

Evaluation of Pine AFG2 Superpave Gyratory Compactor

Prepared for:

PINE INSTRUMENT COMPANY

Submitted by:

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EXECUTIVE SUMMARY

This report documents work performed by the Department of Civil Engineering at the University of Arkansas related to an evaluation of the Pine Instrument Company's AFG2 Superpave Gyratory Compactor. The study was based on the principles of AASHTO PP35-98 (2005), which presents a "...method for evaluating the suitability of a Superpave gyratory compactor (SGC) with respect to its ability to produce compacted specimens at various compaction levels according to T 312, which are equivalent to two models of gyratory compactors which...are known to have met the specification."

Replicate specimens of four hot-mix asphalt (HMA) mixtures were compacted in each of four SGC units, including the AFG2, the Pine Instrument Company's AFG125x, the Pine Instrument Company's AFG1, and the Pine Instrument Company's AFGB1 (the "Brovold" compactor). The HMA mixes ranged in nominal maximum aggregate size from 9.5 mm to 25 mm, and featured binder grades ranging from PG64-22 to PG76-22. Two of the mixes were 'field' mixes sampled at the hot-mix asphalt plant and two were mixed in the laboratory. All gyratory compactors were fully calibrated prior to the study; in addition, the internal angle of gyration was measured prior to each day's use using the Rapid Angle Measurement (RAM) device in accordance with AASHTO TP 71-07. All internal angle measurements were within the specifications listed in AASHTO T312.

Overall, the compaction data (in terms of the bulk specific gravity of the compacted HMA specimens, G_{mb}) indicates the Pine AFG2 produces compacted HMA specimens having similar density characteristics as specimens compacted in the three comparator SGC models currently used in routine practice. Based on the criteria presented in AASHTO PP35-98 (2005), the Pine AFG2 should be rated 'comparable' to the Pine AFG125x, the Pine AFG1, and the Pine AFGB1. Analysis of Variance (ANOVA) performed on the data shows no statistically significant differences to exist between G_{mb} data generated by the AFG2 and the other compactors used in the study, at the N_{des} (the design gyration level) and N_{ini} (the initial gyration level) gyration values. Overall, it is concluded that the AFG2 compares favorably to the referee compactors used in the study; further, the AFG2 is recommended as a viable Superpave gyratory compactor for use in mixture design, Quality Control (QC) and Quality Assurance (QA) applications.

EVALUATION STUDY METHODOLOGY

The evaluation study was performed, insofar as possible, in accordance with the principles contained in AASHTO PP35-98 (2005), "Evaluation of Superpave™ Gyratory Compactors (SGCs)". Replicate specimens of four hot-mix asphalt (HMA) mixtures were compacted in the Pine AFG2 (the "candidate" compactor) and in each of the following "referee" compactors: Pine AFG125x, Pine AFG1, and Pine AFGB1 ("Brovold"). The evaluation of the AFG2 concerning suitability as a Superpave gyratory compactor is based on comparisons of the bulk specific gravity (G_{mb}) of the replicate compacted specimens at the design gyration (N_{des}) and initial gyration (N_{ini}) levels.

It is noted that all specimen handling, compaction, determination of bulk specific gravity, and determination of maximum specific gravity was performed by a single operator. This meets the requirements specified in AASHTO PP35-98, Section 5.1, which specifies the use of a single operator.

Hot-mix asphalt specimens were selected for testing (which included the order of testing, and the compactor used for a given specimen) using a random-number based selection process which meets the requirements of Section 6.10 of AASHTO PP35-88.

Compaction of the specimens used in this analysis occurred over a span of four days. All specimens for a single hot-mix asphalt mixture were compacted in a single day, using the subject compactor and the three referee compactors. All HMA specimens were processed in the laboratory in an identical manner to minimize outside sources of error.

Table 1 lists specific areas in which the evaluation study departed from the specifications listed in AASHTO PP35-98 (2005) which relate to the laboratory methods to be used.

