Target and Tolerance Study for The Angle of Gyration Used in The Superpave Gyratory Compactor

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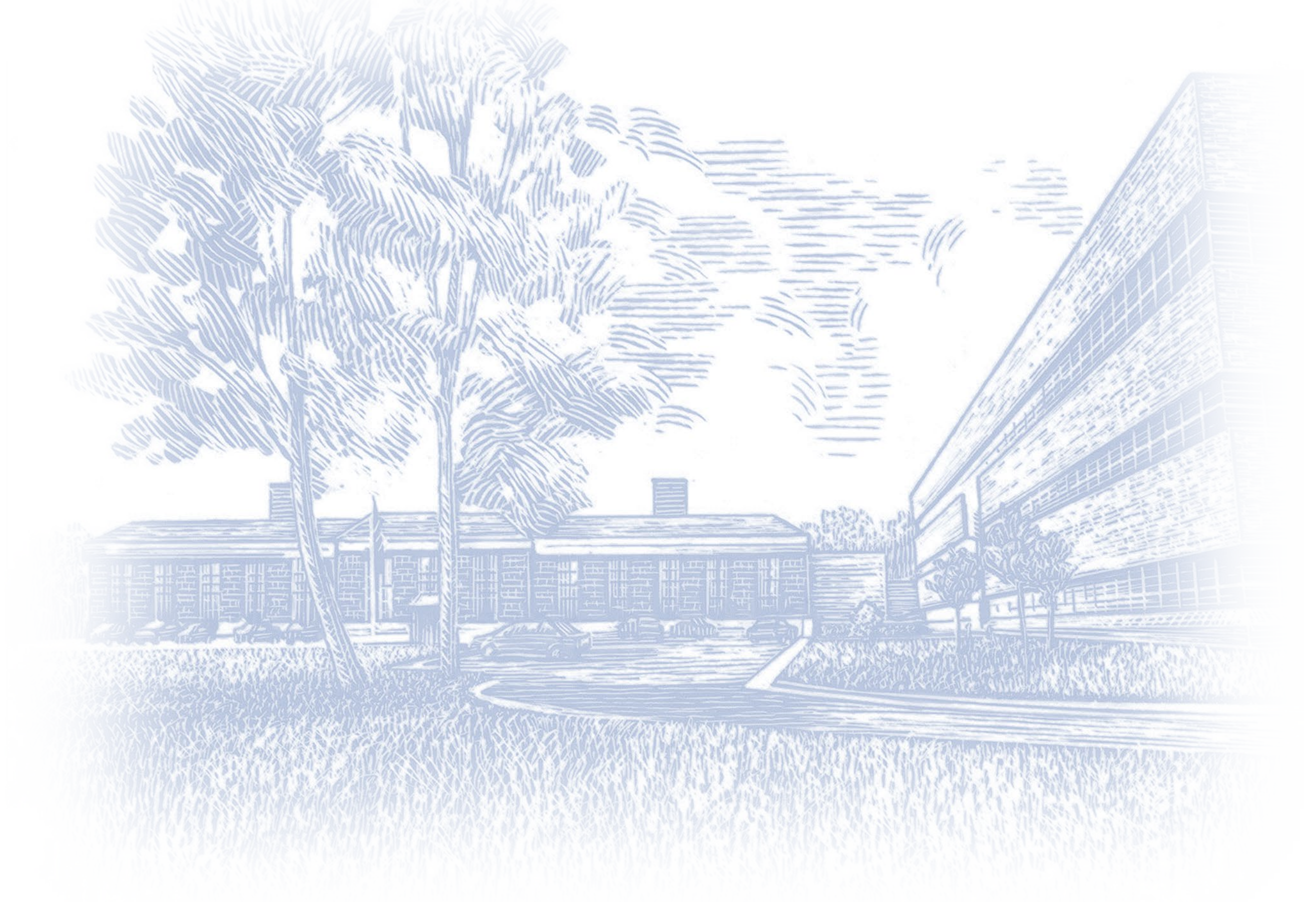

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Foreword

The Superpave gyratory compactor (SGC) is used to compact asphalt specimens for mixture testing in the Superpave system. Five companies currently manufacture SGCs for use in the United States, - offering a total of eight different models. Each model employs a unique method of setting, inducing, and maintaining the specified angle of gyration. Calibration systems are required for each device for the angle of gyration. All angle measurements are made externally relative to the mold and none of the calibration systems can be universally used on all of the models.

The specified external angle of gyration under load (a) is 1.25 degrees, with a tolerance of ± 0.02 degrees. The Federal Highway Administration (FHWA), in partnership with the TestQuip Corporation (New Brighton, MN), developed an angle validation kit (AVK) that measures the dynamic internal angle (DIA) of gyration. The DIA accounts for equipment compliance issues, which are not apparent in measuring the external angle. Bending in the upper and lower mold platens during compact reduces the compactive effort imparted to a specimen. Differences in specimen bulk specific gravities produced by different compactors have been attributed to differences in compliance between SGCs measured with the AVK.

This necessitates a revision of American Association of State Highway and Transportation Officials (AASHTO) standard method 312-01[(1)] to ensure uniformity in compaction effort in the Superpave system. However, it would be inappropriate to assign the external angle target and tolerance to the DIA; compliance issues have existed throughout the development and implementation of the Superpave system. Assignment of the external specifications to the DIA would result in an increase in the compactive effort of all SGCs and in turn would invalidate the N_{design} table.

The Transportation Research Board (TRB) Superpave Mixture/Aggregate expert task group (ETG) (the TRB Superpave Mixture/Aggregate ETG replaced the FHWA Superpave Mixture in 1999) directed FHWA to investigate the DIAs of the original pooled fund SGCs: Pine Instrument Company SGC model AFGC125X and the Troxler Electronic Company SGC model 4140 (figure 1). These models were developed in response to a national pooled fund equipment purchase conducted by the FHWA and were integral in the experiments that refined the N_{design} table that is used today.

FHWA conducted a comprehensive testing program to establish recommendations for the DIA target and tolerance. The DIAs for the Pine and the Troxler SGCs were determined to be 1.176° and 1.140°, respectively, resulting in a proposed target of 1.16°. The sensitivity of the DIA on bulk specific gravity was also investigated, resulting in a proposed tolerance of ± 0.03°.

