CHAPTER 6: G*/SINδ VERSUS LABORATORY MIXTURE TESTS FOR RUTTING

1. Background

ALF pavement performance was the principal means used to validate G*/sinδ. Rankings for the five binders based on G*/sinδ were also compared with the rankings for the five surface mixtures provided by the laboratory mixture tests for rutting listed in chapter 4. Mixture tests that did not correlate with ALF pavement performance were excluded.

The G*/sinδ's at the temperature and angular frequency of each laboratory mixture test are given in table 94. The DSR angular frequencies were based on a speed of 80 km/h being equivalent to 10.0 rad/s. The speed of each mixture test was divided by eight to obtain the DSR angular frequency to be used. The loading frequency of 10.0 Hz used by the repeated load compression test and SST is generally equated to 80 km/h. Therefore, the data from these tests were compared with the G*/sinδ's at 10.0 rad/s. As discussed in chapter 2, Superpave equates 10.0 rad/s to approximately 10 Hz. The Frequency Sweep data at a frequency of 2.0 Hz were also evaluated because this could be considered the loading frequency of the ALF. A frequency of 2.0 Hz was used in lieu of 2.25 Hz (18.0 km/h ÷ 8) because 2.0 Hz is one of the standard SST frequencies and the conversion from km/h to Hz is approximate.

ALF pavement performance was based on the wheel passes at a 20-mm rut depth and on the rut depths at 2,370 and 10,000 wheel passes. Pavement performances based on rut depths at constant numbers of ALF wheel passes were used in this part of the study so that the rut depths from the ALF and the three wheel-tracking devices could be examined together. The ALF pavement rut depths are given in table 95.

The rut depths at 2,370 wheel passes were evaluated because this number of wheel passes provided an average rut depth of 20 mm in the pavement with the AC-20 (PG 70) surface mixture. This mixture was considered the control mixture, and a rut depth of 20 mm was defined as the failure level. The rut depths at 10,000 wheel passes were also evaluated. This was the maximum number of wheel passes that could be used because at higher numbers of wheel passes, the rut depths for three out of the five mixtures would have to be obtained by extrapolation. At 2,370 wheel passes, the rut depth for the AC-5 (PG 59) surface mixture had to be calculated by extrapolation. At 10,000 wheel passes, the rut depths for the AC-5 (PG 59) and AC-10 (PG 65) surface mixtures had to be calculated by extrapolation.

2. French PRT, Georgia LWT, and Hamburg WTD

The statistical rankings in table 96 show a reversed order for Novophalt and Styrelf based on the average values. According to G*/sinδ, the Styrelf

Table 94. G*/sinδ and binder rankings at the angular frequencies and temperatures used in the ALF pavement and laboratory mixture tests.[1]

Pre-Superpave Designation:	AC-5	AC-10	AC-20	Novophalt	Styrelf
Superpave PG:	58-34	58-28	64-22	76-22	82-22
	G*/sinδ's of the RTFO Residues, Pa				
ALF Pavement Tests, G*/sinδ at 2.25 rad/s (18.0 km/h) and 58 °C	664 E	1 384 D	2 702 C	6 826 B	13 710 A
French PRT, G*/sinδ at 0.875 rad/s (7.0 km/h) and 60 °C	212 E	442 D	871 C	2 103 B	6 444 A
Georgia LWT, G*/sinδ at 0.125 rad/s (1.0 km/h) and 40 °C	899 E	2 215 D	5 060 C	10 350 B	21 120 A
Hamburg WTD, G*/sinδ at 0.125 rad/s (1.0 km/h) and 50 °C	130 D	348 DC	635 C	1 744 B	5 243 A
Repeated Load Test, G*/sinδ at 10.0 rad/s (80.0 km/h) and 40 °C	38 640 D	82 800 C	159 900 B	263 600 A	270 900 A
Repeated Load Test, G*/sinδ at 10.0 rad/s (80.0 km/h) and 58 °C	2 600 E	5 285 D	10 010 C	21 090 B	35 170 A
SST, G*/sinδ at 10.0 rad/s (80.0 km/h) and 40 °C	38 640 D	82 800 C	159 900 B	263 600 A	270 900 A
SST, G*/sinδ at 2.0 rad/s (18.0 km/h) and 40 °C	11 910 E	26 350 D	54 470 C	92 470 B	117 700 A

[1] The letters are the statistical ranking, with "A" denoting the binder(s) with the highest G*/sinδ.

Table 95. Rut depths in the asphalt pavement layer at 2,370 and 10,000 ALF wheel passes.

Surface Mixture	Rut Depth at 2,370 Wheel Passes, mm	Rut Depth at 10,000 Wheel Passes, mm
Novophalt	4	5
Styrelf	8	10
AC-20	20	29
AC-10	23	39[1]
AC-5	37[1]	65[1]

[1] From extrapolation.

Table 96. Rankings for the five surface mixtures vs. rankings based on the G*/sinδ's of the binders at the angular frequency and temperature corresponding to the ALF pavement and laboratory mixture tests.[1]

ALF Pavements at 2.25 rad/s, 58 °C		French PRT at 0.875 rad/s, 60 °C		
Binder, G*/sinδ	Wheel Passes at a 20-mm Rut Depth	Binder, G*/sinδ	Percent Rut Depth	Slope
(A) Styrelf	(A) Novophalt	(A) Styrelf	(A) Novophalt	(A) Novophalt
(B) Novophalt	(B) Styrelf	(B) Novophalt	(B) Styrelf	(B) Styrelf
(C) AC-20	(C) AC-20	(C) AC-20	(C) AC-20	(C) AC-20
(D) AC-10	(C) AC-10	(D) AC-10	(D) AC-10	(D) AC-10
(E) AC-5	(D) AC-5	(E) AC-5	(D) AC-5	(D) AC-5

Georgia LWT at 0.125 rad/s, 40 °C		Hamburg WTD at 0.125 rad/s, 50 °C	
Binder, G*/sinδ	Rut Depth	Binder, G*/sinδ	Creep Slope
(A) Styrelf	(A) Novophalt	(A) Styrelf	(-) Novophalt[2]
(B) Novophalt	(B) Styrelf	(B) Novophalt	(A) Styrelf
(C) AC-20	(BC) AC-20	(C) AC-20	(B) AC-20
(D) AC-10	(C) AC-10	(CD) AC-10	(C) AC-10
(E) AC-5	(C) AC-5	(D) AC-5	(D) AC-5

Repeated Load Compression Test at 10.0 rad/s, 40 °C		Repeated Load Compression Test at 10.0 rad/s, 58 °C	
Binder, G*/sinδ	Cumulative Permanent Strain, 10,000 Cycles	Binder, G*/sinδ	Cumulative Permanent Strain, 1,000 Cycles
(A) Styrelf	(A) Styrelf	(A) Styrelf	(A) Novophalt
(A) Novophalt	(A) Novophalt	(B) Novophalt	(A) Styrelf
(B) AC-20	(B) AC-20	(C) AC-20	(B) AC-20
(C) AC-10	(C) AC-10	(D) AC-10	(C) AC-10
(D) AC-5	(D) AC-5	(E) AC-5	(C) AC-5

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

[2] This mixture had the lowest susceptibility to rutting but it was not included in the statistical ranking because of high variability.