Table 1. – Departures from AASHTO PP35-98 (2005)

Section	AASHTO PP35 Criteria	Pine AFG2 Evaluation Study
6.2	Verify the compactor calibration at the end of each day of use.	Each compactor was fully calibrated prior to the study; internal angle of gyration was verified prior to each use.
6.4	Hot-mix asphalt (HMA) mixtures used for the evaluation: <ul style="list-style-type: none"> • 2 mixes with 19.0-mm nominal maximum aggregate size (NMAAS) <ul style="list-style-type: none"> ○ 'Coarse' mix: 109 gyrations ○ 'Fine' mix: 86 gyrations 	Hot-mix asphalt (HMA) mixtures used for the evaluation: <ul style="list-style-type: none"> • Mix 1: 9.5-mm NMAAS <ul style="list-style-type: none"> ○ 'Coarse' mix; 65 gyrations; PG64-22 • Mix 2: 12.5-mm NMAAS <ul style="list-style-type: none"> ○ 'Coarse' mix; 50 gyrations; PG76-22 • Mix 3: 12.5-mm NMAAS <ul style="list-style-type: none"> ○ 'Coarse' mix; 100 gyrations; PG70-22 • Mix 4: 25.0-mm NMAAS <ul style="list-style-type: none"> ○ 'Fine' mix; 100 gyrations; PG70-22
6.5	<ul style="list-style-type: none"> • 1 mix with 12.5-mm NMAAS <ul style="list-style-type: none"> ○ 109 gyrations 	
6.6	<ul style="list-style-type: none"> • 1 mix with 25.0-mm NMAAS <ul style="list-style-type: none"> ○ 109 gyrations • Asphalt binder viscosity: 0.26 to 0.30 Pa-s at 135 C. 	
6.7	Six replicate specimens per mix for gyratory compaction	Replicate specimens used: 3 (Mix 1); 5 (Mix 2); 5 (Mix 3); 4 (Mix 4). The number of replicates was affected by mixture availability.
6.8	Fixed compaction temperature of 135 C	Compaction temperature determined in accordance with the asphalt binder grade
6.11	Compact to N_{max} gyrations; calculate bulk specific gravity (G_{mb}) at both N_{des} and N_{ini} gyration levels.	Specimens were compacted to N_{des} gyrations; bulk specific gravity was measured directly for these specimens. Bulk specific gravity was calculated for N_{ini} gyrations.

LABORATORY COMPACTION RESULTS

Tables 2(a) through 2(d) show the measured and calculated bulk specific gravity, G_{mb} , of specimens compacted to N_{des} and N_{ini} gyrations, respectively – corresponding to the data presentation requirements contained in AASHTO PP35-98 (2005). Section 6.12 of AASHTO PP35 indicates that no individual G_{mb} value should deviate from its group average by more than 0.020 (note, however, that Section 6.12 is predicated on G_{mb} values measured on specimens compacted to N_{max} gyrations, and for groups of six replicate specimens). Only three values shown in Tables 2(a) through 2(d) violate this criteria: specimen 4, Mix 2, Pine AFG2, G_{mb} at N_{ini} ; and specimen 4, Mix 3, Pine AFG125x, G_{mb} at N_{ini} and N_{des} . It was decided to retain the G_{mb} values for these specimens.

Table 2(a). -- Summary of Bulk Specific Gravities (G_{mb})^a – Mix1

Mix No.	Candidate Compactor (Pine AFG2)			Referee SGC (Pine AFG125x)			Referee SGC (Pine AFG1)			Referee SGC (Pine AFGB1 - "Brovold")		
	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}
1	2.292	2.517		2.319	2.519		2.301	2.521		2.287	2.519	
2	2.298	2.521		2.308	2.518		2.291	2.525		2.299	2.523	
3	2.308	2.519		2.305	2.523		2.310	2.520		2.278	2.516	
4												
5												
Avg	2.299	2.519		2.311	2.520		2.301	2.522		2.288	2.519	

^a Bulk Specific Gravity (G_{mb}) was measured on specimens compacted to N_{des} gyrations; G_{mb} at N_{ini} is calculated in accordance with AASHTO T312

Table 2(b). -- Summary of Bulk Specific Gravities (G_{mb})^a – Mix 2

Mix No.	Candidate Compactor (Pine AFG2)			Referee SGC (Pine AFG125x)			Referee SGC (Pine AFG1)			Referee SGC (Pine AFGB1 - "Brovold")		
	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}
1	2.216	2.468		2.224	2.475		2.208	2.475		2.221	2.479	
2	2.219	2.477		2.224	2.471		2.214	2.470		2.226	2.475	
3	2.229	2.480		2.224	2.468		2.225	2.477		2.230	2.472	
4	2.194	2.465		2.209	2.466		2.216	2.472		2.221	2.470	
5	2.224	2.469		2.218	2.470		2.215	2.474		2.229	2.476	
Avg	2.216	2.472		2.220	2.470		2.216	2.474		2.226	2.474	

