STATE OF FLORIDA

EVALUATION OF THE DYNAMIC ANGLE VALIDATOR (DAV)

Research Report
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STATE MATERIALS OFFICE

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ABSTRACT

Current test methods specify that the angle of gyration of a Superpave gyratory compactor (SGC) be measured externally or outside of the mold. The external angle of gyration may not accurately portray the actual angle inside the mold during compaction. Significant differences in compacted density have been seen in specimens compacted with different SGCs. Measuring the angle of gyration inside the mold would provide a better indication of the actual level of compaction being applied to the mixture. The dynamic angle validator (DAV) was developed to measure the internal angle of gyration. The Florida Department of Transportation (FDOT) evaluated the DAV with several mixtures and compactors. Mixture stiffness had an effect on the internal angle measurement in some SGCs. Measuring and setting SGC angles of gyration internally statewide should reduce the variability in compacted density between different SGCs. There are other factors not related to angle of gyration that can contribute to density variability. The compactor needs to be in good working order, clean, and the molds and plates need to be checked for wear. These factors should also be addressed on a statewide basis.

INTRODUCTION AND BACKGROUND

The Superpave gyratory compactor (SGC) is an important tool used by the hot mix asphalt (HMA) industry. It is used during the design of asphalt mixtures and the construction of asphalt pavements. The SGC is typically used to compact a 150 mm diameter specimen to a height of approximately 115 mm. Compaction is achieved by rotating a mold containing HMA, which is angled 1.25° from the vertical, while a load of 600 kPa is applied. The rate of gyration is 30 revolutions per minute, and the number of gyrations varies depending on the traffic level used for the asphalt mix design. The bulk specific gravity (G_{mb}) of the compacted specimen is used in the volumetric analysis of the mixture to determine properties such as air void content (V_a), voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and percent densification levels at $N_{initial}$ and $N_{maximum}$ gyrations. All of these properties must meet specifications during the mixture design stage and during production. Furthermore, 25 percent of the pay for structural layers of asphalt concrete in Florida is based on the air void content during production, underlying the importance of the bulk specific gravity property.

The load, angle, and rate of gyration can have a significant effect on the amount of compaction in a SGC. The rate of gyration is easily measured by counting gyratory revolutions and recording the time with a stopwatch. The load is also easily measured with a load cell or proving ring. The angle of gyration, however, is much more difficult to measure. Currently, the angle of gyration is measured externally or outside of the mold. Each model of SGC comes with different equipment and a unique method to measure the external angle of gyration. However, each method assumes that the top and bottom plates inside the mold remain parallel to each other and normal to the mold's vertical axis during the compaction process.

There are seven different models of gyratory compactors being used in Florida as of June 2003. Research has shown that HMA specimens compacted in different SGCs can have significantly different compacted densities even though the machines are properly calibrated (*1*). This is possible because different models of SGCs can have the same external angle of gyration, but dissimilar internal angles of gyration during the compaction process (*1*,*2*,*3*,*4*). Deflections in both the top and bottom plates during compaction due to incompliance of the assumed rigid structure of the compactor can cause the internal angle to be significantly lower than the measured external angle of gyration (*2*,*4*).

The Federal Highway Administration (FHWA) in conjunction with the TestQuip Corporation developed a device that could measure the internal angle of gyration inside the mold during compaction. The result was the angle validation kit, now known as the dynamic angle validator (DAV). The FHWA conducted research on the initial two SGCs from the original pooled fund study in which the SGCs were developed: a Pine AFGC125X and a Troxler 4140. A target internal angle for all SGCs was determined from the results of the study. Each compactor had an external angle of 1.25° before the study began. The FHWA found that the internal angle of the Pine compactor was 1.176° and the internal angle of the Troxler SGC was 1.14°. Based on the study, an average internal angle of 1.16 ± 0.03° was chosen for the target internal angle for all gyratory models (*2*).

THE MEASUREMENT OF THE INTERNAL ANGLE OF GYRATION

A draft American Association of State Highway and Transportation Officials (AASHTO) procedure has been developed for using the DAV to measure the internal angle of SGCs (*5*). The DAV is currently manufactured by Pine Instruments and can measure internal angles in all of the current SGCs. Each DAV comes with several accessories which are needed in order to measure an internal angle for a particular SGC. The equipment includes the DAV, a calibration block, other calibration pieces, a separation plate, a placement magnet, a serial port connection cable, a battery charger, and DAV software. The DAV and its supporting equipment are pictured in Figure 1. The calibration of the DAV must be verified with a National Institute of Standards and Technology (NIST) traceable calibration block each day before measurements can be taken. The calibration block has four different angles that are checked three times each. In addition, the DAV needs to be recalibrated by the manufacturer once a year. A factory recalibration includes a recalibration of the DAV at room and high temperatures and a recertification of the static angle calibration block.

