Understanding The Performance of Modified Asphalt Binders in Mixtures: High-Temperature Characterization

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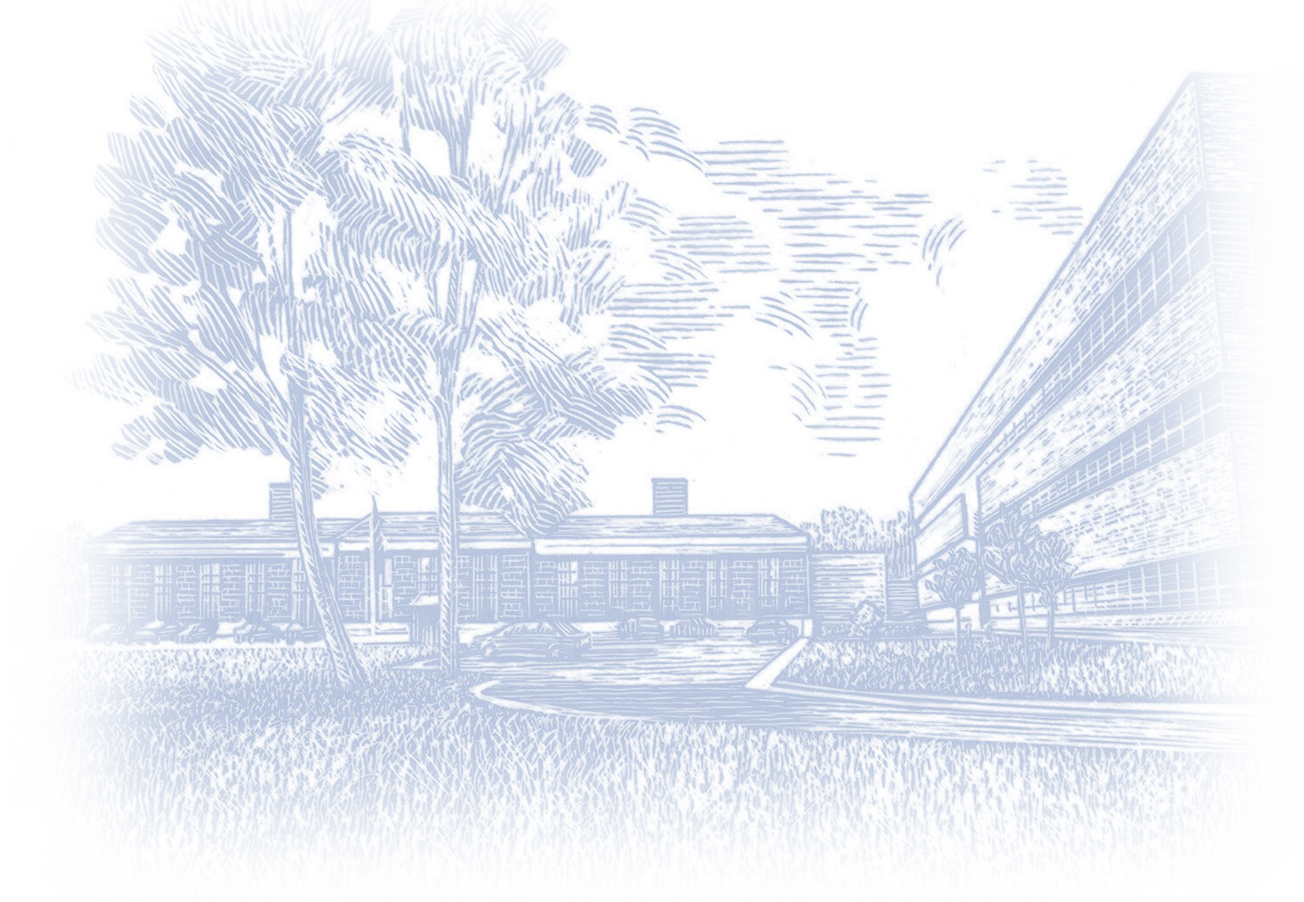

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Foreword

This report documents the effects of polymer-modified asphalt binders on the rutting resistance of mixtures with diabase and limestone aggregate. It is part of a research study titled "Understanding the Performance of Modified Asphalt Binders in Mixtures." This study is partially funded through National Cooperative Highway Research Program (NCHRP) Project 90-07. The objective of NCHRP Project 90-07 is to determine if asphalt binder performance is captured by the Superpave asphalt binder specification developed under the 1987 through 1993 Strategic Highway Research Program, with an emphasis on evaluating the performances of mixtures containing polymer-modified asphalt binders with identical Superpave performance grades, but varied chemistries. Asphalt binder tests developed under NCHRP Project 09-10, titled "Superpave Protocols for Modified Asphalt Binders," are also being evaluated. NCHRP Project 09-10 was completed in February 2001.