^a Bulk Specific Gravity (G_{mb}) was measured on specimens compacted to N_{des} gyrations; G_{mb} at N_{ini} is calculated in accordance with AASHTO T312

Table 2(c). -- Summary of Bulk Specific Gravities (G_{mb})^a– Mix 3

Mix No.	Candidate Compactor (Pine AFG2)			Referee SGC (Pine AFG125x)			Referee SGC (Pine AFG1)			Referee SGC (Pine AFGB1 - "Brovold")		
	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}
1	2.024	2.295		2.013	2.292		2.037	2.296		2.041	2.304	
2	2.035	2.302		2.029	2.302		2.029	2.302		2.037	2.308	
3	2.029	2.309		2.024	2.299		2.009	2.297		2.037	2.302	
4	2.040	2.301		2.065	2.330		2.013	2.304		2.050	2.307	
5	2.023	2.305		2.018	2.294		2.046	2.309		2.027	2.305	
Avg	2.030	2.302		2.030	2.303		2.027	2.302		2.038	2.305	

^a Bulk Specific Gravity (G_{mb}) was measured on specimens compacted to N_{des} gyrations; G_{mb} at N_{ini} is calculated in accordance with AASHTO T312

Table 2(d). -- Summary of Bulk Specific Gravities (G_{mb})^a– Mix 4

Mix No.	Candidate Compactor (Pine AFG2)			Referee SGC (Pine AFG125x)			Referee SGC (Pine AFG1)			Referee SGC (Pine AFGB1 - "Brovold")		
	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}	G_{mb} at N_{ini}	G_{mb} at N_{des}	G_{mb} at N_{max}
1	2.074	2.356		2.064	2.363		2.051	2.355		2.088	2.384	
2	2.078	2.368		2.047	2.367		2.045	2.372		2.073	2.358	
3	2.055	2.373		2.075	2.357		2.074	2.363		2.073	2.359	
4	2.066	2.363		2.063	2.371		2.071	2.366		2.080	2.369	
5												
Avg	2.068	2.365		2.062	2.365		2.060	2.364		2.079	2.368	

^a Bulk Specific Gravity (G_{mb}) was measured on specimens compacted to N_{des} gyrations; G_{mb} at N_{ini} is calculated in accordance with AASHTO T312

Table 3 shows the standard deviation of G_{mb} values for each mixture and compactor listed in Tables 2(a) through 2(d). AASHTO PP35-98 (2005) requires the standard deviation values for the candidate compactor (the Pine AFG2) and the referee compactors to be “comparable”. The data shown in Table 3 indicates this to be the case. For Mixture 2 the standard deviation of G_{mb} at both N_{des} and N_{ini} gyrations is slightly higher for the candidate compactor than for each of the referee compactors; in addition, the standard deviation for the candidate compactor is slightly higher for the following individual cases: (1) Mixture 3, N_{des} gyrations, compared to the AFGB1; (2) Mixture 4, N_{ini} gyrations, compared to the AFGB1; (3) Mixture 4, N_{des} gyrations, compared to the AFG125x.

Table 3. -- Summary of Bulk Specific Gravities (G_{mb}) Standard Deviation

Mix No.	Candidate Compactor (Pine AFG2)			Referee SGC (Pine AFG125x)			Referee SGC (Pine AFG1)			Referee SGC (Pine AFGB1 - "Brovoid")		
	Standard Deviation of G_{mb} at:											
	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}
1	0.008	0.002		0.008	0.003		0.009	0.003		0.010	0.004	
2	0.013	0.006		0.006	0.003		0.006	0.003		0.004	0.004	
3	0.007	0.005		0.020	0.015		0.016	0.005		0.008	0.002	
4	0.010	0.007		0.012	0.006		0.014	0.007		0.007	0.012	

Table 4 lists the average G_{mb} of all replicate specimens, respectively, for each mixture and compactor. AASHTO PP35-98 (2005) requires the difference between the average G_{mb} value for the candidate and referee compactors to be 0.010 or less. The difference in average G_{mb} values, which are summarized in Table 5, ranges from 0.000 to 0.003 for specimens compacted to N_{des} gyrations – well within stated guidelines. Differences approaching and/or slightly exceeding the 0.010 criteria occur for values associated with N_{ini} gyrations for all compactors. It is noted that the criterion in Section 6.20 of AASHTO PP35 is based on six replicate specimens for all cases, and includes values associated with N_{max} gyrations.

