

## CHAPTER 5: EFFECT OF COMPACTION METHOD ON RUTTING SUSCEPTIBILITY

### 1. Background and Objectives

Tables 47 and 59 showed that the data from the ALF and many of the mixture tests provided identical rankings for the five surface mixtures based on the average values, but different statistical rankings based on Fisher's LSD. However, tables 47, 48, 59, and 64 showed that the discrepancies for the five surface mixtures were not as significant as the discrepancies concerning nominal maximum aggregate size. Because of this, it was decided to determine if the method of compaction, mainly laboratory vs. field compaction, could affect the relative laboratory-determined rutting susceptibilities of the surface and base mixtures with AC-5 and AC-20 (PG 59 and 70).<sup>(31,32)</sup>

Table 77 provides rankings for the laboratory mixture tests and a ranking for ALF pavement performance based on the log wheel passes at a 20-mm rut depth. The ALF pavement ranking was provided by tests on lanes 9, 10, 11, and 12. This ranking represents long-term pavement performance. The rankings for the laboratory tests were previously reported in tables 48 and 64.

A second method of ranking the mixtures, based on the rut depths at 2,730 ALF wheel passes, was also used because mixtures tested by the laboratory wheel-tracking devices are evaluated at specified wheel passes. The rut depths at 2,730 ALF wheel passes were evaluated because this number of wheel passes provided a 20-mm rut depth in the asphalt pavement layer with the AC-20 (PG 70) surface mixture. The AC-20 (PG 70) surface mixture was considered the control mixture and a rut depth of 20 mm was defined as the failure level. (Note: A failure level of 15 mm provided the same ranking as a failure level of 20 mm.) The rut depth of 35 mm for the AC-5 (PG 59) surface mixture in table 77 was obtained through extrapolation.

As discussed in chapter 2, the problem encountered when evaluating the mixtures at a constant number of ALF wheel passes was that either excessive extrapolations had to be performed to obtain the rut depths for pavements that failed quickly, or the pavements had to be compared at wheel passes that were low relative to the lives of longest lasting pavements. Statistical rankings for the four mixtures based on the rut depths at 2,730 wheel passes are given in table 78. The validity of both ranking methods is questionable because the variances were not equal. The heterogeneity of the variances and the closeness of the average rut depths for the two base mixtures at 2,730 wheel passes significantly affected the rankings. Because of this, the rankings shown in table 78 were not used. Instead, the rutting performance of each base mixture relative to the surface mixture having the same binder grade was evaluated using a *t*-test at a 95-percent confidence level.

Both methods for defining ALF pavement performance provided the same conclusion: each base mixture had a significantly lower susceptibility to rutting compared with its associated surface mixture. Table 77 shows

that none of the wheel-tracking devices or the SST measurements duplicated this finding.

This study included two potentially confounding factors. All specimens prepared in the laboratory for all mixture tests were short-term oven aged for 2 h at 135 °C. However, the pavement slabs and beams tested by the wheel-tracking devices were taken after the pavements had been inservice for approximately 2 years. The cores to be tested by the SST were taken when the pavements were approximately 3.5 years old. Therefore, there were differences in the degree of age hardening. Furthermore, the level and variability of the air voids for the pavement specimens could not be controlled to the degree they were controlled in the laboratory.

## 2. French PRT

The slabs previously tested by the French PRT, as discussed in chapter 4, had been compacted using the French Plate Compactor. To determine the effect of compaction method on the data from the French PRT, mixtures were compacted in the laboratory using a SLAB-PAC™ Linear Kneading Compactor. This compactor was purchased after the original tests were performed. To use the Linear Kneading Compactor, vertically aligned steel plates are placed on top of the mixture. A steel roller then transmits a rolling action force through the steel plates, one plate at a time. The mixture is kneaded and compressed into a flat slab of predetermined thickness and density. The compactor is illustrated in figure 63, and additional information is included in appendix A. Slabs were also cut from the ALF pavements, thereby providing three compaction methods. All slabs prepared in the laboratory were tested 3 to 5 days after fabrication. A minimum of two replicate slabs was tested per mixture and compaction method. It was hypothesized that the data from the pavement slabs should correlate best with ALF pavement performance if the method of compaction does affect rutting susceptibility.

The rut depths from the French PRT are presented in table 79. The results of *t*-tests performed on the data at 30,000 cycles are presented in table 80. These comparisons show whether a change from a surface mixture gradation to a base mixture gradation would either decrease (D), increase (I), or not significantly (NS) affect rutting susceptibility.

The test results using slabs compacted by the French Plate Compactor and the Linear Kneading Compactor did not agree with each other. These data are labeled data set #1 in table 80. Because the data did not agree, and the tests on slabs compacted by the French Plate Compactor were performed 2 years prior to the tests on slabs compacted by the Linear Kneading Compactor, it was decided to retest the mixtures using new slabs. The tests on slabs compacted by the Linear Kneading Compactor were also repeated even though the data for this compactor were new data. The data from the second set of tests are labeled data set #2 in table 80.

Table 77. Statistical rankings for the surface and base mixtures based on rutting susceptibility.<sup>1</sup>

ALF Pavement Performance at 58 °C							
Ranking Based on ALF Wheel Passes at a Rut Depth of 20 mm		ALF Wheel Passes at a Rut Depth of 20 mm	Rut Depth at 2,730 ALF Wheel Passes, mm	French PRT	Georgia LWT	Hamburg WTD	
AC-20 Base	A	57,520	12	AB	A	B	
AC-5 Base	B	11,990	14	C	AB	C	
AC-20 Surface	C	2,730	20	A	A	A	
AC-5 Surface	D	670	35	B	B	C	

		Simple Shear at Constant Height and 40 °C			Repeated Shear at Constant Height and 40 °C	
Ranking Based on ALF Wheel Passes at a Rut Depth of 20 mm		Compliance Parameter	Permanent Shear Strain	Maximum Axial Stress	Slope of Permanent Strain	Cumulative Permanent Strain at 5,000 Cycles
AC-20 Base	A	A	A	A	A	A
AC-5 Base	B	BC	BC	A	A	A
AC-20 Surface	C	AB	B	A	A	A
AC-5 Surface	D	C	C	B	B	B

Frequency Sweep at Constant Height and 40 °C							
Ranking Based on ALF Wheel Passes at a Rut Depth of 20 mm		Log Shear Modulus, G*, at 10.0 Hz	Log Shear Modulus, G*, at 2.0 Hz	Log G*/sinδ at 10.0 Hz	Log G*/sinδ at 2.0 Hz	Slope of Log G* vs. Log Frequency	
AC-20 Base	A	A	A	A	A	B	
AC-5 Base	B	C	B	C	B	A	
AC-20 Surface	C	B	A	B	A	AB	
AC-5 Surface	D	D	C	D	C	A	

<sup>1</sup>The letters are the statistical ranking, with "A" denoting the mixture(s) with the lowest susceptibility to rutting.