Table 96. Rankings for the five surface mixtures vs. rankings based on the G*/sinδ's of the binders at the angular frequency and temperature corresponding to the ALF pavement and laboratory mixture tests (continued).[1]

Simple Shear at Constant Height and 40 °C

Binder, G*/sinδ at 10.0 rad/s	Compliance Parameter	Permanent Shear Strain	Maximum Axial Stress
(A) Styrelf	(A) Novophalt	(A) Styrelf	(A) Novophalt
(A) Novophalt	(B) Styrelf	(AB) Novophalt	(AB) Styrelf
(B) AC-20	(C) AC-20	(B) AC-20	(AC) AC-20
(C) AC-10	(D) AC-10	(C) AC-5	(BCD) AC-10
(D) AC-5	(D) AC-5	(C) AC-10	(AD) AC-5

Frequency Sweep at Constant Height and 40 °C

Binder, G*/sinδ at 10.0 rad/s	Shear Modulus, G*, at 10.0 Hz	Mixture G*/sinδ at 10.0 Hz	Slope of Log G* vs. Log Frequency
(A) Styrelf	(A) Novophalt	(A) Novophalt	(A) Novophalt
(A) Novophalt	(B) Styrelf	(B) Styrelf	(AB) AC-5
(B) AC-20	(C) AC-20	(C) AC-20	(AB) Styrelf
(C) AC-10	(D) AC-10	(D) AC-10	(AB) AC-20
(D) AC-5	(E) AC-5	(E) AC-5	(B) AC-10

Frequency Sweep at Constant Height and 40 °C

Binder, G*/sinδ at 2.0 rad/s	Shear Modulus, G*, at 2.0 Hz	G*/sinδ at 2.0 Hz
(A) Styrelf	(A) Novophalt	(A) Novophalt
(B) Novophalt	(B) Styrelf	(B) Styrelf
(C) AC-20	(C) AC-20	(C) AC-20
(D) AC-10	(D) AC-10	(CD) AC-10
(E) AC-5	(D) AC-5	(D) AC-5

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

Table 96. Rankings for the five surface mixtures vs. rankings based on the G*/sinδ's of the binders at the angular frequency and temperature corresponding to the ALF pavement and laboratory mixture tests (continued).[1]

Repeated Shear at Constant Height and 40 °C

Binder, G*/sinδ at 10.0 rad/s	Slope of Cumulative Permanent Strain	Cumulative Permanent Strain at 5,000 cycles
(A) Styrelf	(A) Novophalt	(A) Novophalt
(A) Novophalt	(A) AC-20	(A) Styrelf
(B) AC-20	(A) AC-10	(AB) AC-20
(C) AC-10	(A) AC-5	(B) AC-10
(D) AC-5	(A) Styrelf	(C) AC-5

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

binder should provide the most resistance to rutting, followed by Novophalt. All three wheel-tracking tests and ALF show that the mixture with Novophalt was most resistant to rutting, followed by the mixture with Styrelf. The degree of correlation between G*/sinδ and the wheel-tracking tests, based on the statistical rankings, varied from test to test.

Figures 64 and 65 show the rut depths from the ALF and the wheel-tracking devices vs. G*/sinδ after RTFO. The rut depths from the three wheel-tracking devices provided a single relationship with G*/sinδ. The rut depths from the ALF were greater than the rut depths from the wheel-tracking devices for a given mixture at both 2,730 and 10,000 ALF wheel passes.

The rut depths provided by the wheel-tracking devices suggest that the 2.20-kPa minimum specification level for G*/sinδ after RTFO is valid. The failure level rut depths of 10 mm for the French PRT and Hamburg WTD and 7.6 mm for the Georgia LWT indicate that 2.20 kPa is conservative. The rut depths provided by the ALF suggest that 2.20 kPa is low, but a firm relationship was not provided because the number of data points was too low. Figures 64 and 65 each show two possible relationships for the rut depths provided by the ALF vs. G*/sinδ. The reversal for the Novophalt and Styrelf materials was less pronounced when performance was based on 2,370 or 10,000 ALF wheel passes rather than on the number of wheel passes at a rut depth of 20 mm.

3. Repeated Load Compression Test

The rankings in table 96 based on G*/sinδ and cumulative permanent strain at 40 °C are identical. The rankings at 58 °C provided the same discrepancy for Novophalt and Styrelf that was provided by the wheel-tracking devices.

4. SST

The G*/sinδ's of the binders at 40 °C were compared with the rankings provided by the following tests performed at 40 °C. Specimens compacted by the Superpave Gyratory Compactor were used. Each specimen had a diameter and height of 150 and 50 mm, respectively.

- 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 of the mixtures 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 shear strain vs. cycles.
  - Cumulative permanent shear strain at 5,000 cycles (load repetitions).

The Simple Shear test had no associated frequency so the data were compared with the G*/sinδ's at the standard DSR angular frequency of 10.0 rad/s. The rankings for the SST measurements are included in table 96. The mixtures were also tested at 58 °C, but the results were not used because the data did not correlate to ALF pavement performance and was highly variable.

How the mixtures grouped together based on statistics, and how each statistical ranking compared to the ranking based on G*/sinδ, depended on the particular SST measurement. In general, the SST provided the same conclusion as the laboratory wheel-tracking tests. Most rankings show a reversed order for the Novophalt and Styrelf materials.

5. Rankings Based on an Angular Frequency of 10.0 rad/s

The five binders were ranked based on G*/sinδ at the standard DSR angular frequency of 10.0 rad/s and the test temperatures used in the ALF, French PRT, Georgia LWT, and Hamburg WTD tests. These G*/sinδ's are given in table 97. Tables 94 and 97 show that the change in frequency did not change the rankings for the G*/sinδ's used in the ALF and French PRT comparisons. Therefore, the change in angular frequency had no effect on the degree of correlation between G*/sinδ and these two tests.

Different rankings for G*/sinδ were obtained using 10.0 rad/s for the Georgia LWT and Hamburg WTD comparisons. Tables 96 and 98 show that the use of 10.0 rad/s, at best, marginally improved the relationship with the Hamburg WTD, but it did not improve the relationship with the Georgia LWT.

Normally, 10.0 Hz is equated to 62.8 rad/s. If 62.8 rad/s were to be equated to 80 to 100 km/h instead of 10.0 rad/s, the DSR angular frequency for the ALF comparison would be in the range of 11 to 14 rad/s. Angular frequencies in this range provided the same ranking for G*/sinδ as 2.25 and 10.0 rad/s. Thus, angular frequencies from 2 to 14 rad/s did not affect the degree of correlation between G*/sinδ and ALF pavement performance.

6. Comment on Loading Time and Frequency

The loading time for a point on a pavement is generally based on vehicle speed and on the deflection basin or some other measure that shows how the stresses at the point change as a tire rolls over it. Stresses at the point will start to occur before the tire reaches it and will not completely relax until the tire is some distance past it. Thus, the loading time for a pavement is a function of vehicle speed and the size of the deflection basin. An additional complication that arises when calculating loading times is that the size of the deflection basin should vary with vehicle speed.

The stress patterns in the ALF pavements and specimens tested by the wheel-tracking tests were not known. Furthermore, the specimens tested by the wheel-tracking devices could not deflect because the underlying support in each device was rigid. The DSR angular frequencies used to represent these machines were based solely on speed; thus, they can only be considered approximate angular frequencies. This comment also applies to the standard DSR test. The standard frequency of 10.0 rad/s only represents some average pavement condition even if the resulting high-temperature PG is adjusted based on vehicle speed.

7. Conclusions

- The French PRT, Georgia LWT, Hamburg WTD, the cumulative permanent strains from the repeated load compression test at 58 °C, and most of the SST data ranked the five surface mixtures the same as ALF based on the average data. The mixture with Novophalt had the greatest resistance to rutting, followed by the mixture with Styrelf. According to G*/sinδ, the Styrelf binder should have provided the most resistance to rutting, followed by Novophalt. The degree of correlation between the mixture tests and G*/sinδ using statistical rankings varied from mixture test to mixture test. However, the reversal for the Novophalt and Styrelf materials was the most significant discrepancy found.

- The rankings based on G*/sinδ and the cumulative permanent strains from the repeated load compression test at 40 °C were identical.

- A DSR angular frequency of 2.25 rad/s was used in this study to account for the relatively slow speed of the ALF. The range of possible angular frequencies that could be used to represent the ALF is 2 to 14 rad/s. Angular frequencies in this range did not change the ranking for the binders based on G*/sinδ. Thus, angular frequency did not affect the degree of correlation between G*/sinδ and ALF pavement performance.