Figure 1 – DAV Equipment

The DAV is placed inside the mold with hot mix during compaction. Depending on its location in the mold, the DAV can measure the internal angle of gyration for either the top or bottom of the mold. It is extremely important that the DAV, mold, and plates be completely clean before an angle is measured. Any asphalt residue, dirt, or sand can significantly affect an angle measurement. During compaction an angle is measured for each gyration. The proposed AASHTO procedure specifies that 100 gyrations be used for all internal angle measurements. The data, which includes internal angle and temperature measurements, is downloaded into a computer after the DAV is removed from the mold. The angles between 10 and 90 gyrations are averaged to determine the top or bottom internal angle of gyration. A graph of the bottom angle measurements in the big Pine, big Troxler, and Brovold SGC is usually flat. A graph of the top angle measurements for the big Pine resembles a sine wave, but is flat in the big Troxler and Brovold gyratory compactors. The draft AASHTO procedure requires that three replicate angles be measured at each position in the mold. The angles for the top and bottom of the mold are then averaged to determine the internal angle of the compactor.

The temperature of the DAV rises significantly during an internal angle measurement, due to heat transfer from the HMA sample and gyratory mold. Consequently, the DAV must be cooled to below 50°C before another measurement can be started. The DAV will shut down automatically at extremely high temperatures (usually $\geq$ 70°C), and all of the measurement data will be lost if the DAV is shut down before the data can be downloaded into a computer. If placed in front of a fan, the DAV typically needs about 10 to 15 minutes to cool adequately before another internal angle measurement can be taken.

The Extrapolation Method

A full charge of HMA (compacted sample height of 115 $\pm$ 5 mm) is needed to determine an internal angle. Some SGCs cannot accommodate a full charge of loose HMA as well as the DAV and separation plate (75 mm total). Table 1 (*5*) lists the available mold heights for each model of SGC used in Florida. A full charge of HMA and the DAV apparatus can be placed in a mold if the available mold height is greater than 225 mm. An alternate procedure, known as the extrapolation method, was developed for gyratory compactors whose molds cannot accommodate a full charge of HMA and the DAV apparatus. The extrapolation method uses two smaller heights of compacted HMA that will fit in the SGC mold with the DAV. The most important requirement for the two smaller heights is that their difference must be at least 35 mm. Typical heights of compacted HMA samples for the extrapolation method are 30 and 70 mm. The angle corresponding to 115 mm is then extrapolated from the other two heights. An example of the extrapolation method is provided in Figure 2. Research has shown that the full charge method and the extrapolation method will yield the same angle (*3*).

Table 1 – List of Available SGC Mold Heights

Manufacturer	Model Number	Common Name	Available Mold Height (mm)	Full Charge or Extrapolation Method
Troxler Electronic Laboratories, Inc.	4140	Big Troxler	163	Extrapolation
Pine Instrument Company	AFG1A	Baby Pine	250	Full Charge
Troxler Electronic Laboratories, Inc.	4141	Baby Troxler	216	Extrapolation
Pine Instrument Company	AFGC125X	Big Pine	250	Full Charge
Pine Instrument Company	AFGB1A	Brovold	215	Extrapolation
Rainhart Company	144	Rainhart	Unknown	Unknown
IPC, Ltd.	Servopac	Servopac	197	Extrapolation