Table 78. Statistical rankings for the surface and base mixtures.

Mixture Type	Average Rut Depth at 2,730 Wheel Passes, mm	Ranking by Fisher's LSD	Ranking <sup>1</sup> Based on Rut Depth $\pm 2\sigma_{(n-1)}$
AC-20 Base	12	A	A
AC-5 Base	15	A	AB
AC-20 Surface	20	A	B
AC-5 Surface	35	B	C

<sup>1</sup>The rut depths of the mixtures are not significantly different if their  $\pm 2\sigma_{(n-1)}$  confidence limits overlap.

Table 79. Rut depths (mm) from the French PRT at 60 °C (data set #2).

Cycles	AC-20 Surface Mixture			AC-20 Base Mixture		
	French Plate Compactor	Linear Kneading Compactor	Pavement Slab	French Plate Compactor	Linear Kneading Compactor	Pavement Slab
300	3.0	2.2	6.3	2.3	1.6	3.9
1,000	3.8	3.0	8.4	2.9	2.2	5.3
3,000	5.1	4.2	10.9	3.4	3.1	6.6
10,000	7.6	6.9	13.9	4.5	4.2	8.7
30,000	10.2	10.7	17.5	6.3	5.9	10.6
Air Voids, %	6.3	7.2	11.3	7.6	7.4	8.9
Cycles	AC-5 Surface Mixture			AC-5 Base Mixture		
	French Plate Compactor	Linear Kneading Compactor	Pavement Slab	French Plate Compactor	Linear Kneading Compactor	Pavement Slab
300	3.7	3.5	5.3	2.5	3.1	4.6
1,000	5.0	5.8	6.7	3.9	5.2	6.1
3,000	6.9	8.9	8.8	6.2	9.2	7.8
10,000	12.0	16.8	11.7	10.4	16.8	10.5
30,000	>20	>20	17.6	>20	>20	13.3
Air Voids, %	8.0	6.9	9.9	6.2	7.1	9.3

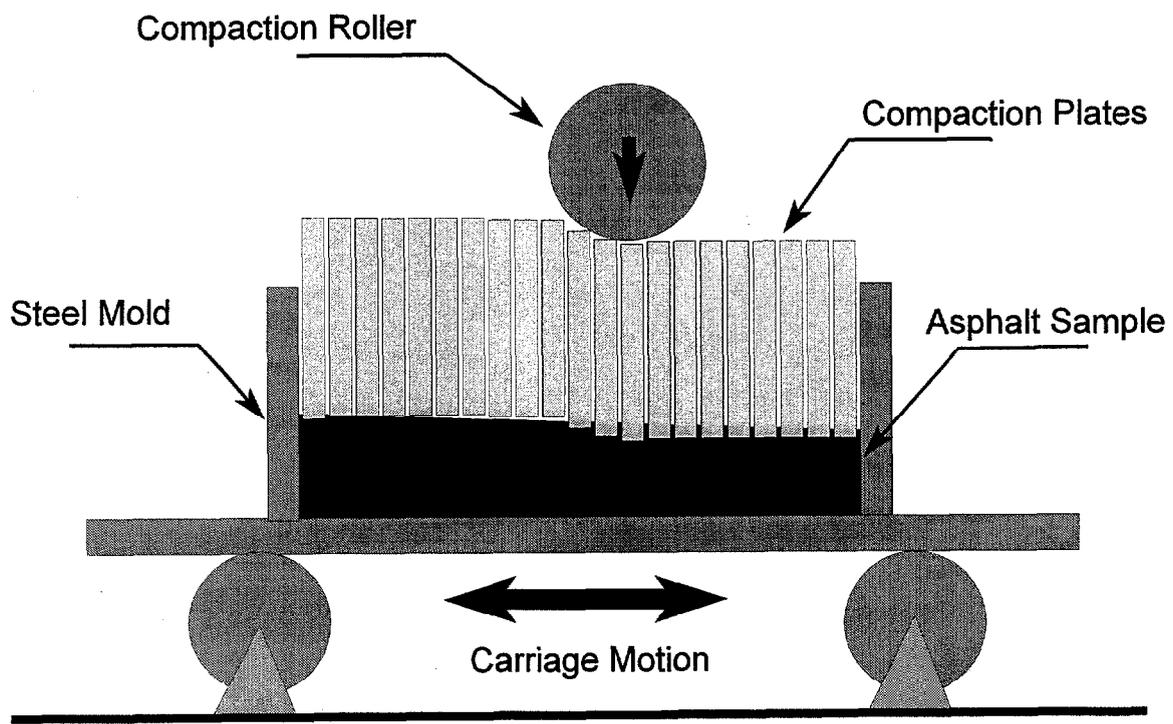


Figure 63. Linear compression provided by the linear kneading compactor.

Table 80. Results from the French PRT at 60 °C and 30,000 cycles.