Table 4. -- Summary of Average Bulk Specific Gravities (G_{mb})

Mix No.	Candidate Compactor (Pine AFG2)			Referee SGC (Pine AFG125x)			Referee SGC (Pine AFG1)			Referee SGC (Pine AFGB1 - "Brovoid")		
	Average Bulk Specific Gravity (G_{mb}) at:											
	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}
1	2.299	2.519		2.311	2.520		2.301	2.522		2.288	2.519	
2	2.216	2.472		2.220	2.470		2.215	2.474		2.226	2.474	
3	2.030	2.302		2.030	2.303		2.027	2.302		2.038	2.305	
4	2.068	2.365		2.062	2.365		2.060	2.364		2.079	2.368	

It is problematic to apply the evaluation criteria contained in AASHTO PP35-98 (2005) to the data sets generated in this study. As noted in Table 1 and subsequently in previous discussion regarding the data, the bases for the criteria in the AASHTO specification (type of mixtures, compaction/gyration levels, number of replicates) are not exactly reproduced in this study. Therefore, an Analysis of Variance (ANOVA) was performed using the data sets shown here to determine whether a statistically significant difference exists in G_{mb} data generated by the candidate and referee compactors.

Table 5. -- Summary of Differences in Bulk Specific Gravities - Candidate vs Referee Compactors

Mix No.	Difference in Average G_{mb} Between AFG2 Compactor and Referee Compactors					
	G_{mb} at N_{ini}			G_{mb} at N_{des}		
	AFGC125X	AFG1	AFGB1	AFGC125X	AFG1	AFGB1
1	-0.011	-0.002	0.011	-0.001	-0.003	0.000
2	-0.003	0.001	-0.009	0.002	-0.002	-0.003
3	0.000	0.003	-0.008	-0.001	0.000	-0.003
4	0.006	0.008	-0.010	0.001	0.001	-0.002
Average ^a	0.005	0.004	0.010	0.001	0.002	0.002

^aThe average shown represents the average of the *absolute values* of the differences shown

Table 6 shows the results from the ANOVA. The data contained in Table 6 indicate that no statistically significant differences exist in G_{mb} values for specimens compacted with the candidate and referee compactors for at the N_{ini} and N_{des} gyration levels.

Table 6. – Analysis of Variance (ANOVA) Results

Mixture	F_{crit}	For G_{mb} at N_{ini} Gyration		For G_{mb} at N_{des} Gyration	
		F_{test}	Significant?	F_{test}	Significant?
1	4.0662	3.139	No	0.6991	No
2	3.2389	1.4712	No	1.0724	No
3	3.2389	0.6446	No	0.1619	No
4	3.4903	2.1254	No	0.1362	No

The data generated in this evaluation study, when examined in light of the criteria contained in AASHTO PP35-98 (2005) and by an Analysis of Variance, provide sufficient evidence that the Pine AFG2 produces compacted hot-mix asphalt specimens having similar and comparable density characteristics to specimens compacted using the Pine AFG125x, Pine AFG1, and Pine AFGB1 compactors. Therefore, the Pine AFG2 should be accepted as a viable Superpave Gyration Compactor (SGC) meeting all requirements of AASHTO T 312.

EVALUATION STUDY HOT-MIX ASPHALT MIXTURES

Four hot-mix asphalt (HMA) mixtures were used in the evaluation. The set of mixes features nominal maximum aggregate sizes ranging from 9.5 mm to 25.0 mm, and binder grades ranging from PG 64-22 to PG 76-22. Each of the mix designs have been approved for use by a user agency. Mixes (1) and (2) represent 'production' mixes, sampled at the hot-mix plant and subsequently transported to the laboratory, reheated, split into gyratory compaction specimens, and compacted. Mixes (3) and (4) represent 'laboratory' mixes, and were batched, mixed, aged, and compacted in accordance with AASHTO T312 (and associated specifications).

It is noted that the gyration levels used for compacting mixes (1) and (2) were different than the N_{des} levels shown on the mixture design. Initial specimens compacted for both mixes exhibited low air void levels, typically ranging from less than 2 percent to slightly above 3 percent. A series of specimens were then compacted at varying gyration levels; the final gyration levels used – 65 gyrations for mix (1) and 50 gyrations for mix (2) yielded air void levels approximating design values.

Mixture designations, descriptions, and volumetric/mix design properties are shown in Table 7. Mixture gradations are shown in Figures 1 through 4.