This report will be of interest to highway personnel who use polymer-modified asphalt binders and Superpave. Overall, good correlations between the high-temperature properties of the asphalt binders and mixture rutting resistance were found, but the two laboratory mixture tests did not provide the same conclusions concerning which asphalt binders do not behave as expected. Full-scale pavement tests are needed to determine this.

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16. Abstract
The overall objective of this study was to determine if the Superpave high-temperature rheological properties of polymer-modified asphalt binders correlate to asphalt mixture rutting resistance. An emphasis was placed on evaluating polymer-modified asphalt binders with identical (or close) high-temperature performance grades (PG's), but varied polymer chemistries. Eleven asphalt binders were obtained for this study: two unmodified asphalt binders, an air-blown asphalt binder, and eight polymer-modified asphalt binders. High-temperature asphalt binder properties were measured by a dynamic shear rheometer (DSR). Mixture rutting resistance was measured by repeated shear at constant height (RSCH), and the French Pavement Rutting Tester (French PRT).

The first objective was to verify the findings of a previous study using a different aggregate. In the previous study, it was found that the Superpave high-temperature asphalt binder properties correlated to mixture rutting resistance with few outliers, and a change in high-temperature PG from 70 to 76 increased rutting resistance. However, the correlation between RSCH and asphalt binder $G^*/\sin\delta$ (delta) depended on DSR frequency. The data suggested that a low DSR frequency, such as 0.1 rad/s, might provide a better grading system than the standard DSR frequency of 10.0 rad/s. This would require a change in the current asphalt binder specification. A diabase aggregate was used in a previous study. The data using a second aggregate, a limestone aggregate, in combination with four of the asphalt binders, agreed with the findings from the diabase mixtures.

The second objective was to retest the diabase mixtures at 70 degrees Celsius using RSCH. The test temperatures used in the previous study were 50 degrees Celsius for RSCH and 70 degrees Celsius for the French PRT. The polymer-modified asphalt binders had continuous high-temperature PG's ranging from 71 to 77. Therefore, it was recommended that the test temperature for RSCH be increased to 70 degrees Celsius. Again, the correlation between RSCH and G*/sinδ was dependent on DSR frequency. The data suggested that a low DSR frequency, such as 0.1 rad/s, might provide a better grading system. However, it is not known whether this finding applies to pavements, or is related to the accelerated nature of the RSCH test. Furthermore, G*/sinδ (delta) at 0.1 rad/s did not clearly provide a better correlation to RSCH than the high-temperature PG's of the asphalt binders. The degree of correlation between the French PRT and G*/sinδ at 70 degrees Celsius did not depend on DSR frequency, and there was only one outlier. A correlation between the French PRT and high-temperature PG provided no obvious outliers. No changes to the specification are recommended based on the French PRT results.

17. Key Words Superpave, asphalt binder specification, permanent deformation, Superpave Shear Tester, SST, French Pavement Rutting Tester, polymer-modified asphalt binders.	**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161..

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SI* (Modern Metric) Conversion Factors

Approximate Conversions to SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
Area				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

Volume				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
Mass				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
Temperature (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
Illumination				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
Force and Pressure or Stress				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
Area				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2

ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
Volume				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
Mass				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
Temperature (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
Illumination				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
Force and Pressure or Stress				
N	newtons	02.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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Phase 1--Evaluation of High-Temperature Asphalt Binder Tests Using Mixtures With Limestone and Diabase Aggregate

A. Background

This report supplements a Federal Highway Administration (FHWA) report titled *Understanding the Performance of Modified Asphalt Binders in Mixtures: Permanent Deformation Using a Mixture With Diabase Aggregate* (Publication No. FHWA-RD- 02-042).[1] The research findings in FHWA-RD-02-042 and in this report were obtained under a study that is partially funded through National Cooperative Highway Research Program (NCHRP) Project 90-07. The objective of the study is to determine if asphalt binder performance is captured by the Superpave asphalt binder specification developed under the 1987 through 1993 Strategic Highway Research Program, with an emphasis on evaluating the performances of mixtures containing polymer-modified asphalt binders with identical Superpave performance grades (PG's), but varied modification chemistries.[2] Although identical PG's were desired, the high-temperature PG's of the polymer-modified asphalt binders ranged from 71 to 77 after rolling thin-film oven (RTFO) aging.