Mix Type, Data Set	Rut Depth at 30,000 Cycles, mm			ALF Pavement Rut Depth at 2,730 Passes, mm
	French Plate Compactor	Linear Kneading Compactor	Pavement Slabs	
AC-20 Base #1	10.9 <i>NS</i>	9.4 <i>D</i>		
AC-20 Surface #1	6.4	14.0		
AC-20 Base #2	6.3 <i>NS</i>	5.9 <i>D</i>	10.6 <i>D</i>	12 <i>D</i>
AC-20 Surface #2	10.2	10.7	17.5	20
AC-5 Base #1	>20.0 <sup>1</sup>	>20.0 <sup>1</sup>		
AC-5 Surface #1	15.5 <sup>1</sup>	>20.0 <sup>1</sup>		
AC-5 Base #2	>20.0 <sup>1</sup>	>20.0 <sup>1</sup>	13.3 <i>NS</i>	14 <i>D</i>
AC-5 Surface #2	>20.0 <sup>1</sup>	>20.0 <sup>1</sup>	17.6	35

<sup>1</sup>These data could not be statistically analyzed.  
*NS* = Not Significant, and *D* = Decrease.

Table 81. Results from the French PRT at 60 °C and 10,000 cycles.

Mix Type, Data Set	Rut Depth at 10,000 Cycles, mm			ALF Pavement Rut Depth at 2,730 Passes, mm
	French Plate Compactor	Linear Kneading Compactor	Pavement Slabs	
AC-20 Base #1	6.2 <i>NS</i>	6.8 <i>D</i>		
AC-20 Surface #1	4.9	9.0		
AC-20 Base #2	4.5 <i>NS</i>	4.2 <i>D</i>	8.7 <i>D</i>	12 <i>D</i>
AC-20 Surface #2	7.6	6.9	13.9	20
AC-5 Base #1	16.0 <i>NS</i>	>19.0 <sup>1</sup>		
AC-5 Surface #1	8.2	>18.0 <sup>1</sup>		
AC-5 Base #2	10.4 <i>NS</i>	16.8 <i>NS</i>	10.5 <i>NS</i>	14 <i>D</i>
AC-5 Surface #2	12.0	16.8	11.7	35

<sup>1</sup>These data could not be statistically analyzed.  
*NS* = Not Significant, and *D* = Decrease.

Data set #1 shows that the AC-20 (PG 70) surface mixture compacted by the French Plate Compactor had a lower average rut depth than the AC-20 (PG 70) base mixture, while data set #2 shows the reverse. Even so, the pairs of rut depths in either data set were not significantly different. The rut depths for data set #2 using the Linear Kneading Compactor were more than 3 mm lower than those for data set #1 for the AC-20 (PG 70) mixtures. These findings suggested that changes of this magnitude may be typical with the current equipment and laboratory procedures, and further investigations on this subject are needed. The data also showed the importance of using statistical analyses. Conclusions based only on average values could be misleading.

The difference in rut depth provided by the ALF at 2,730 wheel passes was 8 mm (20 mm minus 12 mm) for the mixtures with AC-20 (PG 70). Rutting susceptibility significantly decreased with an increase in nominal maximum aggregate size. Data set #2 showed that the differences provided by the pavement slabs, slabs compacted by the Linear Kneading Compactor, and slabs compacted by the French Plate Compactor were 6.9, 4.8, and 3.9 mm, respectively, but the difference of 3.9 mm provided by the French Plate Compactor was not statistically significant.

In an attempt to increase the difference in rut depth for slabs compacted by the Linear Kneading Compactor, additional slabs were compacted in two layers. This modification decreased the difference from 4.8 to 2.8 mm. The AC-20 (PG 70) surface mixture had a rut depth of 10.5 mm, while the AC-20 (PG 70) base mixture had a rut depth of 7.7 mm. These rut depths were not significantly different.

Most of the rut depths for the two AC-5 (PG 59) mixtures compacted by either laboratory compactor were so deep that they exceeded the range of the measuring device. The laboratory data did not show a decrease in rutting susceptibility with an increase in nominal maximum aggregate size. The AC-5 (PG 59) base mixture did have a lower rut depth than the AC-5 (PG 59) surface mixture for tests performed on pavement slabs, but the difference of 4.3 mm (17.6 mm minus 13.3 mm) was not statistically significant and was not close to the 21-mm difference provided by the ALF.

It was decided to evaluate the data at 10,000 cycles because the data for the AC-5 (PG 59) mixtures at 30,000 cycles could not be statistically analyzed. The data are given in table 81. Only the pavement slabs with AC-20 (PG 70) provided a decrease in rutting susceptibility with an increase in nominal maximum aggregate size. Analyzing the data at 10,000 cycles did not improve the ability of the test to match ALF pavement performance.

Data sets #1 and #2 in table 80 show that the AC-20 (PG 70) surface mixture exceeded the 10-mm maximum allowable rut depth in four of five tests using the French PRT, although the rut depths from two of the failing tests were close to 10 mm. The AC-20 (PG 70) base mixture passed and failed the 10-mm specification depending on the compaction method. All mixtures with AC-5 (PG 59) failed the specification. The AC-5 (PG 59) base mixture was

not inhibited from shearing laterally and upward as expected, and there was no evidence that the AC-20 (PG 70) base mixture was inhibited from shearing either.

In summary, the rut depths from the French PRT at 10,000 and 30,000 cycles for the AC-5 (PG 59) surface and base mixtures did not provide a statistically significant decrease in rutting susceptibility with increased nominal maximum aggregate size. This was found for all three compaction methods: French Plate Compactor, Linear Kneading Compactor, and pavement slabs. However, the rut depths at 30,000 cycles for slabs compacted in the laboratory generally exceeded the measuring capability of the machine, which means that differences between the two mixtures could not be established. The rut depths for the AC-20 (PG 70) surface and base mixtures did provide a statistically significant decrease in rutting susceptibility with increased nominal maximum aggregate size when testing pavement slabs and slabs compacted by the Linear Kneading Compactor. A statistically significant decrease was not provided by slabs compacted by the French Plate Compactor.

### 3. Georgia LWT

All beams previously tested by the Georgia LWT had been compacted in two lifts using a vibratory tamper and a steel wheel roller. In this part of the study, beams were cut from the ALF pavements, thereby providing two compaction methods. All slabs prepared in the laboratory were tested 3 to 5 days after fabrication. A minimum of two replicate slabs was tested per mixture and compaction method.

The rut depths from the Georgia LWT are presented in table 82. Each base mixture had a lower average rut depth compared with its associated surface mixture for both compaction methods. However, the differences were not statistically significant and they did not match the large differences in performance provided by the ALF. All four mixtures met the 7.60-mm maximum allowable rut depth at 8,000 cycles as specified by the Georgia Department of Transportation.

