CHAPTER 4: VALIDATION OF LABORATORY MIXTURE TESTS FOR RUTTING SUSCEPTIBILITY

1. Mixture Tests Evaluated

ALF pavement performance was used to validate a variety of asphalt mixture tests used to predict rutting. Pavement performance was defined as the number of wheel passes required to obtain a rut depth of 20 mm in the asphalt pavement layer at 58 °C. Rut depth was defined as the downward distance from the original surface elevation of the pavement. This rut depth does not include any uplift outside of the wheelpath due to shearing. This rut depth was chosen because the laboratory wheel-tracking devices only measure the downward rut depth. The following tests were evaluated using practices and temperatures that were recommended at the time of testing:

- Marshall Stability and Flow at 60 °C.

- U.S. Corps of Engineers Gyratory Testing Machine (GTM) at 60 °C.
    - Maximum Static Shear Strength (Sg).
    - Gyratory Stability Index (GSI).
    - Gyratory Elasto-Plastic Index (GEPI).
    - Refusal Air-Void Level.

- French Pavement Rutting Tester (French PRT) at 60 °C.
    - Percent Rut Depth at 30,000 Cycles (60,000 Wheel Passes).
    - Slope of Log Rut Depth vs. Log Cycles Relationship.

- Georgia Loaded-Wheel Tester (Georgia LWT) at 40 °C.
    - Rut Depth at 8,000 Cycles (16,000 Wheel Passes).

- Hamburg Wheel-Tracking Device (Hamburg WTD) at 50 °C.
    - Rut Depth at 10,000 and 20,000 Wheel Passes.
    - Creep Slope.

- Asphalt-Aggregate Mixture Analysis System (AAMAS) at 40 °C.
    - Unconfined Compressive Strength Test.
    - Unconfined Compressive Repeated Load Test.
    - Unconfined Compressive Creep Test.

- Repeated Load Compression Test at 40 °C.
    - Dynamic Modulus at 200 Cycles.
    - Cumulative Permanent Strain at 10,000 Cycles.
    - Slope from the Linear Portion of the Log Permanent Strain vs. Log Time Relationship.

- Superpave Shear Tester (SST) at 40 and 58 °C.
    - Simple Shear at Constant Height.
    - Frequency Sweep at Constant Height.
    - Repeated Shear at Constant Height.

The testing strategy was to use recommended test procedures and laboratory-prepared mixtures whose compositions met the overall average compositions of the mixtures in the pavements. Based on the results of these tests, it would be decided whether the test procedures, the compositions of the mixtures, or the degree of aging should be changed to better match the conditions for each individual ALF pavement test.

Binder contents of 4.85 and 4.00 percent by mass were used in the surface and base mixtures, respectively. The target air-void level was 8 ±1 percent, except for the Marshall tests. Specimens were tested 3 to 5 days after fabrication so that the amount of aging was consistent from test to test.

The mixtures were ranked according to their performance in each test based on the average data and Fisher's LSD, which is performed in conjunction with an analysis of variance at a 95-percent confidence level. Mixtures assigned the letter "A" were the least susceptible to rutting. When the variances could not be pooled because of heterogeneity, the statistical ranking was based on comparing averages with confidence limits provided by two standard deviations ($\mu \pm 2\sigma_{(n-1)}$) instead of Fisher's LSD. Linear and nonlinear regressions were also performed but were not used because the number of data points was generally insufficient for making valid conclusions.

2. Short-term Oven Aging Study

At the time of construction in 1993, Superpave recommended that loose mixtures in the mixture design process be oven aged for 4 h at 135 °C prior to compaction.(19) This procedure is called short-term oven aging (STOA). It reportedly produces an amount of aging that will occur somewhere between 6 and 24 months after construction. To better simulate the degree of aging that occurred during plant production of the mixtures used in this study, an STOA study was performed.

The STOA study consisted of aging laboratory mixtures in a forced draft oven at 135 °C for 0, 1, 2, and 4 h, recovering the binders, recovering binders from ALF pavement cores, performing Superpave tests on the recovered binders, and comparing the test results to determine the appropriate aging period. Three replicate samples were tested for each aging period. The mixtures chosen for this study were the surface mixture with AC-5 (PG 59), the base mixture with AC-5 (PG 59), and the surface mixture with AC-20 (PG 70). Cores were taken from four ALF pavements constructed with these mixtures, including two pavements with the AC-20 (PG 70) surface mixture as a check on pavement-to-pavement variability.

The recovered binders were tested using the DSR at 10, 30, 50, and 70 °C, Bending Beam Rheometer at -24 °C, and the Brookfield Viscometer at 135 °C. These tests were performed to fully examine the capability of simulating hot-mix plant aging using a forced draft oven, even though the pavements were only to be tested in the range of 10 to 76 °C. All three tests should provide the same aging period if oven aging duplicates plant aging and provides the same binder chemistry. The three tests were also chosen because they should provide the effects of aging at low, intermediate, and high temperatures.

The recovered binder properties from the aged laboratory mixtures were plotted with respect to the aging period. A regression was performed to generate a second order polynomial equation. The aging periods needed to duplicate the properties of the binders in the ALF pavements were computed for each binder and test. The differences among the data for the two AC-20 (PG 70) pavements were not significant; thus, averaged data were evaluated.

The DSR data in table 44 indicated that the STOA period needed to simulate the degree of aging that occurred during hot-mix plant production and laydown should be from 0.3 to 2.5 h. The average period was 1.3 h. An evaluation of the creep stiffnesses from the Bending Beam Rheometer provided no definitive STOA period. The slopes from the Bending Beam Rheometer led to STOA periods of 3.0 to 4.0 h, but the changes in these slopes with aging period were low. The Brookfield Viscosities indicated that a STOA period of 2.3 h was needed for the AC-20 (PG 70) surface mixture. However, the AC-5 (PG 59) binders recovered from both laboratory mixtures were stiffer than the AC-5 (PG 59) binders recovered from the cores even at an STOA of 0 h.

Overall, the required oven aging period depended on the mixture type and the binder test performed. A previous National Cooperative Highway Research Program (NCHRP) study found that the absolute viscosity at 60 °C and penetration at 25 °C can also give different short-term oven-aging periods for a given mixture.(20) This indicates that oven aging may not accurately simulate hot-mix plant aging. An aging period of 2 h was chosen as a compromise. Therefore, STOA consisted of oven aging the loose mixtures at 135 °C for 2 h before compaction.

3. Marshall Stability and Flow

Table 8 in chapter 1 shows that all seven mixtures had Marshall stabilities greater than 11 000 N compared with the 8006-N minimum stability specified for heavy traffic pavements. The stabilities and flows did not discriminate the mixtures. The differences in these properties from mixture to mixture were relatively small compared with the variability of the replicate measurements.(11) Thus, the Marshall properties were eliminated from further consideration.

4. GTM

The shear susceptibilities of the mixtures were measured using the static shear strength (Sg), gyratory stability index (GSI), gyratory elasto-plastic index (GEPI), and refusal air-void levels provided by the GTM, Model 8A-6B-4C. The GTM is a combination compaction and plane strain shear testing machine that applies stresses simulating pavement conditions.

Table 44. Short-term oven aging study.

Binder/ Mixture Type	Laboratory Aging Period, h				Pavement Core Property	Required Hours of Lab Aging
	0	1	2	4		
Average G* from the Dynamic Shear Rheometer at 10.0 rad/s, Pa						
AC-5 Surface						
at 10 °C	2 974 000	2 682 000	4 192 000	4 422 000	3 181 000	1.3
at 30 °C	118 500	110 300	181 500	221 800	125 800	1.2
at 50 °C	7 062	6 798	10 930	14 760	7 319	1.1
at 70 °C	630	627	916	1 301	626	1.0
AC-5 Base						
at 10 °C	2 990 000	4 295 000	5 546 000	5 516 000	3 453 000	0.3
at 30 °C	97 360	152 900	211 900	246 100	144 600	0.7
at 50 °C	5 234	8 462	12 120	15 150	8 534	0.9
at 70 °C	464	726	1 038	1 284	709	0.8
AC-20 Surface						
at 10 °C	8 359 000	8 922 000	10 730 000	11 580 000	9 827 000	1.4
at 30 °C	302 800	372 900	423 600	585 300	455 800	2.4
at 50 °C	15 690	20 810	22 750	35 240	26 210	2.5
at 70 °C	1 160	1 549	1 650	2 526	1 868	2.4
Average Creep Stiffness, S, at 60 s and -24 °C Determined by the Bending Beam Rheometer, MPa						
AC-5 Surface	92	98	124	110	139	ND
AC-5 Base	139	183	218	206	165	0.6
AC-20 Surface	284	288	312	353	333	2.5
Average Slope, m, of Log Creep Stiffness vs. Log Time at 60 s and -24 °C Determined by the Bending Beam Rheometer						
AC-5 Surface	0.40	0.40	0.38	0.36	0.36	4.0
AC-5 Base	0.38	0.37	0.36	0.34	0.35	3.0
AC-20 Surface	0.33	0.31	0.31	0.29	0.30	3.0
Average Absolute Viscosity at 135 °C Determined by the Brookfield Viscometer, Pa-s						
AC-5 Surface	0.36	0.33	0.41	0.44	0.29	<0
AC-5 Base	0.34	0.49	0.65	0.64	0.31	<0
AC-20 Surface	0.45	0.51	0.52	0.63	0.55	2.3

ND = No data; a laboratory aging period could not be predicted from the data.
Note: AC-5 = PG 59 and AC-20 = PG 70

The GTM was operated in accordance with the AAMAS with one modification.(20) NCHRP AAMAS specified a 0.035-radian gyratory angle. An angle of 0.012 radian was used instead of 0.035 radian because FHWA studies on previous pavements tested by the ALF indicated that this angle provided closer agreements between the GTM refusal densities and the ultimate pavement densities. A 0.035-radian angle provided densities that were too high. The diameter and height of each specimen were 152.4 mm. A vertical pressure of 0.83 MPa and the GTM oil-filled roller were used. Tests were performed in triplicate. The NCHRP AAMAS procedure is based on ASTM Method D 3387.(6)

The GSI is the ratio of the maximum angle that occurs at the end of the test to the minimum intermediate angle. It is a measure of shear susceptibility at the refusal density. The minimum intermediate angle is the smallest angle that occurs after the compaction process has started. The GSI at 300 revolutions is close to 1.0 for a stable mixture and is significantly above 1.1 for an unstable mixture.(21) When designing a mixture, the manufacturer states that the optimum binder content should be less than the binder content where the GSI begins to exceed 1.0. The GSI and the Sg are the principal GTM parameters used to evaluate rutting susceptibility.

The GEPI is the ratio of the minimum intermediate angle to the initial machine angle set by the operator. A GEPI of 1.0 indicates high internal friction. A GEPI significantly above 1.0 indicates lower internal friction, generally resulting from the use of rounded aggregates or from moisture damage. The manufacturer suggests using an acceptable range of 1.0 to 1.5. Appendix A provides additional information on the GTM including a photograph of it.

The mixtures were first compacted to an 8 ±1-percent air-void level at 135 °C. They were cooled to 60 °C in an oven over a 3-h period and then compacted and tested until their refusal densities were reached. A trace of the gyratory angle vs. revolutions was obtained to determine the maximum and minimum intermediate angles.

The GTM data are given in table 45. There was very little variation in each parameter from mixture to mixture and no relationship to ALF pavement performance. The tests on the Novophalt surface mixture and AC-20 (PG 70) base mixture were repeated because they had GEPI's significantly less than 1.00, which is the minimum value that can theoretically be obtained. GEPI's below 1.00 were again obtained, and the refusal air voids were not the same as those provided by the original tests. The low GEPI's indicated a machine compliance problem. The GTM was eliminated from further consideration.

5. French PRT

a. Description of the Equipment

The French PRT tests a slab for permanent deformation at 60 °C using a smooth, pneumatic, rubber tire having a diameter of 415 mm and a width of 109 mm. The slabs were compacted by the French Plate Compactor, which is a rolling wheel compactor having the same type of tire as the French PRT. The slabs had a length of 500 mm, a width of 180 mm, and a thickness of 100 mm. The AC-5, AC-10, AC-20, Novophalt, and Styrelf surface mixtures had average air-void levels of 8.4, 7.1, 7.3, 8.1, and 8.4 percent, respectively.

The French PRT tests two slabs simultaneously using two reciprocating tires. The tires are inflated to 600 ±30 kPa. Each slab is confined in a steel mold that rests on a steel base plate. A hydraulic jack underneath the steel base plate pushes upward to provide a load of 5000 ±50 N. The rut depth in each slab is measured at 300, 1000, 3000, 10,000, and 30,000 cycles by averaging measurements taken at 15 standard positions. This rut depth is based on the initial surface elevation of a slab. It does not include any upward heaving outside the wheelpath. One cycle is defined as two passes of the wheel (back and forth). A mixture is acceptable in France if the average percent rut depth at 30,000 cycles is less than or equal to 10 percent of the slab thickness.

Slopes taken from log rut depth vs. log cycle plots can also be compared. Rut-susceptible mixtures generally have higher slopes, but there is no French specification on the slope. When comparing slopes from the French PRT with slopes provided by other tests, it must be remembered that the slopes from the French PRT may be based on cycles and not on passes.

French researchers state that the tester is not valid for mixtures with nominal maximum aggregate sizes greater than 20 mm. The slab width of 180 mm is relatively small compared with the tire width of 110 mm. A space of only 35 mm exists on each side of the slab between the tire and the steel mold. Therefore, mixtures with aggregates greater than 20 mm may be inhibited from shearing laterally and upward. The AC-5 and AC-20 (PG 59 and 70) base mixtures were tested in this study to confirm this principle. Both base mixtures had an average air-void level of 7.6 percent and a nominal maximum aggregate size of 37.5 mm. Appendix A provides additional information on the French PRT including a photograph of it.

b. Results From the French PRT

The French PRT data are given in table 46. The AC-5 and AC-10 (PG 59 and 65) surface mixtures and AC-5 and AC-20 (PG 59 and 70) base mixtures exceeded the 10-mm maximum allowable percent rut depth at 30,000 cycles; the other three surface mixtures met the French criteria. ALF pavement performance in terms of wheel passes and the percent rut depths from the French PRT are shown in figures 31 through 34. As the ALF wheel passes in figures 31 and 32 increase, the percent rut depths from the French PRT in figures 33 and 34 should decrease.

Tables 47 and 48 provide rankings based on the French PRT and ALF pavement performance. The rankings provided by the rut depths and slopes from the French PRT were identical; therefore, only one ranking is shown in each table. The ranking in table 47 shows that the French PRT correctly ranked the five

Table 45. Rutting performance based on the Gyratory Testing Machine (GTM) at 60 °C.

	Surface Mixture					Base Mixture	
Pre-Superpave:	AC-5	AC-10	AC-20	Novophalt	Styrelf	AC-5	AC-20
Superpave PG:	59	65	70	77	88	59	70
Sg, kPa	370	430	370	370	370	400	410
GSI	1.10	1.15	1.15	0.95	1.10	1.10	0.95
GEPI	1.00	1.05	0.90	0.80	0.95	0.95	0.65
Air Voids, %	2.1	2.0	3.3	5.9	6.0	4.2	5.5
Repeated GTM Tests							
Sg, kPa				430			380
GSI				1.00			1.10
GEPI				0.70			0.85
Air Voids, %				7.0			2.6

Table 46. Rutting performance based on the French PRT, Georgia LWT, and Hamburg WTD.

	Surface Mixture					Base Mixture	
Pre-Superpave:	AC-5	AC-10	AC-20	Novophalt	Styrelf	AC-5	AC-20
Superpave PG:	59	65	70	77	88	59	70
French PRT at 60 °C and 0.875 rad/s							
Cycles	Percent Rut Depth						
300	3.0	3.0	2.6	1.4	1.8	2.8	2.4
1,000	3.8	4.0	3.2	1.7	2.2	4.5	3.1
3,000	4.9	5.3	4.1	2.2	3.0	7.4	4.0
10,000	8.2	9.2	4.9	2.4	3.2	ND	6.2
30,000 (spec)	15.5	13.8	6.4	2.6	3.7	ND	10.9
Slope, Percent RD vs. Cycles	0.35	0.34	0.19	0.14	0.16	0.42	0.32
G*/sinδ, Pa	212	442	871	2 103	6 444	212	871
Georgia LWT at 40 °C, 0.125 rad/s, and 8,000 cycles							
Rut Depth, mm	7.4	5.4	3.7	1.4	1.9	6.3	3.5
G*/sinδ, Pa	899	2 215	5 060	10 350	21 120	899	5 060
Hamburg WTD at 50 °C and 0.125 rad/s							
RD at 10,000, mm	>30	22.8	6.8	1.4	2.6	24.6	4.9
RD at 20,000, mm	>30	>30	8.5	1.9	2.8	>30	8.6
Creep Slope	300	630	6 220	24 600	17 900	470	3 780
Visual Stripping, %	0	0	0	0	0	0	0
G*/sinδ, Pa	130	348	635	1 744	5 243	130	635

RD at 10,000 = Rut Depth at 10,000 Wheel Passes.
RD at 20,000 = Rut Depth at 20,000 Wheel Passes.
Creep Slope = Wheel Passes per 1-mm Rut Depth.

ND = No data because the mixture failed rapidly.

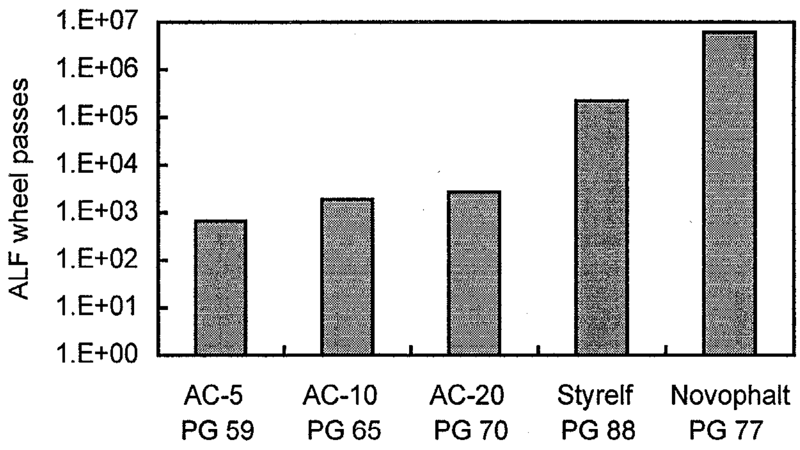

Figure 31. ALF wheel passes at a 20-mm rut depth vs. surface mixture.

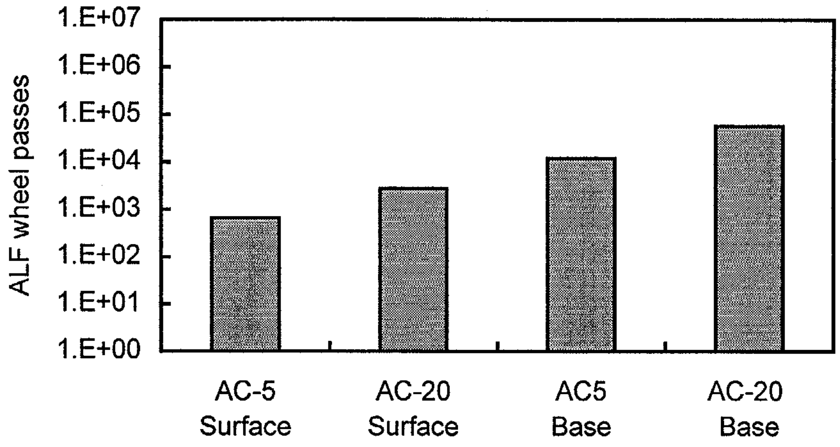

Figure 32. ALF wheel passes at a 20-mm rut depth vs. mixture type.

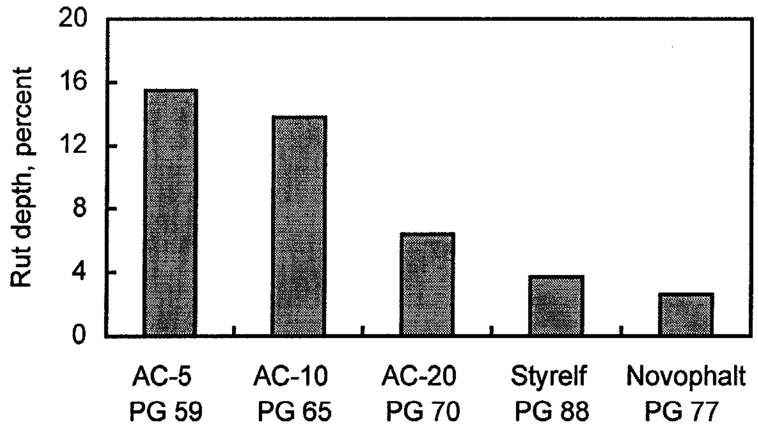

Figure 33. Percent rut depth from the French PRT vs. surface mixture.

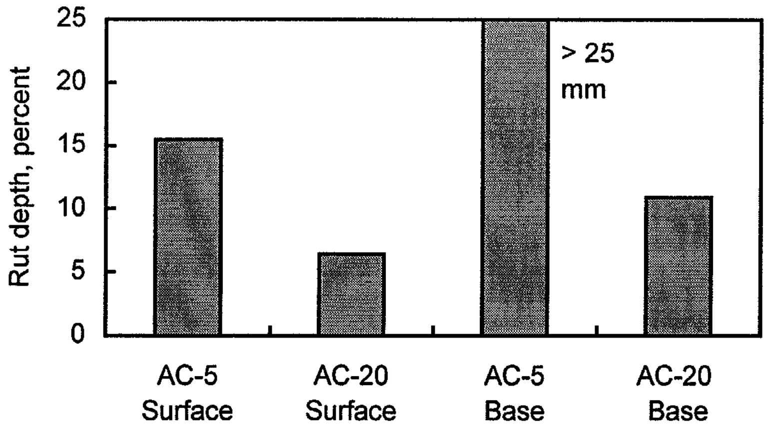

Figure 34. Percent rut depth from the French PRT vs. mixture type.