- Use of the standard DSR angular frequency of 10.0 rad/s, in lieu of lower angular frequencies that account for the relatively slow speeds of the ALF and the three wheel-tracking devices, had no overall negative or positive effect on the degree of correlation between of G*/sinδ and rutting susceptibility. Changing the angular frequency changed the G*/sinδ's, but not the degree of correlation.

- The data from the French PRT, Hamburg WTD, and Georgia LWT indicated that the 2.20-kPa minimum specification level for G*/sinδ after RTFO is valid. The rut depths provided by the ALF suggested that 2.20 kPa is low, but a different minimum specification level could not be suggested due to the limited number of mixtures tested.

8. Recommendations

- Because of the limited number of mixtures tested in this study, it is recommended that the speeds of full-scale accelerated pavement testers and laboratory wheel-tracking devices be taken into account when making comparisons to G*/sinδ, even though the data in this study did not show this to be of benefit. Theoretically, adjustments should be made.

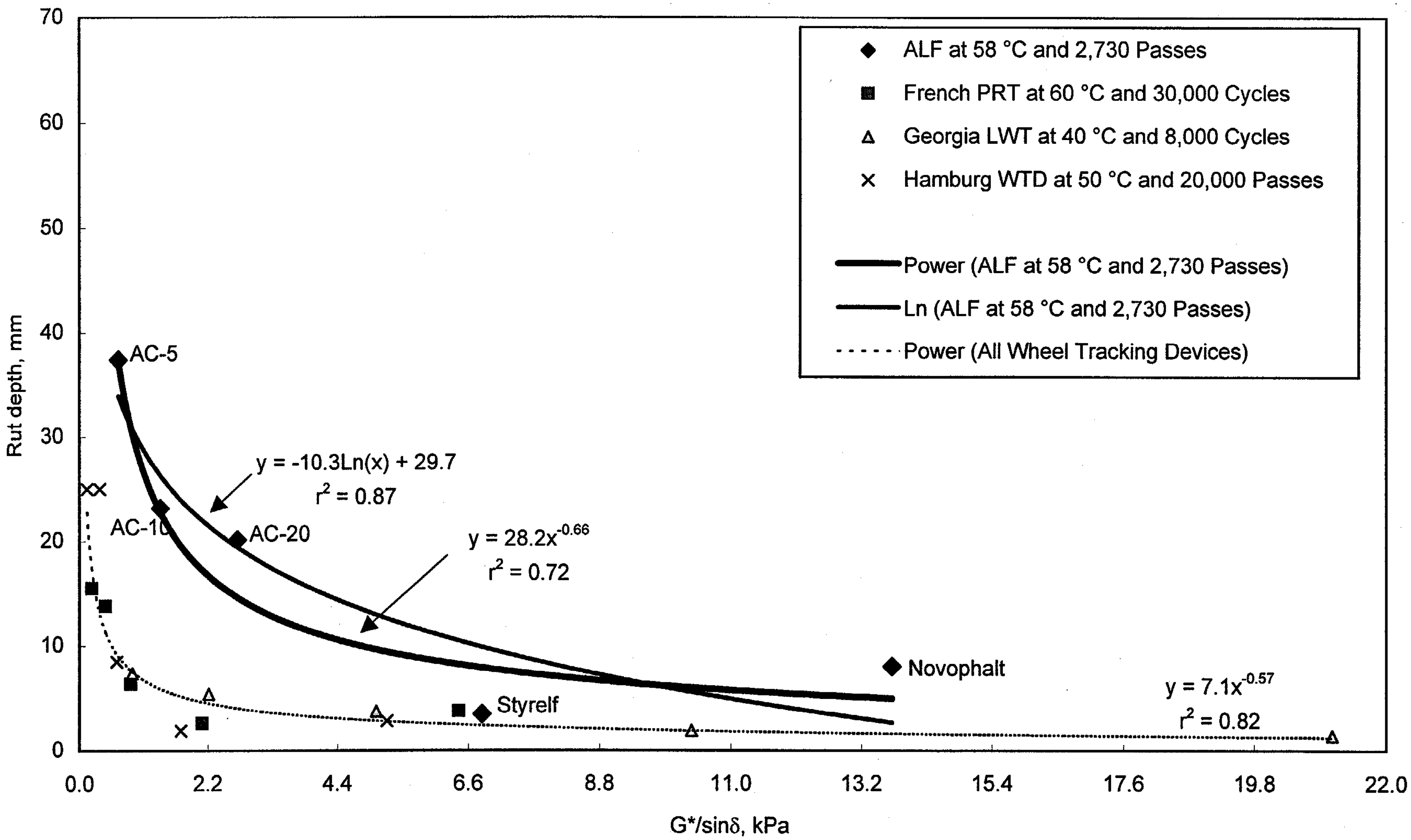

Figure 64. Rut depths at 2,730 ALF wheel passes and from the wheel-tracking devices vs. G*/sinδ after RTFO.

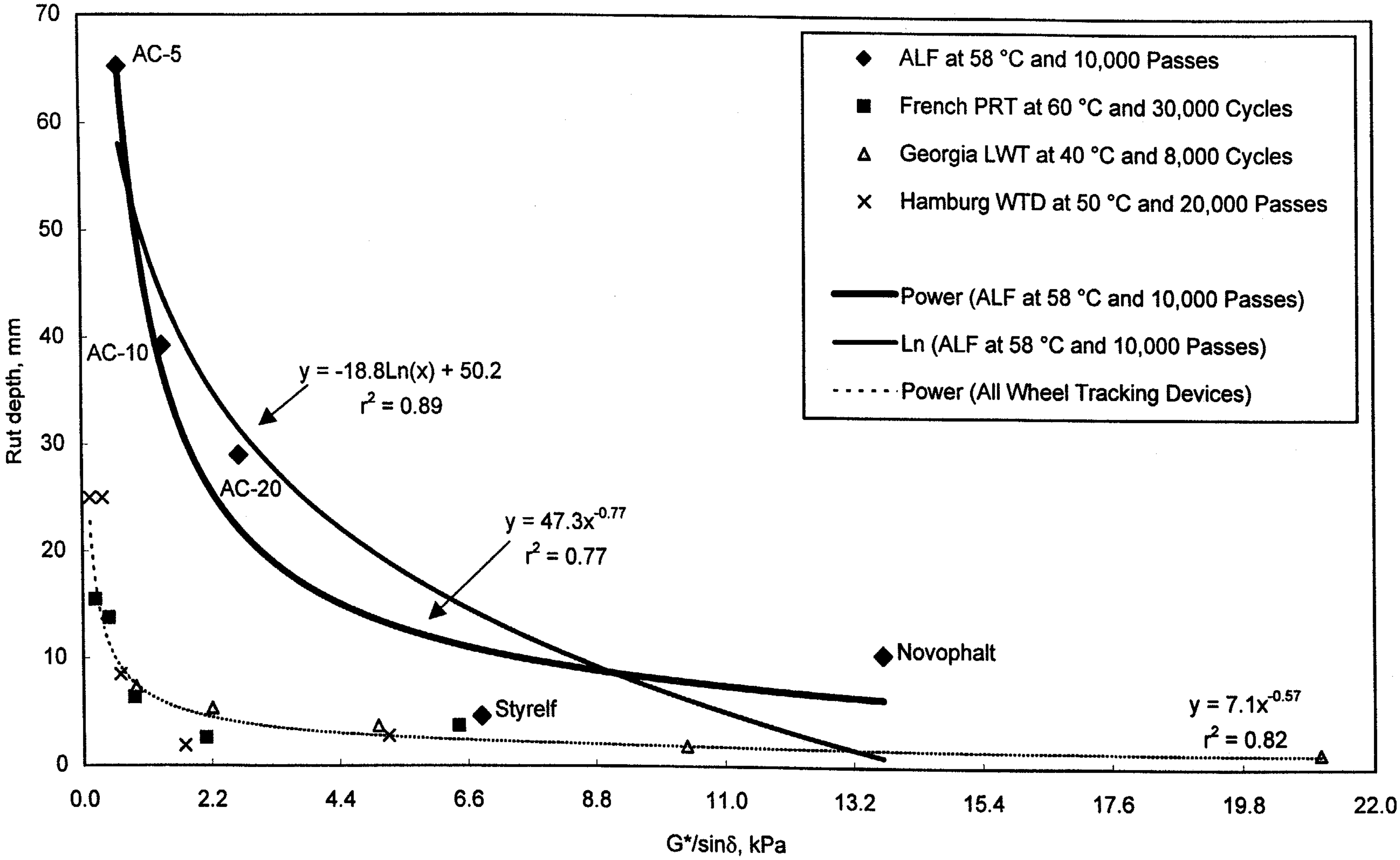

Figure 65. Rut depths at 10, 000 ALF wheel passes and from the wheel-tracking devices vs. G*/sinδ after RTFO.