Superpave uses the parameter G*/sinδ to grade asphalt binders according to their resistance to rutting at high pavement temperatures. At high temperatures, rutting resistance should increase as G*/sinδ increases. The asphalt binder with the highest G*/sinδ should have the most resistance to rutting. During the study documented in FHWA-RD-02-042, it was found that G*/sinδ at 50°C had a high correlation to mixture rutting resistance as measured by the cumulative permanent shear strains from repeated shear at constant height (RSCH) at 50°C .[1] RSCH is applied by the Superpave Shear Tester. The r^2 was 0.89, but the degree of correlation was highly dependent on dynamic shear rheometer (DSR) frequency. G*/sinδ at 70°C had a weak correlation to mixture rutting resistance as measured by the French Pavement Rutting Tester (French PRT) at 70°C .[1] The r^2 was 0.70, although it increased to 0.88 after removing the data for 1 of 11 asphalt binders.

The objective of the rutting study was to determine which asphalt binders provide high-temperature properties that do not agree with mixture rutting resistance.[1] This would indicate what types of modification provide properties that are, or are not, correctly captured by the current Superpave asphalt binder specification. In general, the number of discrepancies between G*/sinδ and mixture rutting resistance was low. The data indicated that the current Superpave asphalt binder specification and testing protocols are valid for most of the asphalt binders tested in the referenced study.[1]

This report is divided into two phases. In phase 1, asphalt binders were combined with a limestone aggregate to verify the conclusions provided by a mixture with diabase aggregate. Phase 2 addresses recommendations that the diabase mixtures be retested using RSCH at a test temperature closer to the PG's of the asphalt binders.

B. Objective

The objective of phase 1 was to verify the findings provided by a mixture with diabase aggregate using a second mixture with limestone aggregate. For the diabase mixture, the high-temperature properties of the asphalt binders correlated to mixture rutting resistance. Furthermore, a change in high-temperature PG from 70 to 76 increased rutting resistance at 50°C based on RSCH and at 70°C based on the French PRT.

C. Materials

Eleven asphalt binders were tested. This included one air-blown asphalt and eight polymer-modified asphalt binders: (1) styrene-butadiene-styrene [SBS] Linear, (2) SBS Linear Grafted, (3) SBS Radial

Grafted, (4) ethylene vinyl acetate [EVA], (5) EVA Grafted, (6) Elvaloy, (7) ethylene styrene interpolymer [ESI], and (8) chemically modified crumb rubber asphalt [CMCRA]. There were two control asphalt binders: an unmodified PG 70-22 and an unmodified PG 64-28. The polymer-modified asphalt binders include elastomeric and plastomeric modifiers. Grafting includes any mode of chemically reacting a polymer with an asphalt binder, for example, vulcanization. The target PG for the polymer-modified asphalt binders was PG 73-28. The PG 64-28 asphalt binder and a PG 52-34 asphalt binder from the same crude source were modified. The air-blown asphalt was originally the PG 52-34 asphalt binder.

Four of the 11 asphalt binders were chosen for use with the limestone aggregate: Elvaloy, EVA Grafted, SBS Linear, and PG 64-28. These binders were selected because they provided relatively high and low levels of cumulative permanent shear strain using the diabase aggregate. Additional information on the asphalt binders, and information on the aggregates and mixture designs are given elsewhere.[1-2]

D. Tests

High-temperature asphalt binder properties were measured by a DSR after RTFO aging.[3] Mixture rutting resistance was based on the cumulative permanent shear strains from RSCH and on the rut depths from the French PRT.[4-5] All mixtures were subjected to 2 hours (h) of short-term oven aging (STOA) at 135°C . Specimens were tested approximately 48 h after compaction.

E. Cumulative Permanent Shear Strain

Cumulative permanent shear strain from RSCH was measured at 7.0-percent air voids, 50°C , and 5,000 cycles. The applied shear stress was 69 ±5 kilopascals (kPa). The loading time was 0.1 second (s) and the rest time was 0.6 s. Three replicate specimens were tested per mixture. Lower cumulative permanent shear strains indicate more resistance to rutting. This test mimics fast, heavy pavement loads.