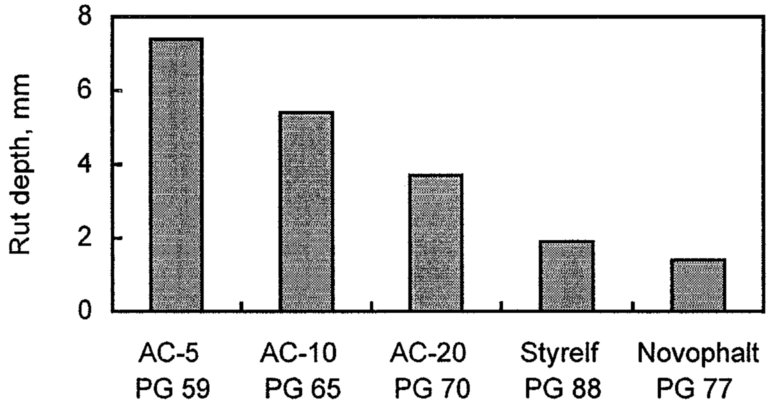

Figure 35. Rut depth from the Georgia LWT vs. surface mixture.

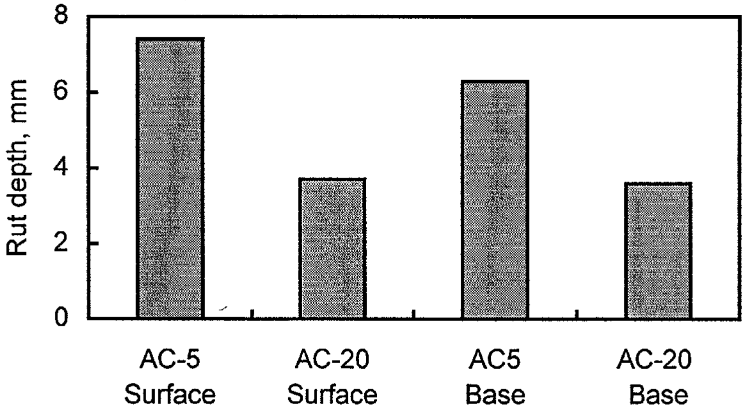

Figure 36. Rut depth from the Georgia LWT vs. mixture type.

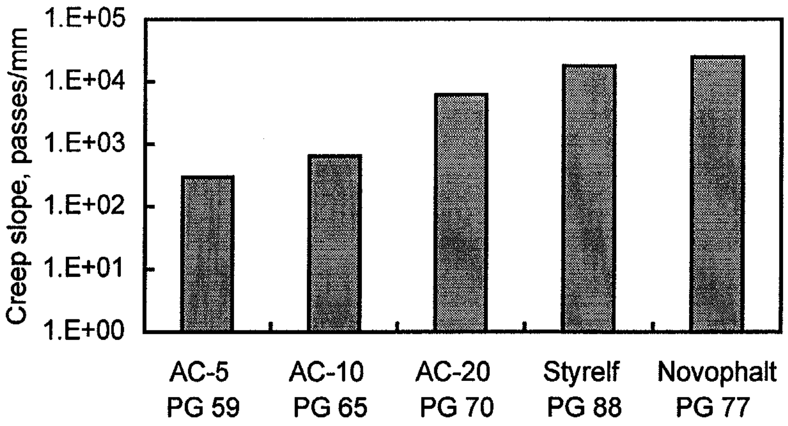

Figure 37. Creep slope from the Hamburg WTD vs. surface mixture.

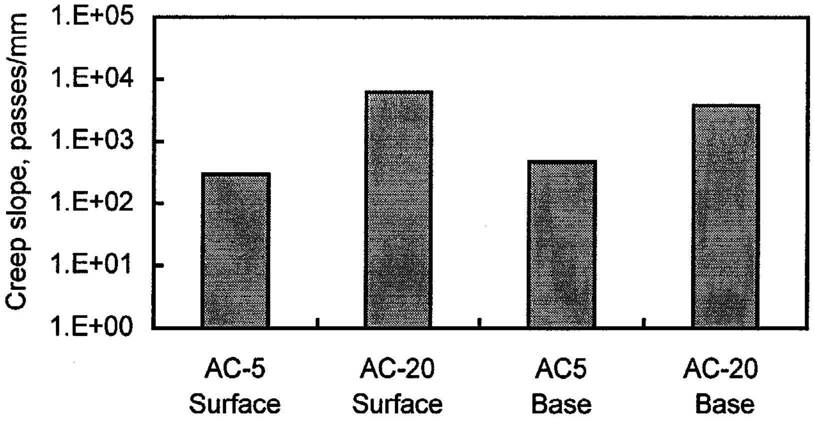

Figure 38. Creep slope from the Hamburg WTD vs. mixture type.

Table 47. Statistical rankings for the five surface mixtures provided by the ALF and the three wheel-tracking devices.[1]

ALF at 58 °C	French PRT at 60 °C	Georgia LWT at 40 °C	Hamburg WTD at 50 °C
(A) Novophalt	(A) Novophalt	(A) Novophalt	(-) Novophalt[2]
(B) Styrelf	(B) Styrelf	(B) Styrelf	(A) Styrelf
(C) AC-20	(C) AC-20	(BC) AC-20	(B) AC-20
(C) AC-10	(D) AC-10	(C) AC-10	(C) AC-10
(D) AC-5	(D) AC-5	(C) AC-5	(D) AC-5

[1] The letters are the statistical ranking, with "A" denoting the mixture with the lowest susceptibility to rutting.

[2] Not included in the statistical ranking because of high variability.

Table 48. Statistical rankings for the surface and base mixtures provided by the ALF and the three wheel-tracking devices.

ALF at 58 °C		French PRT at 60 °C	Georgia LWT at 40 °C	Hamburg WTD at 50 °C
AC-20 Base	A	AB	A	B
AC-5 Base	B	C	AB	C
AC-20 Surface	C	A	A	A
AC-5 Surface	D	B	B	C

Table 49. Slopes and intercepts provided by the ALF and the French PRT.

Ranking Based on Pavement Rut Depth at 58 °C	Slope		Intercept	
	ALF, 58 °C	French PRT, 60 °C	ALF, 58 °C	French PRT, 60 °C
Novophalt	0.23	0.13	0.6	0.7
Styrelf	0.21	0.15	1.6	0.8
AC-20 Base	0.18	0.39	2.9	0.2
AC-5 Base	0.27	0.43	1.6	0.2
AC-20	0.28	0.20	2.2	0.8
AC-10	0.41	0.37	0.9	0.3
AC-5	0.43	0.45	1.3	0.2

Table 50. Rutting Susceptibility Based Upon the French PRT at 60 °C.

	Surface Mixture					Base Mixture	
Pre-Superpave:	AC-5	AC-10	AC-20	Novophalt	Styrelf	AC-5	AC-20
Superpave PG:	59	65	70	77	88	59	70
Cycles	**Percent Rut Depth Using 100-mm Slabs, mm**						
300	3.0	3.0	2.6	1.4	1.8	2.8	2.4
1,000	3.8	4.0	3.2	1.7	2.2	4.5	3.1
3,000	4.9	5.3	4.1	2.2	3.0	7.4	4.0
10,000	8.2	9.2	4.9	2.4	3.2	ND	6.2
30,000 (spec)	15.5	13.8	6.4	2.6	3.7	ND	10.9
Cycles	**Percent Rut Depth Using 50-mm Slabs, mm**						
300	3.6	3.4	3.3	1.7	1.8	NT	NT
1,000	5.4	4.5	4.1	2.1	2.3		
3,000 (spec)	8.3	6.0	5.1	2.5	2.6		
10,000	ND	10.1	7.4	3.5	3.2		
30,000	ND	ND	11.2	4.4	4.0		
Ratio of the percent rut depth at 3,000 cycles using 50-mm slabs to the percent rut depth at 30,000 cycles using 100-mm slabs							
	0.5	0.4	0.8	1.0	0.7		
Cycles	Ratios of Rut Depths (50-mm data divided by 100-mm data)						
300	1.2	1.1	1.3	1.2	1.0		
1,000	1.4	1.1	1.3	1.3	1.0		
3,000	1.7	1.1	1.3	1.2	0.9		
10,000	ND	1.1	1.5	1.5	1.0		
30,000	ND	ND	1.8	1.7	1.1		

NT = Not tested because specimens could not be fabricated at this thickness.
ND = No data because the mixture failed rapidly.

surface mixtures based on the average data. The statistical rankings, shown by the letters A through D, were not identical, but they were reasonably close. (The variance for the AC-5 mixture was greater than the variances for the other mixtures. Therefore, the statistical ranking for the surface mixtures tested by the French PRT was based on $\mu \pm 2\sigma_{(n-1)}$.) The ranking provided by the French PRT in table 48 for the surface vs. base mixture study did not agree with ALF pavement performance. (Different presentation styles are used in tables 47 and 48; the style that best facilitated a visual comparison of the rankings was used.)

c. Comparison of the Rut Depths From the French PRT and ALF

The rut depths from the French PRT were significantly lower than those produced by the ALF at 58 °C at an equal number of wheel passes. (This was also found to be true for the Hamburg WTD and Georgia LWT.) For example, less than 1,000 ALF wheel passes at 58 °C were needed to provide rut depths in the five pavements with the surface mixtures equaling those provided by the French PRT at the end of the test. Table 49 shows that the slopes and intercepts from the rut depth curves provided by the French PRT and ALF were not the same. These data, which are regression coefficients, were obtained using the Gauss-Newton statistical method. The main discrepancies were provided by the two base mixtures. The differences in the slopes and intercepts indicate that trying to develop equations that predict pavement rut depths from the French PRT data is not possible. The slopes and intercepts provided by all of the ALF pavement tests are discussed in detail in chapter 3.

d. Comparison of French PRT Data Using 50- and 100-mm-Thick Slabs

A slab thickness of 100 mm is specified in the French method of analysis when the total pavement thickness for the mixture to be placed will be greater than 50 mm. (The mixture can be placed in more than one lift.) A 50-mm-thick slab is specified for mixtures that will be placed at a thickness equal to, or less, than 50 mm. The pavements in this study had a thickness of 200 mm; therefore, a slab thickness of 100 mm was used. However, it was decided to test the five surface mixtures using a thickness of 50 mm to determine the effect of slab thickness on rut depth. The AC-5, AC-10, AC-20, Novophalt, and Styrelf surface mixtures at this thickness had average air-void levels of 7.4, 7.2, 7.9, 8.3, and 8.1 percent, respectively. The AC-5 and AC-20 base mixtures were not tested due to its 37.5-mm nominal maximum aggregate size.

Rut depths are measured at 30, 100, 300, 1,000, and 3,000 cycles when testing 50-mm-thick slabs. The test normally ends at 3,000 cycles, whereas 30,000 cycles are applied when testing 100-mm-thick slabs. When testing 50-m-thick slabs, a mixture is acceptable according to the French procedure if the average rut depth at 1,000 is less than or equal to 5 mm and the average rut depth at 3,000 cycles is less than or equal to 10 mm. In this study, rut depths at 10,000 and 30,000 cycles were also measured when testing 50-mm-thick slabs in order to be consistent with the tests performed on 100-mm-thick slabs.

Table 50 shows the data at both thicknesses and the ratio of the percent rut depth at 3,000 cycles using 50-mm slabs to the percent rut depth at 30,000 cycles using 100-mm slabs. For example, the ratio for the AC-5 (PG 59) surface mixture was 0.5 (8.3 mm divided by 15.5 mm). The ratios were variable, indicating that the two methodologies could provide different conclusions concerning the rutting potential of a mixture. A ratio of 1.0 indicates that the two tests provided the same rut depth at the specified maximum numbers of cycles. Ratios less than 1.0 indicate that the test using thick slabs is a more severe test. Four out of five surface mixtures had ratios less than 1.0. This result is consistent with the French philosophy of allowing little to no rutting to occur in thick, lower pavement layers. The pass/fail criteria also reflect this philosophy. Using 100-mm-thick slabs, both the AC-5 (PG 59) and AC-10 (PG 65) surface mixtures exceeded the 10-mm maximum allowable rut depth at 30,000 cycles. Using 50-mm-thick slabs, only the AC-5 (PG 59) surface mixture exceeded the 5-mm maximum allowable rut depth at 1,000 cycles, and all five mixtures met the 10-mm requirement at 3,000 cycles.

Table 50 also gives the ratios of the rut depths at each number of cycles. A ratio of 1.0 indicates that the two tests provided the same rut depth. A ratio greater than 1.0 indicates that there was more rutting using 50-mm slabs compared with 100-mm slabs. The data show that the rut depths tended to be greater using 50-mm slabs at an equal number of wheel passes, even though the test was more lenient in terms of passing or failing a mixture.

6. Georgia LWT

a. Description of the Equipment

The Georgia LWT tests a beam for permanent deformation at 40 °C. The beams were sawed from slabs compacted using a vibratory tamper and a steel wheel roller. The beams had a length of 320 mm, a width of 120 mm, and a thickness of 80 mm. The AC-5, AC-10, AC-20, Novophalt, and Styrelf surface mixtures had average air-void levels of 7.0, 7.5, 7.1, 7.2, and 7.3 percent, respectively. The AC-5 and AC-20 (PG 59 and 70) base mixtures had average air-void levels of 7.0 and 7.7 percent. Air-void levels closer to the 8-percent target level were not obtainable. Attempts to increase the air-void levels led to increased porosity around the edges and sides of the slabs without a significant increase in air voids in the middle of the slabs.

Each beam is confined by steel plates during testing, except for the top 12.7 mm. A stiff rubber hose pressurized at 0.69 MPa with air is positioned across the top of the beam, and a loaded steel wheel runs back and forth on top of this hose for 8,000 cycles to create a rut. One cycle is defined as two passes of the wheel. The diameter of the hose is 29 mm, and the average load is 700 N.

Deformations are measured at three locations: at the center of the beam and 51 mm left and right of center in the longitudinal direction. The rut depth does not include any upward heaving outside the wheelpath. If the average rut depth exceeds 7.6 mm, the mixture is considered susceptible to rutting by the Georgia Department of Transportation.(22) Appendix A provides additional information on the Georgia LWT including a photograph of it. More advanced models are now being produced.

b. Results From the Georgia LWT

The data from the Georgia LWT are given in table 46. All mixtures met the Georgia Department of Transportation pass/fail specification. As the ALF wheel passes in figures 31 and 32 increase, the rut depths from the Georgia LWT in figures 35 and 36 should decrease.

Tables 47 and 48 provide rankings based on the Georgia LWT and ALF pavement performance. The ranking in table 47 shows that the Georgia LWT ranked the five surface mixtures correctly based on the average data, but the statistical ranking was not the same as ALF. (The variances for the rut depths from the Georgia LWT were not equal; therefore, the statistical ranking for the surface mixtures tested by the Georgia LWT was based on $\mu \pm 2\sigma_{(n-1)}$.) The ranking provided by the Georgia LWT in table 48 for the surface vs. base mixture study did not agree with ALF pavement performance.

7. Hamburg WTD

a. Description of the Equipment

The Hamburg WTD measures the combined effects of rutting and moisture damage by rolling a steel wheel across the surface of a slab that is submerged in water at 50 °C. The slabs were compacted by the same method used to compact slabs for the Georgia LWT. The slabs had a length of 320 mm, a width of 260 mm, and a thickness of 80 mm. The AC-5, AC-10, AC-20, Novophalt, and Styrelf surface mixtures had average air-void levels of 7.3, 6.9, 7.1, 7.4, and 7.4 percent, respectively. The AC-5 and AC-20 (PG 59 and 70) base mixtures had average air-void levels of 6.3 and 7.0 percent.

The device tests two slabs simultaneously using two reciprocating solid steel wheels. The wheels have a diameter of 203.5 mm and a width of 47.0 mm. The applied load is 685 N. The standard, maximum number of wheel passes is 20,000. The measurements are customarily reported vs. wheel passes, unlike the preceding two wheel-tracking devices that use cycles.

The rut depth in each slab is measured by a linear variable differential transformer. Like the French PRT and the Georgia LWT, the rut depth does not include any upward heaving outside the wheelpath. A maximum allowable rut depth of 4 mm at 20,000 wheel passes is specified by the city of Hamburg, Germany. The Colorado Department of Transportation recommends a maximum allowable rut depth of 10 mm at 20,000 wheel passes.(23)

The creep slope, stripping slope, and stripping inflection point can also be evaluated.(24) However, no moisture damage was observed in the slabs, and there was no stripping slope or stripping inflection point. The creep slope is the number of wheel passes required to create a 1-mm rut depth due to viscous flow. It is actually an inverse slope because the slope for this type of relationship is usually defined in terms of rut depth per wheel pass or ESAL. Higher creep slopes indicate less rutting. Creep slopes have been used instead of rut depths to evaluate viscous flow because the number of wheel passes at which moisture damage starts to affect performance varies widely from mixture to mixture. Furthermore, the rut depths often exceed the maximum measurable rut depth of 25 to 30 mm, even if there is no moisture damage. Appendix A provides additional information on the Hamburg WTD including a photograph of it and a drawing that shows the slopes.

b. Results From the Hamburg WTD

The Hamburg WTD data are given in table 46. The AC-5, AC-10, and AC-20 (PG 59, 65, and 70) surface mixtures and the AC-5 and AC-20 (PG 59 and 70) base mixtures exceeded the maximum allowable rut depth of 4 mm at 20,000 wheel passes used in Hamburg, Germany. The AC-5 and AC-10 (PG 59 and 65) surface mixtures and the AC-5 (PG 59) base mixture exceeded the maximum allowable rut depth of 10 mm at 20,000 wheel passes used by the Colorado Department of Transportation.

The rut depths at 20,000 passes could not be evaluated because the rut depths for the AC-5 and AC-10 (PG 59 and 65) surface mixtures and the AC-5 (PG 59) base mixture exceeded the 30-mm limit of the device. Therefore, it was decided to evaluate the rut depths at 10,000 wheel passes. Only the AC-5 (PG 59) surface mixture exceeded the 30-mm limit at 10,000 passes. The AC-20 (PG 70) base mixture and the Novophalt, Styrelf, and AC-20 (PG 70) surface mixtures fell into one statistical group. This indicated that 10,000 wheel passes were inadequate for evaluating the mixtures.

It was concluded that the creep slopes should be used for evaluating rutting susceptibility. These slopes are presented in figures 37 and 38. As the ALF wheel passes in figures 31 and 32 increase, the creep slopes from the Hamburg WTD in figures 37 and 38 should increase.

Tables 47 and 48 provide rankings based on the Hamburg WTD and ALF pavement performance. The ranking in table 47 shows that the Hamburg WTD correctly ranked the five surface mixtures based on the average data. The statistical rankings were difficult to compare. The variance for the Novophalt mixture was very large because the creep slope was very high. This mixture did not rut. Therefore, it was not included in the statistical ranking. The ranking provided by the Hamburg WTD in table 48 for the surface vs. base mixture study did not agree with ALF pavement performance.

8. AAMAS

a. Description of the AAMAS Tests

Unconfined compressive tests were conducted at 40 °C in accordance with AAMAS and a modified AAMAS. The AAMAS procedure for evaluating rutting potential was developed by the Texas Transportation Institute under an NCHRP study.(20) They later modified the procedure under a study for the Texas Department of Transportation.(25) Although the tests conducted for each methodology are identical, the analyses of the data are slightly different.

Specimens with a height and diameter of 152.4 mm were compacted using the GTM. The AC-5, AC-10, AC-20, Novophalt, and Styrelf surface mixtures had average air-void levels of 7.8, 7.6, 7.4, 7.8, and 7.8 percent, respectively. The AC-5 and AC-20 (PG 59 and 70) base mixtures both had an average air-void level of 7.8 percent.

All tests were performed using a Materials Testing System™ having a closed-loop, servo-hydraulic actuator and the Teststar™ program. Three replicate specimens were tested per test. The following properties were measured for the AAMAS:

- Unconfined Compressive Strength Test at 40 °C.
  - Strain at failure, ϵ_{qu}.
- Unconfined Compressive Repeated Load Test at 40 °C and 140 kPa.
  - Total resilient strain at 200 cycles, ϵ_{rt}.
- Unconfined Compressive Creep Test at 40 °C and 140 kPa.
  - Creep modulus vs. time.
  - Total creep strain at 3600 s of loading, ϵ_c.
  - Recoverable creep strain at 3600 s after unloading, ϵ_r.
  - Slope and intercept at 1 s from the linear portion of the log total creep strain vs. log time relationship.

The following properties were measured for the modified AAMAS:

- Unconfined Compressive Strength Test at 40 °C.
  - Strain at failure, ϵ_{qu}.
- Unconfined Compressive Repeated Load Test at 40 °C and 140 kPa.
  - Total resilient strain at 200 cycles, ϵ_{rt}.
- Unconfined Compressive Creep Test at 40 °C and 140 kPa.
  - Creep modulus at 3,600 s of loading.
  - Total creep strain at 3,600 s of loading, ϵ_c.
  - Slope from the log total creep strain vs. log time relationship in the region where the data is linear on an arithmetic plot (generally between 1,000 and 3,000 to 3600 s).