Table 97. G*/sinδ and binder rankings at 10.0 rad/s and the temperatures used in the ALF pavement and laboratory wheel-tracking tests.[1]

Pre-Superpave Designation:	AC-5	AC-10	AC-20	Novo-phalt	Styrelf
Superpave PG:	58-34	58-28	64-22	76-22	82-22
	G*/sinδ's of the RTFO Residues, Pa				
ALF Pavement Tests, 58 °C	2 600 E	5 285 D	10 010 C	21 090 B	35 170 A
French PRT, 60 °C	2 096 E	4 202 D	7 897 C	16 580 B	28 504 A
Georgia LWT, 40 °C	38 640 D	82 800 C	159 900 B	263 600 A	270 900 A
Hamburg WTD, 50 °C	7 528 E	15 880 D	30 660 C	60 150 B	75 960 A

[1] The letters are the statistical ranking, with "A" denoting the binder(s) with the highest G*/sinδ.

Table 98. Rankings for the five surface mixtures vs. rankings based on the G*/sinδ's of the binders at 10.0 rad/s and the temperature used in the ALF pavement and laboratory wheel-tracking tests.[1]

ALF, 58 °C

Binder, G*/sinδ at 10.0 rad/s	Pavement Performance
(A) Styrelf	(A) Novophalt
(B) Novophalt	(B) Styrelf
(C) AC-20	(C) AC-20
(D) AC-10	(C) AC-10
(E) AC-5	(D) AC-5

French PRT, 60 °C

Binder, G*/sinδ at 10.0 rad/s	Percent Rut Depth	Slope
(A) Styrelf	(A) Novophalt	(A) Novophalt
(B) Novophalt	(B) Styrelf	(B) Styrelf
(C) AC-20	(C) AC-20	(C) AC-20
(D) AC-10	(D) AC-10	(D) AC-10
(E) AC-5	(D) AC-5	(D) AC-5

Georgia LWT, 40 °C

Binder, G*/sinδ at 10.0 rad/s	Rut Depth
(A) Styrelf	(A) Novophalt
(A) Novophalt	(B) Styrelf
(B) AC-20	(BC) AC-20
(C) AC-10	(C) AC-10
(D) AC-5	(C) AC-5

Hamburg WTD, 50 °C

Binder, G*/sinδ at 10.0 rad/s	Creep Slope
(A) Styrelf	(-) Novophalt[2]
(B) Novophalt	(A) Styrelf
(C) AC-20	(B) AC-20
(D) AC-10	(C) AC-10
(E) AC-5	(D) AC-5

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

[2] This mixture had the lowest susceptibility to rutting but it was not included in the statistical ranking because of high variability.

CHAPTER 7: EFFECT OF AGE HARDENING ON PAVEMENT RUTTING SUSCEPTIBILITY

1. Background and Objectives

The pavement rutting data given in chapter 3 indicated that binder age hardening may have affected the results of the pavement tests, which were performed from 1994 to 1997. However, most of the pavement tests consisted of testing the five surface mixtures at three different temperatures with no replication. The conclusion that age hardening affected the data was based on a comparison of the data collected in 1997 with the data collected in prior years. The G*/sinδ's of binders recovered from pavement cores taken after failure did not conclusively indicate that binder age hardening was a problem.

Lanes 9, 10, and 11 were the only lanes that were tested more than once at a given test temperature. These lanes were tested at 58 °C in both 1994 and 1995. To further examine the effect that age hardening can have on rutting susceptibility, these lanes were retested at 58 °C in 1998.

One additional site, namely, site 4 of lane 10, was tested in 1998 using a tire pressure of 520 kPa compared with the pressure of 690 kPa that was used when testing all other sites. Testing this site at a reduced tire pressure was a mini-study added to the project after the main experiments were completed. The data from this site were compared with the data from site 3 of lane 10, which was also tested in 1998, but at a tire pressure of 690 kPa.

2. Results and Conclusions for the Age-Hardening Study

The high-temperature continuous PG's of the neat binders and binders recovered from the pavements are given in table 99. Table 100 gives the G*/sinδ's of the binders at the pavement test temperature of 58 °C. The data show that the AC-20 (PG 70) surface mixture and the AC-5 (PG 59) base mixture hardened approximately one high-temperature PG over the 4-year period. (The increment between PG's is 6 °C.) The AC-5 (PG 59) surface mixture exhibited no trend in age hardening with time.

The pavement data are presented in table 101. The air voids show that densification generally decreased with an increase in age, although the air voids of cores taken from out of the wheelpath, which were considered the initial air-void levels, tended to be lower for the sites tested in 1998.

The wheel passes needed to produce rut depths of 10, 15, and 20 mm at 58 °C are given in table 101. Figures 66, 67, and 68 show the relationships using the rut depths in the asphalt pavement layer. The wheel passes for lane 9 were low and showed no trend with time. The wheel passes for lane 10 were substantially higher in 1998 compared with 1994 and 1995, while the wheel passes in 1994 and 1995 were close to each other. The wheel passes for lane 11 increased with time, except for the 1994 and 1995 wheel passes based on total rut depth. The data show that the time between the pavement tests can significantly affect the results provided by the ALF. For example, the wheel passes needed to obtain a 20-mm rut depth in the AC-5 (PG 59) base mixture layer increased from 8,984 in 1994 to 61,400 in 1998.

The increases in wheel passes over time were attributed to binder age hardening. Therefore, the wheel passes in table 101 were linearly regressed against the PG's in table 99 and the G*/sinδ's at 10 rad/s in table 100. The coefficients of determination, r^2, are given in table 102 with high coefficients shown in bold type. The wheel passes at rut depths of 15 and 20 mm for lane 9 highly correlated with both PG and G*/sinδ, even though there was no trend in the wheel passes with time. Therefore, the wheel passes were a function the variation in PG and G*/sinδ from test site to test site for this lane. The correlations were poor for lane 10 because the wheel passes in 1995 were relatively low compared with the PG and G*/sinδ of the recovered binder. The wheel passes for lane 11 highly correlated with G*/sinδ, while the correlations with PG were generally mediocre. Higher r^2's could be expected using G*/sinδ because the actual pavement test temperature of 58 °C was used when determining G*/sinδ. In conclusion, G*/sinδ highly correlated with the rutting data for two out of the three pavement tests.

The binder contents, aggregate gradations, and air voids of the mixtures did not explain the discrepancies provided by the 1997 pavement data. The data presented in this chapter indicated that binder age hardening could possibly be the reason, although a reason why the properties of the binders recovered from the pavements in 1997 did not explain the discrepancies was not found.

3. Results and Conclusions for the Tire Pressure Study

The high-temperature continuous PG's of the binders recovered from sites 3 and 4 of lane 10 were both 78 °C. The G*/sinδ's of the recovered binders at 58 °C were 10.4 and 10.7 °C using 2.25 rad/s, and 33.6 and 34.8 °C using 10 rad/s. The binder properties for these two sites were not significantly different.