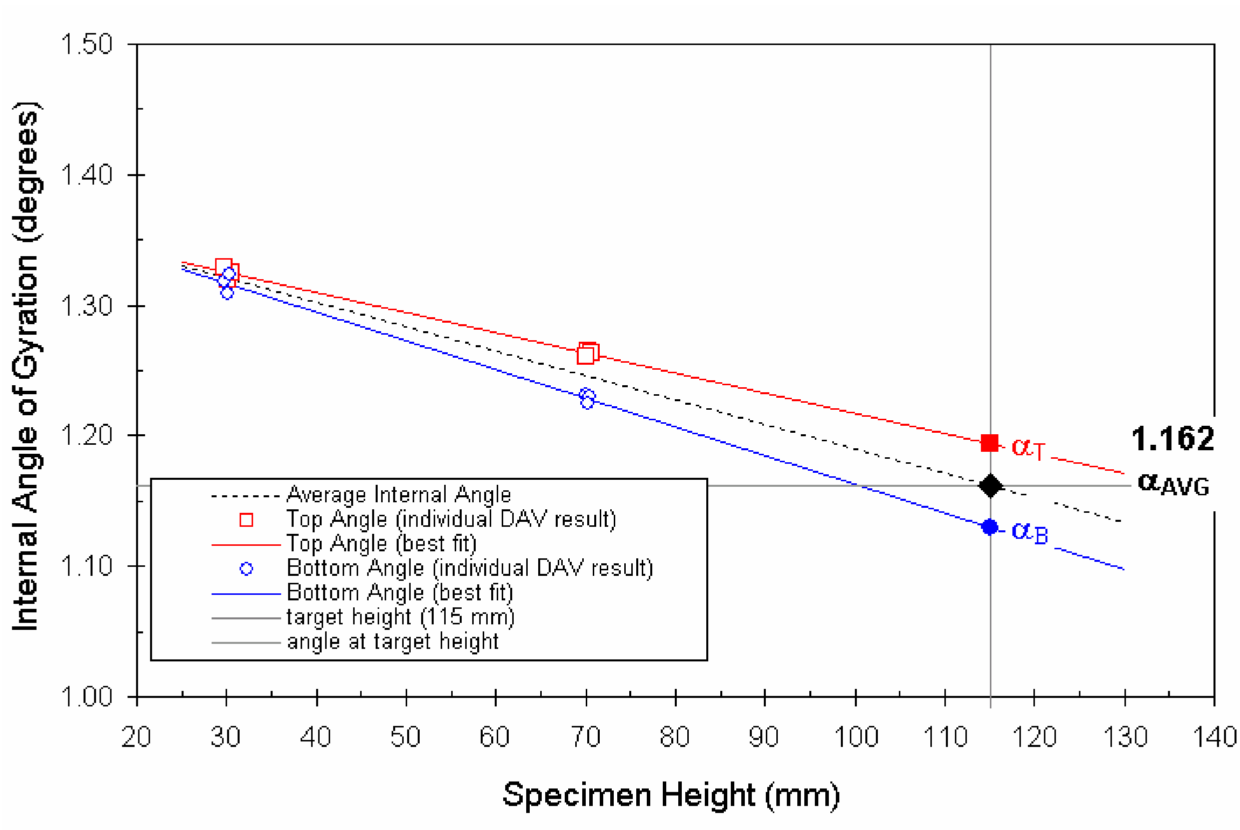

Figure 2 – The Extrapolation Method

INITIAL RESEARCH PERFORMED BY THE DEPARTMENT

The Department evaluated the use of the DAV in two SGCs, a Pine AFGC125X (big Pine) and a Troxler 4140 (big Troxler). The experimental plan focused on two different studies, a comparison of the full charge method versus the extrapolation method and a comparison of density between the two compactors set at the same internal angle. Before the research began, the calibrations for height, pressure, rate of gyration, and angle were verified for each SGC used. Molds and plates were also checked for wear. Research conducted by NCAT and Pine Instruments and verified by the Department has shown that wear in the molds can cause significant differences in the compacted densities of SGC pills (*6*,*7*). A coarse-graded 12.5 mm, traffic level D mix (N_{design} = 100) was chosen for both studies. The mixture consisted of 100 percent limestone from south Florida. Samples were fabricated in the laboratory. Table 2 lists the properties for this mixture.

Comparison of the Full Charge Method and the Extrapolation Method

The purpose of this study was to compare the two methods using the DAV for measuring the internal angle of gyration in a Pine SGC. (It should be noted that the study was not performed on the Troxler SGC because it cannot accommodate a full charge of HMA and the DAV.) An internal angle of gyration of 1.181° was measured using the full charge method. When the comparison was performed, the most current procedure for the extrapolation method was an American Society for Testing and Materials (ASTM) draft procedure (*8*). The ASTM draft procedure required two angles to be measured at three different heights for both the top and bottom angle, resulting in a total of 12 measured angles. The heights used were 30, 68, and 105 mm. The extrapolated internal angle was 1.176°. The two methods compared favorably as the difference between the two measured angles was only 0.005°.

Density Comparison

Six specimens were compacted in each SGC with the external angle of gyration set to 1.25 ± 0.02°. The Troxler had an internal angle of 1.089° while the Pine internal angle was 1.204°. The results are shown in Table 3. The specimens compacted in the Pine SGC had a higher average G_{mb} by 0.012. Consequently, the resulting air voids in the Pine were lower by 0.5 percent based on a common maximum theoretical density (G_{mm}). This result was expected because of the higher internal angle of gyration in the Pine SGC.