The strength test was performed to measure the strain at failure (ϵ_{qu}) using the specified strain rate of 3.81 mm/min/mm of specimen height. This was calculated to be 580.6 mm/min. The strengths were also recorded to determine the loading stress required for the repeated load and creep tests. According to the AAMAS methodologies, the stress for these two tests must be between 5 and 25 percent of the compressive strength.

The repeated load test was performed to measure the total resilient strain (ϵ_{rt}) at 200 cycles. This strain is the sum of the instantaneous and recoverable viscoelastic strains. A haversine waveform load with a total loading time of 0.1 s, followed by a 0.9-s rest period, was used. The load peaked at 0.05 s. Both AAMAS methodologies terminate the test at 200 cycles.

The creep test was performed by applying a fixed load for 3600 s, and measuring the resulting strains. The load was then released and the rebound strain was recorded for an additional 3600 s. Vertical strains were measured at 1, 3, 10, 30, and 100 s, and then at increments of 100 s until the test was completed at 7200 s.

Both ends of the specimens to be used in the repeated load and creep tests were covered with a 0.25-mm-thick sheet of Teflon™ to reduce platen restraint. AAMAS suggested the use of either a thin Teflon™ layer, silicon grease, or graphite, as a friction-reducing material, but only Teflon™ tape was used in the AAMAS study.(20) The specimens were then preconditioned at 40 °C using a haversine waveform load with a total loading time of 0.1 s, followed by a 0.9-s rest period. Twenty-five cycles were applied using a peak stress of 70 kPa. For the actual repeated load and creep tests, a loading stress of 140 kPa was used. This stress was 22.4, 20.3, 13.7, 12.9, and 9.3 percent of the compressive strengths of the AC-5, AC-10, AC-20, Novophalt, and Styrelf surface mixtures, respectively. It was 13.7 and 11.9 percent of the compressive strengths of the AC-5 and AC-20 (PG 59 and 70) base mixtures.

Vertical compressive strains were measured by averaging the outputs of two Schaevitz model 100 MHR linear variable differential transformers (LVDT's), located on opposites of the specimen. Each LVDT had a full range of 5 mm and a gauge length of 100 mm. A typical instrumented specimen used in the tests is shown in figure 39.

b. AAMAS Analyses

The NCHRP AAMAS has two procedures for evaluating mixtures. The first procedure provides a rough estimate of rutting susceptibility.(20) The creep moduli vs. time relationships are plotted on a chart to determine if they fall in the area of low, moderate, or high rutting susceptibility. The report gives charts for lower, intermediate, and surface layers of asphalt pavements, and for layers placed over rigid pavements or rigid base materials. The methodology does not state what to do if a modulus falls into two areas of rutting susceptibility. The chart for asphalt surface layers, shown in figure 40, was used in this study.

In the second and primary procedure, mixtures are evaluated based on their rutting rates:

$$\epsilon_p = AN^m$$

where:

ϵ_p = rutting rate (mm of rut depth)/(mm of pavement layer thickness),
N = number of 18-kip ESAL's = 10,000,000, and
A,m = regression coefficients.

The coefficients "A" and "m" are normally found by performing long-term repeated load tests and calculating the slope and intercept. In pre-AAMAS studies, rutting rates based on repeated load tests were correlated to field performance data. The NCHRP AAMAS avoided testing difficulties associated with long-term repeated load tests by estimating the coefficients from creep and short-term repeated load test data. Although this procedure avoided the problems with testing, it added another correlation to the relationship between the laboratory data and yield performance. The following two equations were developed:

$$A = a(t_1)^b - \epsilon_{rt}$$

$$m = \frac{\log[a(1-X)/(a(0.1)^b - \epsilon_{rt})] + 3.5563b}{4.5563}$$

where:

a = intercept at 1 s from the steady state portion of the log total creep strain vs. log time relationship;
b = slope from the steady state portion of the log total creep strain vs. log time (s) relationship;
t_1 = traffic load duration = 0.1 s;
ϵ_{rt} = total resilient strain from the repeated load test;
X = recoverable creep strain or recovery efficiency, defined as ϵ_r/ϵ_c;
ϵ_r = recoverable creep strain at 3600 s after unloading, and
ϵ_c = total creep strain at 3600 s of loading.

To use the previous three equations, the creep strains must be in the linear range. To prevent nonlinearity, where the strains increase at an increasing rate, the following limiting compressive strain criteria must be met:

$$\epsilon_p < 0.5\epsilon_{qu} - \epsilon_{rt}$$

The modified AAMAS evaluates rutting susceptibility based on traffic intensity. The slope of the steady state creep curve and the creep strain at 3600 s are used as inputs to table 51, which gives the highest traffic intensity for which a mixture will be acceptable.(25) This intensity is then compared against the user's required traffic intensity. The highest intensity in the table, which is for traffic greater than 1 x 10^6 ESAL's was used in this study. This modified AAMAS uses the following equation to prevent nonlinearity:

$$\epsilon_c + \epsilon_{rt} < 0.5\epsilon_{qu}$$

The modified AAMAS suggests calculating the rutting rate, ϵ_p, as an additional check on rutting susceptibility. The methodology also includes the same charts used by the unmodified NCHRP AAMAS to estimate rutting susceptibility, but only the creep modulus at 3600 s is plotted on them.

c. Results From AAMAS

The NCHRP AAMAS data are given in table 52. The rutting rates, ϵ_p, for the mixtures with AC-5, AC-10, Styrelf, and Novophalt were not statistically different, and all of the rates were low. These low rutting rates indicated that none of the mixtures should be susceptible to rutting. The rates were low primarily because the steady state slopes from the creep tests were very low. The negative "m" coefficients in table 52 indicate the methodology is invalid for the mixtures tested. A negative "m" means that rutting decreases with an increase in traffic level. The traffic intensities using table 51 also showed that the mixtures had low susceptibilities to rutting. All mixtures had traffic intensities greater than 10^6 ESAL's. The strains were in the linear range, which was a requirement of both methodologies.

Since neither methodology could predict performance, the steady state creep slopes "b" were evaluated because they have been used in other studies to determine rutting susceptibility. A higher slope is interpreted to mean a higher potential for rutting. However, the mixtures with Novophalt and Styrelf had the highest slopes.

The stress and strain at failure, creep modulus, total creep strain, and permanent creep strain after unloading were evaluated. ALF pavement performance for the five surface mixtures is shown in figure 41, while the data from the laboratory tests are shown in figures 42 through 46. As the ALF wheel passes at failure in figure 41 increase, the stress at failure in figure 42 and the creep modulus in figure 44 should increase, while the total creep strain in figure 45 and the permanent creep strain in figure 46 should decrease. There is no hypothesis for how the strain at failure from the strength test, shown in figure 43, should relate to rutting performance.

Table 53 shows that the compressive stress at failure reversed the order for the Novophalt and Styrelf mixtures and statistically ranked the Novophalt mixture with the AC-20 mixture. The strain at failure provided a very poor ranking. The creep modulus and total creep strain at 3,600 s did not match ALF pavement performance, but the measurements did separate the mixtures with the modified binders from the mixtures with the unmodified binders. The permanent strains after unloading were highly variable and did not discriminate the mixtures. The variances were also not equal. None of the five measurements differentiated the four mixtures used in the surface vs. base mixture study. The only measurement that ranked the four mixtures correctly based on the averages was the stress at failure. However, the stresses at failure, shown in table 52, for the AC-20 (PG 70) surface and base mixtures and the AC-5 (PG 59) base mixture were not significantly different at a 95-percent confidence level.

The estimates of rutting susceptibility, based on the creep moduli and the chart shown in figure 40, are included in table 52 in terms of low, moderate, and high susceptibility. Although the conclusions that they provided were less than adequate, they agreed with ALF pavement performance better than the primary methods of analysis.

Additional creep tests were performed on the AC-5 (PG 59) and Novophalt surface mixtures to try to obtain data that correlated better with ALF pavement performance. The vertical stress level was increased from 140 to 450 kPa. The rutting rate, ϵ_p, (mm of rut depth per mm of pavement layer thickness) for the AC-5 (PG 59) mixture increased from 665 E-06 to 1580 E-06, while the rate for the Novophalt mixture increased from 449 E-06 to 750 E-06. These new rates were also very low and the "m" coefficients were negative. At either vertical stress, the rutting rates provided by the two mixtures were not significantly different. The mixtures were then retested at 140 kPa, but the average air-void level was reduced from 7.7 percent to 4.0 percent. This provided worse results because the rutting rates decreased. The mixtures were then tested using the original stress and air-void level, but the test temperature was increased from 40 to 50 °C. The rutting rates from these tests provided the erroneous conclusion that the Novophalt mixture was more susceptible to rutting than the AC-5 (PG 59) mixture. The air voids in the specimens, based on bulk specific gravity, did not decrease during testing for any mixture or variation of the test procedure.

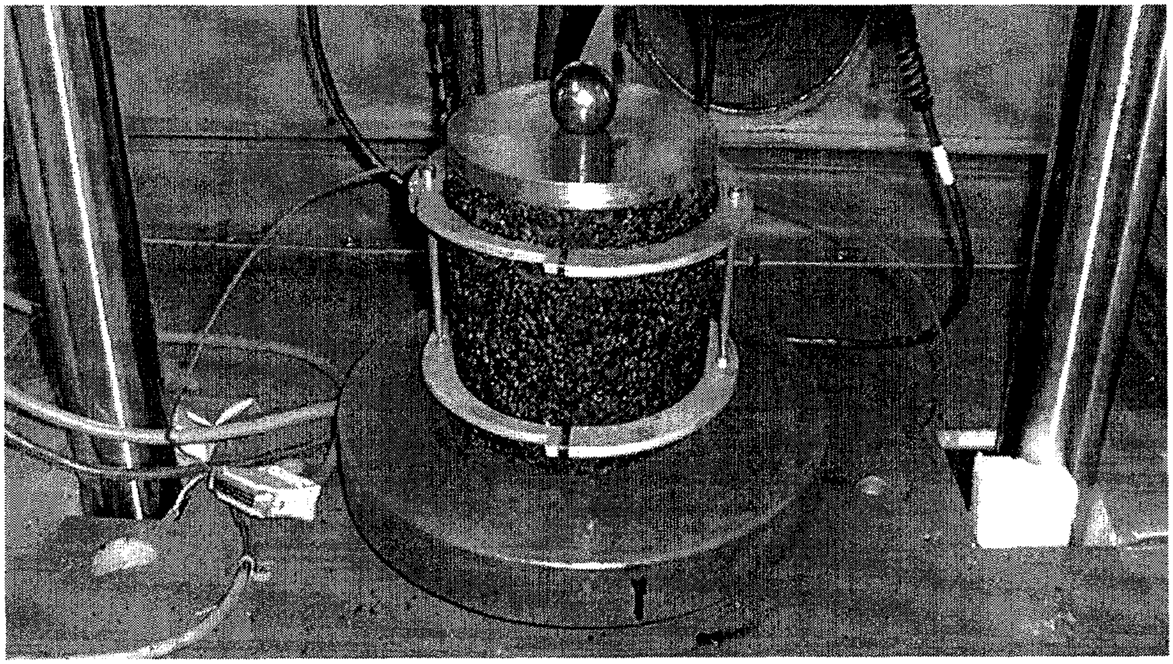

Figure 39. Instrumented specimen for the AAMAS repeated load and creep tests.

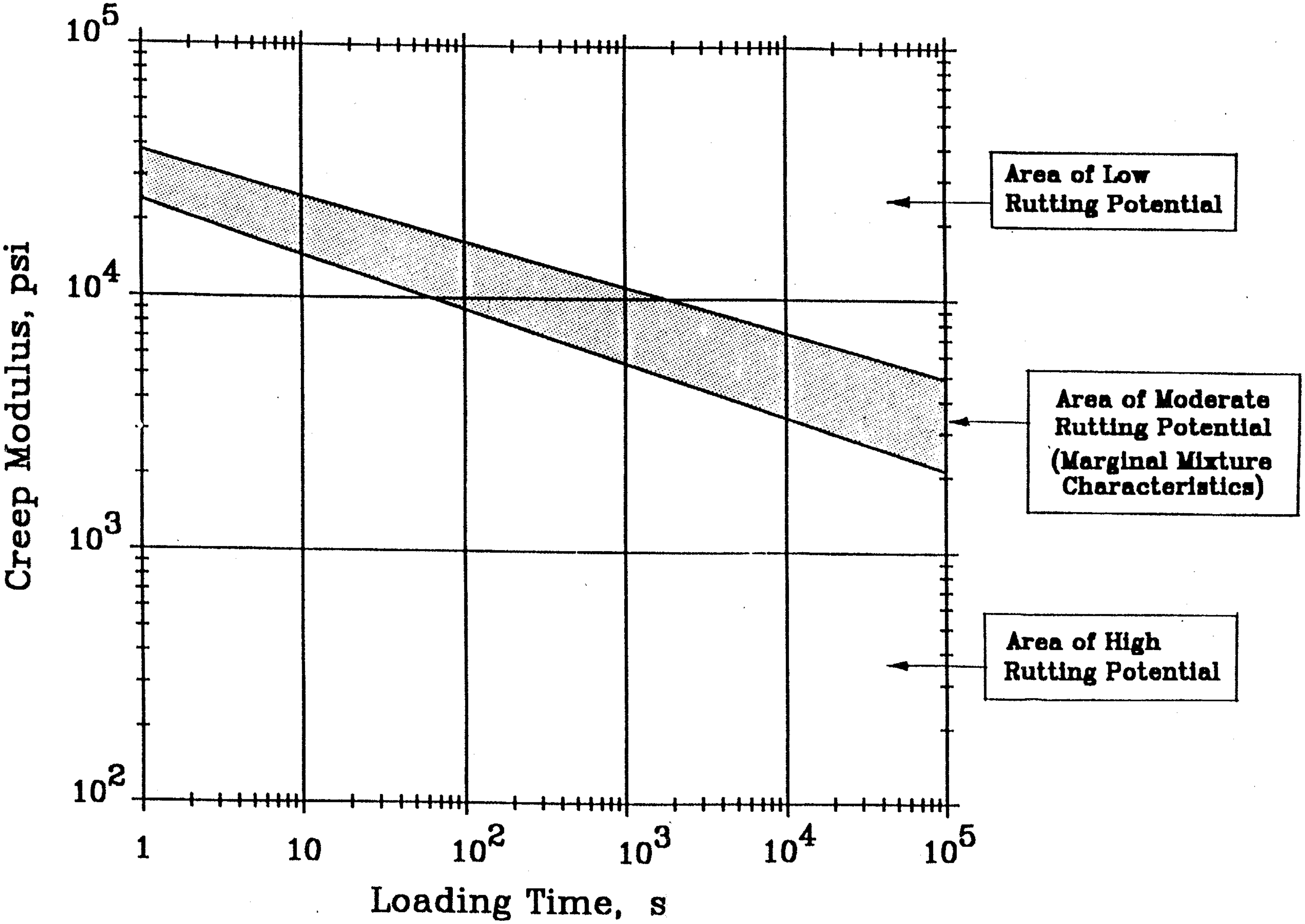

Figure 40. Rutting potential chart for asphalt concrete surface layers.(20)

Table 51. Modified AAMAS traffic intensities.(25)

Total Strain at 3600 s of Loading, %	Slope from the Steady State Portion of the Creep Curve				
	< 0.20	< 0.25	< 0.30	< 0.35	< 0.40
< 0.25	IV[2]	IV[2]	IV[2]	IV[2]	III
< 0.40	IV[2]	IV[2]	III[2]	III[2]	III[2]
< 0.50	IV[2]	III[2]	III[2]	III[2]	II
< 0.80	III[2]	II	II	II	II
< 1.0	I	I	I	I[1]	
< 1.2	I[1]	I[1]			

[1] Must also have $\epsilon_p < 0.8$ percent at 1,800 s of creep loading.
[2] The following criteria should be met: $\epsilon_p + \epsilon_{rt} < 0.5\ \epsilon_{qu}$.

Definitions for Traffic Intensity:(25)

I = < 1 x 10^5 ESAL's (Low Traffic)
II = 1 x 10^5 to 5 x 10^5 ESAL's (Moderate Traffic)
III = 5 x 10^5 to 1 x 10^6 ESAL's (Heavy Traffic)
IV = > 1 x 10^6 ESAL's (Very Heavy Traffic)

Table 52. Rutting performance based on AAMAS, Modified AAMAS, and the repeated load compression test at 40 °C.

Pre-Superpave:	AC-5	AC-10	AC-20	Novophalt	Styrelf
Superpave PG:	59	65	70	77	88
Strength Test					
Stress at Failure, kPa	624	690	1 019	1 084	1 506
Strain at Failure[1], ϵ_{qu}	24 400	28 200	28 200	22 100	34 700
Repeated Load Test					
Total Resilient Strain[1], ϵ_{rt}	310	200	200	110	90
Creep Test					
Creep Modulus, 3600 s, MPa	58.1	68.9	49.3	123.0	85.7
Total Creep Strain[1], ϵ_c	2 500	2 080	2 940	1 180	1 330
Permanent Strain[1]	880	780	1 590	470	400
Recoverable Strain[1], ϵ_r	1 620	1 300	1 350	710	930
Recovery Efficiency, ϵ_r/ϵ_c	0.646	0.613	0.469	0.603	0.738
Intercept[1], a	1 890	1 640	2 130	720	710
Steady State Slope[1], b	32 400	27 390	37 790	58 670	74 190
Coefficient[1] A	1 440	1 340	1 750	520	520
Coefficient[1] m	-48 100	-54 400	-13 100	-9 700	-167 200
NCHRP AAMAS Analysis					
Rutting Potential, Chart	Mod/High	Mod/High	High	Low/Mod	Low/Mod
Rutting Rate[1], ϵ_p	667	612	1 522	449	478
$0.5\epsilon_{qu} - \epsilon_{rt}$	11 890	13 900	13 900	10 940	17 260
Modified AAMAS Analysis					
Rutting Potential, Chart	Mod	Mod	High	Low	Low
Traffic Intensity, ESAL's	$>10^6$	$>10^6$	$>10^6$	$>10^6$	$>10^6$
$\epsilon_c + \epsilon_{rt}$	2 810	2 280	3 140	1 290	1 420
$0.5\epsilon_{qu}$	12 200	14 100	14 100	11 050	17 350
Repeated Load Compression Test					
Dynamic Modulus, MPa	464	800	1 900	1 720	2 760
Cumulative Permanent Strain[1]	7 730	5 150	2 700	630	525
Slope, Linear Region	0.307	0.269	0.281	0.201	0.194
$G^*/\sin(\delta)$	38 640	82 810	159 900	263 600	270 900

[1] These data were multiplied by 10^6. The unit for strain is x10^6 mm/mm.

Table 52. Rutting performance based on AAMAS, Modified AAMAS, and the repeated load compression test at 40 °C (continued).

Pre-Superpave: Superpave PG:	AC-5 Base 59	AC-20 Base 70
Strength Test		
Stress at Failure, kPa	1 021	1 180
Strain at Failure[1], ϵ_{qu}	24 700	23 300
Repeated Load Test		
Total Resilient Strain[1], ϵ_{rt}	250	140
Creep Test		
Creep Modulus, 3600 s, MPa	46.8	76.8
Total Creep Strain[1], ϵ_c	3 010	2 190
Permanent Strain[1]	620	1 020
Recoverable Strain[1], ϵ_r	2 390	1 170
Recovery Efficiency, ϵ_r/ϵ_c	0.796	0.621
Intercept[1], a	2 480	1 660
Steady State Slope[1], b	24 900	31 900
Coefficient[1] A	2 090	1 400
Coefficient[1] m	-117 300	-94 800
NCHRP AAMAS Analysis		
Rutting Potential, Charts	High	Mod/High
Rutting Rate[1], ϵ_p	327	952
$0.5\epsilon_{qu} - \epsilon_{rt}$	12 100	11 510
Modified AAMAS Analysis		
Rutting Potential, Charts	High	Mod
Traffic Intensity, ESAL's	$>10^6$	$>10^6$
$\epsilon_c + \epsilon_{rt}$	3 260	2 330
$0.5\epsilon_{qu}$	12 350	11 650
Repeated Load Compression Test		
Dynamic Modulus, MPa	600	2 320
Cumulative Permanent Strain[1]	7 540	1 760
Slope, Linear Region	0.320	0.246
G*/sin(δ)	38 640	159 900

[1] These data were multiplied by 10^6. The unit for strain is $x10^6$ mm/mm.

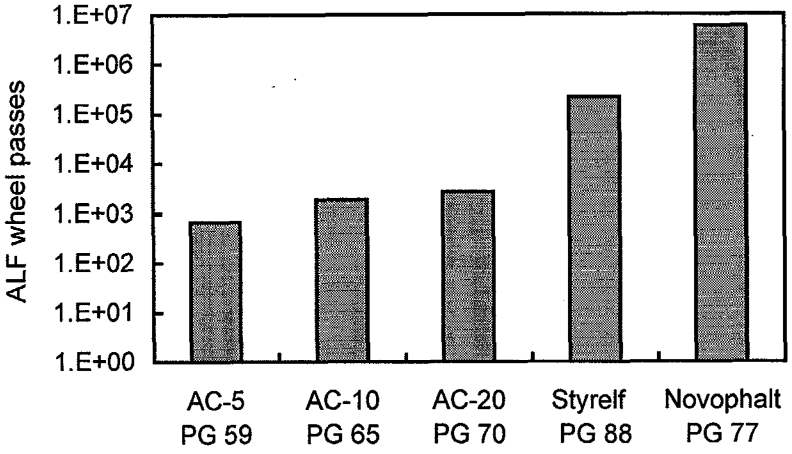

Figure 41. ALF wheel passes at a 20-mm rut depth vs. surface mixture.