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STUDY OBJECTIVES

The objectives of this study are as follows:

1) To determine an appropriate target for the DIA using the angle validation kit based upon results from the pooled fund models of the Superpave gyratory compactor: Pine Instruments Company SGC model AFGC125X and Troxler Electronic Company SGC model 4140.

2) To determine an appropriate tolerance for the DIA based upon limiting the net effect of the angle of gyration on the design asphalt binder content to 0.1 percent, and using the Strategic Highway Research Program (SHRP) rule-of-thumb, where a 0.4-percent change in asphalt binder content equates approximately to a 1.0-percent change in air-void content.

MATERIALS, EQUIPMENT, AND TEST METHODS

Materials and Equipment

P. Flanigan and Sons, Inc., Baltimore, MD, supplied a large production sample of hot-mix asphalt for the study. The sample was a 12.5-mm nominal-maximum size, coarse-graded Superpave mixture designed to an N_{design} of 100 gyrations. The asphalt binder was an unmodified PG 64-22 at a content of 4.4 percent by weight of mix.

Two laboratories participated in the study: FHWA Turner-Fairbank Highway Research Center's Bituminous Mixtures Laboratory (BML) and the FHWA Office of Pavement Technology's Mobile Asphalt Laboratory (DP 90). Two SGCs were used to establish the proposed target and tolerance for the DIA: the Pine AFGC125X SGC (BML) and the Troxler 4140 SGC (DP 90). Commercial grade AVKs, manufactured by TestQuip, were used.

Additional testing was conducted on the BML's Troxler 4140 and the Pine AFGC125X SGC to validate the proposed target and to assess the interrelationship between specimen height, bulk specific gravity, and DIA. *(Any reference to a Troxler SGC refers to the DP 90 compactor. The BML's unit is referred to as the BML Troxler.)*

Test Methods

Four 2000-gram samples were obtained randomly from the large production sample to conduct the maximum theoretical specific gravity test (G_{mm}). The G_{mm} test was conducted according to AASHTO T209-99[2]. The average G_{mm} was 2.616.

Two additional samples were obtained randomly to determine the asphalt binder content and aggregate gradation for the samples (figure 2).

The Pine and Troxler SGCs were both serviced and set to an external angle of gyration of 1.25° by their manufacturers prior to testing using the manufacturer's procedures for calibration. The AVK calibration was verified prior to use on a daily basis.

Four different compaction modes were employed:

a) AVK only, to measure the DIA without mix;

b) HMA only, to measure the mix bulk specific gravity without the AVK introduced into the mold;

c) HMA with the AVK on top of the mix to measure the top DIA; and

d) HMA with the AVK on bottom of the mix to measure the bottom DIA.

The mixture was designed to have 4-percent air voids at 100 gyrations with a 115-mm- height specimen using the contractor's SGC. Four replicates were compacted using the Pine and Troxler SGC to assess the compact ability of the production sample. The average number of gyrations to produce 4-percent air voids was determined and rounded to the nearest 5 gyrations. This rounded value of 80 gyrations was designated as N_4 and was used as the total compaction effort throughout the laboratory evaluation.

Testing was conducted at the recommended compaction temperature of 141°C, within a tolerance of $\pm$ 5°C. Mix was brought to compaction temperature in a force-draft oven. Important testing operations and precautions were taken into consideration throughout the laboratory testing: 1) mix was reheated in the sample boxes and was used for testing within a 5-h time period or it was discarded; 2) SGC molds were heated for a minimum of 1 h in a force-draft oven at the target compaction temperature prior to first use on a testing day; 3) SGC molds were returned to the oven immediately after specimen extrusion; 4) after each compaction cycle, the AVK was placed under a fan to keep the device within its recommended operating temperatures; and 5) all replicates were tested in a random order for each angle of gyration and compaction mode.

The full factorial for the laboratory-testing program is summarized in table 1. For each test combination, nine replicates were fabricated.

The maximum, minimum, and average DIA were measured and recorded by the software provided by the AVK manufacturer. The standard deviation was also determined. The bulk specific gravity (G_{mb}) was determined according to AASHTO T166-00[3]. The average and standard deviation for G_{mb} was calculated and recorded.

ANALYSIS, RESULTS, AND DISCUSSION

Outliers Analysis

A large sample of production mix was used to fabricate the gyratory specimens for this study. Nine replicates were obtained for each combination of the study to ensure repeatability and accuracy of the test results. A total of 558 gyratory specimens was randomly fabricated for the target and tolerance study to avoid any bias induced through sampling. The outlier analysis determines if any of the replicates is considered an outlier or extreme data point based first on engineering judgment and second on the statistical analysis methods of outliers for such a statistically small sample size.

Chauvenet's Method for Outliers

Chauvenet's method was used to test a single value in the sample to determine if it was from the same population as the remainder of the sample data points. This method assumes a normal distribution of the population. The data point to be tested for outlier is the value that deviates the most from the mean of the data points (mean a). This method required the computation of the mean and the standard deviation of the data points, which are used to calculate the standard normal deviate (Z) as:

$$Z = \frac{\alpha - mean\,\alpha}{S} \tag{1}$$

Where:

Z Standard normal deviate of α;

α Extreme value for angle of gyration;

mean α Mean value of all angle of gyrations, estimate of the corresponding population mean, μ; and

S Standard deviation, estimate of the corresponding population standard deviation, σ.

Chauvenet's method defines the regions for acceptance and rejection of the null statistical hypothesis (H_o - all sample points are from the same normal population) based on the critical normal deviate (Z_c), which is obtained using a probability, *p* of 1/2n (n = sample size) divided equally between the upper and the lower tails of the standard normal distribution. The acceptance region is defined as the region where the absolute value of the standard normal deviate (Z) is smaller than the critical value of $Z_{p/2}$ obtained from the tables for standard normal distribution. When the absolute value of Z is greater than $Z_{p/2}$, the region of rejection is defined.