Table 7. -- Summary of Hot-Mix Asphalt Mixture Design Data

Mix Designation	1	2	3	4
Source Location	VA	MD	AR	AR
Binder Grade	PG 64-22	PG 76-22	PG 70-22	PG 70-22
Binder Source	Citgo	Citgo	SEM	SEM
N_{des}	100 ^a	75 ^b	100	100
NMAS (mm)	9.5	12.5	12.5	25.0
P_b (%)	5.2	5.5	5.6	4.7
Air Voids (%)	4	3.5	4.5	4.5
VMA (%)	16.6	15.6	14.5	12.7
VFA (%)	75.7		70	64.6
G_{mb}	2.494	2.452	2.282	2.305
G_{mm}	2.598	2.541	2.390	2.414
G_b		1.033	1.035	1.035
G_{sb}	2.833	2.739	2.523	2.521
G_{se}		2.787	2.591	2.584
Dust Proportion		0.9	1.1	1.4
TSR		93.1	87.4	99.5
Mix Temp (F)		325	310	310
Comp Temp (F)		310	295	295

^amixes were compacted to 65 gyrations to achieve design air voids

^bmixes were compacted to 50 gyrations to achieve design air voids

Figure 1. - Gradation for Mix 1

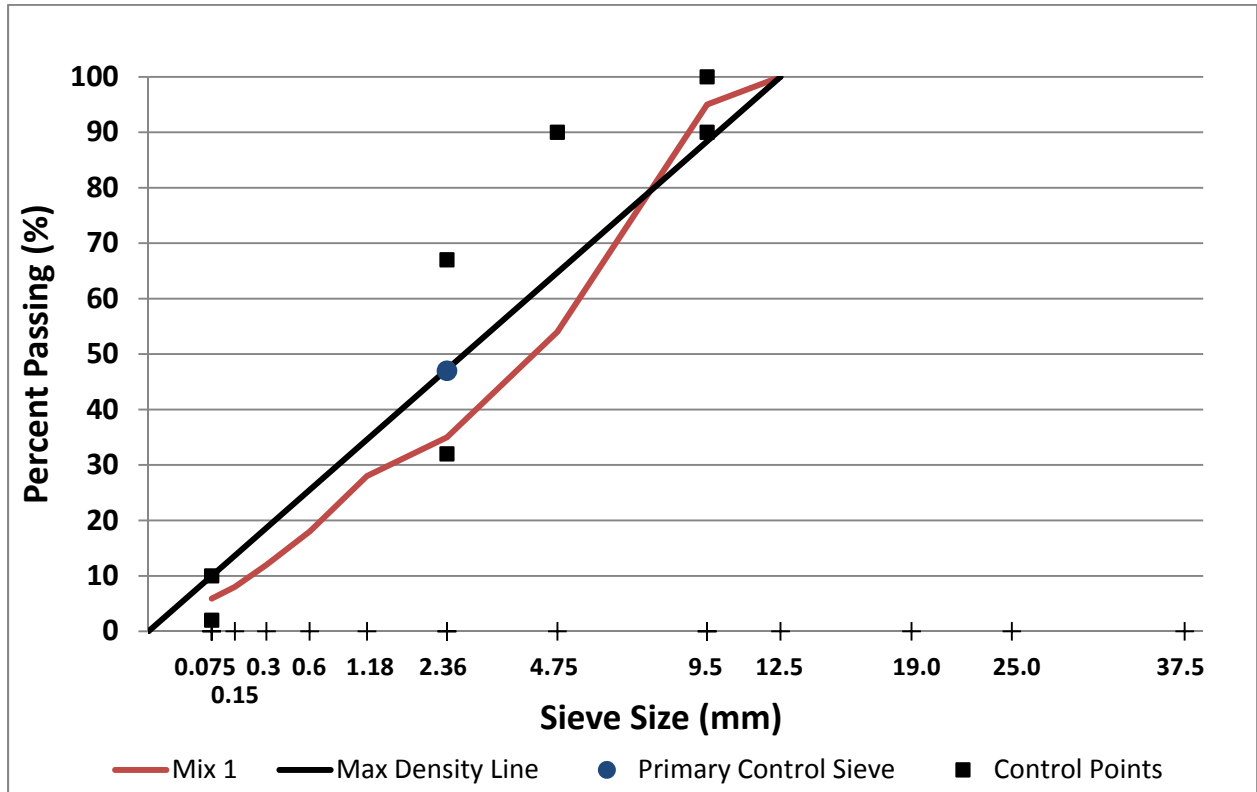


Figure 2. - Gradation for Mix 2

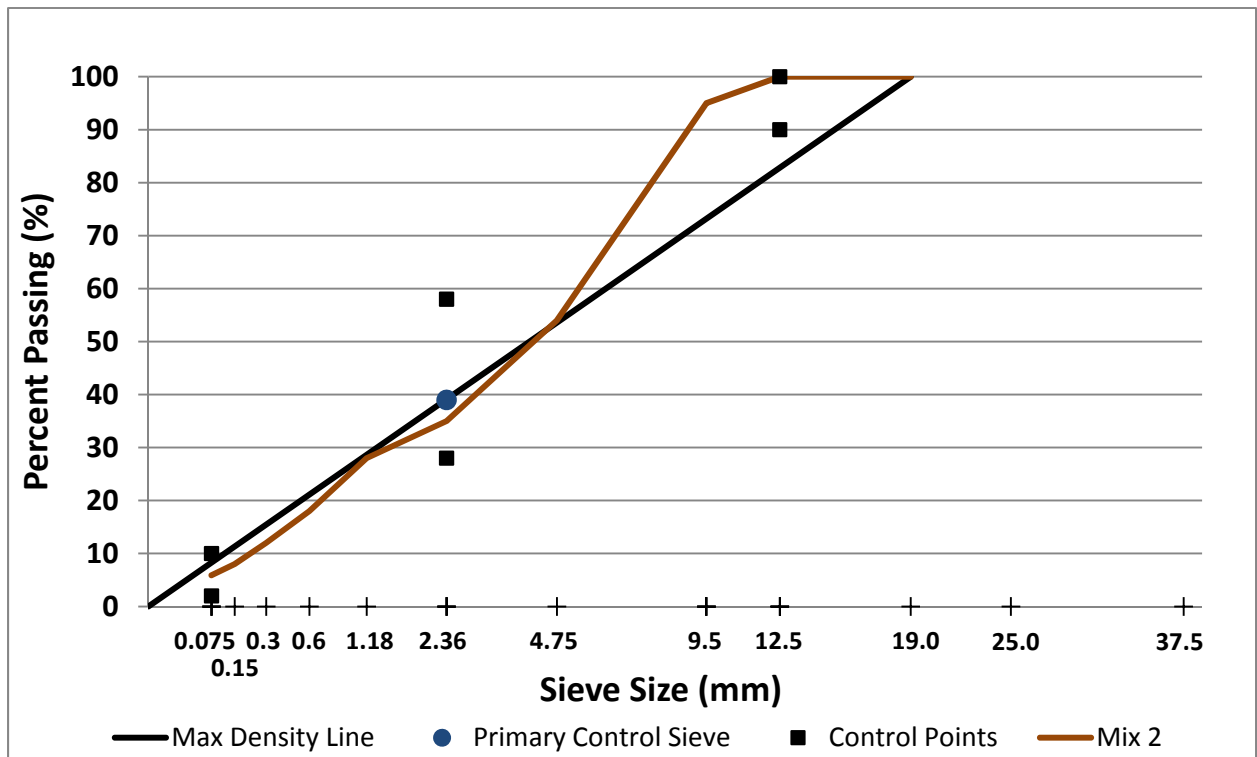


Figure 3. - Gradation for Mix 3

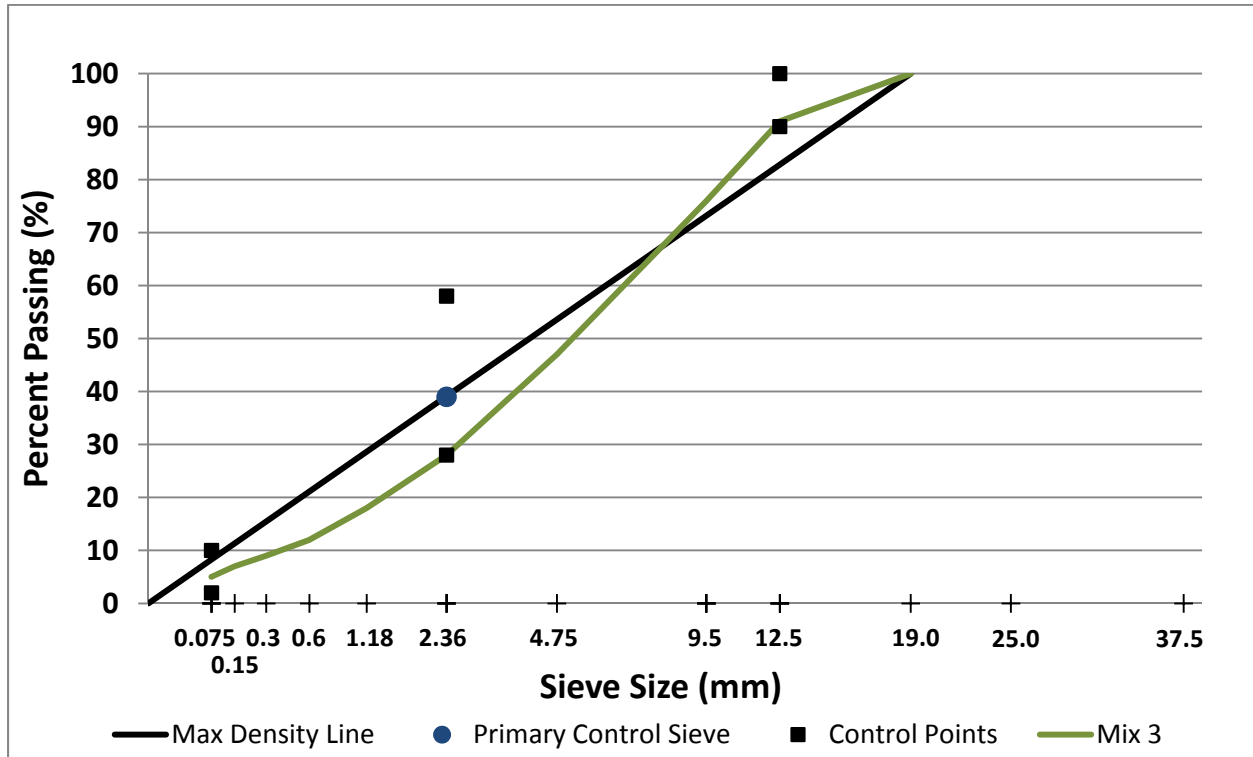
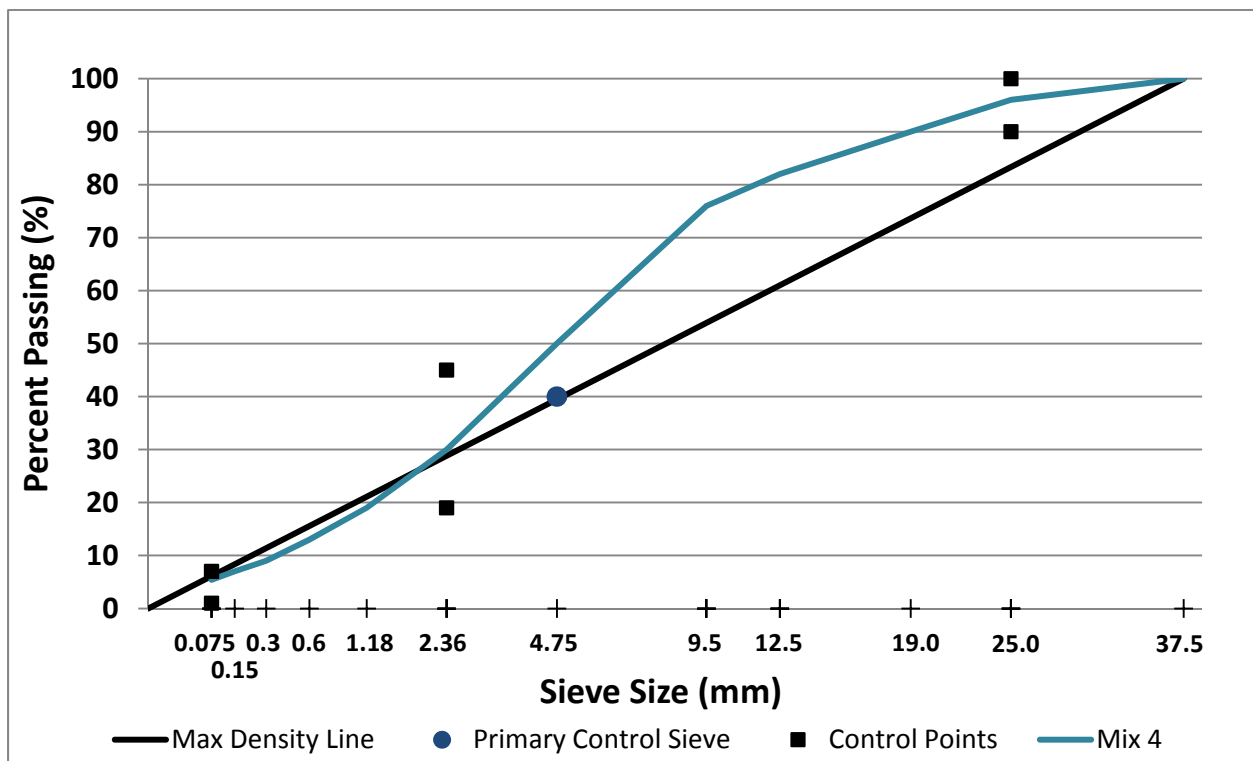