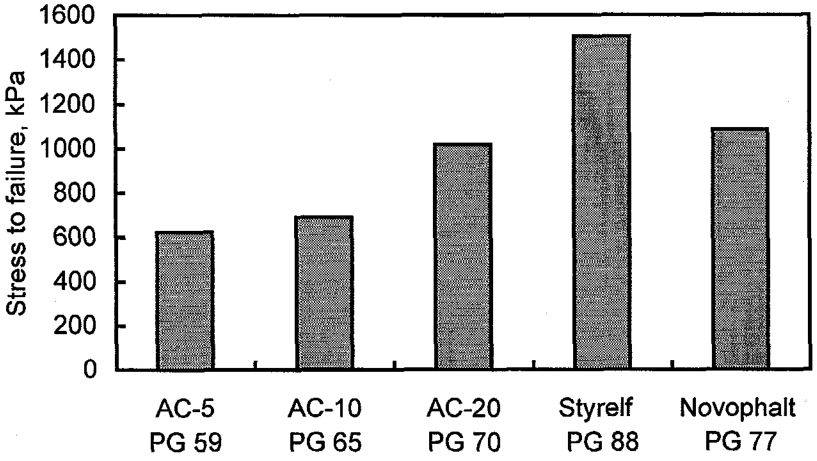

Figure 42. Stress at failure from the strength test vs. surface mixture.

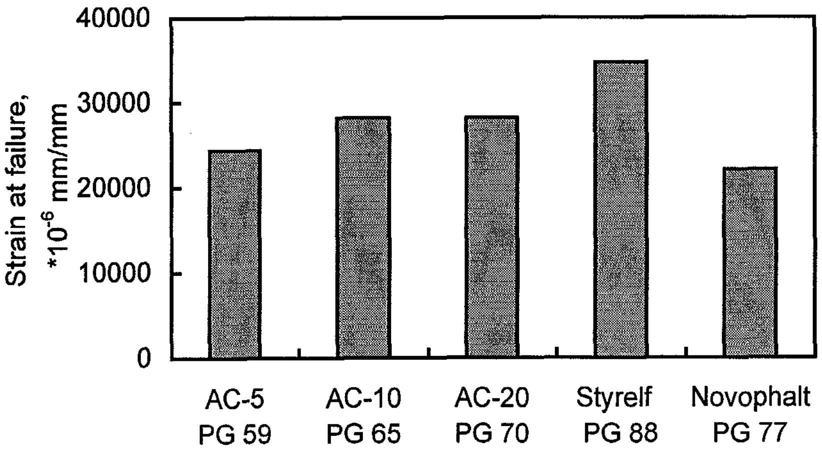

Figure 43. Strain at failure from the strength test vs. surface mixture.

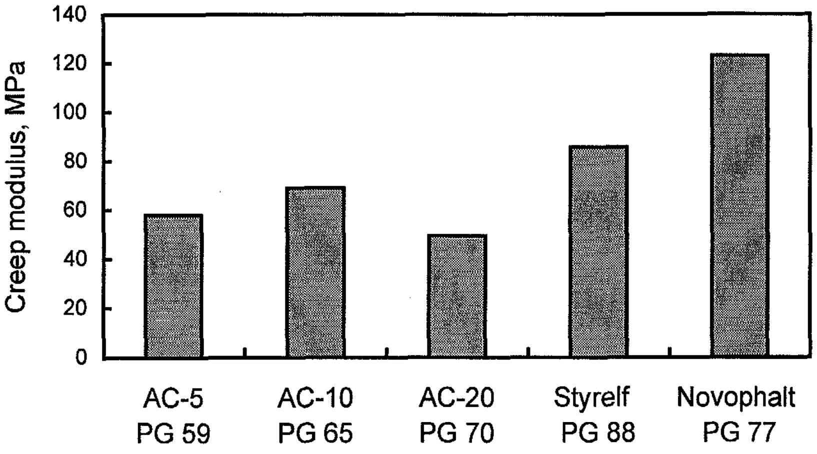

Figure 44. Creep modulus from the creep test vs. surface mixture.

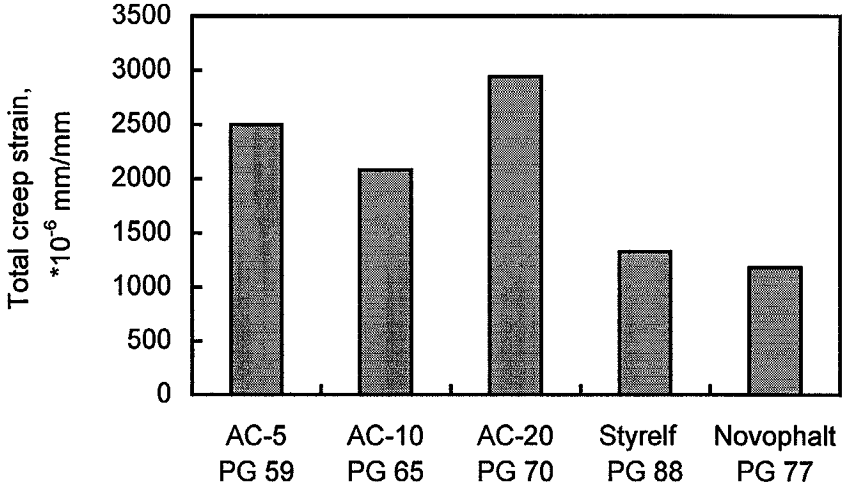

Figure 45. Total creep strain from the creep test vs. surface mixture.

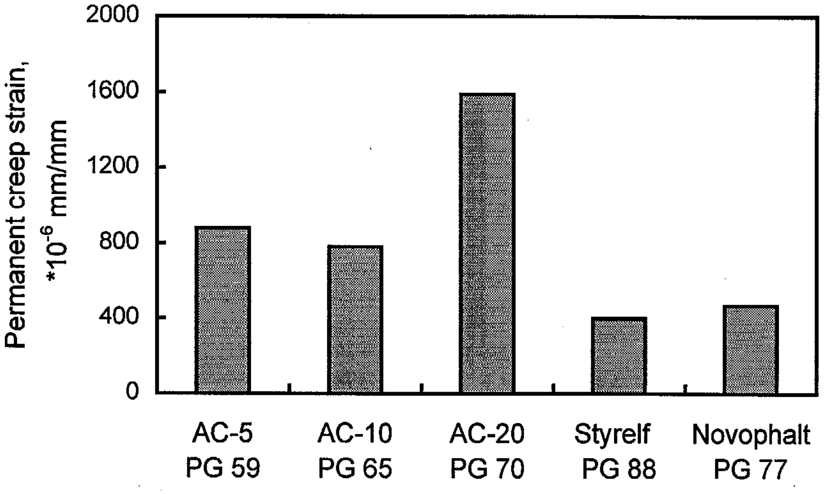

Figure 46. Permanent strain from the creep test vs. surface mixture.

Table 53. Statistical rankings for selected AAMAS tests at 40 °C.[1]

	Compressive Strength Test		Creep Test	
ALF at 58 °C	Stress at Failure,	Strain at Failure,	Creep Modulus or Total Creep Strain	Permanent Strain After Unloading
(A) Novophalt	(A) Styrelf	(A) Novophalt	(A) Novophalt	(A) Styrelf
(B) Styrelf	(B) Novophalt	(AB) AC-5	(A) Styrelf	(A) Novophalt
(C) AC-20	(B) AC-20	(B) AC-10	(B) AC-10	(A) AC-10
(C) AC-10	(C) AC-10	(B) AC-20	(BC) AC-5	(A) AC-5
(D) AC-5	(C) AC-5	(C) Styrelf	(C) AC-20	(A) AC-20

[1] The letters are the statistical ranking, with "A" denoting the mixture with the lowest susceptibility to rutting.

Table 54. Statistical rankings for the five surface mixtures provided by the ALF, the wheel-tracking devices, and repeated load compression test.

ALF at 58 °C	French PRT at 60 °C	Georgia LWT at 40 °C	Hamburg WTD at 50 °C	Repeated Load Test at 40 °C
(A) Novophalt	(A) Novophalt	(A) Novophalt	(-) Novophalt	(A) Styrelf
(B) Styrelf	(B) Styrelf	(B) Styrelf	(A) Styrelf	(A) Novophalt
(C) AC-20	(C) AC-20	(BC) AC-20	(B) AC-20	(B) AC-20
(C) AC-10	(D) AC-10	(C) AC-10	(C) AC-10	(C) AC-10
(D) AC-5	(D) AC-5	(C) AC-5	(D) AC-5	(D) AC-5

Table 55. Statistical rankings for the surface and base mixtures provided by the ALF, the wheel-tracking devices, and repeated load compression test.

ALF at 58 °C		French PRT at 60 °C	Georgia LWT at 40 °C	Hamburg WTD at 50 °C	Repeated Load Test at 40 °C
AC-20 Base	A	AB	A	B	A
AC-5 Base	B	C	AB	C	B
AC-20 Surface	C	A	A	A	A
AC-5 Surface	D	B	B	C	B

Table 56. Rankings for the repeated load compression tests at 40 °C.

DSR at 40 °C and 10.0 rad/s		Cumulative Permanent Strain at 10,000 Cycles, Ranking by LSD or $\mu \pm 2\sigma_{(n-1)}$	Dynamic Modulus at 200 Cycles, Ranking by LSD	Dynamic Modulus at 200 Cycles, Ranking by $\mu \pm 2\sigma_{(n-1)}$
Binder Ranking	G*/sinδ, kPa			
(A) Styrelf	270.9	(A) Styrelf	(A) Styrelf	(A) Styrelf
(A) Novophalt	263.6	(A) Novophalt	(B) AC-20	(AB) AC-20
(B) AC-20	159.9	(B) AC-20	(B) Novophalt	(B) Novophalt
(C) AC-10	82.8	(C) AC-10	(C) AC-10	(B) AC-10
(D) AC-5	38.6	(D) AC-5	(C) AC-5	(C) AC-5

Ranking Based on ALF at 58 °C	Ranking Based on the Average Slope, μ		Statistical Ranking Based on $\mu \pm 1\sigma_{(n-1)}$		Statistical Ranking Based on $\mu \pm 2\sigma_{(n-1)}$	
	Slope	All Mixtures	All Mixtures	Surface Mixtures	All Mixtures	Surface Mixtures
Novophalt	0.201	B	A	A	A	A
Styrelf	0.194	A	AB	AB	A	A
AC-20 Base	0.246	C	AC		A	
AC-5 Base	0.320	G	C		A	
AC-20	0.281	E	BC	BC	A	A
AC-10	0.269	D	BC	BC	A	A
AC-5	0.307	F	C	C	A	A

$\mu \pm 2\sigma_{(n-1)}$ = average ± two times the sample standard deviation, where "n" is the number of samples.

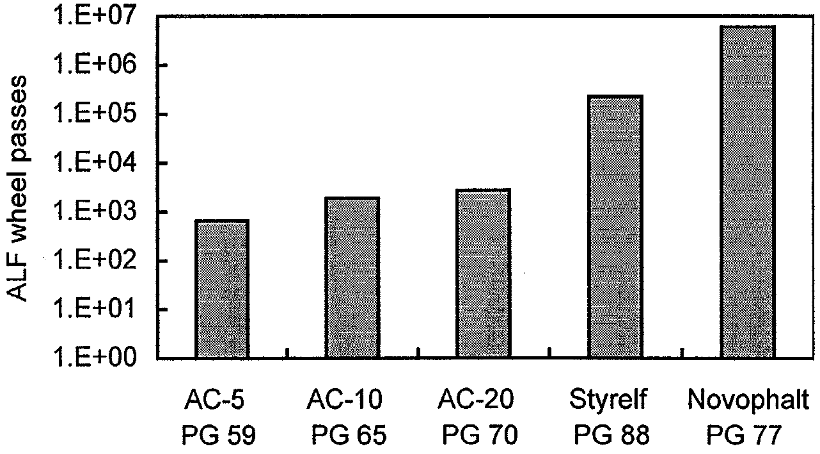

Figure 47. ALF wheel passes at a 20-mm rut depth vs. surface mixture.

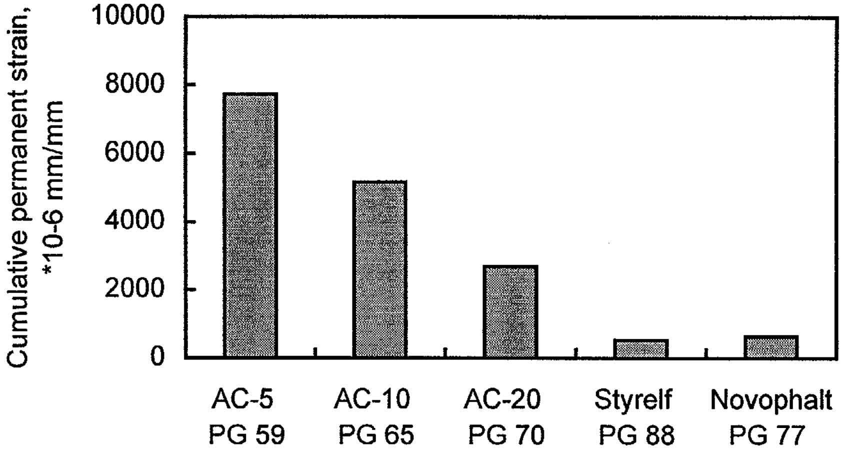

Figure 48. Cumulative permanent strain from the repeated load compression test vs. surface mixture.

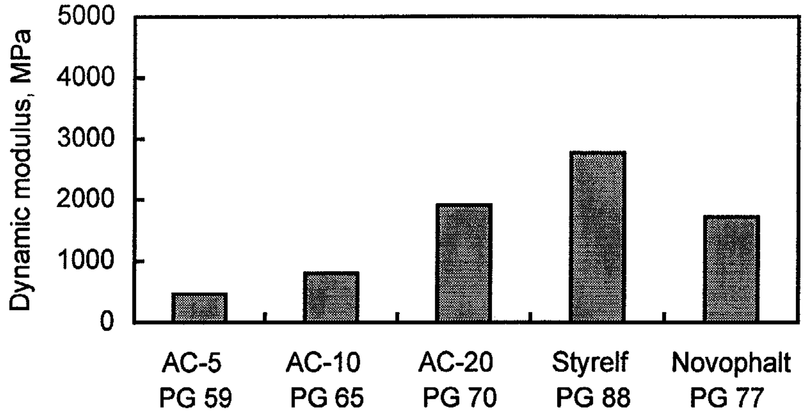

Figure 49. Dynamic modulus from the repeated load compression test vs. surface mixture.

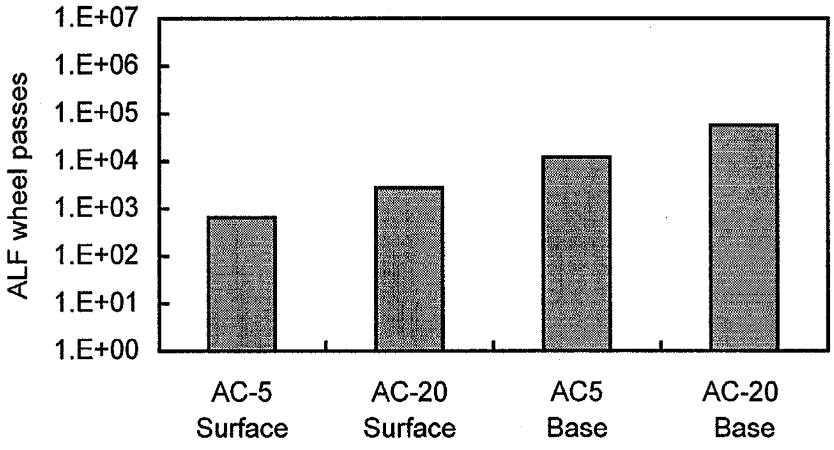

Figure 50. ALF wheel passes at a 20-mm rut depth vs. mixture type.

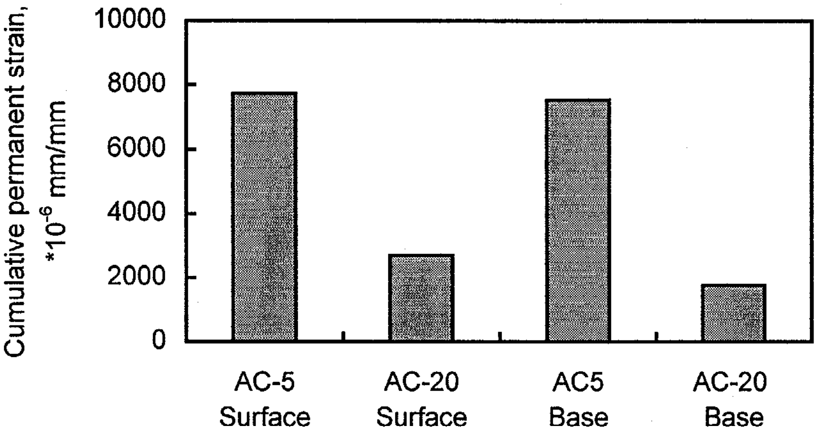

Figure 51. Cumulative permanent strain from the repeated load compression test vs. mixture type.

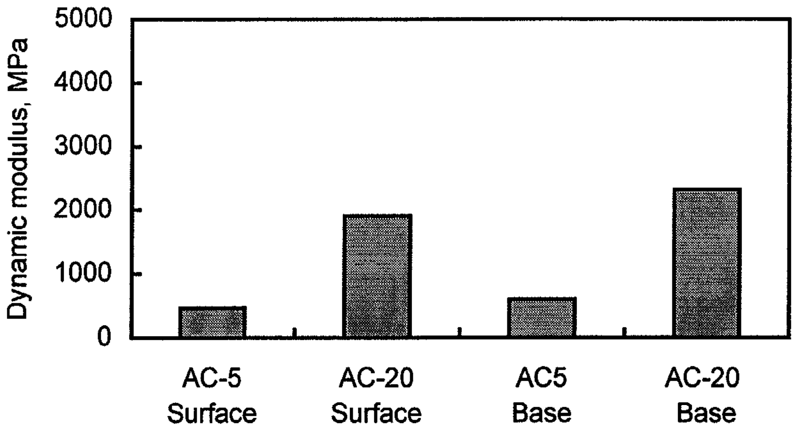

Figure 52. Dynamic modulus from the repeated load compression test vs. mixture type.

The AAMAS methodologies were eliminated from the study. The G*/sinδ's given in table 52 were determined using a frequency of 10.0 rad/s. If the NCHRP AAMAS had not been eliminated, it was not clear what DSR frequency should be used because creep tests do not have a frequency of loading. If the frequency is assumed to be very slow, the G*/sinδ's of the binders would be very low and probably equivalent. However, creep tests are used to predict rutting, or permanent deformation, due to traffic at typical highway traffic speeds.

9. Repeated Load Compression Test

Both AAMAS methodologies included a short-term repeated load test that ended at 200 cycles. This test was extended to 10,000 cycles so that the mixtures could be compared based on cumulative permanent strain.(26) The dynamic modulus at 200 cycles, based on the valley-to-peak total strain, was included in the evaluation. A stress of 140 kPa was applied to the specimens in the form of a haversine wave with a 0.1-s load duration. Each cycle of loading was followed by a 0.9-s rest period. The instrumented specimen is shown in figure 39.

The test data are included in table 52. ALF pavement performance for the five surface mixtures in terms of wheel passes is shown in figure 47, while the cumulative permanent strains and dynamic moduli are shown in figures 48 and 49. As the ALF wheel passes in figure 47 increase, the cumulative permanent strain in figure 48 should decrease. A hypothesis for how the dynamic modulus relates to pavement rutting performance does not exist, although in other studies, an increase in the dynamic modulus has been equated to a decrease in rutting susceptibility. The data for the surface vs. base mixture study are shown in figures 50, 51, and 52. As the ALF wheel passes in figure 50 increase, the cumulative permanent strain in figure 51 should decrease. The air voids in the specimens did not change during testing for any mixture based on the bulk specific gravity of each specimen measured before and after testing.

Tables 54 and 55 provide rankings for the repeated load test based on cumulative permanent strain. Table 54 shows that the ranking for the five surface mixtures was not the same as the rankings provided by the ALF and the three wheel-tracking devices. The order based on the average data was reversed for the Novophalt and Styrelf mixtures. The ranking in table 55 for the surface vs. base mixture study did not agree with ALF pavement performance.

Table 56 shows that the ranking provided by cumulative permanent strain at 40 °C matched the ranking for the five binders based on G*/sinδ at 40 °C. This suggested that the repeated load compression test should be tried at a temperature of 58 °C. Comparisons between G*/sinδ and the other mixture tests are discussed in chapter 6.

Rankings for the dynamic moduli, shown in table 56, did not agree with ALF pavement performance or the cumulative permanent strains. The fallacy of using the dynamic modulus to predict rutting is that it must be assumed that at a given temperature, all mixtures have the same amount of recoverable strain so that the differences in modulus from mixture to mixture are only a function of the differences in permanent strain.

The slopes from the linear portion of the log permanent strain vs. log time relationship were also evaluated. The slopes and the results of statistical analyses performed on them are included in table 56. None of the slopes were significantly different from each other at a 95-percent confidence level. This is shown by the ranking under "$\mu \pm 2\sigma_{(n-1)}$" in table 56. The poor repeatabilities of the slopes make them an inadequate measure of rutting performance.