Table 1 gives the cumulative permanent shear strains from RSCH for the four asphalt binders with both the limestone and diabase aggregates. Table 2 shows that the replicate data for the limestone mixture with SBS Linear had one high strain relative to the other two strains. This high strain was considered a potential outlier. Therefore, averages with and without the high strain were calculated for this mixture.

Aggregate type did not affect the cumulative permanent shear strains from RSCH at a 5-percent level of significance. Thus, rutting performance was independent of aggregate type. The shear strains of 38,600 micrometers per meter (μm/m) and 28,400 μm/m using PG 64-28 are not significantly different because of the high variability of the shear strains for the limestone mixture. (See table 2.)

Table 1 shows that high-temperature PG provided a correct ranking, and an increase in PG from 70 to 76 would significantly decrease cumulative permanent shear strain. (Linear regression analyses were not performed because the number of data points are too low.) The PG's agree with the shear strains better than the G-star divided by sine delta's ($G^*/\sin\delta$'s) of the asphalt binders measured at the RSCH test temperature of 50°C and 10.0 radians per second (rad/s). The use of other frequencies did not provide a correct ranking. $G^*/\sin\delta$'s at a relatively low frequency of 0.1 rad/s are included in table 1. Based on the shear strains from RSCH in table 1 and on the full set of data for the diabase mixture at 50°C , it was concluded that the $G^*/\sin\delta$'s for Elvaloy are low. (The full set of data are given in phase 2 of this study and in reference 1.)

RSCH applies a rest period after each cycle of loading while the standard DSR test for asphalt binders does not. The rest period allows a mixture to recover time-dependent recoverable elastic deformations. Because the DSR test does not include a rest period, these deformations will be part of the permanent deformation. To determine whether this was the cause of the discrepancy for Elvaloy, the four asphalt binders were tested by a method titled "Determining the Rutting Resistance of Asphalt Binder Subjected to Repeated Creep (RC) Using a Dynamic Shear Rheometer (DSR)."[6] This test applies repeated loads with rest periods like RSCH. Each loading cycle had a duration of 1.0 s followed by a 9.0-s rest period. The applied shear stress was 25.0 Pascals (Pa). This test was used to measure the cumulative permanent shear strain at 100 cycles. This means that the asphalt binders and the mixtures were evaluated by the same parameter. Table 1 shows that the test did not provide an improved ranking.

F. French PRT

The French PRT tests a slab for permanent deformation using a rubber tire inflated to 600 ±30 kPa.(5) Each slab had a length of 500 millimeters (mm), a width of 180 mm, and a thickness of 50 mm. The applied load was 5000 ±50 Newtons (N) and the test temperature was 70°C . The air-void level was 7.0 percent. The test normally ends at 6,000 wheel passes, but it was continued to 20,000 wheel passes to determine if this would change the relative performances of the mixtures. Although the measurement from the French PRT is generally called the "rut depth," it is actually a percent rut depth, which is the deformation in millimeters times 100 divided by the slab thickness of 50 mm.

Table 1. DSR and RSCH data.

Asphalt Binder or Mixture	DSR After RTFO Aging				RSCH After 2.0 h of STOA		
	High-Temp.PG (°C)	G*/sinδ at 50°C (Pa)		CPSS[1] at 50°C (μm/m)	Cumulative Permanent Shear Strain at 50°C (μm/m)		
		10.0 rad/s	0.1 rad/s		Diabase	Limestone With Outlier	Limestone Without Outlier
Elvaloy	77	28 700	1 340	218	14 600	14 500	14 500
EVA Grafted	74	35 800	1 680	88	15 400	14 900	14 900
SBS Linear	72	25 400	660	305	26 500	29 600	23 400
PG 64-28	67	22 200	320	1 060	38 600	28 400	28 400

[1]Cumulative permanent shear strain of the asphalt binder.

Table 2. Cumulative permanent shear strain from RSCH for the mixtures with limestone aggregate.

Replicate Number	RSCH Cumulative Permanent Shear Strain at 50°C (μm/m)			
	Elvaloy	EVA Grafted	SBS Linear	PG 64-28
1	15 950	12 450	20 710	36 010
2	13 870	16 870	42 080[1]	21 090
3	13 770	15 370	26 040	28 240
Average	14 500	14 900	29 600	28 400
Coefficient of Variation, %	8.5	15.1	37.6	26.2

[1]Possible outlier.