Dixon-Thompson Method

The second method for outliers used in this analysis is the Dixon-Thompson method. This method can be used for sample sizes as small as 3. It is based on the variation between the extreme value and another value and the variation within the sample. Rationale, R, is defined as the ratio of the variation between to the variation within. The critical value, R_c, for this method is determined from polynomial functions for ranges of sample sizes. For example, for sample size of 3 to 10, R_c is determined from the polynomial shown in the equation below:

$$R_c = 1.23 - 0.125n + 0.005n^2 \tag{2}$$

The value R is determined from the equations below for the same sample size:

For low outlier test,

$$R = \frac{X_2 - X_1}{X_{n-1} - X_1} \tag{3}$$

For high outlier test,

$$R = \frac{X_n - X_{n-1}}{X_n - X_2} \tag{4}$$

Where:

X_1 = Smallest value;

X_2 = Value next to smallest value;

X_n = Largest value; and

X_{n-1} = Value next to largest value.

This method was used in the outlier analysis of this study as a one-tailed test (it can also be used as a two-tailed test if the direction of the outlier is not specified) since the outlier direction was specified in all cases. If R is smaller than the critical value (R_c) obtained from equation (2), the value is considered not an outlier and the null hypothesis is accepted; otherwise, it is an outlier and the null hypothesis is rejected.

For this study, these outlier approaches identified 17 of the 558 specimens as outliers. The outliers were reviewed, using engineering judgment, and subsequently removed from the data set.

Proposed Target for the DIA

115-mm height specimens with the AVK were used to determine the top and bottom DIA (figure 3) for the Pine SGC. For this mixture, the average DIA for the Pine SGC is 1.176° when the external angle is set at 1.25°. The mold height and ram configuration of the Troxler SGC does not facilitate the use of full-height specimens with the AVK. Specimens compacted at three heights (45, 60, 75 mm) were used to extrapolate the DIA for a specimen height of 115 mm using a linear regression, R^2 of 0.99 (figure 4). Using this approach, for this mixture, the average DIA for the Troxler SGC is 1.140° when the external angle is set at 1.25°. Similar linear relationships are reported by Pine[(4)] (Report 2000-03) for the Pine AFGC125X and AFG1 SGCs, and by TestQuip for the Brovold gyratory compactor and Troxler SGC model 4140[(5)].

The proposed target for the DIA is the average Pine and Troxler DIAs rounded to the nearest hundredth, so the proposed target DIA is 1.16°.

Proposed Tolerance for the DIA

The DIA in both gyratory compactors appears to change linearly with the external angle, as shown in figures 5, 6, 7 and 8 (R^2 values of 0.99 and 0.98).

The tolerance of the angle of gyration was determined using the SHRP rule-of-thumb: “a 0.4-percent change in asphalt binder content (P_b) equates to approximately a 1.0-percent change in air-void content (V_a).” The tolerance is based on limiting the net effect of the angle of gyration on the design asphalt binder content to 0.1 percent, which equals a 0.25-percent change in air- void content.

The following equations calculate the tolerance of the angle of gyration:

$$\Delta G_{mb} = m\Delta\alpha \qquad (5)$$

Þ

$$\Delta\alpha = \frac{\Delta G_{mb}}{m} \qquad (5'')$$

$$V_a = 100(1 - \frac{G_{mb}}{G_{mm}}) \qquad (6)$$

Þ

$$\Delta V_a = -\frac{100}{G_{mm}} \Delta G_{mb} \quad (6')$$

or

$$\Delta G_{mb} = -\frac{G_{mm}}{100} \Delta V_a \quad (6'')$$

By substituting DG$_{mb}$ from equation (6’’) in equation (5’’), the equation below is produced:

$$\Delta \alpha = \left| -(\frac{G_{mm}}{100})(\frac{1}{m}) \Delta V_a \right| \quad (5''')$$

Where:

G_{mb} = Bulk specific gravity of the mix;

α = Dynamic internal angle;

m = Slope of G_{mb} versus α curve: average for Pine and Troxler compactors;

V_a = Air-void content; and

G_{mm} = Maximum specific gravity of the mix.

Substitution of the values m = 0.15, G_{mm} = 2.616, ΔV_a = 0.25 % yielded the tolerance below:

Δa = (2.616/100)(1/0.15)(0.25) = 0.044° = Angle range

Tolerance = ± Angle range / 2

Tolerance = ±0.022° rounding up @ ±0.03°

Verification of Proposed Target

The proposed target angle was validated using the Flanigan production mix and a laboratory prepared mix from the FHWA’s Accelerated Loading Facility (ALF). The ALF mix is a 75-gyration, 19.0-mm nominal maximum size, coarse-graded Superpave mixture, consisting of a Virginia diabase aggregate and an unmodified PG 64-22 asphalt binder (binder content of 4.6 percent). The BML Troxler 4140 and the Pine AFGC125X SGCwere used for the validation process. Full-height specimens (115 mm) were fabricated at the proposed target DIA of 1.16°. Bulk specific gravities were measured for all specimens according to AASHTO T166-00[3]. For the Flanigan production mix, the average bulk specific gravities were found to be 2.521 and 2.522 for Pine and BML Troxler SGCs, respectively. The standard deviation was determined to be 0.003 for both SGCs. For the ALF mix, the average bulk specific gravities were 2.617 for the Pine and 2.618 for the BML Troxler. The standard deviations were 0.005 and 0.011 for the Pine and BML Troxler, respectively.

Interrelationship Between Specimen Height, DIA, And Bulk Specific Gravity

Based upon the results of this study, a correlation between the specimen height, DIA, and bulk specific gravity (G_{mb}) was found. This correlation was investigated for the BML Troxler SGC to predict the DIA as well as the G_{mb} at full-height (115-mm) specimens since it was not possible to produce 115-mm-height specimens using the Troxler SGC. The relationship between the compacted specimen height and the DIA was found to be linear as shown in figure 4. As compacted specimen height increases, the measured DIA decreases. In other words, the compactive effort is proportionally correlated with the specimen height; it increases as the specimen height increases.

The results obtained from the Pine and the Troxler SGC show that the bulk specific gravity increases linearly with the DIA for a constant specimen height (figures 9 and 10). The relationship was obtained for 115-mm- and 80-mm-height specimens using the Pine and the Troxler SGC, respectively. A similar relationship was reported by Pine[6].

On the other hand, a proportional non-linear relationship obtained between the compacted specimen height and the bulk specific gravity was obtained as shown in figure 11. The bulk specific gravity increases steeply with the specimen height up to 75-mm height, where the G_{mb} tends to stabilize. Higher DIAs associated with lower specimen heights obtain lower bulk specific gravities although higher DIAs produce higher bulk specific gravities (more compactive effort) with a constant specimen height. This fact is again due to the interrelationship between the specimen height, DIA, and bulk specific gravity.