Based on the findings at 40 °C, the tests were repeated at 58 °C. The data at both 40 and 58 °C are given in table 57. The cumulative permanent strains for the AC-5, AC-10, and AC-20 (PG 59, 65,and 70) surface mixtures and the AC-5 and AC-20 (PG 59 and 70) base mixtures exceeded the range of the LVDT's at 3,000 cycles or less. The data could only be compared at 1,000 cycles. The tests at 58 °C provided rankings for the five surface mixtures that were closer to ALF pavement performance at 58 °C than the rankings provided by the tests at 40 °C. This shows the importance of test temperature. However, no improvement in the rankings was found for the surface vs. base mixture comparisons. The air voids in the AC-5 and AC-10 (PG 59 and 65) surface mixture specimens increased 1.0 percent during testing, which was probably related to the high amount of specimen bulging that occurred. The air voids for the other mixtures did not change during testing.

10. SST(27,28)

a. Description of the SST

The SST was used to test specimens with a diameter of 150 mm that were compacted by the Superpave Gyratory Compactor. Each gyratory specimen was sawed to provide two test specimens, each with a height of 50 mm. The air-void level of each specimen was 7 ±0.5 percent after sawing. Specimens not meeting this requirement were discarded. Three to seven replicate specimens were tested, depending upon the repeatability of the SST data.

All tests were performed at both 40 and 58 °C. A temperature of 40 °C was used because this was the highest temperature used in the Superpave complete mixture analysis. A temperature of 58 °C was used because all seven mixtures were tested by the ALF at this temperature. The SST was operated in accordance with AASHTO Provisional Standard TP7-94, "Standard Test Method for Determining the Permanent Deformation and Fatigue Characteristics of Hot-Mix Asphalt (HMA) Using the Simple Shear Test (SST) Device."(3) Appendix A provides additional information on the SST including a photograph of it.

Table 57. ALF rutting performance vs. the repeated load compression test at 40 and 58 °C.

ALF at 58 °C	Dynamic Modulus, MPa	
	200 Cycles and 40 °C	200 Cycles and 58 °C
(A) Novophalt	(A) 2 760 Styrelf	(A) 258 Novophalt
(B) Styrelf	(B) 1 900 AC-20	(B) 176 Styrelf
(C) AC-20	(B) 1 720 Novophalt	(C) 65 AC-20
(C) AC-10	(C) 800 AC-10	(C) 58 AC-10
(D) AC-5	(C) 464 AC-5	(C) 61 AC-5

ALF at 58 °C	Cumulative Permanent Strain x 10^6 mm/mm		
	10,000 Cycles and 40 °C	1,000 Cycles and 58 °C	10,000 Cycles and 58 °C
(A) Novophalt	(A) 525 Styrelf	(A) 2 200 Novophalt	(A) 3 120 Novophalt
(B) Styrelf	(A) 630 Novophalt	(A) 3 590 Styrelf	(B) 5 890 Styrelf
(C) AC-20	(B) 2 700 AC-20	(B) 12 840 AC-20	
(C) AC-10	(C) 5 150 AC-10	(C) 15 950 AC-10	
(D) AC-5	(D) 7 730 AC-5	(C) 16 280 AC-5	

ALF at 58 °C		Dynamic Modulus, MPa				Cumulative Permanent Strain x 10^6 mm/mm			
		200 Cycles and 40 °C		200 Cycles and 58 °C		10,000 Cycles and 40 °C		1,000 Cycles and 58 °C	
AC-20 Base	A	2 320	A	80	A	1 760	A	10 170	A
AC-5 Base	B	600	B	55	B	7 540	B	16 020	B
AC-20 Surface	C	1 900	A	65	AB	2 700	A	12 840	AB
AC-5 Surface	D	464	B	61	AB	7 730	B	16 280	B

The following tests were performed:

- 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 and 2.0 Hz.
  - G*/sinδ at 10.0 and 2.0 Hz.
  - Slope of log G* vs. log frequency.

- Repeated Shear at Constant Height (Repeated Shear).
  - Slope of cumulative permanent strain vs. cycles.
  - Cumulative permanent strain at 5,000 cycles (load repetitions).

(1) Simple Shear

The Simple Shear test consisted of applying a horizontal shear stress to a specimen at a rate of 70 kPa/s up to a stress level of 35 kPa for tests at 40 °C, and up to a stress level of 15 kPa for the tests at 58 °C. The maximum stress level was maintained for 10 s, after which it was reduced to 0 kPa at a rate of 25 kPa/s. The height of the specimen is kept constant throughout the test to within 0.0013 mm. Because AASHTO TP7-94 did not consider tests with temperatures as high as 58 °C at the time of this study, the stress level for tests at 58 °C was determined by trial-and-error with the goal of determining a stress level that could be applied to all mixtures regardless of their stiffnesses. The 15-kPa stress level met this goal.

The compliance parameter was obtained by dividing the maximum shear strain, which occurred at 10 s, by the applied shear stress. It was hypothesized that as the compliance parameter decreased, rutting susceptibility would decrease.

All tests at a given temperature were performed using the same applied stress history, therefore, the permanent shear strains after loading could be compared. It was hypothesized that as the permanent shear strain decreased, rutting susceptibility would decrease. The permanent shear strain was measured 10 s after unloading.

The SST measures the vertical axial stress needed to maintain a constant specimen height during testing. This axial stress is hypothesized to be the result of aggregates trying to roll past each other as the mixture shears.(29) It is equated to the capability of a mixture to exhibit dilatancy due to shearing. Dilatancy is prohibited in the vertical direction during the test by the application of the axial stress. It was hypothesized that as the vertical axial stress decreased, rutting susceptibility would decrease. A mixture with aggregates having a high degree of interlock should have a low vertical axial stress.

(2) Frequency Sweep

The Frequency Sweep test consisted of applying a sinusoidal shear strain with a peak-to-peak amplitude of 0.1 µm/mm at the following frequencies: 10.0, 5.0, 2.0, 1.0, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz. The height of the specimen is kept constant throughout the test to within 0.0013 mm.

The complex shear modulus, G*, was measured as a function of frequency. The G*'s at all frequencies were analyzed, but emphasis was placed on the G*'s at 10.0 and 2.0 Hz because 10.0 Hz is the most widely used frequency for repeated load tests for asphalt mixtures, while 2.0 Hz could be considered the loading frequency of the ALF. A frequency of 2.0 Hz was chosen instead of 2.25 Hz (18 km/h ÷ 8.0 km/(h·Hz) = 2.25 Hz), because 2.0 Hz was one of the standard SST frequencies. It was hypothesized that as G* increased, rutting susceptibility would decrease. However, as discussed for the dynamic moduli from the repeated load compression test, it must be assumed that at a given temperature and frequency, all mixtures have the same amount of recoverable strain so that the differences in modulus from mixture to mixture are only a function of the differences in permanent strain.

The G*/sinδ's of the mixtures at 10.0 and 2.0 Hz were evaluated because the Superpave binder specification uses this parameter to grade binders according to permanent deformation. It is not known if the rheological states of the mixtures at 40 °C allow this parameter to be interpreted in the same manner used when evaluating binders. The rheological state, or rheological model, would have to be the same for all mixtures. For binders, an increase in G*/sinδ should decrease rutting susceptibility.

The slopes from the relationships between log G* and log frequency were also examined. No hypothesis exists for how this slope should relate to pavement performance, although it has been suggested that a lower slope may indicate a greater resistance to rutting.(30) This hypothesis was used to analyze the slopes in this study. Superpave used this slope, defined as the "m-value," in its original performance model for rutting.

(3) Repeated Shear

The Repeated Shear test applies a haversine shear stress of 70 kPa for 0.1 s followed by a 0.6 s rest period. The height of the specimen is kept constant throughout the test to within 0.0013 mm. The process is repeated for 5,000 cycles or until the specimen suffers a permanent shear strain of 5 percent. The slope for each relationship between cumulative permanent shear strain and cycles was determined by fitting the data to a rutting model of the form:

$$PS = aN^b$$

where:

PS = permanent shear strain;
a = intercept, and
N = number of cycles;
b = slope of cumulative permanent shear strain.

The slope is considered to represent the rate of rutting as a function of load applications. It was hypothesized that as the slope decreased, rutting susceptibility would decrease. However, as discussed in chapter 3, both the slope and the intercept may be needed to predict rutting susceptibility.

The cumulative permanent shear strain at 5,000 cycles is another indicator of the resistance of a mixture to permanent deformation. This strain accounts for both the slope and intercept. It was hypothesized that as the cumulative permanent shear strain at 5,000 cycles decreased, rutting susceptibility would decrease.

b. Results From the SST for the Five Surface Mixtures at 40 °C

The data for all measurements at 40 °C are shown in table 58. Some measurements exhibited heteroscedasticity, where the standard deviation increased with an increase in the average. When this was encountered, the $\log_{10}$ of the measurement was ranked using an analysis of variance and Fisher's LSD.

(1) Simple Shear

Table 59 shows that all three measurements ranked the mixtures the same as ALF pavement performance based on the averages. The statistical rankings provided by the compliance parameter and permanent shear strain matched the ranking provided by ALF. The maximum axial stress provided a lower degree of correlation with ALF based on the statistical rankings. The main discrepancy was that the Novophalt and Styrelf mixtures ranked the same.

(2) Frequency Sweep

Table 59 shows that the rankings based on both G* and G*/sinδ at 10.0 and 2.0 Hz were the same as ALF pavement performance based on the averages. Figures 53 and 54 show that the rankings were the same at all measured frequencies. The statistical rankings in table 59 for G* and G*/sinδ were not identical to the ranking provided by ALF, but the degree of correlation was good.

The slopes from the relationship between log G* and log frequency did not agree with ALF pavement performance. The hypothesis that a lower slope may indicate a greater resistance to rutting was not valid for these data.

(3) Repeated Shear

Table 59 shows that the slopes from the relationship between cumulative permanent strain and cycles did not agree with ALF pavement performance. The cumulative permanent strains at 5,000 cycles ranked the mixtures the same as ALF based on the averages. The statistical ranking provided by these strains was not identical to the ranking provided by ALF, but the degree of correlation was good.

c. Results From the SST for the Five Surface Mixtures at 58 °C

The data at 58 °C are shown in table 60. The Frequency Sweep data are also shown in figures 55 and 56. Table 61 shows that no SST measurement ranked the mixtures the same as ALF based on the averages unless the hypothesis for the Frequency Sweep slope is reversed. The data show that a higher slope indicates a greater resistance to rutting. All of the statistical rankings correlated poorly to ALF pavement performance. The best data were provided by the maximum axial stress from Simple Shear. The Repeated Shear tests at 58 °C were terminated because the data were extremely variable.

Table 62 provides the coefficients of variation for each SST measurement at both 40 and 58 °C. The coefficients of variation were higher at 58 °C compared with 40 °C, except for the maximum axial stresses from Simple Shear, where the coefficients were virtually equal.

The coefficient of variation is used to judge the repeatability of a test. Although there is no standard maximum value, a maximum value of 20 percent is often used. Most measurements at 58 °C had coefficients of 20 percent and above, whereas the measurements at 40 °C were generally less than 20 percent. Even so, the cumulative permanent strains from Repeated Shear provided a coefficient of variation of 33 percent at 40 °C. This test could be considered one of the leading candidate tests for evaluating rutting potential without a performance-predicting model, yet it had a high coefficient of variation. (Note that the coefficients of variation were a function of five binder grades with a single aggregate gradation and binder content.)

d. Results From the SST for the Surface vs. Base Mixture Study at 40 °C

The data for the surface vs. base mixture study at 40 °C are shown in table 63. Table 64 shows that no SST measurement at 40 °C provided a ranking that agreed with ALF pavement performance. (Two formats for presenting the rankings are used in this chapter. The choice of the format depended upon which one best facilitated visual comparisons of the rankings.)

Table 65 shows rankings based only on the averages. The results from the French PRT, Georgia LWT, Hamburg WTD, and repeated load compression test are included. Only the cumulative permanent strain at 5,000 cycles from Repeated Shear provided a ranking that was the same as ALF. The data are also presented in figures 57 and 58. As ALF wheel passes increased, the strains decreased.

Table 66 gives the results of *t*-tests that were used to compare the data from each base mixture with the data from the surface mixture having the same binder grade. The decrease in pavement rutting susceptibility provided by each base mixture was not duplicated by the French PRT, Georgia LWT, Hamburg WTD, or repeated load compression test. Thus, each pair of data for these tests in table 66 has the same ranking "A." The Georgia LWT and the cumulative permanent strains from the repeated load compression test did provide better average data for both base mixtures relative to their associated surface mixture, but the differences in the averages were small.

The results from the *t*-tests for the SST data varied from measurement to measurement. Simple Shear measurements provided better average data for the base mixtures relative to their associated surface mixture in five out of six comparisons. The only exception was the maximum axial stress using the AC-20 (PG 70) binder. Only two of the six comparisons were significantly different. G^* and $G^*/\sin\delta$ from Frequency Sweep provided better average data for the base mixtures for all eight comparisons shown in table 66. The differences were significant for five of these eight comparisons. The slopes from Frequency Sweep and Repeated Shear did not give consistent trends. It was concluded that these slopes cannot be used as indicators of rutting performance. The cumulative permanent strains at 5,000 cycles from Repeated Shear provided better average data for both base mixtures relative to their associated surface mixture, but the effect was only significant for the mixtures with AC-20 (PG 70).

The *t*-tests show that some SST measurements were affected by nominal maximum aggregate size, but the rankings for the four mixtures in table 64 show that the effect was not as great as the effect on ALF pavement performance.

e. Results From the SST for the Surface vs. Base Mixture Study at 58 °C

The data for the surface vs. base mixture study at 58 °C are shown in table 67. Only the maximum axial stress ranked the mixtures correctly based on the averages. Figures 57 and 59 present the ALF wheel passes and the maximum axial stresses. As the ALF wheel passes increased, the maximum axial stress decreased. Table 68 shows that no SST measurement at 58 °C provided a statistical ranking that agreed with ALF pavement performance.

f. Results From the SST for the Surface vs. Base Mixture Study at 40 and 58 °C Using Specimens With a Diameter of 150 mm and a Height of 75 mm

AASHTO Provisional Standard TP7-94 stated that specimens with a diameter of 150 mm and height of 75 mm should be used when the maximum aggregate size is 38 mm.(3) Gyratory-compacted specimens were sawed to provide specimens of this size. The data from these tests are given in tables 69 and 70 along with the statistical rankings. One set of specimens was used for all tests shown in both tables. The Repeated Shear test was only performed at 58 °C because this test is destructive. The use of a larger size specimen did not improve the degree of correlation to ALF pavement performance. The best results were provided by the compliance parameter and permanent shear strain from Simple Shear at 40 °C.

Table 58. SST results for the five surface mixtures at 40 °C.

ALF Ranking at 58 °C and a 20-mm Rut Depth	Simple Shear at Constant Height and 40 °C: Compliance Parameter, 1/MPa	Permanent Shear Strain, 10^{-6} mm/mm	Maximum Axial Stress, kPa
(A) Novophalt	0.127	2 020	13.1
(B) Styrelf	0.224	4 020	14.5
(C) AC-20	0.702	19 200	28.9
(C) AC-10	0.766	20 400	40.7
(D) AC-5	1.030	25 500	48.5

ALF Ranking at 58 °C and a 20-mm Rut Depth	Frequency Sweep at Constant Height and 40 °C: Shear Modulus G*, at 10.0 Hz, MPa	Shear Modulus G*, at 2.0 Hz, MPa	G*/sinδ, 10.0 Hz, MPa	G*/sinδ, 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency
(A) Novophalt	409	236	644	378	0.28
(B) Styrelf	281	150	396	212	0.33
(C) AC-20	222	103	256	119	0.35
(C) AC-10	134	60	156	69	0.35
(D) AC-5	62	34	71	39	0.31

ALF Ranking at 58 °C and a 20-mm Rut Depth	Repeated Shear at Constant Height and 40 °C: Slope of Cumulative Permanent Strain	Cumulative Permanent Strain at 5,000 Cycles, 10^{-6} mm/mm
(A) Novophalt	0.30	1 830
(B) Styrelf	0.36	3 480
(C) AC-20	0.35	14 820
(C) AC-10	0.34	17 040
(D) AC-5	0.35	22 200

Table 59. Statistical rankings for the five surface mixtures provided by the SST at 40 °C.[1]

	Simple Shear at Constant Height and 40 °C		
ALF Ranking at 58 °C and a 20-mm Rut Depth	Log Compliance Parameter, 1/MPa	Log Permanent Shear Strain, 10^{-6} mm/mm	Maximum Axial Stress, kPa
(A) Novo	(A) Novo	(A) Novo	(A) Novo
(B) Sty	(B) Sty	(B) Sty	(A) Sty
(C) AC-20	(C) AC-20	(C) AC-20	(B) AC-20
(C) AC-10	(C) AC-10	(C) AC-10	(C) AC-10
(D) AC-5	(D) AC-5	(D) AC-5	(D) AC-5

	Frequency Sweep at Constant Height and 40 °C				
ALF Ranking at 58 °C and a 20-mm Rut Depth	Shear Modulus G*, at 10.0 Hz, MPa	Log Shear Modulus G*, at 2.0 Hz, MPa	G*/sinδ, 10.0 Hz, MPa	Log G*/sinδ, 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency
(A) Novo	(A) Novo	(A) Novo	(A) Novo	(A) Novo	(A) Novo
(B) Sty	(B) Sty	(B) Sty	(B) Sty	(B) Sty	(AB) AC-5
(C) AC-20	(C) AC-20	(C) AC-20	(C) AC-20	(C) AC-20	(AB) Sty
(C) AC-10	(D) AC-10	(D) AC-10	(D) AC-10	(D) AC-10	(AB) AC-20
(D) AC-5	(E) AC-5	(E) AC-5	(E) AC-5	(E) AC-5	(B) AC-10

	Repeated Shear at Constant Height and 40 °C	
ALF Ranking at 58 °C and a 20-mm Rut Depth	Slope of Cumulative Permanent Strain	Log Cumulative Permanent Strain at 5,000 Cycles, 10^{-6} mm/mm
(A) Novo	(A) Novo	(A) Novo
(B) Sty	(A) AC-10	(B) Sty
(C) AC-20	(A) AC-20	(C) AC-20
(C) AC-10	(A) AC-5	(CD) AC-10
(D) AC-5	(A) Sty	(D) AC-5

[1] The letters are the statistical ranking, with "A" denoting the mixture with the lowest susceptibility to rutting.

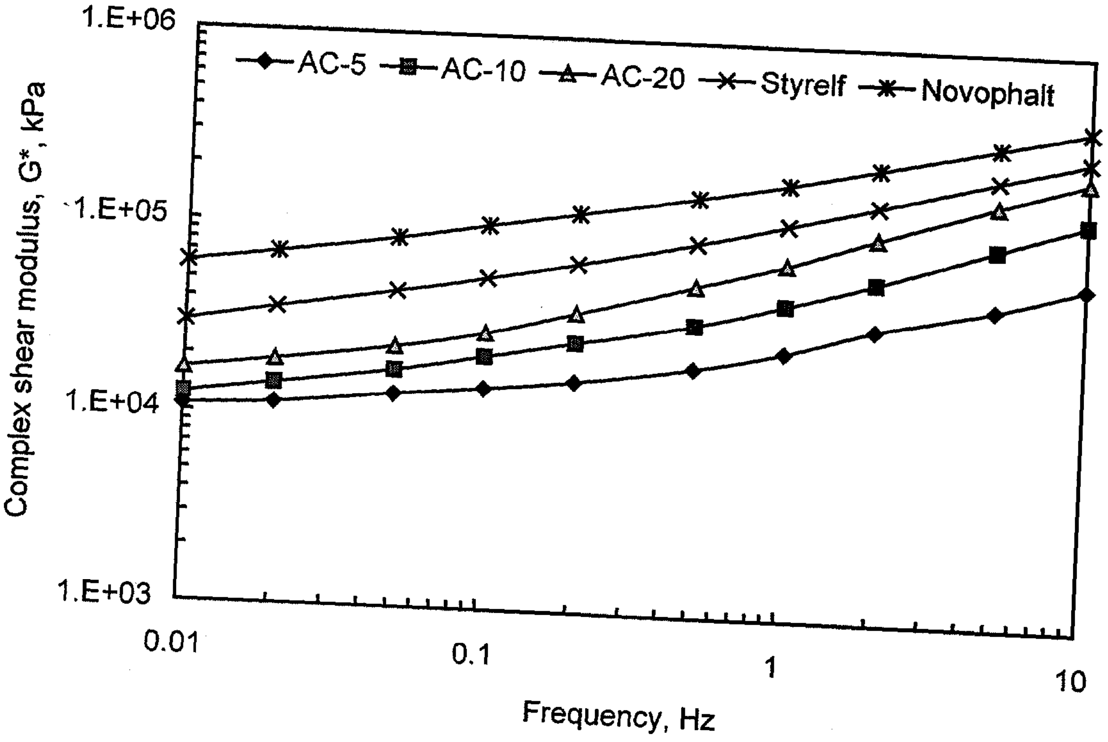

Figure 53. Complex shear modulus, G*, at 40 °C.