A comparison of the pavement data in table 101 showed that the decrease in tire pressure from 690 kPa (site 3) to 520 kPa (site 4) only provided a 3.6-percent increase in wheel passes based on a 20-mm rut depth in the asphalt pavement layer. The wheel passes increased from 12,720 to 13,182. Most likely, this difference is smaller than the repeatability of the ALF data.

The decrease in tire pressure increased the wheel passes from 6,206 to 7,926 based on a total rut depth of 20 mm. This is a 28-percent increase in wheel passes. Whether this increase was at least partially due to differences in the properties of the underlying crushed aggregate base layer was not known. Therefore, a firm conclusion regarding this increase could not be made.

Table 99. High-temperature continuous PG's at three different ages.

Mixture	Lane	High-Temperature Continuous PG's of Neat Binders at 10 rad/s after RTFO, °C	Year of ALF Pavement Test and High-Temperature Continuous PG's of Recovered Binders at 10 rad/s,		
			1994	1995	1998
AC-5 Surface	9	59	63	68	64
AC-20 Surface	10	70	72	78	78
AC-5 Base	11	59	67	72	74

Table 100. G*/sinδ's at three different ages.

Mixture	Lane	G*/sinδ's of the Neat Binders after RTFO at 58 °C, kPa	Year of ALF Pavement Test and the G*/sinδ's of the Recovered Binders at 58 °C, kPa		
			1994	1995	1998
		DSR Frequency = 2.25 rad/s			
AC-5 Surface	9	0.66	1.3	ND	1.4
AC-20 Surface	10	2.70	4.3	ND	10.4
AC-5 Base	11	0.66	1.7	5.5	6.4
		DSR Frequency = 10.0 rad/s			
AC-5 Surface	9	2.6	4.3	7.9	5.2
AC-20 Surface	10	10.0	12.4	25.0	33.6
AC-5 Base	11	2.6	6.9	12.7	19.7

ND = No data; binder samples were tested.
Note: AC-5 = PG 59; AC-20 = PG 70.

Table 101. ALF pavement data at 58 °C and three ages.

	Surface Mixture AC-5 (PG 59) Lane 9 Year and Site			Surface Mixture AC-20 (PG 70) Lane 10 Year and Site				Base Mixture AC-5 (PG 59) Lane 11 Year and Site		
	1994 2	1995 1	1998 4	1994 2	1995 1	1998 3	1998 4	1994 2	1995 1	1998 3
Pavement Depth	**Pavement Temperature, °C**									
0 mm	62	61	57	61	59	64	64	62	58	62
20 mm	59	57	56	59	57	60	60	60	56	59
102 mm	55	55	55	55	55	57	58	58	55	55
197 mm	51	52	53	51	51	54	57	52	50	54
Difference, 0 to 197 mm	11	9	4	10	8	10	7	10	8	8
	Air Voids, Top 100 mm of Pavement, Percent									
OWP	7.7	7.8	5.8	9.3	8.8	7.4	8.4	6.0	7.3	5.7
IWP	3.6	3.2	4.0	3.4	3.9	5.3	5.8	2.2	4.0	4.1
Densification	4.1	4.6	1.8	5.9	4.9	2.1	2.6	3.8	3.3	1.6
	Air Voids, Bottom 100 mm of Pavement, Percent									
OWP	7.9	6.1	5.2	9.5	7.2	6.0	6.7	6.0	6.1	4.2
IWP	3.1	2.5	2.6	3.7	3.2	3.0	3.2	1.9	2.6	3.1
Densification	4.8	3.6	2.6	5.8	4.0	3.0	3.5	4.1	3.5	1.1
Average Densification	4.4	4.1	2.2	5.8	4.4	2.6	3.0	4.0	3.4	1.4
Rut Depth in Asphalt Layer	**Number of ALF Wheel Passes**									
10 mm	115	143	87	262	206	1010	1344	612	1363	2217
15 mm	279	395	275	1031	937	4445	5111	2946	5544	15472
20 mm	521	814	619	2724	2741	12720	13182	8984	15000	61400
Total Rut Depth	**Number of ALF Wheel Passes**									
10 mm	85	140	56	226	169	546	982	707	676	914
15 mm	212	310	186	739	687	2263	3331	2224	2399	5217
20 mm	407	546	435	1713	1859	6206	7926	5012	5895	17950

OWP = Out of wheelpath.
IWP = In wheelpath.

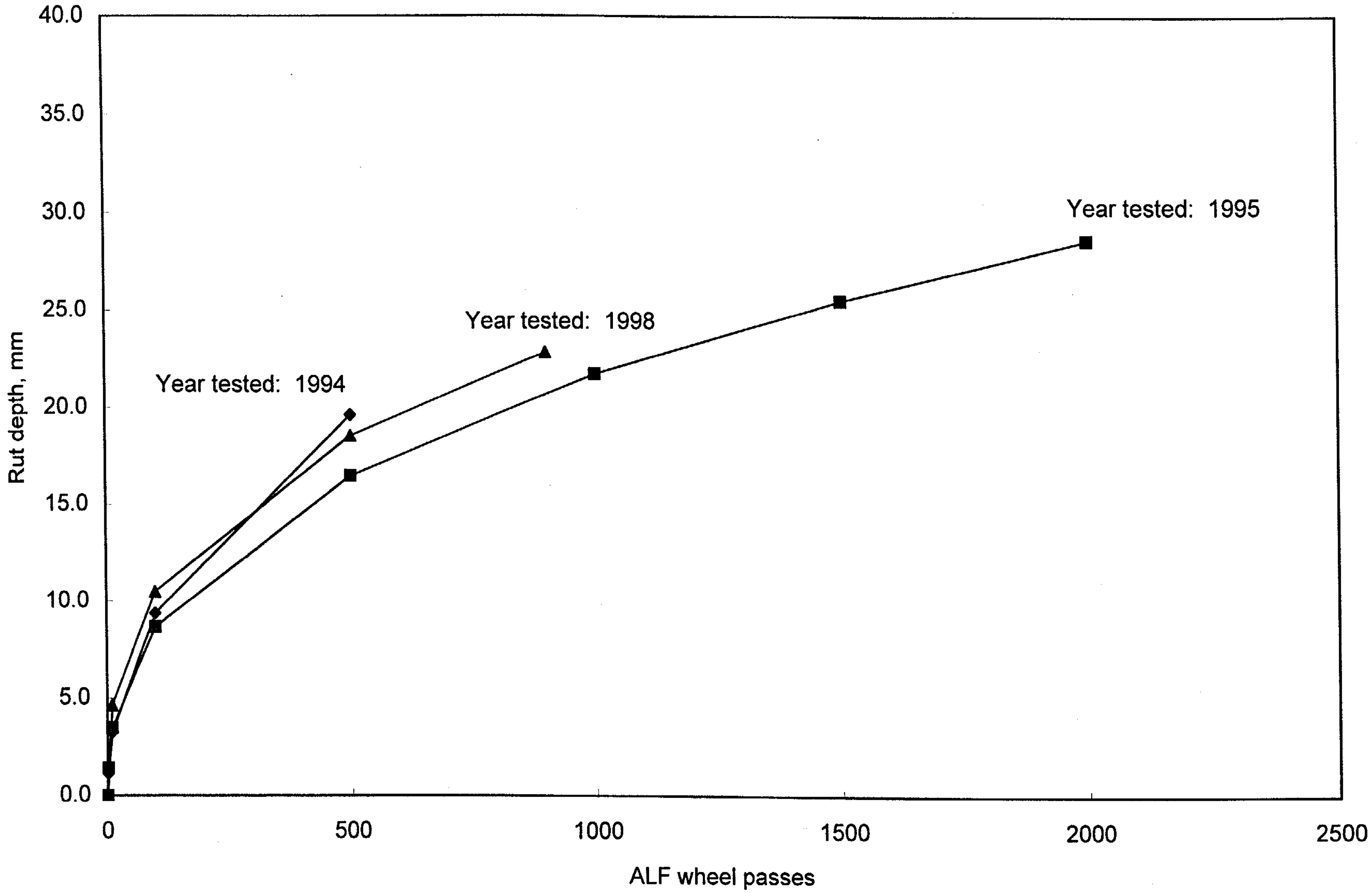

Figure 66. Rut depth in the asphalt pavement layer from the model vs. ALF wheel passes for lane 9.