Table 2 – Mixture Properties

Mixture	South FL limestone	North and South FL limestone / local sand	Pennsylvania limestone	Nova Scotia granite
Mix Size	12.5 coarse	9.5 fine	12.5 coarse	12.5 coarse
% AC	7.2	8.8	5.3	5.4
N_{design}	100	100	55	100
G_{mb} at N_{design}	2.235	2.180	2.366	2.357
G_{mm}	2.328	2.272	2.464	2.456
G_{sb}	2.444	2.343	2.639	2.637
VMA	15.1	15.2	15.1	15.4
Sieve Size (mm)	**Gradation (Percent Passing)**			
19.0	100	100	100	100
12.5	93	100	96	92
9.5	81	96	87	84
4.75	65	76	49	52
2.36	33	53	32	32
1.18	23	41	23	23
0.600	16	34	16	16
0.300	10	22	10	11
0.150	4	9	7	8
0.075	3.0	4.5	4.4	5.4

Table 3 - Density Results with a Target External Angle of 1.25°

Troxler			Pine		
External Angle		1.249^{o}	**External Angle**		1.241^{o}
Internal Angle		1.089^{o}	**Internal Angle**		1.204^{o}
Specimen	**Gmb**	**Air Voids**	**Specimen**	**Gmb**	**Air Voids**
1	2.218	4.7	2	2.237	3.9
3	2.233	4.1	4	2.246	3.5
5	2.226	4.4	6	2.217	4.8
7	2.226	4.4	8	2.237	3.9
9	2.228	4.3	10	2.248	3.4
11	2.231	4.2	12	2.248	3.4
Average	2.227	4.3	**Average**	2.239	3.8
St. Dev.	0.005	0.21	**St. Dev.**	0.012	0.53

Subsequently, the internal angles of each compactor were set internally to a target value of 1.16 ± 0.02°. The internal angle for the Troxler was set to 1.165° while the internal angle for the Pine was set to 1.181°. The corresponding external angles were 1.346° and 1.198° respectively. Setting the internal angle on the Pine SGC is difficult. Six more specimens were then produced in each machine. Table 4 lists the results. The results were not expected. Even though the internal angles of gyration were approximately the same, the average densities were significantly different. The G_{mb} of the specimens compacted in the Troxler were higher by 0.013, and the corresponding air voids were lower by 0.55 percent compared to the specimens compacted in the Pine SGC.

TABLE 4 - Density Results with a Target Internal Angle of 1.16°

Troxler			**Pine**		
Internal Angle		1.165°	**Internal Angle**		1.181°
External Angle		1.346°	**External Angle**		1.198°
Specimen	**Gmb**	**Air Voids**	**Specimen**	**Gmb**	**Air Voids**
1	2.274	2.3	2	2.248	3.5
3	2.269	2.5	4	2.243	3.7
5	2.261	2.9	6	2.261	2.9
7	2.233	4.1	8	2.266	2.7
9	2.272	2.4	10	2.244	3.6
11	2.268	2.6	12	2.239	3.8
Average	2.263	2.8	**Average**	2.250	3.4
St. Dev.	0.015	0.67	**St. Dev.**	0.011	0.45

SECONDARY RESEARCH PERFORMED BY THE DEPARTMENT

Four different mixtures were evaluated by the Department to determine if mixture stiffness could have an effect on the measured internal angle. The properties for each mixture are reported in Table 2. Figure 3 shows each mixture's gradation. Since it was not clear which properties would have an actual effect on the internal angle, several different variables were investigated. Three of the mixtures were coarse-graded and one mixture was fine-graded. Four different aggregate combinations were examined: 1) south Florida limestone, 2) a combination of north and south Florida limestone and natural sand, 3) Pennsylvania limestone, and 4) Nova Scotia granite. Three mixtures were fabricated in the laboratory while one was produced at an asphalt plant. The asphalt content was varied in two of the mixtures produced in the laboratory.