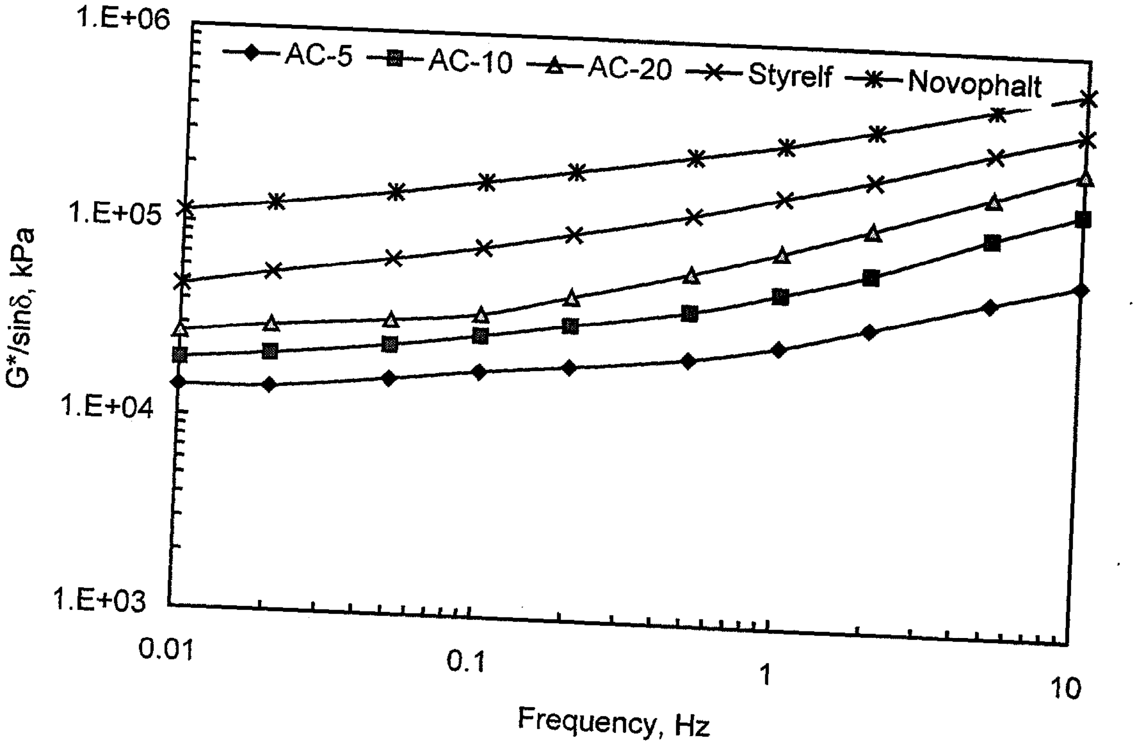

Figure 54. G*/sinδ at 40 °C.

Table 60. SST results for the five surface mixtures at 58 °C.

ALF Ranking at 58 °C and a 20-mm Rut Depth	Simple Shear at Constant Height and 58 °C		
	Compliance Parameter, 1/MPa	Permanent Shear Strain, 10^{-6} mm/mm	Maximum Axial Stress, kPa
(A) Novophalt	0.351	3 070	4.9
(B) Styrelf	0.910	8 060	10.9
(C) AC-20	1.720	22 700	16.1
(C) AC-10	1.450	16 400	14.2
(D) AC-5	1.390	18 800	17.3

ALF Ranking at 58 °C and a 20-mm Rut Depth	Frequency Sweep at Constant Height and 58 °C				
	Shear Modulus G*, at 10.0 Hz, MPa	Shear Modulus G*, at 2.0 Hz, MPa	G*/sinδ, 10.0 Hz, MPa	G*/sinδ, 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency
(A) Novophalt	170	124	251	172	0.22
(B) Styrelf	93	61	136	98	0.16
(C) AC-20	89	70	125	116	0.10
(C) AC-10	66	58	111	108	0.09
(D) AC-5	71	60	138	127	0.08

ALF Ranking at 58 °C and a 20-mm Rut Depth	Repeated Shear at Constant Height and 58 °C	
	Slope of Cumulative Permanent Strain	Cumulative Permanent Strain at 5,000 Cycles, 10^{-6} mm/mm
(A) Novophalt	NT	NT
(B) Styrelf	NT	NT
(C) AC-20	0.35	34 200
(C) AC-10	0.39	31 800
(D) AC-5	NT	NT

NT = Not tested.

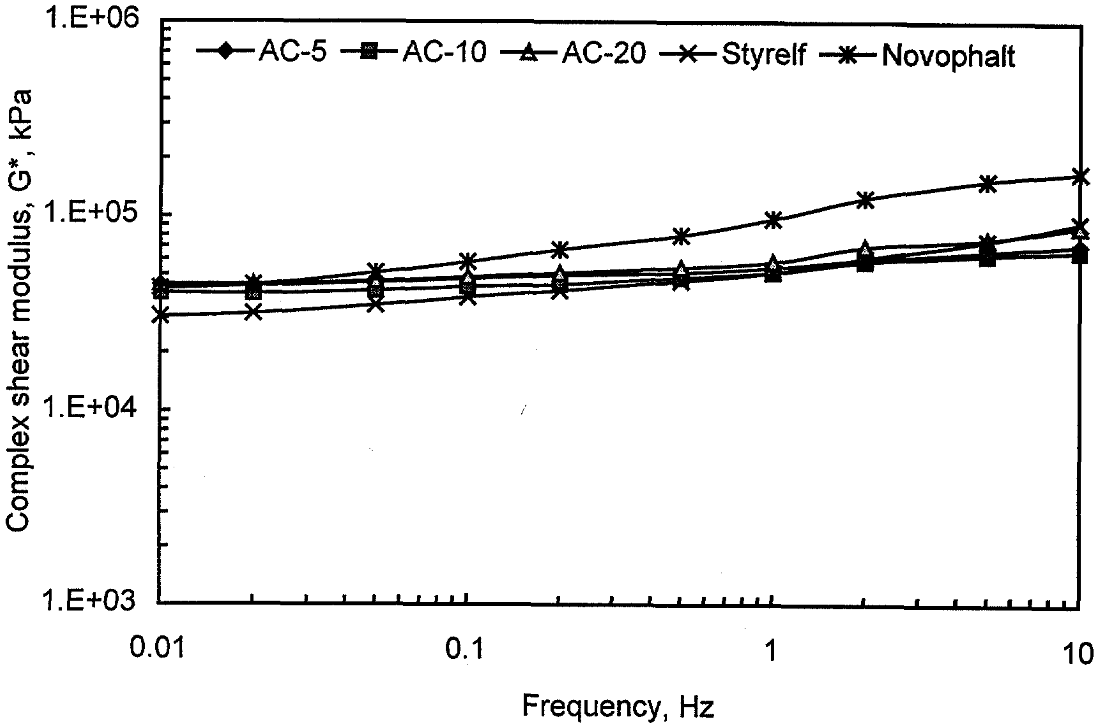

Figure 55. Complex shear modulus, G*, at 58 °C.

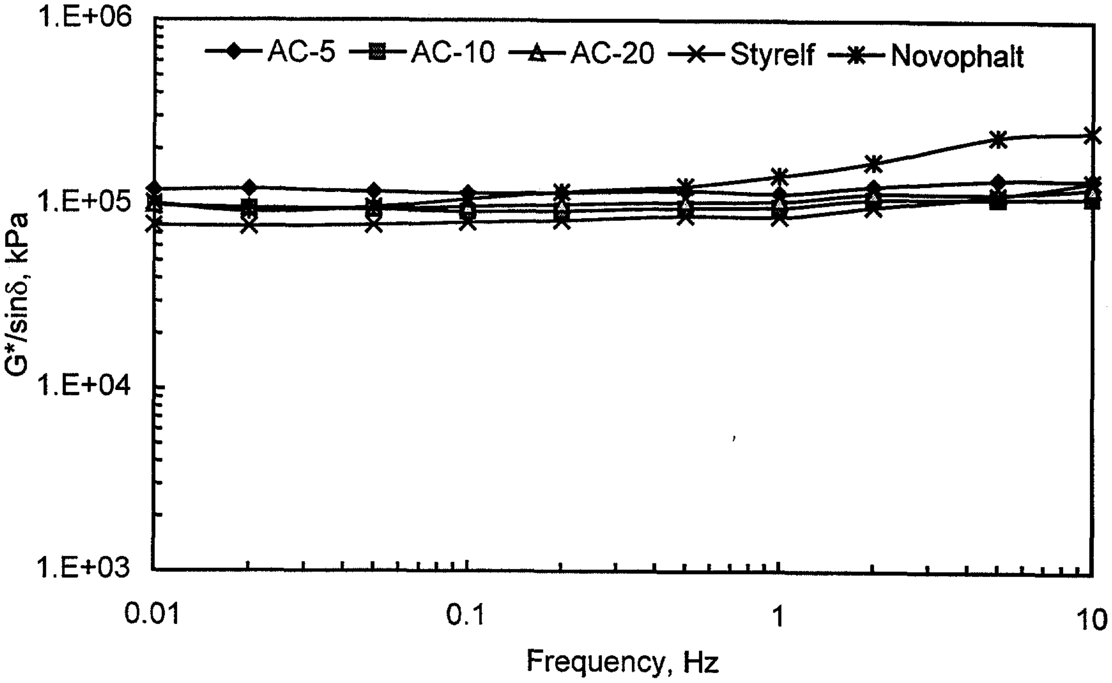

Figure 56. G*/sinδ at 58 °C.

Table 61. Statistical rankings for the five surface mixtures provided by the SST at 58 °C.[1]

	Simple Shear at Constant Height and 58 °C		
ALF Ranking at 58 °C and a 20-mm Rut Depth	Log Compliance Parameter, 1/MPa	Log Permanent Shear Strain, 10^{-6} mm/mm	Maximum Axial Stress, kPa
(A) Novo	(A) Novo	(A) Novo	(A) Novo
(B) Sty	(B) Sty	(B) Sty	(B) Sty
(C) AC-20	(BC) AC-5	(C) AC-10	(C) AC-10
(C) AC-10	(C) AC-10	(C) AC-5	(C) AC-20
(D) AC-5	(C) AC-20	(C) AC-20	(C) AC-5

	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	G*/sinδ, 10.0 Hz, MPa	G*/sinδ, 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency
(A) Novo	(A) Novo	(A) Novo	(A) Novo	(A) Novo	(A) AC-5
(B) Sty	(BD) Sty	(B) AC-20	(B) AC-5	(AB) AC-5	(A) AC-10
(C) AC-20	(B) AC-20	(B) Sty	(B) Sty	(AB) AC-20	(A) AC-20
(C) AC-10	(BC) AC-5	(B) AC-5	(B) AC-20	(B) AC-10	(B) Sty
(D) AC-5	(CD) AC-10	(B) AC-10	(B) AC-10	(AB) Sty	(C) Novo

	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, 10^{-6} mm/mm
(A) Novo	No Ranking	No Ranking
(B) Sty		
(C) AC-20		
(C) AC-10		
(D) AC-5		

[1] The letters are the statistical ranking, with "A" denoting the mixture with the lowest susceptibility to rutting.

Table 62. Coefficients of variation in terms of percentages for the SST based on the data for the five surface mixtures.

	Simple Shear at Constant Height		
Test Temperature	Compliance Parameter, 1/MPa	Permanent Shear Strain, 10^{-6} mm/mm	Maximum Axial Stress, kPa
40 °C	15	18	18
58 °C	27	43	17

	Frequency Sweep at Constant Height				
Test Temperature	Shear Modulus G*, at 10.0 Hz, MPa	Shear Modulus G*, at 2.0 Hz, MPa	G*/sinδ, 10.0 Hz, MPa	G*/sinδ, 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency
40 °C	14	17	18	24	15
58 °C	20	26	20	38	98

	Repeated Shear at Constant Height	
Test Temperature	Slope of Cumulative Permanent Strain	Cumulative Permanent Strain at 5,000 Cycles, 10^{-6} mm/mm
40 °C	14	33
58 °C	NA	NA

NA = Not applicable because of a lack of sufficient data.

Table 63. SST results for the surface and base mixtures at 40 °C.

	Simple Shear at Constant Height and 40 °C		
ALF Ranking at 58 °C and a 20-mm Rut Depth	Compliance Parameter, 1/MPa	Permanent Shear Strain, 10^{-6} mm/mm	Maximum Axial Stress, kPa
AC-20 Base A	0.490	9 370	29.5
AC-5 Base B	0.794	23 000	31.6
AC-20 Surface C	0.702	19 200	28.9
AC-5 Surface D	1.030	25 500	48.5

	Frequency Sweep at Constant Height and 40 °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	G*/sinδ, 10.0 Hz, MPa	G*/sinδ, 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency
AC-20 Base A	291	126	353	147	0.44
AC-5 Base B	93	48	113	60	0.27
AC-20 Surface C	222	103	256	119	0.35
AC-5 Surface D	62	34	71	39	0.31

	Repeated Shear at Constant Height and 40 °C	
ALF Ranking at 58 °C and a 20-mm Rut Depth	Slope of Cumulative Permanent Strain	Cumulative Permanent Strain at 5,000 Cycles, 10^{-6} mm/mm
AC-20 Base A	0.30	9 640
AC-5 Base B	0.45	14 460
AC-20 Surface C	0.35	14 820
AC-5 Surface D	0.35	22 200

Table 64. Statistical rankings for the surface and base mixtures provided by the SST at 40 °C.[1]

ALF Ranking at 58 °C and a 20-mm Rut Depth		Simple Shear at Constant Height and 40 °C: Compliance Parameter, 1/MPa	Permanent Shear Strain, 10^{-6} mm/mm	Maximum Axial Stress, kPa
AC-20 Base	A	A	A	A
AC-5 Base	B	BC	BC	A
AC-20 Surface	C	AB	B	A
AC-5 Surface	D	C	C	B

ALF Ranking at 58 °C and a 20-mm Rut Depth		Frequency Sweep at Constant Height and 40 °C: Log Shear Modulus G*, at 10.0 Hz, MPa	Log Shear Modulus G*, at 2.0 Hz, MPa	Log G*/sinδ, 10.0 Hz, MPa	Log G*/sinδ, 2.0 Hz, MPa	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

ALF Ranking at 58 °C and a 20-mm Rut Depth		Repeated Shear at Constant Height and 40 °C: Slope of Cumulative Permanent Strain	Cumulative Permanent Strain at 5,000 Cycles, 10^{-6} mm/mm
AC-20 Base	A	A	A
AC-5 Base	B	A	A
AC-20 Surface	C	A	A
AC-5 Surface	D	B	B

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[1] The letters are the statistical ranking, with "A" denoting the mixture with the lowest susceptibility to rutting.

Table 65. Non-statistical rankings for the surface and base mixtures provided by the SST at 40 °C.[1]

ALF Ranking at 58 °C and a 20-mm Rut Depth		French PRT at 60 °C	Georgia LWT at 40 °C	Hamburg WTD at 50 °C	Repeated Load Test at 40 °C or 58 °C
AC-20 Base	A	B	A	B	A
AC-5 Base	B	D	C	C	C
AC-20 Surface	C	A	B	A	B
AC-5 Surface	D	C	D	D	D

Simple Shear at Constant Height and 40 °C

ALF Ranking at 58 °C and a 20-mm Rut Depth		Compliance Parameter, 1/MPa	Permanent Shear Strain, 10^{-6} mm/mm	Maximum Axial Stress, kPa
AC-20 Base	A	A	A	B
AC-5 Base	B	C	C	C
AC-20 Surface	C	B	B	A
AC-5 Surface	D	D	D	D

Frequency Sweep at Constant Height and 40 °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	G*/sinδ, 10.0 Hz, MPa	G*/sinδ, 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency
AC-20 Base	A	A	A	A	A	D
AC-5 Base	B	C	C	C	C	A
AC-20 Surface	C	B	B	B	B	C
AC-5 Surface	D	D	D	D	D	B

[1] The letters are the ranking according to the averages, with "A" denoting the mixture with the lowest susceptibility to rutting.

Table 65. Non-statistical rankings for the surface and base mixtures provided by the SST at 40 °C (continued).[1]

		Repeated Shear at Constant Height and 40 °C	
ALF Ranking at 58 °C and a 20-mm Rut Depth		Slope of Cumulative Permanent Strain	Cumulative Permanent Strain at 5,000 Cycles, 10^{-6} mm/mm
AC-20 Base	A	A	A
AC-5 Base	B	C	B
AC-20 Surface	C	B	C
AC-5 Surface	D	B	D

[1] The letters are the ranking according to the averages, with "A" denoting the mixture with the lowest susceptibility to rutting.

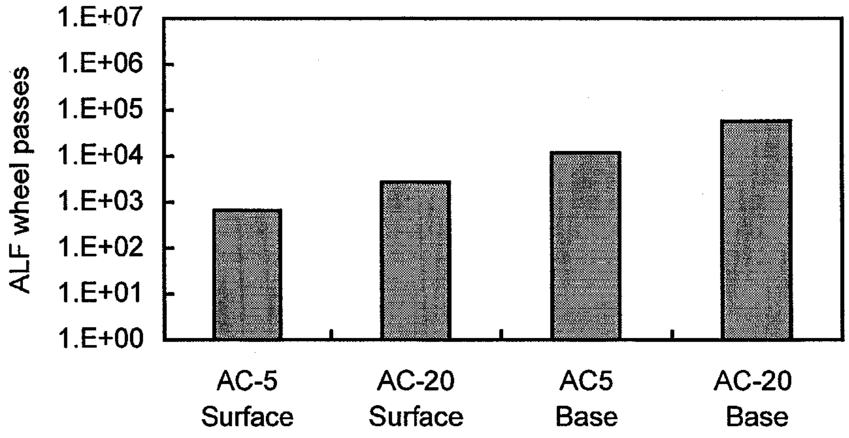

Figure 57. ALF wheel passes at a 20-mm rut depth vs. mixture type.

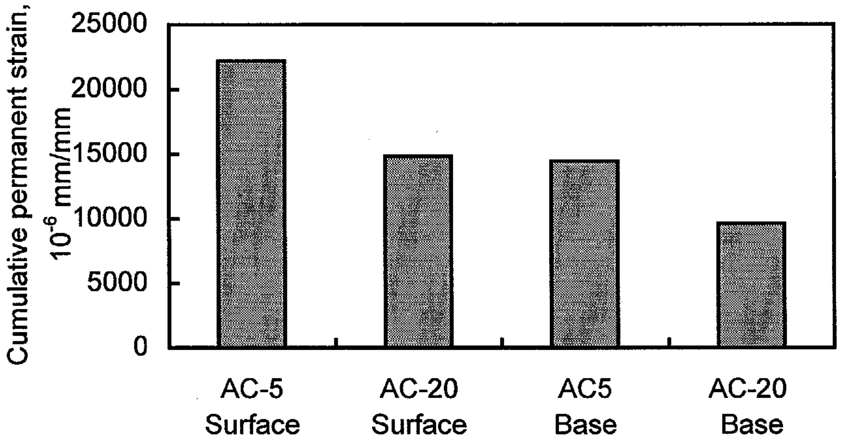

Figure 58. Cumulative permanent strain at 40 °C and 5,000 cycles.

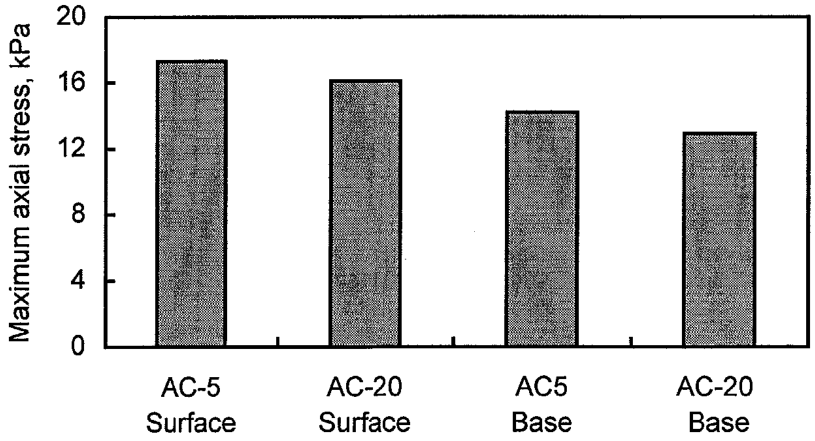

Figure 59. Maximum axial stress at 58 °C.

Table 66. Results from *t*-tests showing the effect of nominal maximum aggregate size and the associated decrease on optimum binder content (continued).[1]

		Frequency Sweep at Constant Height and 40 °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	G*/sinδ, 10.0 Hz, MPa	G*/sinδ, 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency
AC-20 Base	A	291* A	126* A	353* A	147* A	0.44 B
AC-20 Surface	B	222 A	103 A	256 B	119 A	0.35 A
AC-5 Base	A	93* A	48* A	113* A	60* A	0.27 A
AC-5 Surface	B	62 B	34 B	71 B	39 B	0.31 B

		Repeated Shear at Constant Height and 40 °C	
ALF Ranking at 58 °C and a 20-mm Rut Depth		Slope of Cumulative Permanent Strain	Cumulative Permanent Strain at 5,000 Cycles, 10^{-6} mm/mm
AC-20 Base	A	0.30* A	9 640* A
AC-20 Surface	B	0.35 A	14 820 B
AC-5 Base	A	0.45 B	14 460* A
AC-5 Surface	B	0.35* A	22 200 A

[1] The letters are the statistical ranking, with "A" denoting the mixture with the lowest susceptibility to rutting.

*Better average value in terms of lower rutting susceptibility.

Table 67. SST results for surface and base mixtures at 58 °C.