SUMMARY AND CONCLUSIONS

Based upon the analysis and results of the study, the following findings and conclusions were drawn:

1) The proposed target for the DIA of gyration measured by the FHWA AVK is 1.16°.

2) The proposed tolerance for the DIA, based on limiting the net effect of the angle of gyration on the design asphalt binder content to 0.1 percent, is ± 0.03°.

3) The DIA changes proportionally with the external angle of gyration in the SGC.

4) The presence of the HMA in the gyratory mold causes the DIA to be lower than the DIA without the HMA.

5) There is an interrelationship between specimen height, the DIA, and bulk specific gravity that must be considered in the development of an AASHTO procedure for AVKs use.

6) A verification of the proposed target was conducted using two mixes. The Pine and BML Troxler SGCs, adjusted to 1.16°, provided very similar compactive efforts.

ACKNOWLEDGMENT

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FIGURE 1. Pine and Troxler Superpave gyratory compactors.

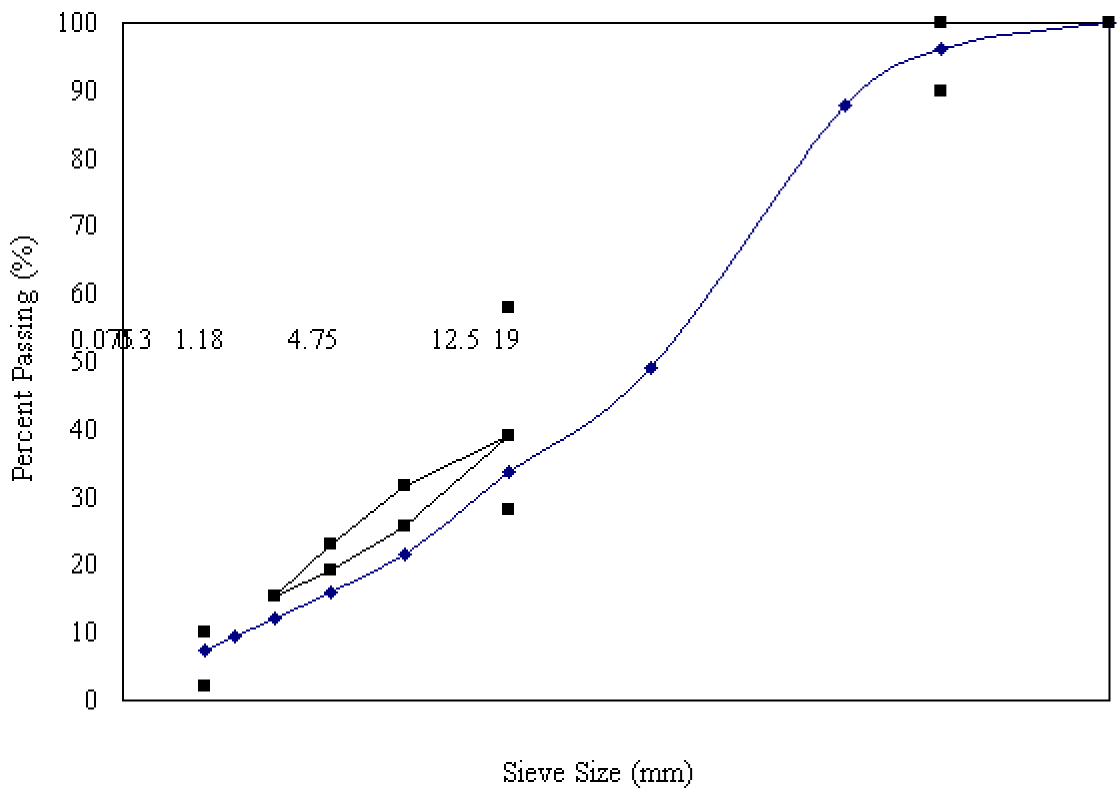

Figure 2. 0.45 Power chart for the Flanigan production mix.

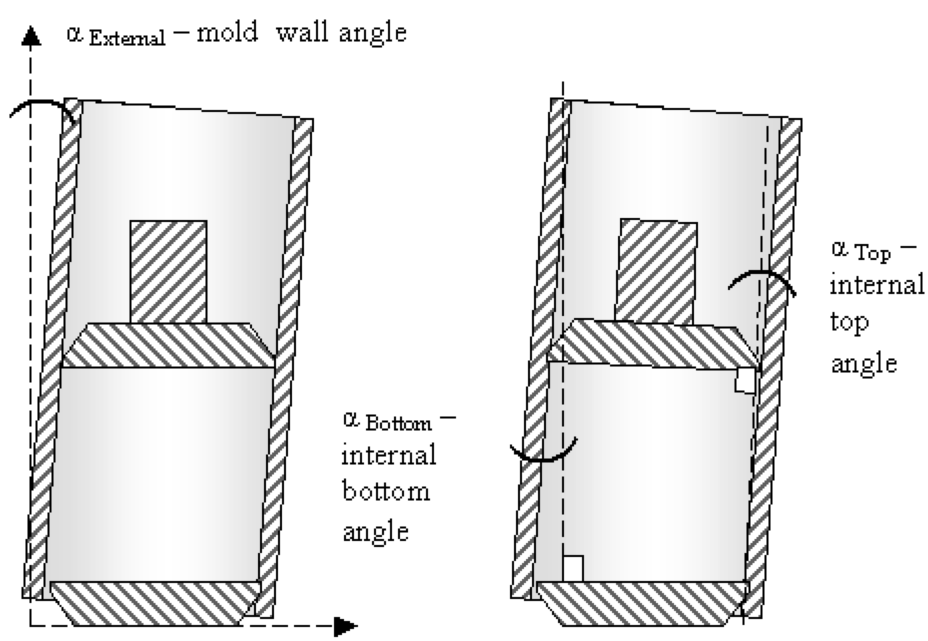

FIGURE 3. DIA as measured inside the SGC mold.