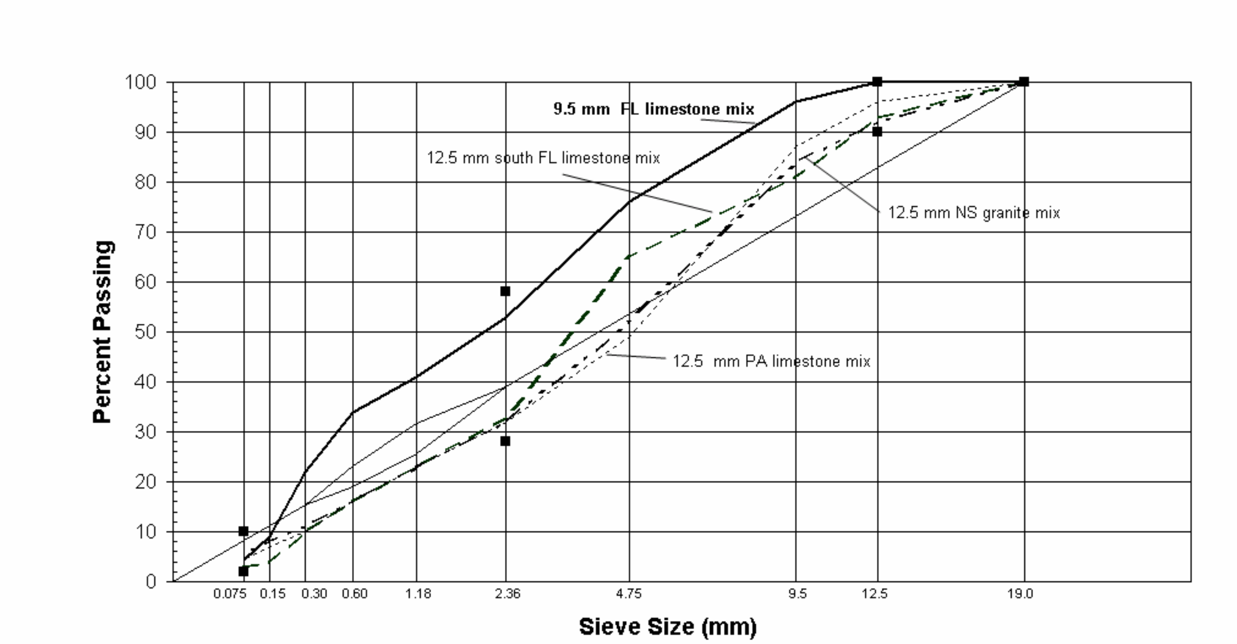

Figure 3 – Mixture Gradations

Coarse-graded South Florida Limestone Mix

Due to other ongoing research, the external angle of the Pine compactor was reset to 1.242° to comply with current specifications. The resulting internal angle using the 12.5 mm, coarse-graded, south Florida limestone mix was determined to be 1.206°. The Troxler internal angle was then reset with the same mixture to 1.223° to be close to that of the Pine compactor internal angle of 1.206°. The external angle of gyration for the Troxler was 1.405°. A density comparison was then performed between the compactors with the new internal angles. As before, six specimens were compacted in each gyratory compactor. The results of the density comparison are listed in Table 5. The specimens compacted in the Troxler had a higher average G_{mb} by 0.011; consequently the air voids were 0.47 percent lower on average. The higher G_{mb} (lower air voids) seen in the Troxler gyratory compactor was probably the result of the slightly higher internal angle (0.017°) and other unknown factors.

Table 5 - SGC Density Comparison with the Coarse-graded South Florida Limestone Mix

Troxler			**Pine**		
Internal Angle		1.223°	**Internal Angle**		1.206°
External Angle		1.405°	**External Angle**		1.242°
Specimen	**Gmb**	**Air Voids**	**Specimen**	**Gmb**	**Air Voids**
T1	2.250	3.4	P1	2.237	3.9
T2	2.245	3.5	P2	2.239	3.8
T3	2.242	3.7	P3	2.244	3.6
T4	2.247	3.5	P4	2.230	4.2
T5	2.248	3.4	P5	2.233	4.1
T6	2.253	3.2	P6	2.237	3.9
Average	2.248	3.5	**Average**	2.237	3.9
St. Dev.	0.004	0.16	**St. Dev.**	0.005	0.21

Fine-graded Florida Limestone Mix

A 9.5 mm, fine-graded, Florida limestone mix (N_{design} = 100) was compared to the 12.5 mm, coarse-graded, south Florida limestone mixture in each compactor to see if there was a difference in the measured internal angle of compaction. Internal angles were measured with this mix in both SGCs. The internal angles dropped approximately 0.01° in both machines. The asphalt content of the mix was also varied to see if there would be an effect on the internal angle in the Pine SGC. Changing the asphalt content by ± 0.5 percent from the optimum asphalt content of 8.8 percent had little to no effect on the measured internal angle of gyration in the Pine compactor. The internal angle measurements are listed in Table 6.

Table 6 - Measured Internal Angles

Mixture	Internal Angle (degrees)	
	Pine	Troxler
Oolite limestone coarse-graded mix	1.206	1.223
Florida limestone fine-graded mix	1.194	1.215
Florida limestone fine-graded mix (+ 0.5 % AC)	1.199	-
Florida limestone fine-graded mix (- 0.5 % AC)	1.194	-
Pennsylvania limestone coarse-graded mix	1.203	1.219
Nova Scotia granite coarse-graded mix	1.208	1.259
Nova Scotia granite coarse-graded mix (+1.0% AC)	1.210	1.252
Nova Scotia granite coarse-graded mix (-1.0% AC)	1.209	1.240

Coarse-graded Pennsylvania Limestone Mix

Several samples of a plant produced, coarse-graded mixture consisting of Pennsylvania limestone were received from Pine Instruments. Internal angles were measured for this mixture in each compactor. The internal angle for the Pine compactor was 1.203°, while the internal angle for the Troxler was 1.219°. Because the internal angles were within 0.02, a compaction comparison was performed on the two compactors with the measured angles. The results for this study are listed in Table 7. The Troxler compactor had a higher G_{mb} by 0.010 resulting in lower air voids by 0.4 percent. The difference in air void content between the two compactors is probably a combination of the slightly higher internal angle of the Troxler compactor and other unknown reasons. Air void contents for both compactors were low because the internal angles of gyration were higher than the internal angle of the compactor used to design this mixture. This example shows the importance of having the angle of gyration of the design and production SGCs set the same.