ALF Ranking at 58 °C and a 20-mm Rut Depth		Simple Shear at Constant Height and 58 °C		
		Compliance Parameter, 1/MPa	Permanent Shear Strain, 10^{-6} mm/mm	Maximum Axial Stress, kPa
AC-20 Base	A	0.876	11 300	12.9
AC-5 Base	B	1.140	14 500	14.2
AC-20 Surface	C	1.720	22 700	16.1
AC-5 Surface	D	1.390	18 800	17.3

ALF Ranking at 58 °C and a 20-mm Rut Depth		Frequency Sweep at Constant Height and 58 °C				
		Shear Modulus G*, at 10.0 Hz, MPa	Shear Modulus G*, at 2.0 Hz, MPa	G*/sinδ, 10.0 Hz, MPa	G*/sinδ, 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency
AC-20 Base	A	95	82	139	101	0.10
AC-5 Base	B	74	114	134	131	0.04
AC-20 Surface	C	89	70	125	116	0.10
AC-5 Surface	D	71	60	138	127	0.08

ALF Ranking at 58 °C and a 20-mm Rut Depth		Repeated Shear at Constant Height and 58 °C	
		Slope of Cumulative Permanent Strain	Cumulative Permanent Strain at 5,000 Cycles, 10^{-6} mm/mm
AC-20 Base	A	0.33	34 020
AC-5 Base	B	NT	NT
AC-20 Surface	C	0.35	34 200
AC-5 Surface	D	NT	NT

NT = Not tested.

Table 68. Statistical rankings for the surface and base mixtures provided by the SST at 58 °C.[1]

ALF Ranking at 58 °C and a 20-mm Rut Depth		Simple Shear at Constant Height and 58 °C		
		Compliance Parameter, 1/MPa	Permanent Shear Strain, 10^{-6} mm/mm	Maximum Axial Stress, kPa
AC-20 Base	A	A	A	A
AC-5 Base	B	A	AB	AB
AC-20 Surface	C	B	B	B
AC-5 Surface	D	AB	AB	B

ALF Ranking at 58 °C and a 20-mm Rut Depth		Frequency Sweep at Constant Height and 58 °C				
		Shear Modulus G*, at 10.0 Hz, MPa	Shear Modulus G*, at 2.0 Hz, MPa	G*/sinδ, 10.0 Hz, MPa	G*/sinδ, 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency
AC-20 Base	A	A	A	A	A	B
AC-5 Base	B	A	A	A	A	A
AC-20 Surface	C	A	A	A	A	B
AC-5 Surface	D	A	A	A	A	AB

ALF Ranking at 58 °C and a 20-mm Rut Depth		Repeated Shear at Constant Height and 58 °C	
		Slope of Cumulative Permanent Strain	Cumulative Permanent Strain at 5,000 Cycles, 10^{-6} mm/mm
AC-20 Base	A	No Ranking	No ranking
AC-5 Base	B		
AC-20 Surface	C		
AC-5 Surface	D		

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[1] The letters are the statistical ranking, with "A" denoting the mixture with the lowest susceptibility to rutting.

Table 69. SST results at 40 °C for the surface and base mixtures using specimens prepared in the laboratory with a diameter of 150 mm and a height of 75 mm.

ALF Ranking at 58 °C and a 20-mm Rut Depth		Simple Shear at Constant Height and 40 °C: Compliance Parameter, 1/MPa		Permanent Shear Strain, 10^{-6} mm/mm		Maximum Axial Stress, kPa	
AC-20 Base	A	0.530	A	14 000	A	32.8	A
AC-5 Base	B	1.109	B	29 400	B	46.5	B
AC-20 Surface	C	0.941	B	25 900	B	31.6	A
AC-5 Surface	D	1.521	C	42 200	C	43.5	B

ALF Ranking at 58 °C and a 20-mm Rut Depth		Frequency Sweep at Constant Height and 40 °C: Shear Modulus[1] 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	279	A	119	A	0.46	C
AC-5 Base	B	85	C	42	C	0.32	B
AC-20 Surface	C	208	B	89	B	0.42	C
AC-5 Surface	D	61	D	31	D	0.27	A

[1] Statistical ranking is based on $\log_{10}$ of the value.

Table 70. SST results at 58 °C for the surface and base mixtures using specimens prepared in the laboratory with a diameter of 150 mm and a height of 75 mm.

	Simple Shear at Constant Height and 58 °C		
ALF Ranking at 58 °C and a 20-mm Rut Depth	Compliance Parameter, 1/MPa	Permanent Shear Strain, 10^{-6} mm/mm	Maximum Axial Stress, kPa
AC-20 Base A	1.228 A	12 500 A	14.0 A
AC-5 Base B	1.826 A	18 700 A	17.6 BC
AC-20 Surface C	1.559 A	19 200 A	19.9 C
AC-5 Surface D	1.506 A	19 300 A	16.9 B

	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[1] G*, at 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency
AC-20 Base A	69 A	45 A	0.14 C
AC-5 Base B	48 B	37 B	0.10 B
AC-20 Surface C	63 A	44 A	0.12 BC
AC-5 Surface D	60 A	50 A	0.05 A

	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 500 Cycles,[1,2] 10^{-6} mm/mm
AC-20 Base A	0.56 A	6 670 A
AC-5 Base B	0.79 B	15 600 B
AC-20 Surface C	0.56 A	8 200 A
AC-5 Surface D	0.76 B	20 100 B

[1] Statistical ranking is based on $\log_{10}$ of the value.

[2] The data were compared at 500 cycles rather than at 5000 cycles because the specimens failed rapidly.

g. Results From the SST for the Surface vs. Base Mixture Study at 40 and 58 °C Using Specimens With a Diameter of 203 mm and a Height of 75 mm

Tables 71 and 72 show data using specimens compacted by the GTM having a diameter of 203 mm and a height of 75 mm. The use of this specimen size did not improve the degree of correlation to ALF pavement performance.

11. Tests Using the Purdue University Wheel Test Device (PURWheel)

a. Description of the Equipment

Slabs from the pavements were tested by Purdue University using the PURWheel. This work was not part of the original work plan but was added when the device became available. Pavement slabs were used for evaluating the PURWheel, while slabs prepared and compacted in the laboratory were used for evaluating the French PRT, Georgia LWT, and Hamburg WTD. However, slabs sawed from lanes 9, 10, 11, and 12 were also tested by the French PRT, Georgia LWT, and Hamburg WTD for the surface vs. base mixture study. The data are given in chapter 5.

The PURWheel was developed by the Purdue University based on the Hamburg WTD, but it was designed to be more versatile. The PURWheel can test slabs as large as 620 mm by 305 mm with a maximum height of 127 mm. Each wheel is moved by an air cylinder that provides a constant speed over the section of the slab where the rut is measured. Sensors in the air cylinders maintain the speed by controlling the air pressure. Speeds from 0.20 to 0.40 m/s can be applied. A solid steel wheel with a width up to 100 mm, or pneumatic rubber tire with an inflation pressure up to 860 kPa, can be used. The rubber tire can be programmed to wander. A load from 500 to 1900 N can be applied. The rut depths are measured at 10 locations along the wheel path at a spacing of 10 mm using LVDT's. Rut depth measurements are made at equal time intervals, such as at every 250 wheel passes.

A test temperature in the range of 25.0 to 60.0 ±0.2 °C can be chosen. Slabs can be tested in a dry state or under water like the Hamburg WTD. When testing in a dry state, water surrounding the steel container is used to heat the slabs from the bottom, while an enclosed chamber allows the air above the slab to be heated. The slabs are conditioned at the test temperature for 2 h. The temperature above and below the slab is recorded every 250 wheel passes.

The slabs tested in this study were cut longitudinally from the wheelpaths of the pavements, but outside of the area where the ALF would test the pavements. The dimensions were 305 by 290 by 76 mm in height. The AC-5, AC-10, AC-20, Novophalt, and Styrelf surface mixture slabs had initial average air-void levels of 6.5, 7.1, 8.0, 9.5, and 8.5 percent, respectively. The AC-5 and AC-20 (PG 59 and 70) base mixtures had initial average air-void levels of 6.1 and 7.2 percent. Four replicate slabs were tested per mixture at 58 °C.

A pneumatic, saw toothed, rubber tire was used with no wheel wander. The contact pressure was 620 kPa, and the inflation pressure was 830 kPa. The load was 1530 N and the speed was 0.33 m/s (1.2 km/h). All slabs were tested in a dry state. Like the other three wheel-tracking devices used in this study, only the downward rut depth was measured.

b. Results From the PURWheel

The average data and statistical rankings are shown in table 73. The statistical rankings show that the PURWheel divided the seven mixtures into three groups. A linear regression between the ALF rut depths at 2,730 wheel passes and the PURWheel rut depths provided an r^2 of 0.78. The r^2 using log ALF wheel passes at a 20-mm rut depth was 0.82. The statistical ranking for the five surface mixtures reasonably agreed with ALF. The statistical rankings for the four mixtures used in the surface vs. base mixture study were not the same as the rankings provided by the other wheel-tracking devices, the repeated load compression test, and the SST. The PURWheel data matched the ALF pavement results in terms of the effect of nominal maximum aggregate size on rutting susceptibility, but it did not measure the effects of binder grade.

12. Comments on the Validation Effort

Pavement performance at 58 °C was used for validating the mixture tests because this was the only temperature at which all seven mixtures were tested. Comparing the data from the wheel-tracking devices to the pavement data at 58 °C seemed reasonable because the French PRT and Hamburg WTD methodologies were based on heavy traffic volumes and a Superpave high-temperature PG of approximately 58 °C. The Georgia LWT methodology was based on heavy traffic volumes and a temperature of approximately 64 °C. Even so, the rankings provided by the ALF would be different at pavement temperatures above and below 58 °C. This is shown by the hypothetical rankings in table 74 for temperatures other than 58 °C. At temperatures of 46 to 52 °C, the two mixtures with the modified binders would not be expected to fail by rutting. At temperatures of 70 to 76 °C, all three surface mixtures with the unmodified binders would be expected to fail rapidly. Less than 2,800 wheel passes were needed to fail these three surface mixtures at 58 °C. The hypothetical rankings are presented to show that there should be more than one statistical ranking for pavement rutting performance.

The loading frequency and test temperature for the ALF and the mixture tests were not always the same. Since the performance of a binder in an asphalt mixture is dependent on frequency and temperature, it should not be expected that the rankings perfectly agree. Even so, the rankings in table 54 point to one problem. The Georgia LWT correctly ranked the five surface mixtures based on the average data, but the statistical rankings indicated that the rutting performances of the Styrelf and AC-20 (PG 70) mixtures were not significantly different. This is not correct based on ALF pavement performance at 58 °C. The ranking indicated that the Georgia LWT may only be able to measure the effect of binder grade when the grades are widely different. Thus, the test can be considered deficient because a mix designer generally has to choose between binders that have relatively close grades, such as between a PG 64-22 and a PG 70-22. However, the Georgia LWT did rank the Styrelf and AC-20 (PG 70) mixtures differently at a 93-percent confidence level. This indicates that either the variability of data has to be reduced, or the testing protocol, such as the test temperature, has to be changed to increase the range in the data.

13. Supplementary Analysis: Shear Modulus vs. Compression Modulus

The shear moduli, $|G^*|$, of the seven mixtures vs. frequency were measured by the SST Frequency Sweep test at 40 and 58 °C. This included the standard frequency of 10.0 Hz. Resilient compression moduli, E_{res}, and dynamic compression moduli, E_{dyn}, were measured by the unconfined repeated load compression test at 10.0 Hz and 40 and 58 °C using a 0.1-s loading time followed by a 0.9-s rest period. E_{res} is calculated using the recovered strain per cycle of loading, while E_{dyn} is calculated using the total strain per cycle of loading. E_{dyn} can also be described as $|E^*|$. Poisson's ratios were calculated using elastic theory:

$$\mu = [E/2G]-1$$

where: μ = Poisson's ratio,
E = Compression modulus, and
G = Shear modulus.

Two sets of Poisson's ratios were calculated. One set was based on $|G^*|$ and E_{res}, while the other set was based on $|G^*|$ and E_{dyn}. The data at 40 °C are given in table 75. E_{res} and E_{dyn} were not significantly different because the percentage of the total strain that was permanent per cycle of loading was generally small for each mixture. The largest difference in these compression moduli was 21 percent, which was provided by the AC-20 (PG 70) surface mixture. The difference for the other mixtures was 10 percent or less. The high Poisson's ratios in table 75 indicate that the shear and compression moduli do not obey the laws of elasticity for isotropic, elastic materials. Theoretically, the ratios cannot be greater than 0.5.

The repeated load compression test was a stress-controlled test, whereas the SST was a strain-controlled test. However, if both modes of loading are performed in the linear range, where the modulus is independent of the applied stress or strain level, both modes should give the same modulus for a given mixture. The repeated load compression test at 40 °C was performed in the linear range. This was determined prior to testing. The small differences between E_{res} and E_{dyn} for most of the mixtures in table 75 also indicate the data were taken in the linear range.

The Frequency Sweep test was performed using a peak strain of ±0.10 µm/mm. When using this test, it is assumed that the data are recorded in the linear range. To determine if this was true, the AC-5 (PG 59) surface mixture was tested using six peak strains (±0.02, ±0.10, ±0.20, ±0.40, ±0.60, and ±0.80 μm/mm) and four frequencies (10.0, 1.0, 0.1, and 0.01 Hz). The total strain applied to each specimen, also called the peak-to-peak strain, is double the peak strain: 0.04, 0.20, 0.40, 0.80, 1.20, and 1.60 μm/mm. The AC-5 (PG 59) surface mixture was chosen because it had the lowest $|G^*|$. It was hypothesized that the response of this mixture should become nonlinear at a strain that is lower than for the other mixtures.

The results are shown in figures 60, 61, and 62. The data indicate that the moduli were relatively high at a peak strain of ±0.02 μm/mm. The data were also highly variable from replicate to replicate. Most likely, the response at ±0.02 μm/mm was the result of the inability of the equipment to accurately apply this strain or measure the resultant stress. For this reason, both a minimum and a maximum strain are normally used to describe the linear range. Figures 60 and 61 indicate that a strain in the range of ±0.40 to ±0.60 μm/mm should be used instead of ±0.10 μm/mm for this mixture. The moduli were virtually the same at these higher strains. This points out a discrepancy in AASHTO TP7-94. This test limits the strain to 0.10 μm/mm, but then states that a strain of 0.50 μm/mm should be applied to the specimen. It is also unclear whether these strains are peak strains or peak-to-peak strains. Based on figures 60 and 61, a peak strain of ±0.40 to ±0.60 μm/mm should be used. Figure 62 shows that the data were also highly variable using a frequency of 0.01 Hz. This indicated that some adjustment in the equipment is needed when using this frequency.

The use of a peak strain greater than ±0.10 μm/mm for the AC-5 (PG 59) surface mixture would decrease $|G^*|$ slightly. A decrease in $|G^*|$ would increase the Poisson's ratio, which was already too high based on the laws of elasticity for isotropic materials. It was concluded that nonlinearity was not the reason for the high Poisson's ratios.

A reason for the high Poisson's ratios was not evident, but if the tension and compression moduli of an asphalt mixture are not equal, the elastic equation used to calculate Poisson's ratio is not valid. To determine whether these moduli are the same, the repeated load compression test would have to be modified so that both compression and tension are applied to the same specimen. Tension moduli were not measured in this study because they are not used to evaluate rutting.

The data for the tests at 58 °C are given in table 76. The E_{dyn}'s are lower than the E_{res}'s because the percentage of the total strain that was permanent per cycle of loading was high for each mixture. The Poisson's ratios are negative using E_{dyn} for the same reason: the permanent deformations were high in the compression test. $|G^*|$ and E_{res} provided more reasonable ratios, except for the ratios using the two larger SST specimen sizes. As specimen size increased, $|G^*|$ decreased, which increased the ratios. Tables 75 and 76 also show that the $|G^*|$'s of the AC-5 (PG 59) surface mixture at 58 °C were higher than or equal to those at 40 °C using SST specimens sizes of 150 by 50 mm and 150 by 75 mm. More extensive research would be needed to provide reasons for these findings.

Table 71. SST results at 40 °C for the surface and base mixtures using specimens prepared in the laboratory with a diameter of 203 mm and a height of 75 mm.

	Simple Shear at Constant Height and 40 °C		
ALF Ranking at 58 °C and a 20-mm Rut Depth	Compliance Parameter, 1/MPa	Permanent Shear Strain[1], 10^{-6} mm/mm	Maximum Axial Stress, kPa
AC-20 Base A	0.350 A	16 600 A	66.2 A
AC-5 Base B	0.410 A	18 700 A	75.0 A
AC-20 Surface C	0.397 A	18 600 A	71.8 A
AC-5 Surface D	0.595 B	31 800 B	83.0 A

	Frequency Sweep at Constant Height and 40 °C		
ALF Ranking at 58 °C and a 20-mm Rut Depth	Shear Modulus[1] G*, at 10.0 Hz, MPa	Shear Modulus[1] G*, at 2.0 Hz, MPa	Slope of Log G* vs. Log Frequency
AC-20 Base A	265 A	108 A	0.57 C
AC-5 Base B	119 C	49 C	0.44 A
AC-20 Surface C	213 B	82 B	0.53 BC
AC-5 Surface D	92 D	36 D	0.46 AB

	Repeated Shear at Constant Height and 40 °C	
ALF Ranking at 58 °C and a 20-mm Rut Depth	Slope of Cumulative Permanent Strain	Cumulative Permanent Strain at 5000 Cycles, 10^{-6} mm/mm
AC-20 Base A	0.41 A	2 560 A
AC-5 Base B	0.43 A	4 820 B
AC-20 Surface C	0.42 A	3 270 A
AC-5 Surface D	0.42 A	5 960 B

[1] Statistical ranking is based on $\log_{10}$ of the value.

Table 72. SST results at 58 °C for the surface and base mixtures using specimens prepared in the laboratory with a diameter of 203 mm and a height of 75 mm.

ALF Ranking at 58 °C and a 20-mm Rut Depth		Frequency Sweep at Constant Height and 58 °C: Log Shear Modulus[1] G*, at 10.0 Hz, MPa		Log Shear Modulus[1] G*, at 2.0 Hz, MPa		Slope of Log G* vs. Log Frequency	
AC-20 Base	A	55	A	32	A	0.16	B
AC-5 Base	B	34	C	24	B	0.10	A
AC-20 Surface	C	44	B	26	B	0.15	B
AC-5 Surface	D	34	C	24	B	0.11	A

ALF Ranking at 58 °C and a 20-mm Rut Depth		Repeated Shear at Constant Height and 58 °C: Slope of Cumulative Permanent Strain		Cumulative Permanent Strain at 500 Cycles,[2] 10^{-6} mm/mm	
AC-20 Base	A	0.53	A	5 310	A
AC-5 Base	B	0.62	B	8 270	B
AC-20 Surface	C	0.59	AB	8 790	B
AC-5 Surface	D	0.60	AB	7 470	AB

[1] Statistical ranking is based on $\log_{10}$ of the value.

[2] The data were compared at 500 cycles rather than at 5000 cycles because the specimens failed rapidly.

Table 73. Rankings for the rut depths from the Purdue University Wheel Test Device (PURWheel) at 20,000 wheel passes and 58 °C.[1]

Ranking Based on ALF at 58 °C	PURWheel Data		Ranking Based on the Average Rut depth, mm	Statistical Rankings at a 95-Percent Confidence Level Based on Log Rut Depth, mm		
	Rut Depth, mm	Log Rut Depth, mm		All Mixtures	Surface Mixtures	Surface vs. Base Mixtures
Novophalt	1.4	0.15	A	A	A	
Styrelf	2.7	0.42	B	B	B	
AC-20 Base	3.6	0.56	D	B		A
AC-5 Base	3.1	0.49	C	B		A
AC-20[2]	6.5	0.80	E	C	C	B
AC-10	7.4	0.85	G	C	C	
AC-5	6.6	0.82	F	C	C	B

[1] The letters are the ranking, with "A" denoting the mixture with the lowest susceptibility to rutting.

[2] The replicate data showed that there may be one outlier for the AC-20 (PG 70) slabs, but eliminating this datum had no effect on the conclusions or statistical rankings.

Table 74. ALF rankings based on the number of wheel passes needed to obtain rut depths of 10, 15, and 20 mm in the asphalt pavement layer.[1]

Hypothetical Ranking at 46 to 52 °C	Actual Ranking at 58 °C	Actual Ranking at 58 °C	Hypothetical Ranking at 70 to 76 °C
Rut Depth of 10 to 20 mm	Rut Depth of of 10 mm	Rut Depth of 15 to 20 mm	Rut Depth of 10 to 20 mm
(A) Novophalt	(A) Novophalt	(A) Novophalt	(A) Novophalt
(A) Styrelf	(B) Styrelf	(B) Styrelf	(B) Styrelf
(B) AC-20	(C) AC-20	(C) AC-20	(C) AC-20
(C) AC-10	(CD) AC-10	(C) AC-10	(C) AC-10
(D) AC-5	(D) AC-5	(D) AC-5	(C) AC-5

[1] The letters are the ranking, with "A" denoting the mixture with the lowest susceptibility to rutting.

Table 75. Poisson's ratios at 40 °C for the seven mixtures calculated using the shear modulus from the SST and the resilient and dynamic moduli from the repeated load compression test.

Mixture	SST Shear Modulus, |G*|, 10.0 Hz, MPa	Compression Moduli, at 10.0 Hz, MPa		Poisson's Ratio μ = [E/2G)]-1, using	
		E_{res}	E_{dyn}	E_{res}	E_{dyn}
Novophalt[1]	409	1720	1720	1.10	1.10
Styrelf[1]	281	2780	2760	3.95	3.91
AC-20[1]	222	2330	1900	4.25	3.28
AC-20[2]	208	2330	1900	4.60	3.57
AC-20[3]	213	2330	1900	4.47	3.46
AC-10[1]	134	725	800	1.71	1.99
AC-5[1]	62	466	464	2.76	2.74
AC-5[2]	61	466	464	2.82	2.80
AC-5[3]	92	466	464	1.53	1.52
AC-20 Base[1]	291	2370	2320	3.07	2.99
AC-20 Base[2]	279	2370	2320	3.25	3.16
AC-20 Base[3]	265	2370	2320	3.47	3.38
AC-5 Base[1]	93	560	600	2.01	2.23
AC-5 Base[2]	85	560	600	2.29	2.53
AC-5 Base[3]	119	560	600	1.35	1.52
Using SST Specimens with a Diameter and Height of 150 mm by 50 mm:					
Novophalt	409	1720	1720	1.10	1.10
Styrelf	281	2780	2760	3.95	3.91
AC-20	222	2330	1900	4.25	3.28
AC-10	134	725	800	1.71	1.99
AC-5	62	466	464	2.76	2.74
AC-20 Base	291	2370	2320	3.07	2.99
AC-5 Base	93	560	600	2.01	2.23

[1] Using SST specimens with a diameter and height of 150 mm by 50 mm.
[2] Using SST specimens with a diameter and height of 150 mm by 75 mm.
[3] Using SST specimens with a diameter and height of 203 mm by 75 mm.