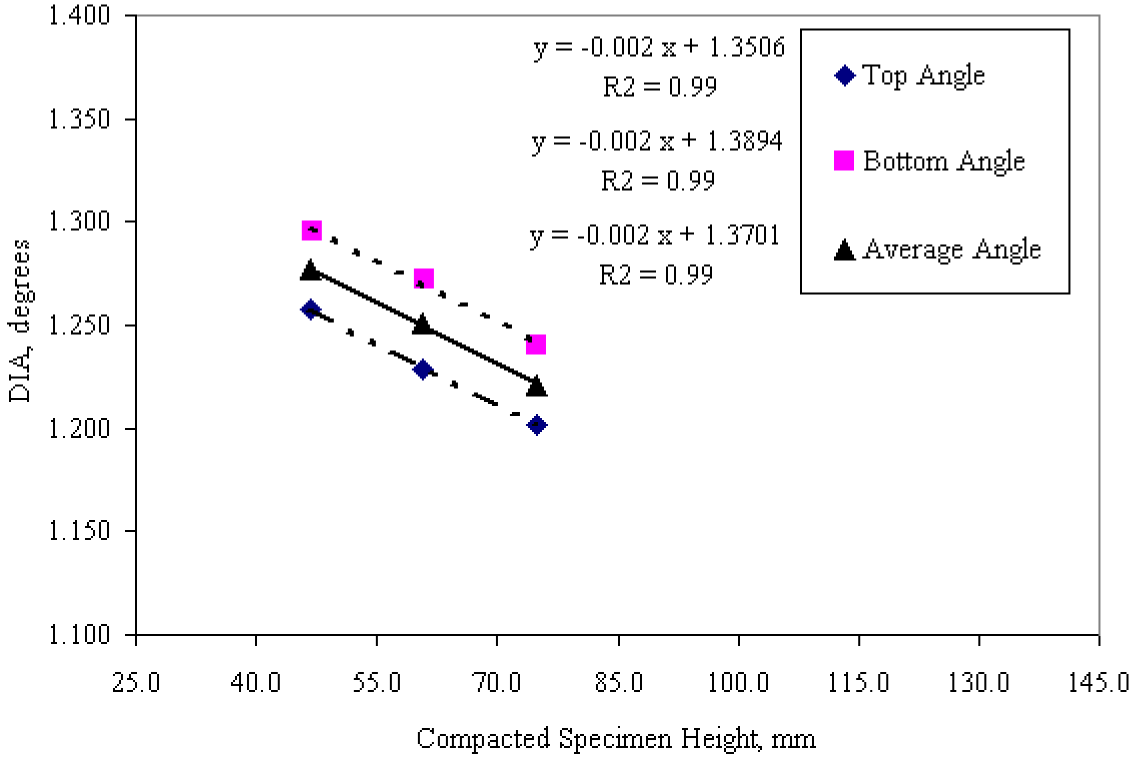

Figure 4. Specimen height vs. DIA for Troxler SGC.

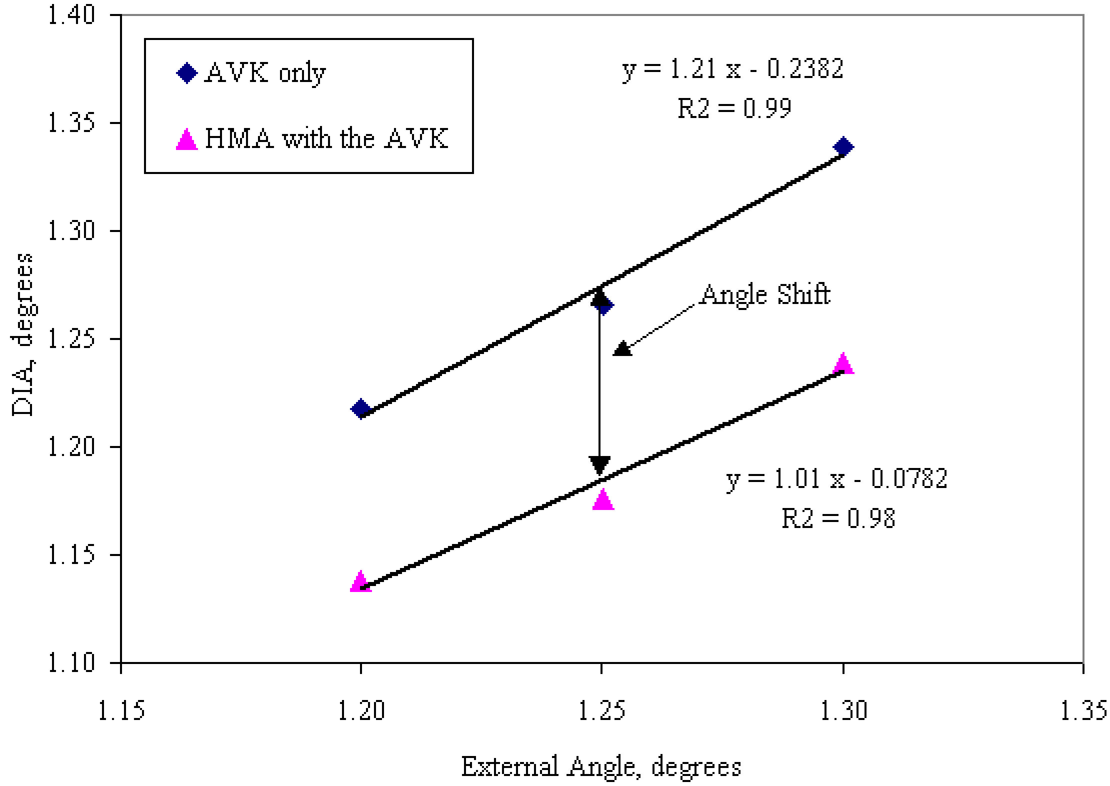

Figure 5 DIA (with and without HMA) vs. external angle with 115-mm-height specimens for Pine SGC.