TABLE 7 - SGC Density Comparison with the Coarse-graded Pennsylvania Limestone Mix

Troxler			**Pine**		
Internal Angle		1.219°	**Internal Angle**		1.203°
External Angle		1.405°	**External Angle**		1.242°
Specimen	**Gmb**	**Air Voids**	**Specimen**	**Gmb**	**Air Voids**
T1	2.393	2.9	P1	2.382	3.3
T2	2.400	2.6	P2	2.389	3.0
T3	2.405	2.4	P3	2.395	2.8
T4	2.406	2.4	P4	2.397	2.7
T5	2.401	2.6	P5	2.391	3.0
T6	2.403	2.5	P6	2.394	2.9
Average	2.401	2.55	**Average**	2.391	2.96
St. Dev.	0.005	0.19	**St. Dev.**	0.005	0.21

Coarse-graded Nova Scotia Granite Mixture

The last mixture evaluated was a 12.5 mm, coarse-graded, Nova Scotia granite mixture (N_{design} = 100). The internal angle of gyration was measured in each compactor at three different asphalt contents, 4.4, 5.4, and 6.4 percent. The results are listed in Table 6. There was virtually no difference in the internal angle for the Pine compactor. There was a difference of 0.019° between high and low asphalt contents for the Troxler compactor. The internal angle of gyration was also 0.051° higher in the Troxler at the optimum AC content compared to the Pine SGC. Because of this difference, the angle of gyration for the Troxler was adjusted to 1.212° internally. The new external angle of gyration was 1.375°. Another Troxler 4140 was also evaluated with this mixture. The second Troxler is used for routine mix design verification by the Department and will be referred to as the "Production Troxler" hereafter. The original Troxler 4140 used throughout this study will be referred to as the "Research Troxler" throughout the rest of this study. The internal angle for the Production Troxler was adjusted to 1.215°. The corresponding external angle of gyration was 1.338°.

Two density comparisons were performed; one with the internal angle of each SGC set to a target of 1.21°, and one with each external angle set to a target of 1.25°. The results for these two comparisons are found in Tables 8 and 9 respectively. Both comparisons turned out as expected. When the internal angles for each compactor were set to a target of 1.21° the densities were virtually identical. When the angles for each compactor were set externally to a target of 1.25°, the densities differed somewhat proportionally to the compactor's corresponding internal angle. The Pine had an internal angle of 1.208° and an air void content of 3.3 percent. The Research Troxler had an internal angle of 1.095° and an air void content of 3.9 percent. The Production Troxler had an internal angle of 1.115° and an air void content of 3.6 percent.

TABLE 8 - Density Comparison with the Coarse-graded Nova Scotia Granite Mix and an Internal Angle Target of 1.21°

Pine			Research Troxler			Production Troxler		
Internal Angle		1.208^o	**Internal Angle**		1.212^o	**Internal Angle**		1.215^o
External Angle		1.242^o	**External Angle**		1.375^o	**External Angle**		1.342^o
Specimen	**Gmb**	**Air voids**	**Specimen**	**Gmb**	**Air voids**	**Specimen**	**Gmb**	**Air voids**
P1	2.380	3.1	RT1	2.365	3.7	PT1	2.372	3.4
P2	2.374	3.3	RT2	2.375	3.3	PT2	2.378	3.2
P3	2.375	3.3	RT3	2.371	3.5	PT3	2.365	3.7
P4	2.370	3.5	RT4	2.383	3.0	PT4	2.371	3.5
P5	2.371	3.5	RT5	2.360	3.9	PT5	2.361	3.9
P6	2.360	3.9	RT6	2.369	3.5	PT6	2.371	3.5
Average	2.372	3.4	**Average**	2.370	3.5	**Average**	2.370	3.5
St. Dev.	0.007	0.3	**St. Dev.**	0.008	0.3	**St. Dev.**	0.006	0.2

TABLE 9 - Density Comparison with the Coarse-graded Nova Scotia Granite Mix and an External Angle Target of 1.25°

