of internal angle measurements. Frame stiffness effects may require SGC calibration specifications to specify or reference the applied loading used. Internal angle measurements using simulated loading may be made with SGC molds at room temperature. The two proposed simulated loading methods may not yield the same value for internal angle on all SGC models. A definitive relationship between HMA stiffness and applied load to the SGC must be established to enable comparisons between internal angle measurements taken using hot-mix asphalt and taken using simulated loading.

KEY WORDS: Superpave Gyratory Compaction, Hot-Mix Asphalt, Internal Angle

1 INTRODUCTION

In some respects, the Superpave Gyratory Compactor (SGC) can be considered to be the “centerpiece” of the Superpave mix design system for hot-mix asphalt (HMA). In the SGC, a hot-mix asphalt specimen is compacted using a combination of pressure and an applied angle of gyration that is rotated through the specimen diameter. The angle of gyration was originally established at 22±0.35 mrad (1.25±0.02 degrees), measured externally on the compaction mold (Cominsky, et al, 1993).

In both the HMA mixture design process and quality control/quality assurance (QA/QC) activities, questions have arisen concerning the ability of different compactors to produce specimens of the same mix having the same density or air void percentage. Such concerns led to the development of the Dynamic Angle Validation (DAV) kit – a device having the ability to measure the angle of gyration on an SGC internally (from inside the SGC mold during compaction). The DAV demonstrated the ability to enable SGC units to be adjusted to a common internal angle in order to produce HMA specimens having similar densities (Al-Khateeb, et al, 2002; Prowell, et al, 2003; Dalton, 2001). The DAV device and procedure were added as an option to the standard specification for gyratory compaction, AASHTO T-312, in 2003. In addition, a provisional standard specification (PP-48) was adopted by AASHTO for the use of the DAV system. Hall (2004) summarized efforts to develop the specification for the DAV and an evaluation of the DAV system through a ruggedness study.

The AASHTO PP-48 DAV procedure requires the use of hot-mix asphalt with the DAV device to measure the internal angle of gyration. The reported internal angle of gyration is the average of replicate angle measurements with the DAV resting on top of the mix within the mold and with the DAV under the mix within the mold, as illustrated in Figure 1.

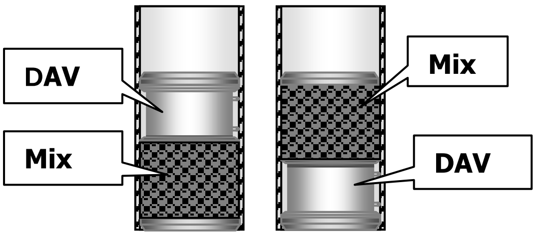

Figure 1. DAV Positions For Measuring Internal Angle with Hot-Mix Asphalt

In order to ensure the load placed on the frame of the SGC is comparable to that experienced during compaction, the internal angle of gyration should be measured using a "full height" HMA specimen, nominally 115±5 mm. However, not all SGC models are physically able to operate with a full-height HMA specimen and the DAV unit (nominally 75 mm in height) in the mold. For those SGC models an "extrapolation" procedure was developed in which internal angles are measured with two lesser specimen heights; the internal angle corresponding to a full-height specimen is then estimated by extrapolating a straight line on a plot of angle-versus-height, as shown in Figure 2.