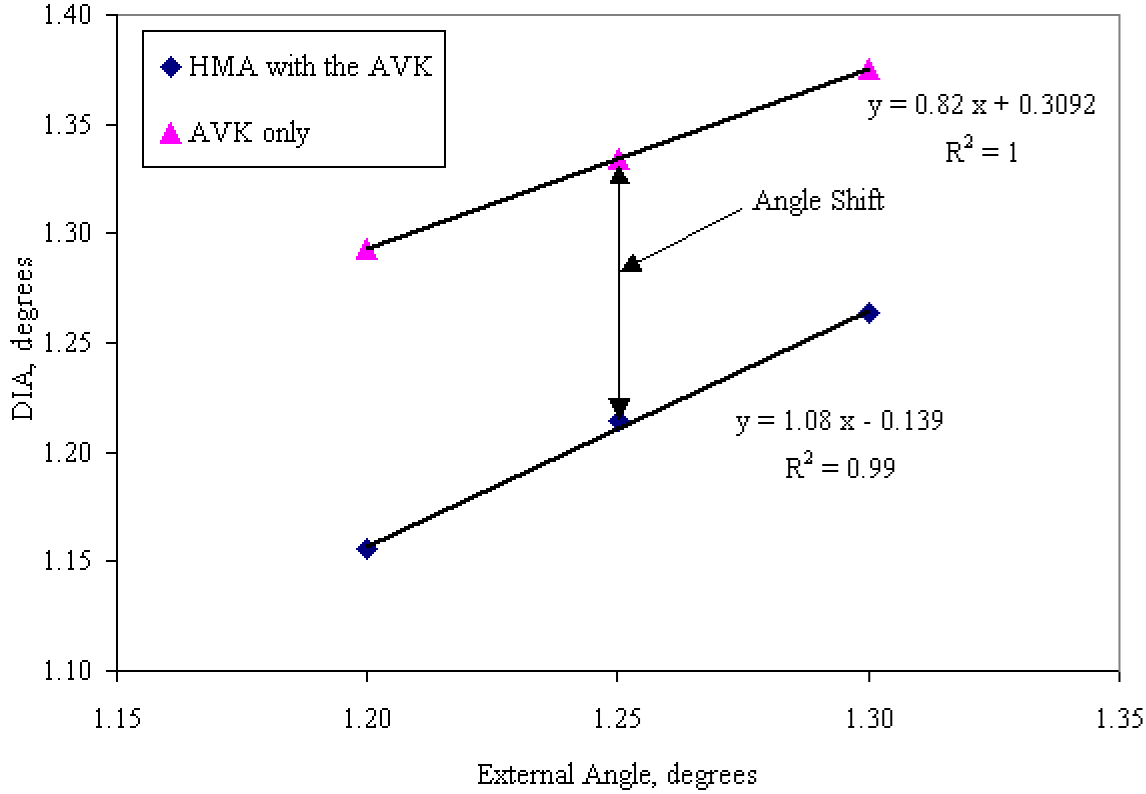

Figure 6. DIA (with and without HMA) vs. external angle with 80-mm-height specimens for Troxler SGC.

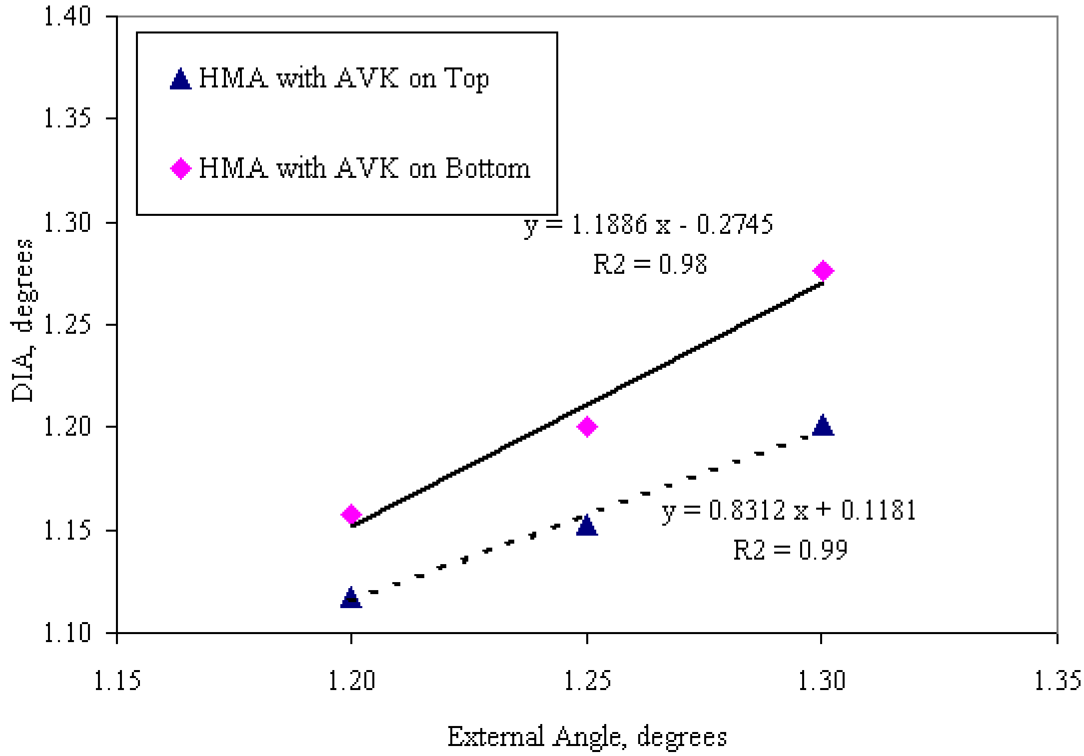

Figure 7. External angle vs. top and bottom DIA with 115-mm-height specimens for the Pine SGC.