Figure 4. - Gradation for Mix 4



CALIBRATION OF SUPERPAVE GYRATORY COMPACTORS

Prior to performing the evaluation study, each Superpave gyratory compactor used in the effort was inspected, serviced, and calibrated by a technician from Pine Instrument Company, Inc. In addition, the internal angle of gyration was checked at the start of each period in which the compactor was to be used. The internal angle of gyration was measured using a Rapid Angle Measurement (RAM) device in accordance with AASHTO TP71.

Table 8 summarizes measurements of the internal angle of gyration recorded during the study. It is noted that all measured angles are within the specification 1.16 ± 0.02 degrees, in accordance with AASHTO T312.

Table 8. -- Internal Angle Measurements

	Compactor:	Pine AFG2	Pine AFG125x	Pine AFG1	Pine AFGB1
Mix 1	Top 1	1.16	1.13	1.17	1.16
	Top 2	1.16	1.12	1.18	1.16
	Bottom 1	1.14	1.15	1.18	1.17
	Bottom 2	1.15	1.15	1.19	1.16
	Avg DIA^a	1.153	1.138	1.180	1.163
Mix 2	Top 1	1.16	1.16	1.17	1.16
	Top 2	1.16	1.14	1.16	1.16
	Bottom 1	1.15	1.15	1.16	1.17
	Bottom 2	1.15	1.15	1.18	1.17
	Avg DIA^a	1.155	1.150	1.168	1.165
Mix 3	Top 1	1.17	1.16	1.17	1.16
	Top 2	1.16	1.14	1.16	1.16
	Bottom 1	1.16	1.15	1.16	1.17
	Bottom 2	1.15	1.15	1.17	1.15
	Avg DIA^a	1.160	1.150	1.165	1.160
Mix 4	Top 1	1.16	1.15	1.16	1.17
	Top 2	1.16	1.13	1.17	1.16
	Bottom 1	1.15	1.16	1.17	1.16
	Bottom 2	1.15	1.16	1.18	1.16
	Avg DIA^a	1.155	1.150	1.170	1.163

^aDynamic Internal Angle



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November 3, 2009

Mr. Roger A. Pyle
Pine Instrument Co
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Dear Mr. Pyle:

As requested, I have reviewed the recent report on the *Evaluation of Pine AFG2 Superpave Gyrotory Compactor* prepared by Dr. Kevin D. Hall. In my judgment, this is a fair and accurate comparison of the AFG2 gyrotory to the original Pine gyrotory compactor (AFG1) as well as the previously approved AFG125x and the AFGB1.

While the former AASHTO protocol PP35 was not followed exactly during this comparison, there were good reasons for the changes that were made. Since the pace of new SGCs coming onto the market has slowed dramatically from the early days, PP35 has been allowed to languish with no champion to keep it up to date and, in fact, has been withdrawn with no replacement. Therefore, PP35 references gyration levels that are no longer used, does not mention measuring the internal angle, uses a fixed compaction temperature, and requires compaction to N_{max} rather than N_{des} . Dr. Hall has appropriately taken all of these changes in the mix design process and standards into account in his conduct of this comparison. In addition, when PP35 was originally developed and used, variability between samples was a much greater issue than it is now, so six replicates were required. Use of the internal angle and increased familiarity with the gyrotory itself have contributed to a reduction in variability. Also, Dr. Hall compared the candidate gyrotory to three other gyrotories while PP35 required comparison to only one referee gyrotory. Comparing the candidate SGC to three other SGCs strengthened the comparison, in my opinion, therefore, I am comfortable with Dr. Hall's use of three to five samples per mix per compactor. Dr. Hall used different mix sizes than specified in PP35, but he actually used a greater range of mixes than that specified, which is again an improvement over the old protocol. Dr. Hall very scrupulously detailed his suitable deviations from the protocol. In all other ways, he complied fully.

In summary have reviewed the conduct of the comparison, the computations and the and data analysis.. I fully concur with the findings.

Sincerely,

A handwritten signature in cursive script that reads "Rebecca S. McDaniel".

Rebecca S. McDaniel
Technical Director