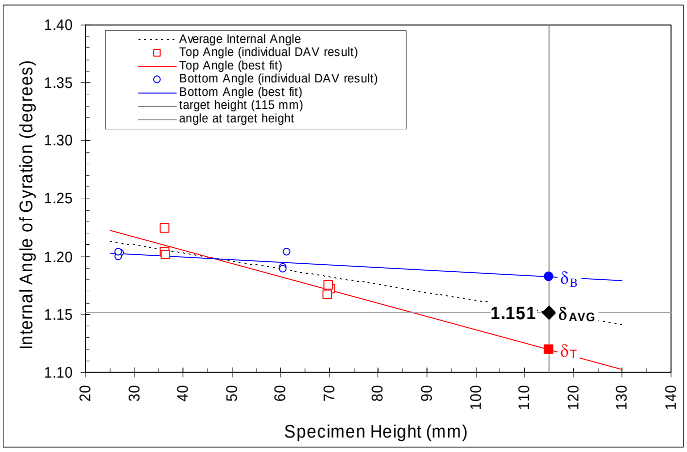

Figure 2. DAV Extrapolation Procedure

Two issues have arisen regarding the required use of hot-mix asphalt during the measurement of internal angle of gyration. One issue concerns the practical limitations and time requirements for performing replicate measurements of top and bottom internal angles using hot SGC molds and hot HMA specimens. For those compactors able to accommodate full-height specimens, the determination of the internal angle can reasonably be accomplished in a period of two to three hours. However, for the extrapolation procedure, a single complete determination of internal angle can easily require over four hours – assuming the HMA specimens are pre-mixed and heating in a dedicated oven.

The second issue concerns the selection of the HMA mix to use in the determination of internal angle. Researchers have generally agreed that a significant factor affecting the magnitude of the internal angle of gyration measured using the DAV system is the stiffness or shear resistance of the particular HMA mixture used in the determination. In other words, two HMA mixtures with different stiffness (used in conjunction with the DAV) could yield two different measurements of internal angle for the same SGC unit. It is hypothesized that this phenomenon may be related to the amount of compliance (or bending) experienced by the SGC frame due to the resistance (load) placed on the SGC by the mixture being compacted.

Recognizing the potential limitations of determining the internal angle of gyration using HMA, research was launched in 2003/2004 related to measuring the internal angle of gyration using simulated loading – that is, provide shear resistance to the SGC which mimics that provided by hot-mix asphalt, but through mechanical means. Two devices reporting the capability of measuring the internal angle using simulated loading have been introduced: the Pine Instrument Company Rapid Angle Measurement (RAM) device, and the TestQuip Hot-Mix Simulator (HMS), which works in conjunction with the Dynamic Angle Validation (DAV) kit.

This paper presents concepts related to the measurement of internal angle of gyration using simulated loading. It also presents comparisons of internal angle measurements obtained using two measurement systems. Finally, the paper identifies significant issues concerning internal angle measurements.

2 MEASURING INTERNAL GYRATION ANGLE USING SIMULATED LOADING

In general, the forces acting within the SGC mold during compaction produce a load gradient across the face of the HMA specimen (Cominski, et al, 1994). 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 3.

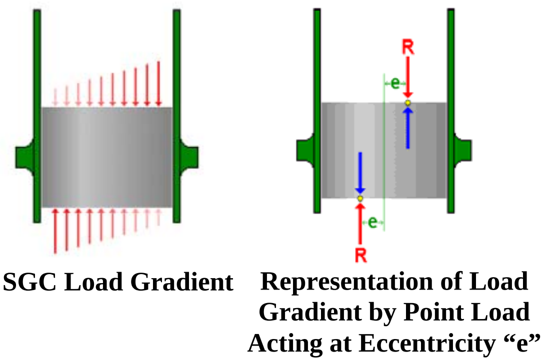

Figure 3. Superpave Gyratory Compactor Eccentric Load Concept *(after Dalton, 2003)*

The eccentric point load creates a moment couple within the SGC mold. This moment couple, referred to hereinafter as the *tilting moment*, simulates the normal and shear resistance provided by the HMA during compaction.

2.1 Rapid Angle Measurement (RAM)

Dalton (2003) provides a complete description of the theory behind the technology used to develop the RAM (shown in Figure 4); a synopsis of the concept used by the RAM to simulate gyratory loading is presented here.

Figure 4. The Rapid Angle Measurement (RAM) Device

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. Figure 4 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 5 illustrates 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 Figure 4.