Pine			Research Troxler			Production Troxler		
External Angle		1.242^o	**External Angle**		1.252^o	**External Angle**		1.251^o
Internal Angle		1.208^o	**Internal Angle**		1.095^o	**Internal Angle**		1.115^o
Specimen	**Gmb**	**Air voids**	**Specimen**	**Gmb**	**Air voids**	**Specimen**	**Gmb**	**Air voids**
P1	2.374	3.3	RT1	2.367	3.6	PT1	2.377	3.2
P2	2.366	3.7	RT2	2.364	3.7	PT2	2.370	3.5
P3	2.385	2.9	RT3	2.360	3.9	PT3	2.376	3.3
P4	2.374	3.4	RT4	2.347	4.4	PT4	2.360	3.9
P5	2.379	3.1	RT5	2.368	3.6	PT5	2.373	3.4
P6	2.376	3.3	RT6	2.356	4.1	PT6	2.349	4.4
Average	2.376	3.3	**Average**	2.360	3.9	**Average**	2.367	3.6
St. Dev.	0.006	0.3	**St. Dev.**	0.008	0.3	**St. Dev.**	0.011	0.5

PROBLEMS ENCOUNTERED USING THE DAV

The Department acquired a DAV in the fall of 2001. Several malfunctions occurred during the first year of testing. Each time the DAV malfunctioned, it was sent to the manufacturer and fixed under warranty. The first problem encountered was the result of cooling the DAV in a freezer between angle measurements. Cooling the DAV in the freezer was a recommended practice in the ASTM draft procedure (8). After several weeks of use, the reference probe began to stick. This malfunction made it impossible to accurately measure the internal angle of gyration. The cause of the problem was a rusted setscrew inside the DAV. Figure 4 shows the rusted setscrew. The draft procedure was changed to only recommend cooling in front of a fan or air conditioner. Other problems encountered included a malfunction in the temperature measurement system, a loose setscrew, and a failed internal power supply dc-dc converter chip. Each time the DAV was repaired, the manufacturer performed a factory recalibration.

Figure 4 – Rusted Setscrew

RUGGEDNESS STUDY

The Department participated in a DAV ruggedness study with six other laboratories. Six compactors were evaluated in the ruggedness study. Table 10 summarizes the ruggedness study participants and their responsibilities. The Department evaluated a different SGC than the ones used in the previous research discussed in this report. The Department performed all of the testing for the ruggedness study with a Troxler 4140B. The 4140B is similar to the original Troxler 4140, but it has a slightly smaller frame.

Table 10 – Ruggedness Study Participants

Participating Laboratory	Responsibility
University of Arkansas	Pine AFGC125X, Troxler 4140 A
FHWA	Brovold
FDOT	Troxler 4140 B
Pine Instruments Inc.	Pine G1
NCAT	Troxler 4141
Asphalt Institute	Mixture Stiffness
APAC Material Services	Sampling and Supplying Mix

The ruggedness study was a Plackett-Burman design from ASTM C1067 (9). The study had seven factors with a high and low level for each factor. Eight factor combinations were tested in the study with two replicates for each combination. The factors evaluated were the starting temperature for the DAV, the number of gyrations, the tall and short heights with the DAV on the bottom and top of the mix, and the nominal maximum aggregate size of the mixture. Table 11 summarizes the ruggedness study and the testing matrix. An upper case letter indicates that the high level was tested. A lower case letter indicates that the low level was tested. Figure 5 compares the gradations of the two different mixtures. When the two mixtures were selected, the intent was to have mixes with similar stiffness. The aggregate types were similar, but modulus testing performed on the Superpave Shear Tester by the Asphalt Institute showed that the 12.5 mm mix was almost twice as stiff as the 9.5 mm mix. Looking at the gradations, this makes since. The 9.5 mm mix plot looks like a fine-graded 12.5 mm mix, while the 12.5 mm mix is coarse-graded. The FDOT found that the number of gyrations used and the nominal maximum aggregate size of the mixture were significant in the Troxler 4140B. However, no other lab had similar findings in the other SGCs. Pine Instruments found that the mixture "short" height with the DAV on bottom was significant. No other lab found any of the factors to be significant.

Table 11 – Ruggedness Study Summary

Factor		High Level (X)	Low Level (x)	Current Specification
A	DAV Temperature Prior to Use (^{o}C)	30	45	< 50
B	Total Number of Gyrations	50	100	100
C	Mix "Short" Height (mm), DAV on Top	25	35	30 ± 5
D	Mix "Tall" Height (mm), DAV on Top	60	70	65 ± 5 - 105 ± 5
E	Mix "Short" Height (mm), DAV on Bottom	25	35	30 ± 5
F	Mix "Tall" Height (mm), DAV on Top	60	70	65 ± 5 - 105 ± 5
G	Mix Nominal Max Aggregate Size (mm)	9.5	12.5	9.5 or 12.5