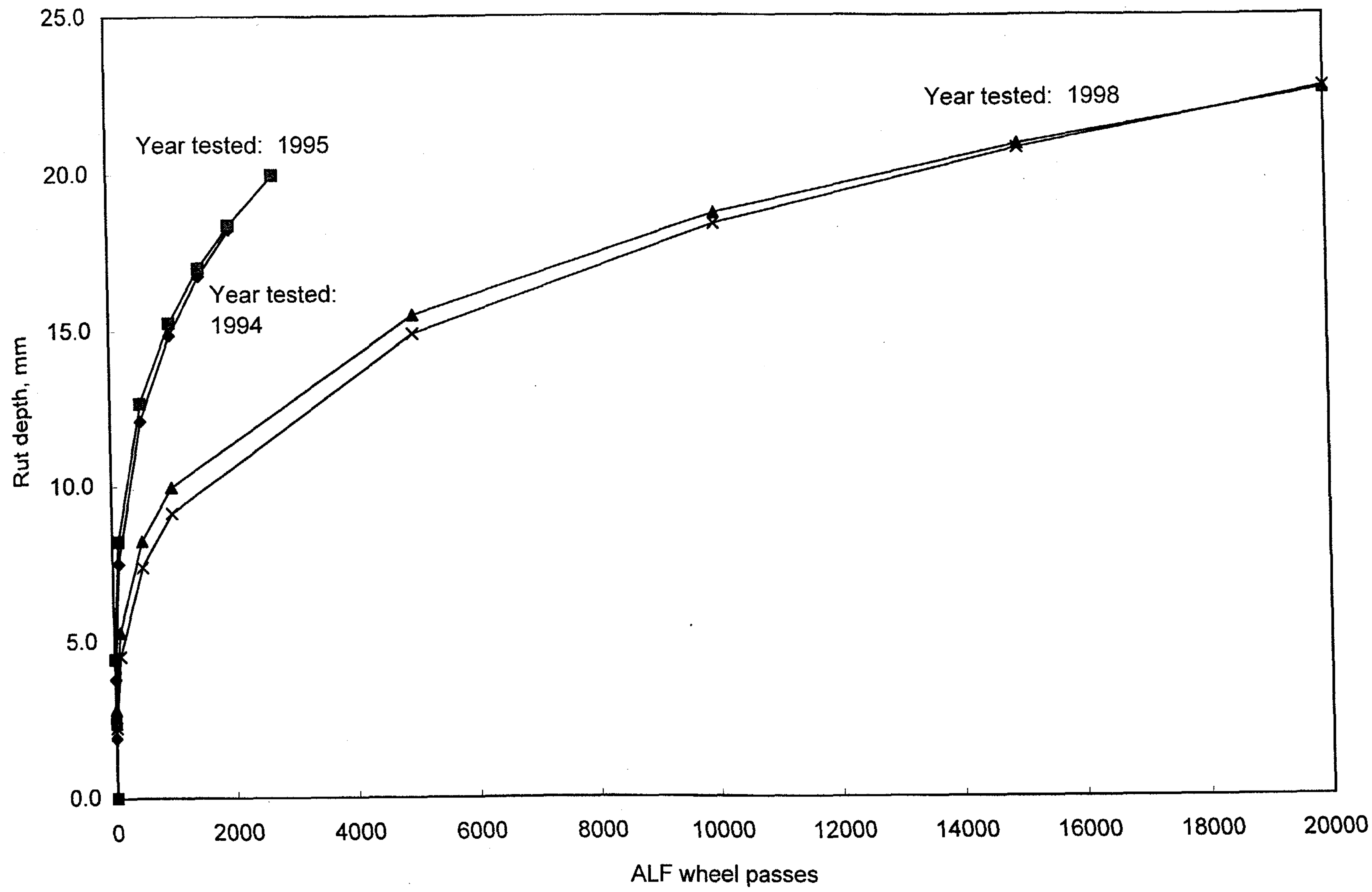

Figure 67. Rut depth in the asphalt pavement layer from the model vs. ALF wheel passes for lane 10.

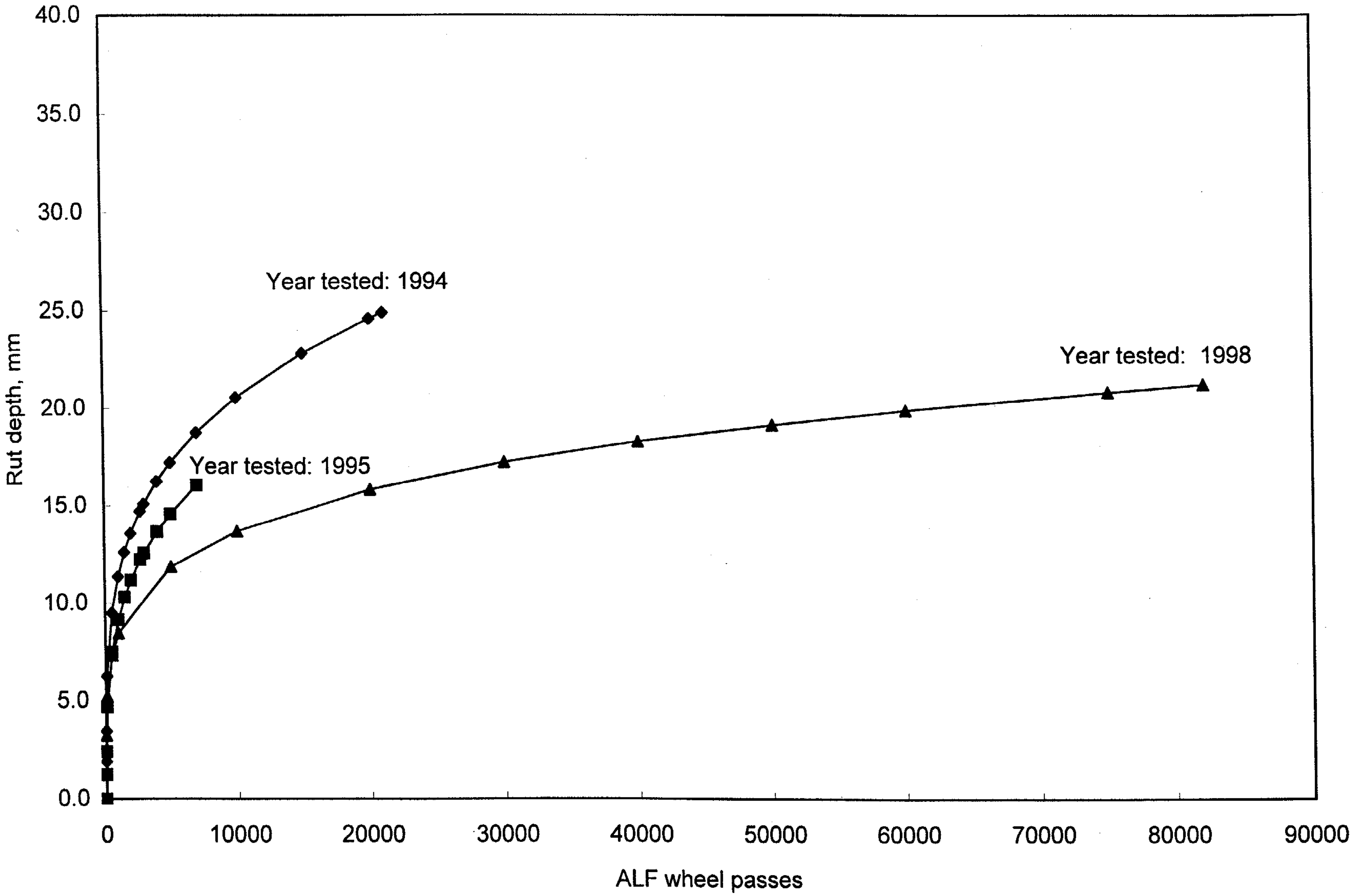

Figure 68. Rut depth in the asphalt pavement layer from the model vs. ALF wheel passes for lane 11.