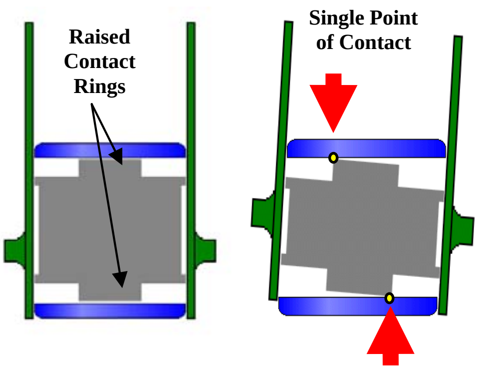

Figure 5. RAM Method for Simulating Load Inside SGC Mold *(after Dalton, 2003)*

2.2 Dynamic Angle Validation / Hot Mix Simulator (DAV/HMS)

The Hot-Mix Simulator (HMS) attachment to DAV is shown in Figure 6. Brovold (2003) 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 7. 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 6). 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. Resolution of forces (and resulting moments) leads to an expression for the eccentricity, shown as Equation 1.

$$e = \tan \delta * 115 / 2 \quad (1)$$

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

Figure 6. Hot-Mix Simulator (HMS) with the Dynamic Angle Validation (DAV) Kit

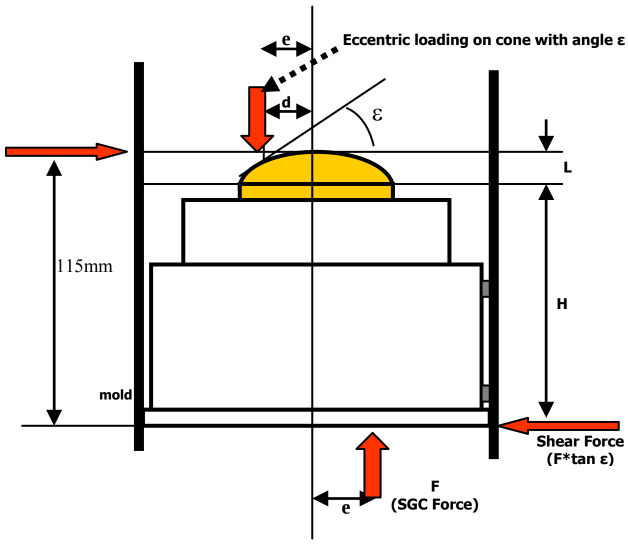

Figure 7. Operational Schematic of DAV/HMS *(after Brovold, 2003)*

3 COMPARISON OF INTERNAL ANGLE MEASUREMENTS

A comparison of angle measurements taken using HMA with DAV with 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 is ongoing; however, a definitive relationship between the stiffness of a given HMA mixture to a particular equivalent eccentricity applied using the RAM or the HMS has yet to be determined.

Comparisons between the RAM and the DAV/HMS system are possible when made on the basis of applied tilting moment. Table 1 shows a comparison of internal angles measured using a RAM (with 44 mm contact ring) and a DAV/HMS system (with a 21-deg HMS cone). The calculated tilting moment for a 44 mm RAM contact ring and the 21-deg HMS cone are very similar, allowing a reasonable direct comparison. The data shown in Table 1 represent the average of three replicate tests on each compactor using each device. The two simulated loading devices do not provide the same value for internal angle. Single-factor analysis of variance (ANOVA) tests performed on the data indicate the differences in average internal angle are significant for the Pine G1, Troxler 4140, and Troxler 4141 compactors.

Table 1. Comparison of RAM and DAV/HMS Internal Angles

	Average Internal Angle, deg *Std. Deviation, 3 replicates*		
Compactor	**RAM**	**DAV/HMS**	**Difference Significant?[a]**
Pine G1	1.163 *0.0029*	1.198 *0.0056*	Yes
Pine 125x	1.143 *0.0029*	1.150 *0.0042*	No
Brovold	1.165 *0.0087*	1.155 *0.0023*	No
Troxler 4140	1.057 *0.0029*	0.962 *0.0029*	Yes
Troxler 4141	1.137 *0.0161*	1.085 *0.0018*	Yes

[a]ANOVA (F-test) with level of significance α= 0.05

Work is ongoing to relate the angle measurements taken with the RAM device and the DAV/HMS system. One word of caution is noted regarding comparisons of RAM and DAV/HMS angles. Currently only the RAM device and test procedure has undergone an interlaboratory study to determine measurement precision. Hall and Easley (2005) provide details of the study and resulting precision statement. In order to fairly and comprehensively compare internal angle measurement procedures, precision statements should be developed for each procedure under consideration. In this way, measurement uncertainty may be considered, both in comparing systems and in developing a SGC calibration specification. An interlaboratory study to determine the precision of the DAV/HMS system is nearing completion; the precision statement arising from the study should be published in 2005.