Testing Matrix

Determination							
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
a	a	a	a	A	A	A	A
b	b	B	B	b	b	B	B
C	c	C	c	C	c	C	c
D	D	d	d	d	d	D	D
e	E	e	E	e	E	e	E
F	f	f	F	F	f	f	F
G	g	g	G	g	G	G	g

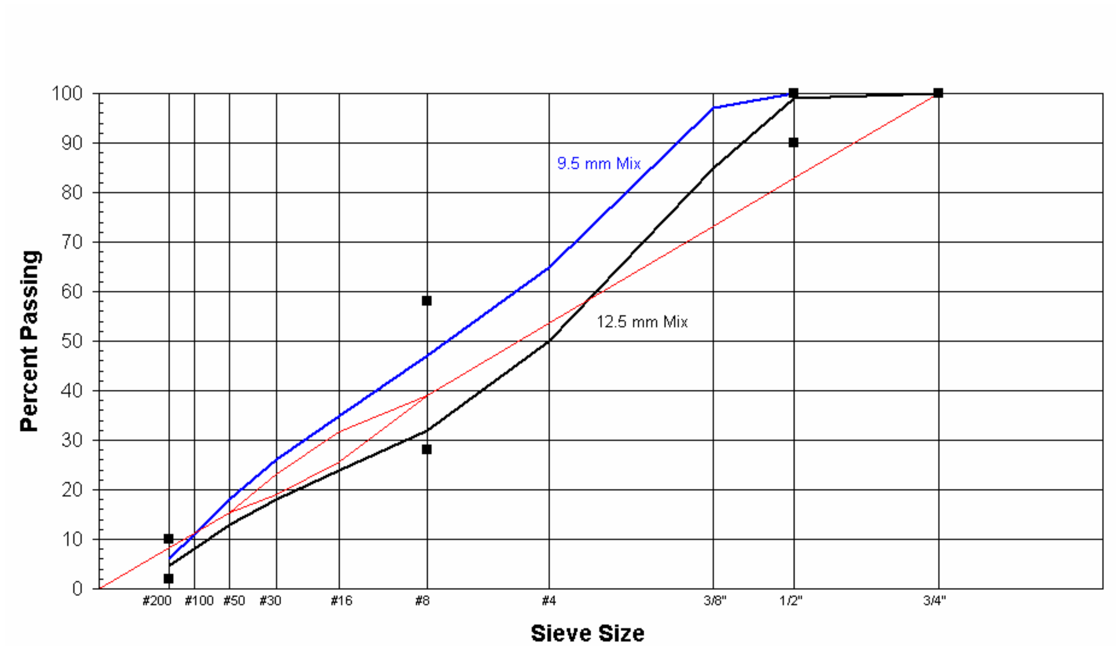

Figure 5 – Comparison of the Ruggedness Study Mixture Gradations

CONCLUSIONS AND RECOMMENDATIONS

The asphalt industry needs a way to verify that each SGC is applying the same compactive effort. Measuring the external mold wall angle alone does not necessarily indicate the actual angle of gyration that is applied to the mixture. The DAV is able to measure the internal angle of gyration, which shows the compactive effort inside the mold. However, it is important that the SGC be clean and in good working condition. The manufacturer should service the SGC on a regular basis. Molds and plates need to be checked for wear regularly, and bad equipment needs to be replaced. Setting the angle of gyration of SGCs internally cannot compensate for defective equipment or for improper sampling and testing techniques, but it can help insure better comparisons of bulk specific gravity between different SGCs if the equipment is maintained properly.

Different SGCs react differently to mixture stiffness. Some compactors are able to hold the same internal angle despite varying mixture stiffness. Other compactors tend to have some variability in the internal angle with mixtures of different stiffness. Setting the internal angle of compaction for each mixture is not feasible, and some judgment needs to be used before a mix is chosen to measure or set the internal angle of compaction. However, measuring the internal angle of gyration would be beneficial for both the Department and the asphalt industry. It is recommended to proceed slowly but eventually measure and set the angle of gyration internally for all SGCs in the state of Florida. Recent work using other internal angle measuring devices not requiring HMA may make the implementation of internal angle measurement easier and less time consuming. As a follow-up to this study, the use of these measuring devices in place of the DAV with HMA should be explored.

Implementation should begin slowly with a small group of SGCs of different types. Originally, each SGC should be set to a target internal angle of 1.16° with the same mixture. Density comparisons should be conducted between the SGCs with several different mixture types. After the internal angle is set to 1.16° with the same mixture, the internal angle of each gyratory compactor in the group should also be measured and compared with different mixture types. If the data looks reasonable, a large-scale implementation could be undertaken. Internal angles could be measured at a minimum of once or twice a year, and a correlation could be established between the internal and external angles of gyration. The internal angle of gyration could be monitored monthly by measuring the external angle and applying a correction factor determined for each SGC at the time of calibration.

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