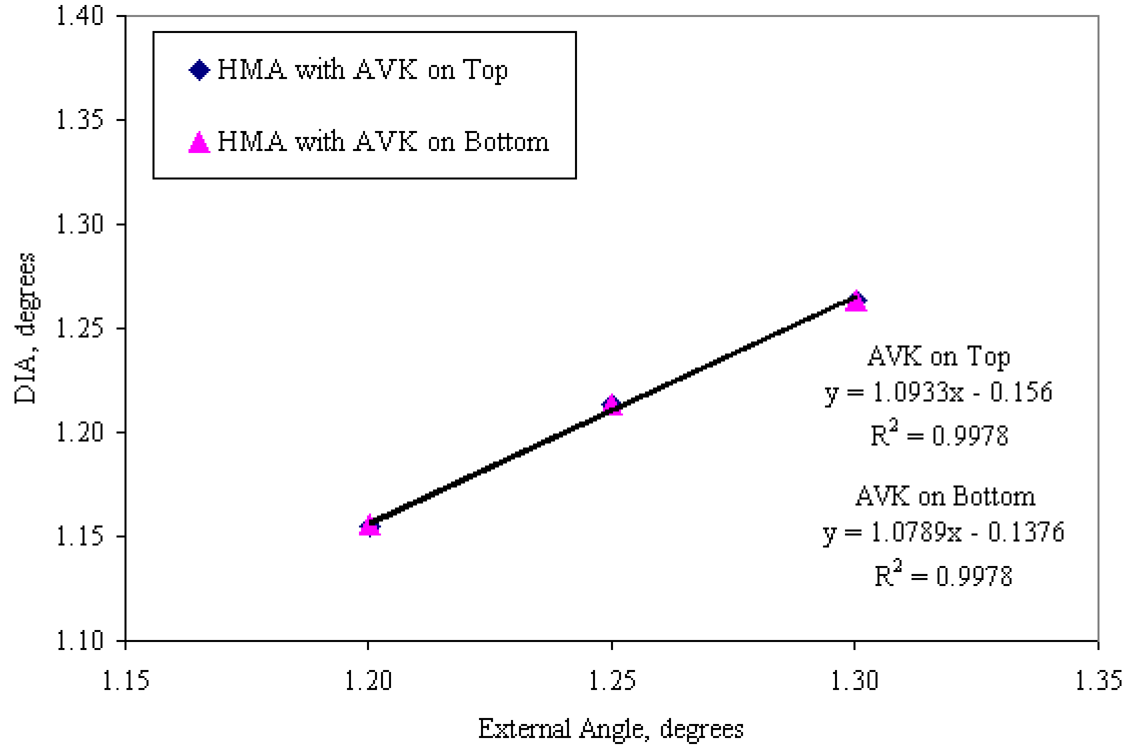

Figure 8. External angle vs. DIA for 80-mm-height specimens in the Troxler SGC.

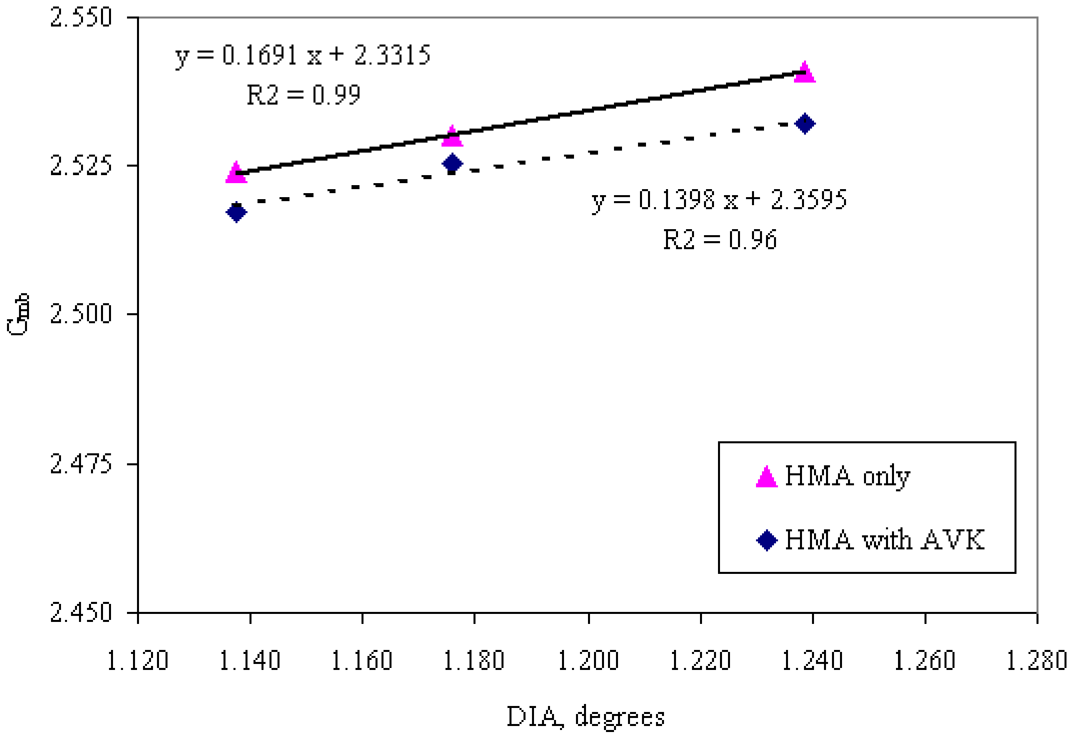

Figure 9. Bulk Specific Gravity with and without the AVK for 115-mm-height specimens in the Pine SGC.