4 ISSUES RELATING TO INTERNAL ANGLE

4.1 Superpave Gyratory Compactor Frame Stiffness

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" (or more correctly, compliance) for a given SGC. The general relationship between tilting moment and eccentricity is shown in Equation 2. A typical value for SGC Force (at 600 kPa pressure) is approximately 10,602 N.

$$\text{Moment (N-m)} = \text{eccentricity (mm)} * \text{SGC Force (N)} / 1000 \qquad (2)$$

Figure 8 shows a plot of tilting moment versus measured internal angle for five models of Superpave gyratory compactor. Each point shown in Figure 8 represents the average of three replicate measurements. The position of each line in Figure 8 relative to the y-axis is a function of the gyration angle set in the compactor. There is not "common" intersection point shown in the data; the compactors used in the study were not calibrated to a common angle. Relative frame stiffness (compliance) is assessed by comparing the slope of the lines shown on the graph. Figure 8 uses only two angle values per compactor; however it has been demonstrated using three simulated load levels that the angle-versus-moment relationship is linear. (Hall, 2005) Table 2 lists the slopes generated using the RAM and DAV/HMS. 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 current internal angle specification for the DAV is 1.16±0.02 deg.

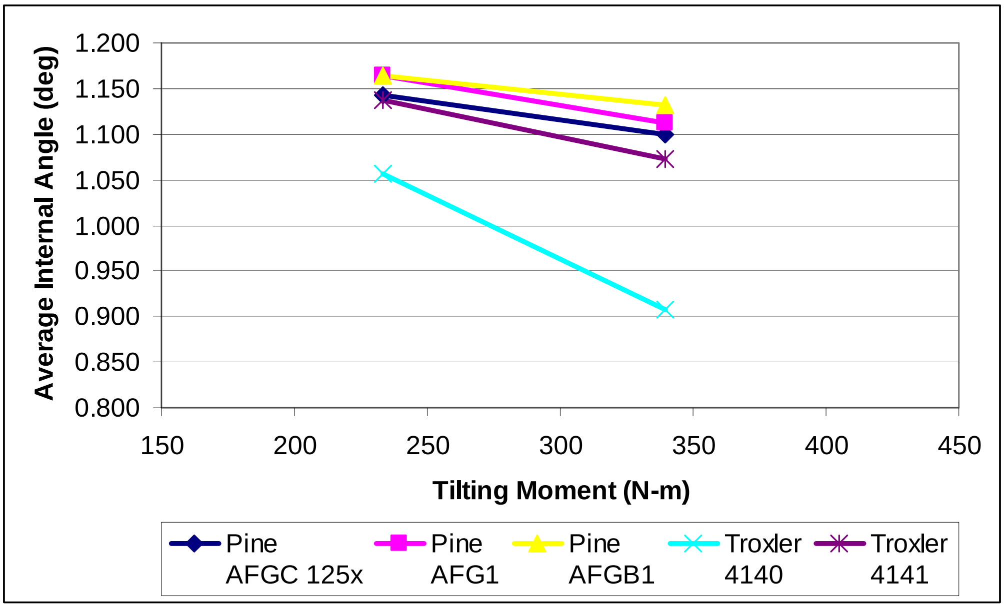

Figure 8. Frame Stiffness (Compliance) for Superpave Gyratory Compactors

Table 2. Frame Stiffness (Compliance) for Superpave Gyratory Compactors

Simulated Load Device	Frame Stiffness (deg/N-m)				
	Pine AFGC 125x	Pine AFG1	Pine AFGB1	Troxler 4140	Troxler 4141
RAM	0.00037	0.00047	0.00031	0.00147	0.00054
DAV/HMS	0.00030	0.00033	0.00028	0.00184	0.00052

The issue of frame stiffness is vital to the question regarding the use of a suitable HMA mix (or simulated load level) for determining the internal angle of gyration. For example, if a given SGC is calibrated using internal angles corresponding to the higher moment shown in