### 4. Hamburg WTD

All slabs previously tested by the Hamburg WTD had been compacted in two lifts using a vibratory tamper and a steel wheel roller. In this part of the study, slabs were cut from the ALF pavements, thereby providing two compaction methods. All slabs prepared in the laboratory were tested 3 to 5 days after fabrication. A minimum of two replicate slabs was tested per mixture and compaction method.

The Hamburg WTD data are presented in table 83. Lower rut depths and higher creep slopes in terms of passes/mm indicate a greater resistance to rutting. Neither base mixture had a rut depth nor creep slope significantly different from its associated surface mixture when compacted by the vibratory hammer plus steel wheel roller method. Based on the average data from the pavement slabs, each base mixture performed better than its associated surface

mixture; however, the differences in the rut depths and creep slopes were only statistically significant for the AC-5 (PG 59) mixtures. The differences were not significant for the AC-20 (PG 70) mixtures.

Because of the large differences in the data provided by the pavement slabs and the slabs compacted by the vibratory hammer plus steel wheel roller, it was decided to compact additional slabs using the Linear Kneading Compactor. As shown in table 83, the results from these slabs did not match the ALF results.

## 5. SST Using Specimens With a Diameter of 150 mm

All 150-mm-diameter cylindrical specimens tested by the SST were compacted using the Superpave Gyrotory Compactor and sawed to obtain specimens with a height of 50 or 75 mm. While the Superpave Gyrotory Compactor was developed to simulate the kneading action of rollers in the field, molding specimens to fit a 150-mm-diameter mold can cause uneven aggregate distributions at the edges of the specimen. The aggregates at the edges tend to conform to the curved shape of the cylindrical mold.

In this part of the study, 150-mm-diameter cores were taken from the pavements and from slabs made in the laboratory using the Linear Kneading Compactor. The height of each specimen was 50 mm. Each slab compacted by the Linear Kneading Compactor provided two cores. The target air-void level for the laboratory prepared slabs was  $7 \pm 0.5$  percent.

The following tests at 40 °C were evaluated:

- Simple Shear at Constant Height (Simple Shear).
  - Compliance parameter (maximum strain/applied stress).
  - Permanent shear strain after unloading.
  - Maximum axial stress.
- Frequency Sweep at Constant Height (Frequency Sweep)
  - Complex shear modulus,  $G^*$ , at 10.0 Hz.
  - $G^*/\sin\delta$  of the mixtures at 10.0 Hz.
  - Slope of  $\log G^*$  vs.  $\log$  frequency.
- Repeated Shear at Constant Height (Repeated Shear).
  - Slope of cumulative permanent shear strain vs. cycles.
  - Cumulative permanent shear strain at 5,000 cycles (load repetitions).

The SST data are given in tables 84 and 85. The air voids for the pavement cores, shown in table 84, provided a confounding effect. The air voids of the base mixtures were lower than for their associated surface mixture.

Table 82. Results from the Georgia LWT at 40 °C.

Mixture Type	Vibratory Hammer- Steel Wheel Roller		Pavement Beams		ALF Pavement Rut Depth at 2,730 Passes, mm
	Rut Depth at 8,000 Cycles, mm	Percent Air Voids	Rut Depth at 8,000 Cycles, mm	Percent Air Voids	
AC-20 Base	3.5 <i>NS</i>	7.7	2.1 <i>NS</i>	6.7	12 <i>D</i>
AC-20 Surface	3.7	7.1	2.7	9.1	20
AC-5 Base	6.3 <i>NS</i>	7.0	3.5 <i>NS</i>	8.8	14 <i>D</i>
AC-5 Surface	7.4	7.1	3.9	6.8	35

*NS* = Not Significant.

*D* = Decrease.

Table 83. Results from the Hamburg WTD at 50 °C.

Mixture Type	Vibratory Hammer-Steel Wheel Roller			Pavement Slabs		
	Rut Depth, 20,000 Passes, mm	Creep Slope Passes/mm	Percent Air Voids	Rut Depth, 20,000 Passes, mm	Creep Slope Passes/mm	Percent Air Voids
AC-20 Base	8.6 <i>NS</i>	3 780 <i>NS</i>	7.0	4.3 <i>NS</i>	11 300 <i>NS</i>	7.7
AC-20 Surface	8.5	6 220	7.1	6.3	7 340	5.6
AC-5 Base	>25	470 <i>NS</i>	6.3	9.1 <i>D</i>	4 100 <i>I</i>	6.5
AC-5 Surface	>25	300	7.3	21.9	1 340	8.6

Mixture Type	Linear Kneading Compactor			ALF Pavement Rut Depth at 2,730 Passes, mm
	Rut Depth, 20,000 Passes, mm	Creep Slope, Passes/mm	Percent Air Voids	
AC-20 Base	5.0 <i>NS</i>	8 700 <i>NS</i>	7.4	12 <i>D</i>
AC-20 Surface	7.5	5 150	6.9	20
AC-5 Base	>25	470 <i>NS</i>	7.1	14 <i>D</i>
AC-5 Surface	>25	630	6.8	35

*NS* = Not Significant; *D* = Decrease, and *I* = Increase.

Table 84. Average percent air voids of the specimens tested by the SST.

Mixture Type	Superpave Gyratory Compactor	Linear Kneading Compactor	Cores
AC-20 Base	7.3	6.6	5.8
AC-20 Surface	7.2	6.8	8.3
AC-5 Base	7.6	6.3	4.6
AC-5 Surface	6.9	7.0	7.3

Table 85. SST data at 40 °C.