Table 102. Coefficient of determination, r^2, between the ALF wheel passes at rut depths of 10, 15, and 20 mm and the PG or G*/sinδ at 10 rad/s.

	Surface Mixture AC-5 (PG 59) Lane 9		Surface Mixture AC-20 (PG 70) Lane 10		Base Mixture AC-5 (PG 59) Lane 11	
	PG	G*/sinδ	PG	G*/sinδ	PG	G*/sinδ
Rut Depth in Asphalt Layer						
10 mm	0.58	0.52	0.20	0.61	**0.92**	**0.99**
15 mm	**0.96**	**0.92**	0.23	0.64	0.71	**0.92**
20 mm	**0.98**	**0.98**	0.25	0.67	0.62	**0.86**
Total Rut Depth						
10 mm	0.74	0.69	0.14	0.53	0.40	0.69
15 mm	**0.85**	**0.81**	0.22	0.64	0.58	**0.83**
20 mm	**0.99**	**0.99**	0.27	0.69	0.58	**0.88**

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

1. Validation of G*/sinδ From the DSR Based on ALF Pavement Rutting Performance at 58 °C

- Unmodified binders with higher G*/sinδ's after RTFO aging provided mixtures with lower pavement rutting susceptibilities for a given nominal maximum aggregate size.

- A discrepancy between G*/sinδ at 58 °C after RTFO aging and ALF pavement rutting performance at 58 °C was found. The G*/sinδ of the Styrelf binder was significantly higher than for Novophalt (13.7 kPa vs.6.83 kPa), but the asphalt pavement layer with Novophalt had a significantly lower susceptibility to rutting. The ALF produced a rut depth of 20 mm in the asphalt pavement layer with Styrelf at 220,000 wheel passes. The rut depth in the asphalt pavement layer with Novophalt was 9.4 mm at 220,000 wheel passes. The rutting performances of both mixtures were excellent at 58 °C.

- The following binder parameters measured at 58 °C using the DSR provided the same discrepancy for the Novophalt and Styrelf materials: G*, δ, sinδ, tanδ, zero shear viscosity, δ using RTFO/PAV residues, cumulative permanent strain after four cycles of repeated loading, and the G*/sinδ's of binders recovered from pavement cores after failure. The use of DSR angular frequencies ranging from 2.5 to 63.0 rad/s was not beneficial. Absolute viscosity also provided the same discrepancy.

- 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 the same discrepancy between G*/sinδ and rutting performance for the Novophalt and Styrelf materials. Test temperature and loading frequency were taken into account in these correlations.

- The use of the standard DSR angular frequency of 10.0 rad/s, in lieu of lower angular frequencies that account for the relatively slow speeds of the ALF and the three wheel-tracking devices compared with highway traffic, had no significant negative or positive effect on the degree of correlation between G*/sinδ and ALF pavement rutting performance. Changing the angular frequency changed the G*/sinδ's, but not the degree of correlation.

- An 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 rutting performance at 58 °C for a given binder. No binder property can be expected to provide the effects of mixture composition and aggregate properties on pavement performance. Binder properties should provide some minimal level of performance.

- Part of the decrease in pavement rutting susceptibility provided by the increase in nominal maximum aggregate size could have been due to differences in binder age hardening. The high-temperature continuous PG of the binder recovered from the AC-5 (PG 59) base mixture was higher than for the AC-5 (PG 59) surface mixture. The same result was found for the two gradations containing the AC-20 (PG 70) binder. Most likely, the 0.85-percent lower binder content used in the base mixtures allowed more aging to occur during construction and early pavement life, even though the air voids were not higher in the base mixtures.

- Although the increase in nominal maximum aggregate size decreased rutting susceptibility, it did not reduce the influence of binder grade on rutting performance on a percentage basis. The increase in ALF wheel passes due to an increase in the high-temperature continuous PG from 59 to 70 was 310 percent for the surface mixtures and 380 percent for the base mixtures.

- The rut depths from the French PRT, Hamburg WTD, and Georgia LWT indicated that rutting should not occur when the G*/sinδ of the binder is greater than the minimum Superpave binder specification criterion of 2.20 kPa. Therefore, the results from these devices supported the current criterion. The number of binders used in this study was not sufficient for determining whether this criterion was valid based on ALF pavement rutting performance at 58 °C. ALF provided a large gap in performance between the unmodified and modified binders.

2. Validation of G*/sinδ Based on ALF Pavement Rutting Performance at All Temperatures

- The overall relationship between G*/sinδ after RTFO aging and ALF pavement rutting performance was poor, although the trend was correct for the unmodified binders.

- The G*/sinδ of the Styrelf binder after RTFO aging was higher than for the Novophalt binder at each pavement test temperature, but the pavement with Novophalt was always more resistant to rutting. This was the major discrepancy that was found.

- When the data from the Novophalt and Styrelf pavement tests were excluded from the analysis, a minimum allowable G*/sinδ of 4.4 kPa eliminated the poorest performing mixtures. Even so, pavement life still varied significantly when the G*/sinδ's of the binders after RTFO aging were above 4.4 kPa.

- Discrepancies between rutting performance and test temperature for the pavements with the Novophalt, Styrelf, and AC-20 binders manifested themselves in 1997, which was 3.5 years after construction. These discrepancies were attributed to asphalt binder age hardening. However, eliminating the 1997 data from the analyses did not change the conclusions concerning G*/sinδ.

- The G*/sinδ's of binders recovered from the pavements after failure were greater than the G*/sinδ's after RTFO aging. This included the initial, 1994 pavement tests. However, these G*/sinδ's did not completely explain the discrepancies between pavement performance and test temperature, and they did not provide a better correlation with pavement performance. Also, some of the pavements failed rapidly even though the G*/sinδ's of the recovered binders were above the minimum criterion of 2.20 kPa.

- The downward only rut depths, based on the initial surface elevations of the pavements, were used to validate G*/sinδ. However, the peak-to-valley rut depths were also examined. These rut depths provided the same discrepancy for the Novophalt and Styrelf materials.

3. Validation of Mixture Tests Based on the ALF Pavement Rutting Performances of the Five Surface Mixtures at 58 °C

- The French PRT at 60 °C, Georgia LWT at 40 °C, and Hamburg WTD at 50 °C ranked the five surface mixtures the same as ALF at 58 °C 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 an unconfined repeated load compression test at 58 °C ranked the five surface mixtures the same as ALF at 58 °C based on the averages. The statistical rankings were slightly different, but the degree of correlation to ALF was good. The slopes from the relationship between cumulative permanent strain and cycles did not differentiate the five surface mixtures according to rutting susceptibility.

- The degree of correlation between the SST data at 58 °C and ALF pavement rutting performance at 58 °C 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 use of additional mixtures may increase these coefficients.

- Six of eight SST measurements at 40 °C ranked the five surface mixtures the same as ALF at 58 °C 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 statistical rankings for the compliance parameter and permanent shear strain from Simple Shear at Constant Height at 40 °C were identical to the statistical ranking provided by the ALF at 58 °C. 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 rutting performance based on the statistical rankings.

- The two SST measurements at 40 °C that did not correlate with ALF at 58 °C 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 PURWheel at 58 °C did not rank the mixtures the same as ALF at 58 °C based on the averages. However, the statistical ranking was reasonably close to the statistical ranking provided by the ALF.

4. Validation of Mixture Tests Based on the ALF Pavement Rutting Performances of the Surface and Base Mixtures With AC-5 and AC-20 (PG 59 and PG 70) at 58 °C

a. Validation Using Laboratory-Prepared Specimens

- 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 rutting performance at 58 °C.