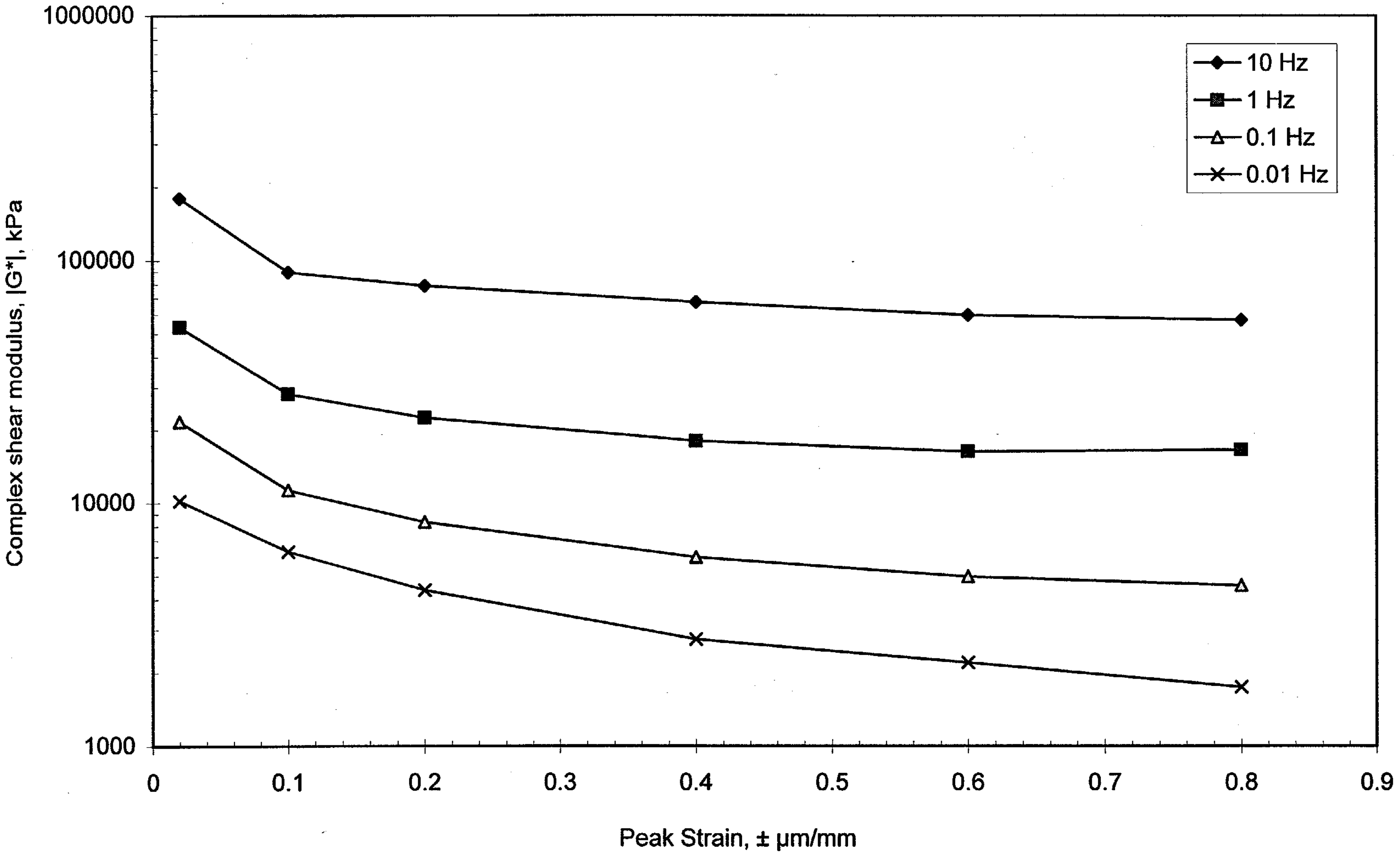

Figure 60. Shear modulus vs. applied strain.

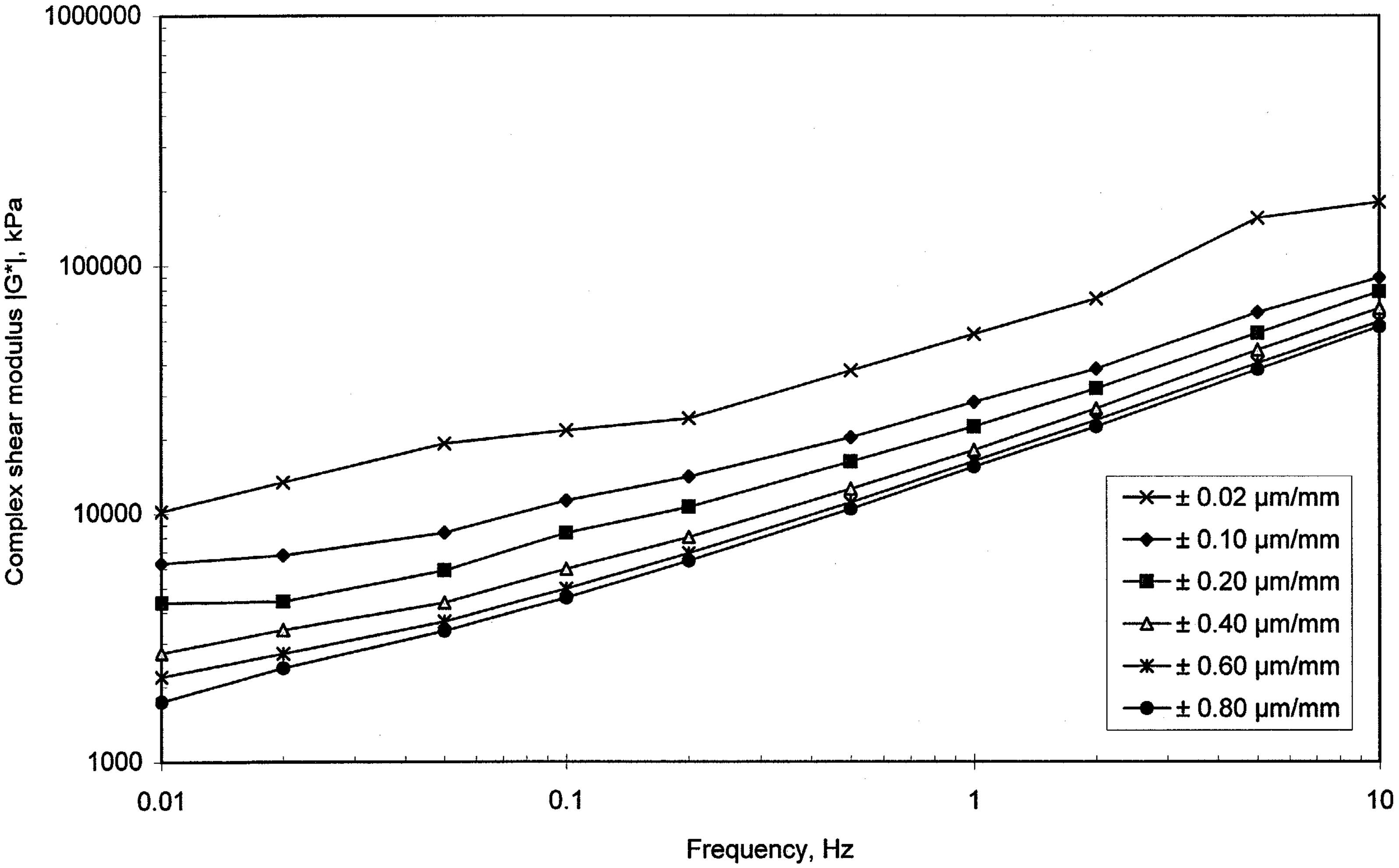

Figure 61. Shear modulus vs. applied frequency.

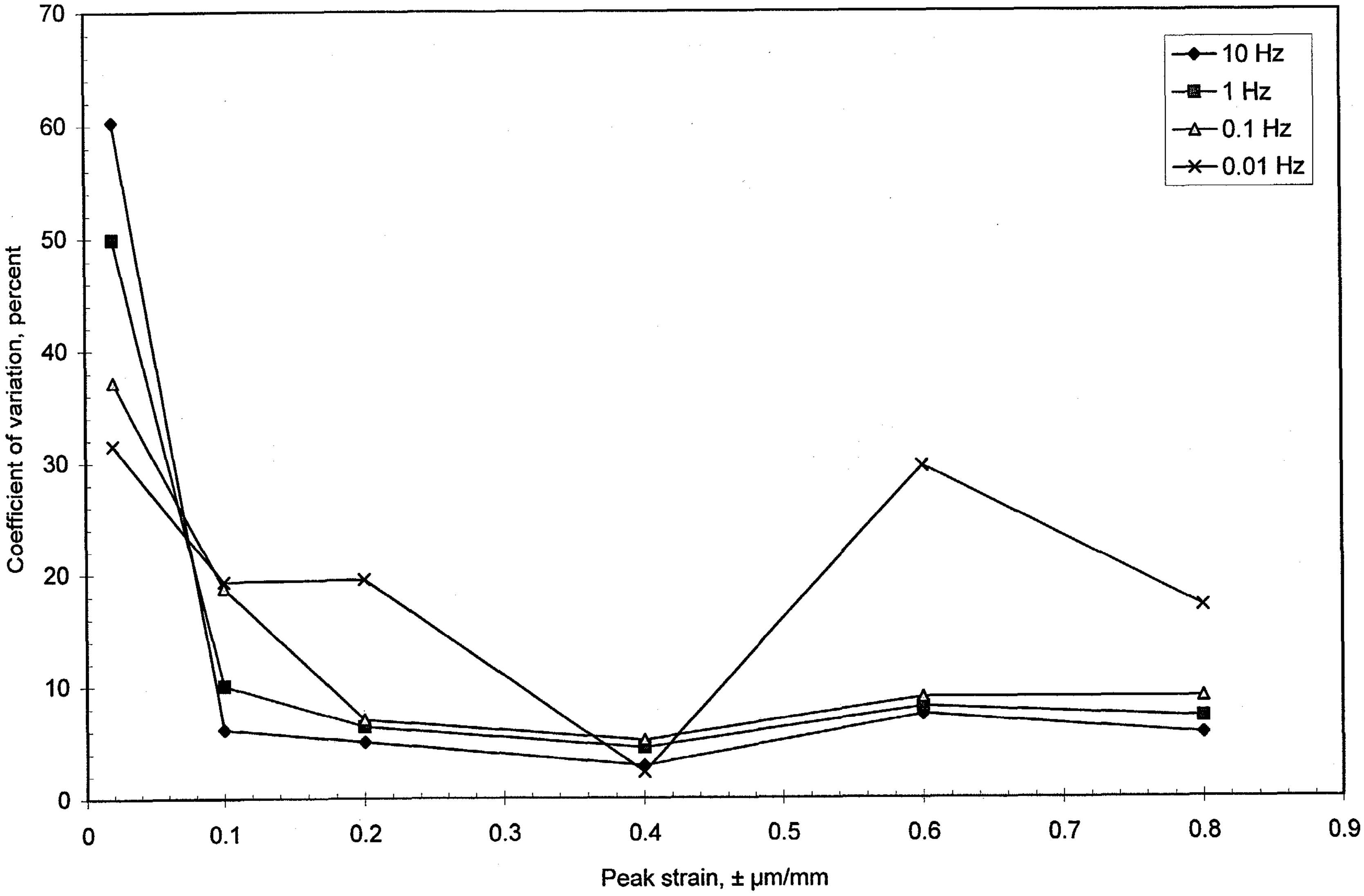

Figure 62. Coefficient of variation for the shear modulus vs. applied strain.

Table 76. Poisson's ratios at 58 °C for the seven mixtures calculated using the shear modulus from the SST and the resilient and dynamic moduli from the repeated load compression test.

Mixture	SST Shear Modulus, |G*|, 10.0 Hz, MPa	Compression Moduli, at 10.0 Hz, MPa		Poisson's Ratio μ = [E/2G)]-1, using	
		E_{res}	E_{dyn}	E_{res}	E_{dyn}
Novophalt[1]	170	427	258	0.26	-0.24
Styrelf[1]	93	370	176	0.99	-0.05
AC-20[1]	89	239	65	0.34	-0.63
AC-20[2]	63	239	65	0.90	-0.48
AC-20[3]	44	239	65	1.72	-0.26
AC-10[1]	66	199	58	0.51	-0.56
AC-5[1]	71	176	61	0.24	-0.57
AC-5[2]	60	176	61	0.47	-0.49
AC-5[3]	34	176	61	1.59	-0.10
AC-20 Base[1]	95	280	80	0.47	-0.58
AC-20 Base[2]	69	280	80	1.03	-0.42
AC-20 Base[3]	55	280	80	1.55	-0.27
AC-5 Base[1]	74	218	55	0.47	-0.63
AC-5 Base[2]	48	218	55	1.27	-0.43
AC-5 Base[3]	34	218	55	2.21	-0.19
Using SST Specimens with a Diameter and Height of 150 mm by 50 mm:					
Novophalt	170	427	258	0.26	-0.24
Styrelf	93	370	176	0.99	-0.05
AC-20	89	239	65	0.34	-0.63
AC-10	66	199	58	0.51	-0.56
AC-5	71	176	61	0.24	-0.57
AC-20 Base	95	280	80	0.47	-0.58
AC-5 Base	74	218	55	0.47	-0.63

[1] Using SST specimens with a diameter and height of 150 mm by 50 mm.
[2] Using SST specimens with a diameter and height of 150 mm by 75 mm.
[3] Using SST specimens with a diameter and height of 203 mm by 75 mm.

14. Conclusions

a. Surface Mixtures

- The French PRT, Georgia LWT, and Hamburg WTD ranked the five surface mixtures the same as ALF based on the averages. Each test provided a slightly different statistical ranking based on Fisher's LSD. The French PRT and Hamburg WTD provided statistical rankings that were slightly better than the Georgia LWT, probably because the range in the data from the best to the worst mixture was smaller for the Georgia LWT.

- The dynamic moduli at 200 cycles and the cumulative permanent strains at 10,000 cycles from the unconfined repeated load compression test at 58 °C ranked the five surface mixtures the same as ALF based on the averages. The statistical rankings were slightly different, but the degree of correlation was good. The slopes from the relationship between cumulative permanent strain and cycles did not differentiate the five surface mixtures according to rutting susceptibility.

- Six of eight SST measurements at 40 °C ranked the five surface mixtures the same as ALF based on the averages: (1) the compliance parameter, permanent shear strain, and maximum axial stress from Simple Shear at Constant Height, (2) G* and G*/sinδ at all frequencies from Frequency Sweep at Constant Height, and (3) cumulative permanent strain at 5,000 cycles from Repeated Shear at Constant Height.

- The two SST measurements at 40 °C that did not correlate with ALF were the slopes from the relationship between log G* and log frequency from Frequency Sweep at Constant Height, and the slopes from the relationship between cumulative permanent strain and cycles from Repeated Shear at Constant Height.

- The statistical rankings for the six promising SST measurements at 40 °C were generally different. However, the statistical rankings for the compliance parameter and permanent shear strain from Simple Shear at Constant Height were identical to the statistical ranking provided by the ALF. The statistical rankings provided by G*, G*/sinδ, and cumulative permanent strain at 5,000 cycles were not identical to ALF, but the degree of correlation was good. The maximum axial stress correlated less with ALF pavement performance based on the statistical rankings.

- The degree of correlation between the SST data at 58 °C and ALF pavement performance was poor. Most SST measurements at 58 °C had coefficients of variation (standard deviation divided by the average) of 20 percent and greater, whereas the coefficients at 40 °C were generally less than 20 percent. The coefficients of variation were based on the data from the surface mixtures which consisted of five binder grades, a single aggregate gradation, and a single binder content.

- The PURWheel did not rank the five mixtures the same as ALF based on the averages. However, the statistical ranking was reasonably close to the statistical ranking provided by the ALF.

b. Surface vs. Base Mixture Study (Four Mixtures Consisting of Two Gradations and Two Binders)

- The increase in nominal maximum aggregate size from 19.0 to 37.5 mm, and the associated 0.85-percent decrease in optimum binder content, significantly decreased rutting susceptibility based on ALF pavement performance. Only two mixture tests ranked the four mixtures the same as ALF based on the averages: the cumulative permanent shear strain at 5,000 cycles and 40 °C from Repeated Shear at Constant Height, and the maximum axial stresses at 58 °C from Simple Shear at Constant Height.

- The majority of the specimens tested by the SST had a diameter and height of 150 mm by 50 mm. For the surface vs. base mixture study, tests were also performed on specimens having a diameter and height of 150 mm by 75 mm and 203 by 75 mm. The use of larger specimens did not provide better correlations to ALF pavement performance. Specimens with a height of 75 mm failed rapidly in Repeated Shear at 58 °C and the data had to be compared at 500 cycles rather than at 5,000 cycles.

- The PURWheel provided conclusions that differed from those provided by the French PRT, Georgia LWT, Hamburg WTD, unconfined repeated load compression test, and SST. For the surface vs. base mixture study, the data from the PURWheel were affected by nominal maximum aggregate size, but not by binder grade.

- No laboratory mixture test provided a statistical ranking for the four mixtures that matched ALF pavement performance. Some of the SST data were significantly affected by nominal maximum aggregate size, but the effect was not as great as the effect of nominal maximum aggregate size on ALF pavement performance.

c. Conclusions Using All Mixtures

- Marshall stabilities and flows did not differentiate the mixtures according to rutting susceptibility.

- The rutting parameters from the U.S. Corps of Engineers Gyratory Testing Machine did not differentiate the mixtures according to rutting susceptibility.

- The NCHRP AAMAS did not predict ALF pavement performance. Individual AAMAS test data, including compressive strength, compressive strain at failure, creep modulus, total creep strain, and permanent creep strain after unloading did not adequately predict ALF pavement performance. All tests were performed unconfined.

- The correlation between the PURWheel and ALF for the seven mixtures was reasonably good because the data were affected by nominal maximum aggregate size. A linear regression provided an r^2 of 0.8. The correlations for the other tests were poor because they could not measure the effects of nominal maximum aggregate size.

- The air voids in the specimens tested by the AAMAS creep test and the repeated load compression test did not decrease during testing. Therefore, these tests measured permanent deformation due to viscous flow (called shape distortion) without volume change (densification or volume distortion). The ALF, French PRT, Georgia LWT, Hamburg WTD, and PURWheel measure the combined effects of viscous flow and volume change. The SST was designed so that changes in volume would not occur during testing; thus, it was designed to measure only permanent deformation due to viscous flow.

- The laboratory mixture tests were performed according to customary procedures. However, most of these tests and the ALF pavement tests had different loading frequencies or test temperatures. Since the performance of a binder in an asphalt mixture is dependent on frequency and temperature, it should not be expected that the rankings from these tests agree perfectly.

d. Miscellaneous Conclusions

- A slab thickness of 100 mm is tested by the French PRT when the total pavement thickness for the mixture to be placed will be greater than 50 mm. A slab thickness of 50 mm is tested when the thickness will be equal to, or less than, 50 mm. The data showed that the rut depths tended to be greater using 50-mm slabs at an equal number of wheel passes.

- Even though the French PRT was found to be more severe using 50-mm-thick slabs, the French pass/fail specification was generally found to be more severe when testing 100-mm slabs. This means that the French methodology is more severe for mixtures to be used in thick, lower pavement layers.

- The resilient modulus at 10.0 Hz from the unconfined repeated load compression test and the shear modulus at 10.0 Hz from SST Frequency Sweep were used to calculate Poisson's ratios based on the laws of elasticity for isotropic materials. It was found that one modulus could not be calculated from the other modulus using an assumed Poisson's ratio. The moduli showed that the laws do not apply to the mixtures tested in this study.

15. Recommendations

- Overall, the French PRT at 60 °C, Georgia LWT at 40 °C, Hamburg WTD at 50 °C, unconfined repeated load compression test at 58 °C, and the SST at 40 °C provided similar conclusions. Therefore, any one of these tests can be used to estimate rutting potential at high temperatures. In this evaluation, the data from the unconfined repeated load compression test and SST were not used in a performance prediction model. The test data were directly compared against the ALF pavement test results.

- The correlation between the PURWheel and ALF for the seven mixtures was reasonably good; therefore, this test can also be used. Based on ALF pavement rutting performance, the PURWheel showed the effects of nominal maximum aggregate size, whereas the other tests did not. However, the other tests were more capable of measuring the effects of binder grade. (Note: Only pavement slabs were tested by the PURWheel. Slabs prepared and compacted in the laboratory were not tested.)

- A compression modulus at high temperatures should not be computed from the shear modulus and an assumed Poisson's ratio. Likewise, a shear modulus at high temperatures should not be computed from the compression modulus and an assumed Poisson's ratio.