Simple Shear at Constant Height									
Mixture Type	Compliance Parameter, 1/MPa			Permanent Shear Strain, 10 <sup>-6</sup> mm/mm			Maximum Axial Stress, kPa		
	SGC	LKC	CORE	SGC	LKC	CORE	SGC	LKC	CORE
AC-20 Base	0.490 <i>NS</i>	0.317 <i>NS</i>	0.170 <i>NS</i>	9370 <i>D</i>	5900 <i>NS</i>	3900 <i>NS</i>	29.5 <i>NS</i>	32.5 <i>NS</i>	13.1 <i>NS</i>
AC-20 Surface	0.702	0.520	0.274	19200	13300	7900	28.9	31.2	16.8
AC-5 Base	0.794 <i>NS</i>	0.738 <i>NS</i>	0.396 <i>NS</i>	23000 <i>NS</i>	18100 <i>NS</i>	10200 <i>NS</i>	31.6 <i>D</i>	32.8 <i>NS</i>	19.7 <i>D</i>
AC-5 Surface	1.030	0.913	0.490	25500	25400	14800	48.5	34.6	29.7

Frequency Sweep at Constant Height									
Mixture Type	Shear Modulus, G*, at 10.0 Hz, MPa			G*/sinδ at 10.0 Hz, MPa			Slope of Log G* vs. Log Frequency		
	SGC	LKC	CORE	SGC	LKC	CORE	SGC	LKC	CORE
AC-20 Base	291 <i>NS</i>	270 <i>I</i>	502 <i>I</i>	353 <i>I</i>	338 <i>I</i>	772 <i>NS</i>	0.44 <i>I</i>	0.33 <i>NS</i>	0.35 <i>D</i>
AC-20 Surface	222	214	350	256	266	523	0.35	0.31	0.36
AC-5 Base	93 <i>I</i>	99 <i>NS</i>	213 <i>NS</i>	113 <i>I</i>	124 <i>NS</i>	293 <i>NS</i>	0.27 <i>D</i>	0.18 <i>NS</i>	0.26 <i>NS</i>
AC-5 Surface	62	100	136	71	140	182	0.31	0.14	0.27

Notes: SGC = Superpave Gyrotory Compactor.  
 LKC = Linear Kneading Compactor.  
 CORE = Pavement Core.

*NS* = Not Significant.  
*D* = Decrease.  
*I* = Increase.

AC-20 = PG 70.  
 AC-5 = PG 59.

Table 85. SST data at 40 °C (continued).

Repeated Shear at Constant Height						
Mixture Type	Slope of Cumulative Permanent Strain			Cumulative Permanent Strain at 5,000 Cycles, 10 <sup>-6</sup> mm/mm		
	SGC	LKC	CORE	SGC	LKC	CORE
AC-20 Base	0.30 <i>NS</i>	0.27 <i>NS</i>	0.44 <i>D</i>	9640 <i>D</i>	1410 <i>NS</i>	2890 <i>NS</i>
AC-20 Surface	0.35	0.35	0.49	14820	4280	5080
AC-5 Base	0.45 <i>I</i>	0.41 <i>NS</i>	0.37 <i>NS</i>	14460 <i>NS</i>	8800 <i>D</i>	4190 <i>NS</i>
AC-5 Surface	0.35	0.43	0.39	22200	16150	9380

Notes: SGC = Superpave Gyrotory Compactor.  
 LKC = Linear Kneading Compactor.  
 CORE = Pavement Core.

*NS* = Not Significant.  
*D* = Decrease.  
*I* = Increase.

AC-20 = PG 70.  
 AC-5 = PG 59.

Table 85 shows that the average Simple Shear compliance parameters provided by the base mixtures were lower than the average compliance parameters provided by the surface mixtures in all six comparisons; however, none of them was statistically significant. The average permanent shear strains provided by the base mixtures were also lower in all six comparisons, with only one effect being statistically significant. The average maximum axial stresses provided by the base mixtures were lower in four out of six comparisons, with two effects being statistically significant. Compaction method had little to no effect on the statistical results, although the data for the pavement cores were lower than for the laboratory compacted specimens. The latter result was expected because of the difference in the degree of aging between the pavement cores and the specimens prepared in the laboratory.

The average shear moduli from Frequency Sweep provided by the base mixtures were higher in five out of six comparisons, with three effects being statistically significant. The average  $G^*/\sin\delta$ 's provided by the base mixtures were also higher in five out of six comparisons, with three effects being statistically significant. The average slopes provided mixed results. The base mixtures provided higher slopes in some comparisons and lower slopes in other comparisons. Compaction method had little to no effect on the statistical results, although the  $G^*$ 's and  $G^*/\sin\delta$ 's for the pavement cores were higher than those provided by the laboratory compacted specimens. Again, the latter result was expected based on the difference in the degree of aging.

The average slopes from Repeated Shear provided by the base mixtures were lower in five of six comparisons, but only one of these five comparisons was statistically significant. The slope was significantly higher for the base mixture in one comparison where the Superpave Gyrotory Compactor was used. The average cumulative permanent strains provided by the base mixtures were lower in all six comparisons, with two being statistically significant.

Although some of the data provided trends that matched ALF pavement performance, for example, the lower permanent strains generally provided by the base mixtures relative to their associated surface mixture, none of the compaction methods was clearly better than the others based on ALF pavement rutting performance. The lower air-void levels for the cores from the base mixture pavements appeared to have little to no effect on the statistical results.

## 6. All Tests

The data from all four mixtures were evaluated as a group using analyses of variance and Fisher's LSD at a 95-percent confidence level. ALF pavement performance was based on the log wheel passes needed to obtain a rut depth of 20 mm. Tables 86 and 87 show the rankings for the wheel-tracking devices based on the averages and Fisher's LSD, respectively. Table 86 shows that only the pavement slabs tested by the French PRT ranked the mixtures the same as ALF based on the averages. Table 87 shows that none of the statistical rankings agreed with ALF pavement performance.

as ALF based on the averages. Table 87 shows that none of the statistical rankings agreed with ALF pavement performance.

Three-way analyses of variance, using binder grade, aggregate gradation, and compaction method as the independent variables, showed that the data from all three wheel-tracking devices were significantly affected by binder grade and compaction method but not by aggregate gradation. The results are given in table 88. The rut depths from the French PRT and Georgia LWT provided an interaction between binder grade and compaction method, while the slopes from the Hamburg WTD provided an interaction between aggregate gradation and compaction method. The French PRT analysis included extrapolated data for tests that exceeded the measurement capability of the machine. If these data were to be excluded, then none of the data from the AC-5 (PG 59) surface mixtures could be used in the analysis. Thus, the effect of binder grade could not be evaluated. An analysis of variance that excluded binder grade showed that both aggregate gradation and compaction method affected the rut depths from the French PRT, but the data in table 80 indicate that binder grade had a greater effect on the rut depths than aggregate gradation.