- Only two mixture tests ranked the four mixtures the same as ALF pavement rutting performance at 58 °C 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 stress at 58 °C from Simple Shear at Constant Height. The averages from the other SST measurements, the wheel-tracking.devices, and the unconfined repeated load compression test did not provide a ranking that was the same as that provided by the ALF.

- No laboratory mixture test provided a statistical ranking for the four mixtures that matched ALF pavement rutting performance at 58 °C. Some of the data from the SST were significantly affected by nominal maximum aggregate size, but the effect was not as great as the effect on pavement performance.

- The majority of the specimens tested by the SST had a diameter and height of 150 mm by 50 mm. However, tests at 40 and 58 °C 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 rutting performance. Specimens with a height of 75 mm failed rapidly in Repeated Shear at Constant Height at 58 °C; thus, the data had to be compared at 500 cycles rather than at 5,000 cycles.

b. Validation Using Both Laboratory-Prepared and Pavement Specimens

- The method of compaction was evaluated using both laboratory and pavement specimens to determine if it could affect the conclusions from the French PRT, Georgia LWT, and Hamburg WTD. It was found that the method of compaction can affect the data from these tests, but it was not the main reason why these devices were generally insensitive to gradation. It was hypothesized that differences in contact area may be one reason for the discrepancy, but the cause of the discrepancy was not found.

- The SST using specimens with a diameter and height of 150 by 50 mm provided the same conclusions as the wheel-tracking devices. The method of compaction can affect the data, but it was not the main reason why the tests were generally insensitive to gradation. The average cumulative permanent strains from Repeated Shear at Constant Height at 40 °C using pavement cores was the only measurement that provided a ranking that agreed with ALF pavement rutting performance at 58 °C. Even so, these strains were not significantly different based on statistical analyses.

- Pavement cores with a diameter of 203 mm provided good correlations between the SST data at 40 and 58 °C and ALF pavement rutting performance at 58 °C. These correlations were the best correlations obtained in this study for any mixture test. Correlations using cores with a diameter of 150 mm were not as good. However, the binders in the base mixtures hardened more rapidly than in the surface mixtures, and the 203-mm diameter cores were taken at the end of the study in January 1999. The 150-mm diameter cores were taken during the summer of 1997. Based on recovered binder properties, it appeared that differences in age hardening led to the seemingly good correlations.

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

5. Validation of Mixture Tests Based on the ALF Pavement Rutting Performances of All Seven Mixtures

- The results from the following tests did not correlate with pavement rutting susceptibility: (1) Marshall stability and flow, (2) U.S. Corps of Engineers Gyratory Testing Machine, (3) NCHRP AAMAS prediction model, and (4) individual AAMAS tests, including compressive strength, compressive strain at failure, creep modulus, total creep strain, and permanent creep strain after unloading. No confining pressure is used when performing AAMAS compression tests.

- The correlation between the PURWheel and ALF for the seven mixtures was reasonably good, primarily 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 generally 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 unconfined repeated load compression test did not decrease during testing. Therefore, these tests measured permanent deformation due to viscous flow (also 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 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 perfectly agree.

6. Additional Conclusions Concerning the Laboratory Mixture Tests

- 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. The ratios ranged from 1.10 to 4.60 at 40 °C and from 0.24 to 2.21 at 58 °C. Theoretically, these ratios cannot be greater than 0.5 for an isotropic, elastic material. This indicated that the elastic laws are not valid for these tests, and one modulus cannot be calculated from the other modulus using an assumed Poisson's ratio.

7. Additional Conclusions Concerning the ALF Pavement Rutting Tests

- The reductions in air voids due to trafficking (densification) in the top and bottom halves of the 200-mm-thick asphalt pavement layer were not significantly different at a 95-percent confidence level for any pavement test. Based on the average densification in the top and bottom halves, it was found that the average densification in the bottom half could be greater than, equal to, or less than the average densification in the top half.

- The decreases in air voids due to trafficking indicated that when the rut depth in the asphalt pavement layer was 20 mm, the range in the percent densification was approximately 20 to 55 percent, which is 4 to 11 mm.

- Based on the rutting data from all pavements, rutting occurred in all asphalt pavement lifts. No particular lift or group of lifts consistently rutted the most. (The surface mixtures were placed in four 50-mm lifts, while the base mixtures were placed in two 100-mm lifts.) The rut depths used in this analysis consisted of both the rut depth due to densification and to viscous flow.

- By dividing the total rut depth into the percent rut depth in the asphalt pavement layer and the percent rut depth in the underlying layers, as expected, it was found that the percent rut depth in the underlying layers increased as the asphalt pavement layer became thinner due to lateral shearing and flow.

- The slopes and intercepts provided by the relationships between pavement rut depth and wheel passes are not fundamental material properties: they are regression coefficients that depend on the type of regression used to calculate them. The slope or intercept alone cannot be used as a rutting performance indicator. Additional conclusions concerning the slope and intercept are given at the end of chapter 3.

8. Recommendations

- The relationship between $G^*/\sin\delta$ after RTFO aging and ALF pavement rutting performance for the unmodified binders suggested that the Superpave $G^*/\sin\delta$ criterion of 2.20 kPa is low. The data indicated that a criterion around 4.40 kPa may be needed. However, the 1997 Superpave binder specification recommended an increase of one high-temperature PG for the ALF traffic level, which was above 10 million ESAL's based on a 20-year design life.(3) An increase of one high-temperature PG is equivalent to doubling the criterion from 2.20 to 4.40 kPa. Thus, the data supported the current criterion of 2.20 kPa if the PG can be adjusted based on both traffic loading (speed) and ESAL's. A potential flaw in this analysis is that it is unknown how the number of ALF wheel passes applied to a pavement at a constant, high temperature relates to Superpave ESAL's.

- If the five binders were to be used in mixtures other than the mixtures tested in this study, different pavement performances would be obtained for a given PG. These mixtures could provide a different criterion. Therefore, additional studies are needed to determine the applicability of the 2.20-kPa criterion even though the data in this study provided no definitive reason for changing the criterion.

- The cause of the discrepancy between G*/sinδ and the pavement rutting performances provided by Novophalt and Styrelf needs to be determined. The average total strain and the average percent permanent strain provided by the DSR were found to be much greater than the average strains for the composite mixture. See appendix D. If the discrepancy is related to an interaction between the effects of the binders and the aggregates, then a binder test may not always be able to properly rank all binders according to relative pavement performance. Appendix E provides DSR data where mastics were tested. These data show an interaction. The G*/sinδ's of four mastics, consisting of the AC-10, AC-20, Novophalt, and Styrelf (PG 58-28, 64-22, 76-22, and 82-22) binders with diabase and hydrated lime, matched ALF pavement rutting performance.

- 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 regarding the effects of the five binders on rutting performance. Based on these results, any of these tests can be used to determine the relative effects of asphalt binders on rutting performance. However, the sensitivities of these tests to all key mixture variables need to be determined in future studies.

- The PURWheel and ALF correlated very well. Compared with the other mixture tests, the PURWheel was better at measuring the effects of nominal maximum aggregate size, but less capable of measuring the effects of asphalt binder grade. Each mixture test may be valid for measuring the effects of some variables on rutting performance, but may not be valid for measuring the effects of other variables. A more fundamental study is needed to determine a reason for the differences. (Note: Only pavement slabs were tested by the PURWheel, while both laboratory and pavement specimens were tested by the French PRT, Georgia LWT, Hamburg WTD, and SST. The degree of correlation between ALF and the PURWheel using specimens prepared in the laboratory was not determined.)

- It is recommended that the speeds of full-scale accelerated pavement testers and laboratory wheel-tracking devices be taken into account when validating G*/sinδ. The data obtained in this study did not show this to be of benefit, but the number of mixtures was limited. Theoretically, adjustments should be made.

- The compression modulus at a high temperature should not be computed from a measured shear modulus and an assumed Poisson's ratio. Likewise, a shear modulus should not be computed from a compression modulus.