Figure 8 – then an HMA mix whose stiffness provides a moment closer to the lower moment shown in Figure 8 is compacted, the internal angle *experienced* by that mix is not the calibrated angle. In such a case, the volumetric properties of the HMA may be in error. This issue is compounded when comparing different SGC models. It is evident from Figure 8 that only one SGC – the Troxler Model 4140 – has a frame stiffness significantly different from other models. To minimize potential HMA problems due to differences in SGC models, at least two courses of action are recommended:

1. It may be necessary to use additional cross-bracing or other mechanical means to stiffen the frame of the 4140 to better match the frame stiffness of other SGC units.
2. Specifications governing the acceptability of a "next generation" gyratory compactor should include a maximum frame stiffness, or other language limiting the difference in measured internal angle between a specified "high" applied moment and "low" applied moment to a level that would not affect the volumetric properties of hot-mix asphalt.

4.2 SGC Mold Temperature

Discussions regarding the measurement of internal angle using simulated loading have included questions related to the use of room-temperature or "cold" molds during the measurement process rather than molds heated to the expected compaction temperature of HMA. Obviously, the most expedient method for measuring internal angle is to use molds at room temperature; however, it is recognized that during compaction, all surfaces will, in fact, be heated. Thus, the question of the suitability of using room temperature molds is valid. "Hot versus cold" studies have been conducted by various agencies (Hall, 2005). Table 3 lists the results of a University of Arkansas effort using the RAM.

Table 3. Comparison of Internal Angle Measurements using Hot and Cold Molds

		Internal Angle (deg)		
SGC Model	**Contact Ring Diameter (mm)**	**Cold Mold**	**Hot 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 AFB1)	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

Differences in internal angle are not consistent across 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 data indicates differences in cold-versus-hot angles are not significant.

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 be considered here. The differences shown in internal angle measurements between hot and cold molds are, in almost all cases, within the repeatability limits for the RAM (Hall and Easley, 2005). Thus, the differences in angle shown cannot be solely assigned to effects of temperature. For these reasons, it is recommended that the measurement of internal angle using simulated loading be performed using room temperature molds.

5 SUMMARY AND CONCLUSIONS

There is interest in using the internal angle of gyration as the basis for calibrating Superpave gyratory compactors. The sole currently-specified method for measuring internal angle requires the use of hot-mix asphalt. Devices which mechanically simulate the shear resistance of hot mix asphalt have been developed. However, a number of issues have arisen regarding the use of these “simulated loading” devices. Based on the information presented here, the following observations/conclusions are offered.

1. The two proposed methods for measuring internal angle using simulated loading may not, in fact, yield the same value for internal angle. Additional study is needed.
2. The precision of any method proposed for measuring the internal angle of gyration must be established in order to make meaningful comparisons of internal angles measured using different equipment and/or procedures. Such information is also needed to develop specifications for performing internal angle measurements.
3. A definitive relationship between HMA mixture stiffness and applied shear resistance and/or tilting moment must be established to make meaningful comparisons between internal angle measurements using hot-mix asphalt and using simulated loading.
4. Differences in internal angle measurements made with different applied loading levels may be related to the stiffness of the SGC frame. Thus, SGC calibration specifications must specify or reference the applied tilting moment used during calibration.
5. Agencies using internal angle for calibrating the Superpave gyratory compactor should establish the frame stiffness (internal angle versus applied load / tilting moment) for their particular SGC units.
6. Additional cross-bracing or other mechanical refurbishments may be necessary to stiffen the Troxler Model 4140 SGC frame to make the applied moment-internal angle relationship similar to that of other SGC models. In this way, comparisons of hot-mix asphalt properties from specimens compacted on different SGC models may be made more effectively.
7. Specifications governing the acceptability of future Superpave Gyratory Compactor models should include a limit on frame stiffness (as defined by the internal angle versus applied tilting moment relationship) or an “maximum allowable difference” of internal angle measurements made using relatively high and low applied tilting moments.
8. Measurements of internal angle using simulated loading may be made with SGC molds at room temperature.

6 ACKNOWLEDGMENTS

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