Table 89 shows the characteristics of the ALF and the laboratory wheel-tracking tests. The numerous differences make it difficult to determine why the rankings provided by the wheel-tracking devices did not match the ranking provided by the ALF. Besides the characteristics shown in table 89, there are other differences such as the sizes of the slabs tested in the laboratory, the type of confinement (steel vs. an actual pavement), and the state of stress.

It was hypothesized that contact area may be one reason for the discrepancies. The contact area for the ALF was much greater than for the French PRT, Hamburg WTD, and Georgia LWT. The larger aggregates may be more difficult to displace laterally under the ALF tire due to the relatively large tire width of 320 mm. The characteristics of the PURwheel are included in table 89. The contact area for this device was between the contact areas for the ALF and the other three wheel-tracking devices. The PURwheel was able to measure the effect of nominal maximum aggregate size but not binder grade. The characteristics shown in table 89 provided no obvious reason for the discrepancies between the machines.

Table 90 provides the rankings for the SST measurements based on the averages. The only measurement that ranked the mixtures the same as ALF was the cumulative permanent strain at 5,000 cycles from Repeated Shear using cores. However, the statistical ranking for this data, which is included in table 90, did not agree with ALF pavement performance.

The results from three-way analyses of variance at a 95-percent confidence level are included in table 88. Only the slope from Repeated Shear was not affected by binder grade, and only the cumulative permanent strain at 5,000 cycles from Repeated Shear was not affected by compaction method. Gradation affected (1) the compliance parameter and permanent shear strain from Simple Shear, (2) cumulative permanent strain at 5,000 cycles from Repeated Shear,

and (3)  $G^*$  and  $G^*/\sin\delta$  from Frequency Sweep. However, the effect of gradation on the SST measurements was relatively small compared with the effect of gradation on ALF rutting performance.

## 7. SST Using Pavement Cores With a Diameter of 203 mm

Cores with a diameter of 203 mm were extracted from the pavements to determine if the use of a larger diameter would improve the degree of correlation between the data from the SST and ALF pavement rutting performance. Specimens with a height of 75 mm were used when testing the two base mixtures, while specimens with a height of 50 mm were used when testing the two surface mixtures. The pavements with the surface mixtures were compacted in four 50-mm lifts. Therefore, the specimens would include a weak shear plane if a height of 75 mm were to be used instead of 50 mm. The base mixtures were compacted in two 100-mm lifts.

The cores were tested using Frequency Sweep at 40 and 58 °C, and Repeated Shear at 58 °C. The data are given in table 91. Based on the results presented in chapter 4, the hypothesis applied to the slopes from Frequency Sweep was that a higher slope indicates lower rutting susceptibility. Tables 91 and 92 show that the tests using the larger diameter pavement cores provided good correlations to ALF pavement performance. The correlations were the best found in this study for any test. Only the slopes from Repeated Shear had no correlation to ALF pavement performance.

Table 93 provides the high-temperature continuous PG's for the four pavements. The PG's for the AC-5 (PG 59) cores from lanes 9 and 11 differed by 4, 4, and 10 °C in 1994, 1995, and 1998, respectively. The PG's for the AC-20 (PG 70) cores from lanes 10 and 12 differed by 6 °C in 1994. The data indicate that the amount of age hardening was greater in the base mixtures. The short-term oven aging period of 2 h was based on the PG's of the binders recovered in 1993. At that time, there were no differences in the amount of aging between lanes 9 and 11, and lanes 10 and 12. Age hardening was a confounding factor in this study.

The SST results in chapter 4 showed that the tests were generally sensitive to changes in binder grade; therefore, it was hypothesized that age hardening was one of the main reasons for the better SST results using the larger diameter cores. These cores were taken from the pavements in 1998. Table 90 shows that the 150- by 50-mm pavement cores did not provide data that correlated with ALF pavement performance except for the average cumulative permanent strains from Repeated Shear. These cores were taken from the pavements in 1996. The results for the larger diameter cores could be a function of differences in both aging and specimen size. The French PRT using pavement slabs was the only other test where the average data provided a ranking that was the same as ALF. The slabs for these tests were taken in 1995.

## 8. Conclusions

- The ALF provided significant decreases in rutting susceptibility with increased nominal maximum aggregate size and the associated 0.85-percent decrease in optimum binder content. The AC-20 (PG 70) base mixture performed significantly better than the AC-20 (PG 70) surface mixture, and the AC-5 (PG 59) base mixture performed significantly better than the AC-5 (PG 59) surface mixture.
- The effect of aggregate gradation on ALF pavement rutting performance was not duplicated by the laboratory mixture tests, except for the SST using 203-mm-diameter pavement cores and the PURwheel using slabs cut from the pavements. However, the PURwheel did not measure the effect of binder grade.
- The rutting performance of each base mixture provided by the French PRT, Georgia LWT, and Hamburg WTD, relative to the surface mixture having the same grade of binder, varied from test to test and with compaction method. Overall, the data from these devices correlated poorly with ALF pavement rutting performance in terms of measuring the effect of gradation and the associated change in binder content. The data showed that the method of compaction can affect the results from these devices, but it was not the main reason why the devices were insensitive to gradation. It was hypothesized that differences in contact area may be one reason for the discrepancy, but a firm reason was not found.
- The SST using specimens with a diameter and height of 150 by 50 mm provided the same conclusions as the wheel-tracking devices. The average cumulative permanent strains from Repeated Shear using pavement cores was the only measurement that provided a ranking that agreed with ALF pavement rutting performance. Even so, these strains were not significantly different based on statistical analyses.
- Pavement cores with a diameter of 203 mm provided good correlations between the SST and ALF pavement rutting performance. The correlations were the best found in this study for any test. However, the binders in the various pavements age hardened to different degrees over time and these cores were taken near the end of the study. Based on recovered binder properties, it was hypothesized that the differences in age hardening was one of the main reasons for the better SST results using the larger cores. Specimen size could be another reason.