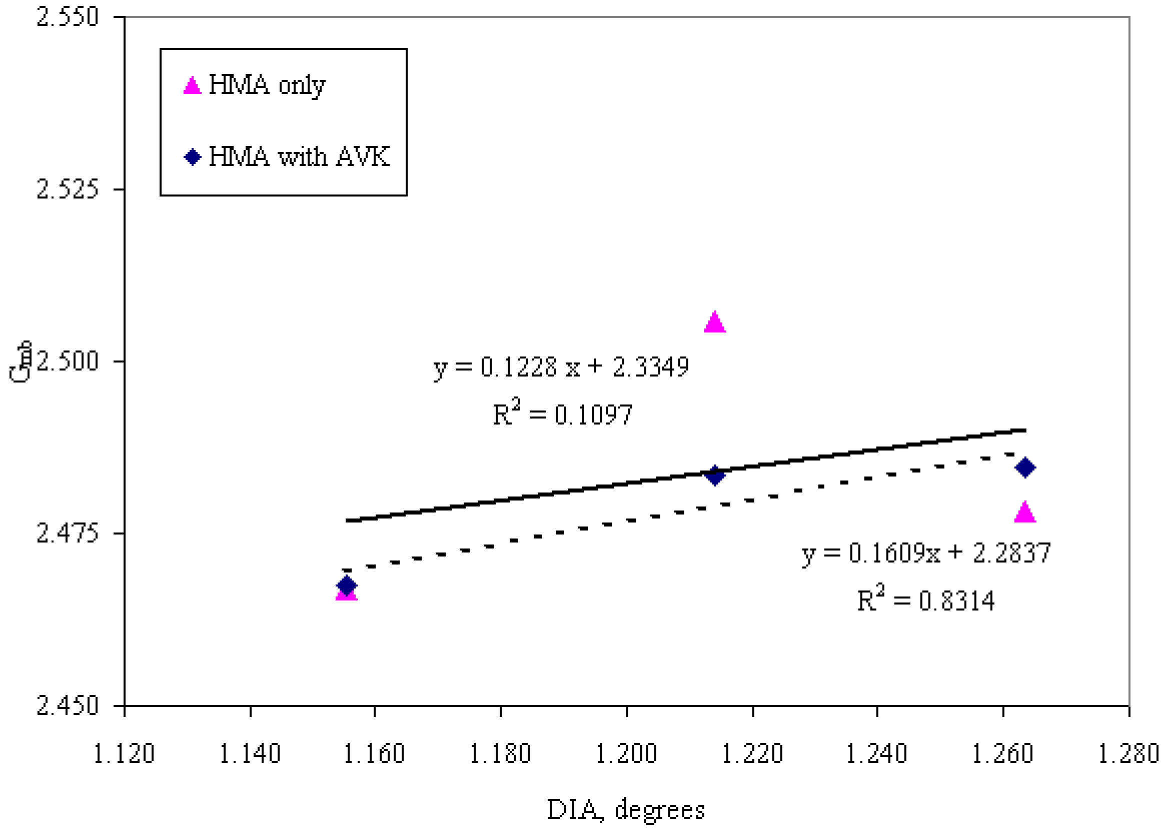

Figure 10. Bulk specific gravity with and without the AVK for 80-mm-height specimens in the Troxler SGC.

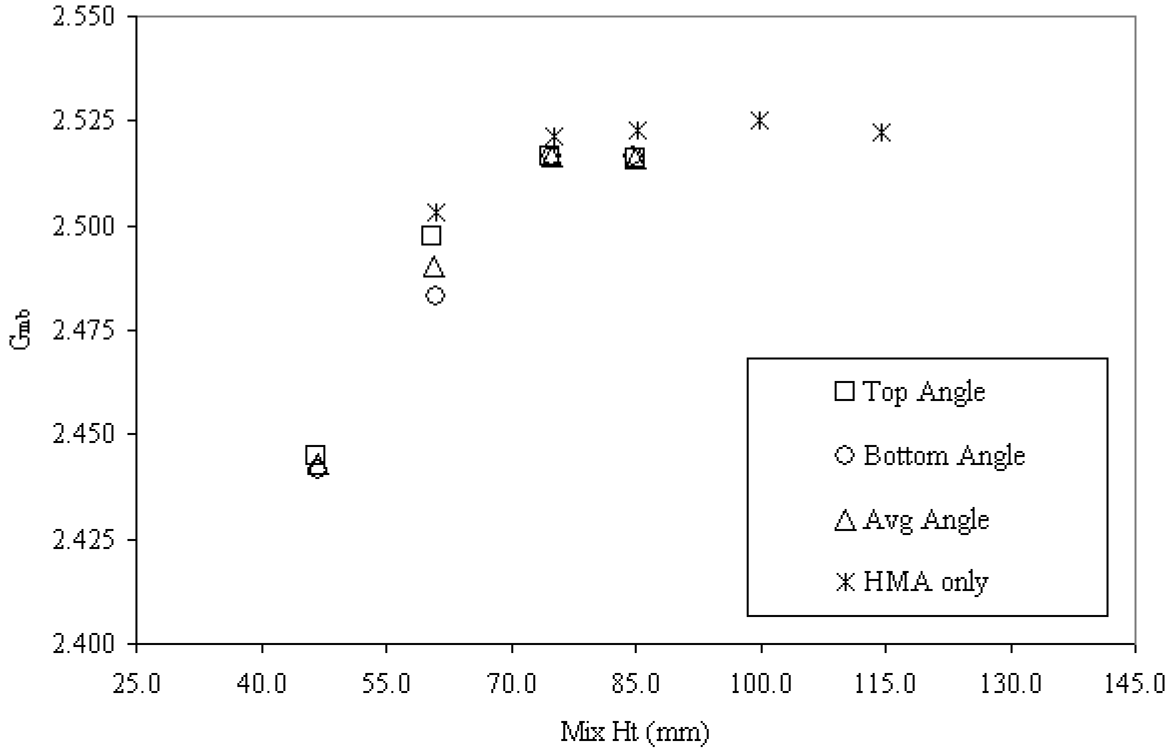

Figure 11. Mix height (Ht) vs. mix bulk specific gravity for Troxler SGC.

TABLE 1. Test Matrix for Target and Tolerance Study

Target Study Test Matrix-External Angle = 1.25°							
Compactor	HMA Height (mm)	Mode of Compaction				Total	Est. Required Mass of HMA (g)
		a	b	c	d		
		AVK only	HMA only	Top	Bottom		
		Number of Replicates					
A	0	9				9	0
	45		9	9	9	27	54000
	80		9	9	9	27	94500
	115		9	9	9	27	132300
B	0	9				9	0
	45		9	9	9	27	54000
	80		9	9	9	27	94500
	115		9	X	X	9	44100
Total		18	54	45	45	162	473400

Tolerance Study Test Matrix-External Angle = 1.20° and 1.30°							
Compactor	HMA Height (mm)	Mode of Compaction				Total	Est. Required Mass of HMA (g)
		A	b	c	d		
		AVK only	HMA only	Top	Bottom		
		Number of Replicates					
A	0	9				9	0
	45		9	9	9	27	54000
	80		9	9	9	27	94500
	115		9	9	9	27	132300
B	0	9				9	0
	45		9	9	9	27	54000
	80		9	9	9	27	94500
	115		9	X	X	9	44100
Total		18	54	45	45	162	473400

TABLE 2. Test Matrix for Validation of Proposed DIA, 1.16°.

Compactor	HMA Height (mm)	Mode of Compaction				Total	Est. Required Mass of HMA (g)
		a	b	c	d		
		AVK only	HMA only	Top	Bottom		
		Number of Replicates					
A	0					0	0
	45		6	6	6	18	36000
	80		6	6	6	18	63000
	115		9	9	9	27	132300
B	0					0	0
	45		6	6	6	18	36000
	80		6	6	6	18	63000
	115		9	X	X	9	44100
Total		0	42	33	33	108	374400