Table 86. Non-statistical rankings for the four mixtures based on the wheel-tracking devices.<sup>1</sup>

ALF Performance		French PRT, Rut Depth at 30,000 Cycles			Georgia LWT, Rut Depth at 8,000 Cycles	
Log ALF Wheel Passes at a Rut Depth of 20 mm		French Plate Compactor	Linear Kneading Compactor	Pavement Slabs	Vibratory-Steel Wheel Roller	Pavement Beams
AC-20 Base	A	A	A	A	A	A
AC-5 Base	B	C	C	B	C	C
AC-20 Surface	C	B	B	C	B	B
AC-5 Surface	D	C	C	D	D	D

ALF Performance		Hamburg WTD, Creep Slope		
Log ALF Wheel Passes at a Rut Depth of 20 mm		Vibratory-Steel Wheel Roller	Linear Kneading Compactor	Pavement Slabs
AC-20 Base	A	B	A	A
AC-5 Base	B	C	D	C
AC-20 Surface	C	A	B	B
AC-5 Surface	D	D	C	D

<sup>1</sup>The letters are the ranking based on the averages with "A" denoting the mixture with the lowest susceptibility to rutting.

Table 87. Statistical rankings for the four mixtures based on the wheel-tracking devices.<sup>1</sup>

ALF Performance	French PRT, Rut Depth at 30,000 Cycles			Georgia LWT, Rut Depth at 8,000 Cycles	
	French Plate Compactor	Linear Kneading Compactor	Pavement Slabs	Vibratory-Steel Wheel Roller	Pavement Beams
Log ALF Wheel Passes at a Rut Depth of 20 mm					
AC-20 Base A	A	A	A	A	A
AC-5 Base B	NA <sup>2</sup>	NA <sup>3</sup>	AB	AB	BC
AC-20 Surface C	A	B	B	A	AB
AC-5 Surface D	NA <sup>2</sup>	NA <sup>3</sup>	B	B	C

ALF Performance	Hamburg WTD, Creep Slope		
	Vibratory-Steel Wheel Roller	Linear Kneading Compactor	Pavement Slabs
Log ALF Wheel Passes at a Rut Depth of 20 mm			
AC-20 Base A	B	A	A
AC-5 Base B	C	B	BC
AC-20 Surface C	A	A	B
AC-5 Surface D	C	B	C

<sup>1</sup>The letters are the statistical ranking, with "A" denoting the mixture(s) with the lowest susceptibility to rutting.

<sup>2</sup>Not Applicable. The data could not be evaluated using statistics because the rut depths from some of the tests exceeded the measurement capabilities of the equipment. The data could be assigned the letter "B" if desired.

<sup>3</sup>Not Applicable. The data could not be evaluated using statistics because the rut depths from some of the tests exceeded the measurement capabilities of the equipment. The data could be assigned the letter "C" if desired.

Table 88. Significant factors provided by three-way analyses of variance.

French PRT, Rut Depth at 60 °C		Georgia LWT, Rut Depth at 40 °C		Hamburg WTD, Slope at 50 °C	
Binder Compaction Binder*Comp		Binder Compaction Binder*Comp		Binder Compaction Grad*Comp	
Simple Shear at Constant Height and 40 °C			Repeated Shear at Constant Height and 40 °C		
Compliance Parameter	Permanent Shear Strain	Maximum Axial Stress	Slope of Permanent Strain	Cumulative Permanent Strain at 5,000 Cycles	
Binder Gradation Compaction	Binder Gradation Compaction Binder*Comp	Binder Compaction	Compaction Binder*Comp	Binder Gradation	
Frequency Sweep at Constant Height and 40 °C					
Shear Modulus, G*, at 10.0 Hz	Shear Modulus, G*, at 2.0 Hz	G*/sinδ at 10.0 Hz	G*/sinδ at 2.0 Hz	Slope of Log G* vs. Log Frequency	
Binder Gradation Compaction	Binder Gradation Compaction Binder*Comp	Binder Gradation Compaction Binder*Comp	Binder Gradation Compaction Binder*Comp Grad*Comp	Binder Compaction Binder*Comp	

Independent Variables:

Binder = Binder Grade  
 Gradation or Grad = Aggregate Gradation  
 Compaction or Comp = Compaction Method

Table 89. Characteristics of the ALF and wheel-tracking tests.

	Thickness of Slab, mm	Load, N	Stress, MPa	Contact Area, mm <sup>2</sup>	Speed, km/h	Test Temp, °C
ALF	200	44 500	0.690	64 500	18.0	58
PURWheel	76	1 530	0.62	20 640	1.2	58
French PRT	100	5 000	0.57	8 770	7.0	60
Hamburg WTD	80	660	0.73	900 <sup>1</sup>	1.1	50
Georgia LWT	80	700	1.0	700 <sup>1</sup>	2.0	40

<sup>1</sup>Maximum contact area; the contact area increases during the test and can vary from mixture to mixture.

Table 90. Non-statistical rankings for the four mixtures based on the SST at 40 °C.<sup>1</sup>

				Simple Shear at Constant Height and 40 °C								
				Compliance Parameter			Permanent Shear Strain			Maximum Axial Stress		
ALF at 58 °C				SGC	LKC	CORE	SGC	LKC	CORE	SGC	LKC	CORE
AC-20	Base	A		A	A	A	A	A	A	B	B	A
AC-5	Base	B		C	C	C	C	C	C	C	C	C
AC-20	Surface	C		B	B	B	B	B	B	A	A	B
AC-5	Surface	D		D	D	D	D	D	D	D	D	D

				Frequency Sweep at Constant Height and 40 °C								
				Shear Modulus, G* at 10.0 Hz			G*/sinδ at 10.0 Hz			Slope of Log G* vs. Log Frequency		
ALF at 58 °C				SGC	LKC	CORE	SGC	LKC	CORE	SGC	LKC	CORE
AC-20	Base	A		A	A	A	A	A	A	A	A	B
AC-5	Base	B		C	C	C	C	D	C	D	C	D
AC-20	Surface	C		B	B	B	B	B	B	B	B	A
AC-5	Surface	D		D	D	D	D	C	D	C	D	C

				Repeated Shear at Constant Height and 40 °C									
				Slope of Cumulative Permanent Strain			Cumulative Permanent Strain at 5,000 Cycles						
							Non-statistical Rankings			Statistical Rankings			
ALF at 58 °C				SGC	LKC	CORE	SGC	LKC	CORE	SGC	CORE		
AC-20	Base	A		C	A	B	A	A	A	A	A	A	
AC-5	Base	B		A	C	D	B	C	B	A	A	A	
AC-20	Surface	C		B	B	A	C	B	C	A	AB		
AC-5	Surface	D		B	D	C	D	D	D	B	B		

<sup>1</sup>The letters are the ranking, with "A" denoting the mixture(s) with the lowest susceptibility to rutting.

Table 91. SST results using pavement cores with a diameter of 203 mm and a height of 50 mm for surface mixtures and 75 mm for base mixtures.

Frequency Sweep at Constant Height and 40 °C					
ALF Ranking at 58 °C and a 20-mm Rut Depth		Shear Modulus <sup>1</sup> G*, at 10.0 Hz, MPa	Shear Modulus <sup>1</sup> G*, at 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency	
AC-20 Base	A	715 A	347 A	0.47	A
AC-5 Base	B	385 B	191 B	0.42	B
AC-20 Surface	C	286 B	141 B	0.42	B
AC-5 Surface	D	85 C	40 C	0.35	C

Frequency Sweep at Constant Height and 58 °C					
ALF Ranking at 58 °C and a 20-mm Rut Depth		Shear Modulus G*, at 10.0 Hz, MPa	Shear Modulus G*, at 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency	
AC-20 Base	A	161 A	73 A	0.34	A
AC-5 Base	B	79 B	43 B	0.22	B
AC-20 Surface	C	56 C	33 C	0.20	B
AC-5 Surface	D	27 D	20 D	0.12	C

Repeated Shear at Constant Height and 58 °C					
ALF Ranking at 58 °C and a 20-mm Rut Depth		Slope of Cumulative Permanent Strain	Cumulative Permanent Strain at 5,000 Cycles, <sup>1</sup> 10 <sup>-6</sup> mm/mm		
AC-20 Base	A	0.44 A	4 320	A	
AC-5 Base	B	0.45 A	5 360	A	
AC-20 Surface	C	0.43 A	14 400	B	
AC-5 Surface	D	0.47 A	28 000	C	

<sup>1</sup>Statistical ranking is based on log<sub>10</sub> of the value.

Table 92. Effect of specimen size and type on the SST results.

Frequency Sweep at Constant Height and 40 °C Shear Modulus, G*, at 10.0 Hz, MPa												
ALF Ranking at 58 °C and a 20-mm Rut Depth			Pavement Core D = 203 mm H = 75 mm <sup>1</sup>		Pavement Core D = 150 mm H = 50 mm		Gyratory Testing Machine D = 203 mm H = 75 mm		Superpave Gyratory Compactor D = 150 mm H = 75 mm		Superpave Gyratory Compactor D = 150 mm H = 50 mm	
AC-20	Base	A	715	A	502	A	265	A	279	A	291	A
AC-5	Base	B	385	B	213	C	119	C	85	C	93	C
AC-20	Surface	C	286	B	350	B	213	B	208	B	222	B
AC-5	Surface	D	85	C	136	D	92	D	61	D	62	D

Frequency Sweep at Constant Height and 58 °C Shear Modulus, G*, at 10.0 Hz, MPa										
ALF Ranking at 58 °C and a 20-mm Rut Depth			Pavement Core D = 203 mm H = 75 mm <sup>1</sup>		Gyratory Testing Machine D = 203 mm H = 75 mm		Superpave Gyratory Compactor D = 150 mm H = 75 mm		Superpave Gyratory Compactor D = 150 mm H = 50 mm	
AC-20	Base	A	161	A	55	A	69	A	95	A
AC-5	Base	B	79	B	34	C	48	B	74	A
AC-20	Surface	C	56	C	44	B	63	A	89	A
AC-5	Surface	D	27	D	34	C	60	A	71	A

Repeated Shear at Constant Height and 58 °C Cumulative Permanent Strain at 5,000 Cycles, 10 <sup>-6</sup> mm/mm										
ALF Ranking at 58 °C and a 20-mm Rut Depth			Pavement Core D = 203 mm H = 75 mm <sup>1</sup>		Gyratory Testing Machine D = 203 mm H = 75 mm		Superpave Gyratory Compactor D = 150 mm H = 75 mm		Superpave Gyratory Compactor D = 150 mm H = 50 mm	
AC-20	Base	A	4 320	A	Failed		Failed		34 020	
AC-5	Base	B	5 360	A	Failed		Failed		Failed	
AC-20	Surface	C	14 400	B	Failed		Failed		34 200	
AC-5	Surface	D	28 000	C	Failed		Failed		Failed	

<sup>1</sup>The height was 75 mm for the base mixtures and 50 mm for the surface mixtures.

Table 93. High-temperature continuous PG's at 10 rad/s for the binders used in the surface vs. base mixture study.

Mixture	Lane	PG of Neat Binder after RTFO	PG of Binder Recovered From Laboratory Mixtures After STOA	PG of Binder Recovered From Pavement Samples			
				1993	1994	1995	1998
AC-20 Base	12	70	67	68	78	NT	NT
AC-5 Base	11	59	61	60	67	72	74
AC-20 Surface	10	70	67	68	72	78	78
AC-5 Surface	9	59	61	59	63	68	64
				Fractional Difference in Asphalt Binder Grade Where 1.0 Indicates a Change of One PG $(\text{Pavement PG} - \text{Lab PG}) \div 6 \text{ } ^\circ\text{C}$			
AC-20 Base	12	-	67	0.2	1.8	-	-
AC-5 Base	11	-	61	-0.2	1.0	1.8	2.2
AC-20 Surface	10	-	67	0.2	0.8	1.8	1.8
AC-5 Surface	9	-	61	-0.3	0.3	1.2	0.5

NT = Not tested by the ALF in 1995 and 1998; therefore, there are no data.

STOA = After 2 h of short-term oven aging.