The average rut depths from the French PRT at 6,000 wheel passes are given in table 3. The data for individual slabs are shown in table 4. The coefficients of variation (CV) in table 4 are remarkably low for testing only two specimens per mixture. Only 2 of 17 mixtures had a CV above 20.0 percent.

Table 3 shows that for each asphalt binder, the average rut depth was lower using the limestone aggregate compared to the diabase aggregate with 4.85-percent asphalt binder. The range in rut depth was also lower using limestone. The asphalt binder content for the diabase mixture was then reduced from 4.85 to 4.55 percent to determine whether the difference in rutting resistance was related to the volumetrics of the mixture. This reduction increased the air-void level after 75 gyratory revolutions from 3.2 percent to the typically used mixture design level of 4.0 percent. The asphalt binder content for the limestone mixture was based on a 4.0-percent air-void level, so it was not changed. Table 3 and figure 1 show that the rut depths for the diabase mixtures with the lower asphalt binder content are very close to the rut depths provided by the limestone mixtures. Figure 1 also shows that the slopes are roughly the same, which indicates that the high-temperature PG's had a similar effect on all three types of mixtures. The data at 20,000 wheel passes provided the same conclusions. These data are given in table 5.

Styrelf, AC-10, and AC-5 (PG 82-22, PG 64-22, and PG 58-34) asphalt binders, which were used in prior FHWA studies, were tested with the limestone aggregate to expand the range in high-temperature PG.[1,5] These data are given at the bottom of table 3. The data for all seven asphalt binders with the limestone aggregate are shown in figure 2, along with all of the data for the diabase aggregate using a 4.85-percent asphalt binder. These data are given in reference 1. The addition of the three data points for the limestone aggregate provided a curvilinear relationship that is roughly flat above PG 70. Both relationships in figure 2 show that asphalt binders with a PG of 70 or greater led to rut depths that were lower than the maximum allowable rut depth of 10 percent. The data appear to validate the Superpave system.

$G^*/\sin\delta$'s at 0.9 rad/s and 70°C were compared to the rut depths from the French PRT because this frequency represents the slow speed of the device.[5] (See table 3.) Figure 3 shows that $G^*/\sin\delta$ provided curvilinear relationships like high-temperature PG. The data for Styrelf are not included in figure 3 because its $G^*/\sin\delta$ was very high (2360 Pa). The $G^*/\sin\delta$ for EVA at 0.9 rad/s is low based on the mixture with the diabase aggregate.

The slow speed of the French PRT does not mean that the results are valid for Superpave standing traffic loads. All small-scale wheel-tracking devices have slow speeds, but the protocols and pass/fail criteria for them are generally based on data from pavements where vehicle speed is variable and the average speed is much higher than the French PRT speed of 7 kilometers per hour (km/h). Even with this confounding factor, it seems reasonable in research studies to adjust the DSR frequency to match the slow speed of a wheel-tracking device. The relationships based on 0.9 rad/s in figure 3 are reasonably good, but so are the relationships based on 10 rad/s in figure 2. The data for these materials do not show that one frequency is more appropriate than the other. (Additional information concerning the appropriate DSR frequency is included in phase 2 of this report.)

The effect of increasing the PG from 70 to 76 is difficult to determine because of the empirical nature of the French PRT. Figure 2 appears to indicate that bumping the PG from 70 to 76 to account for slower traffic speeds or high equivalent single-axle loads (ESAL's) may not provide a more rut-resistant mixture. All asphalt binders with a PG of 70 or greater provided rut depths that passed the test. However, if it is assumed that the French methodology was developed for fast traffic speeds, then the severity of the test, or the pass/fail criterion, is not sufficient for slow traffic speeds. Therefore, no overall conclusion concerning a bump in PG can be made based on figure 2. In order to conclude that a bump in PG would never be beneficial, the French PRT would have to apply the severest conditions. Most likely, it does not apply the severest conditions, although it is not clear what the French methodology represents in terms of vehicle speed and ESAL's. Based on data collected in this and previous FHWA studies, the device may simulate pavement loadings that require, at most, one bump in PG. If the severity of the test is equivalent to one bump in PG, then the bumped grade needed to have both mixtures pass the test is PG 70 and the original grade would be PG 64. This bump may not improve the rutting performance of the limestone mixture, but it is needed for the diabase mixture.

Figure 3 shows that all mixtures passed the test at a G*/sinδ of 200 Pa or greater. This is lower than the G*/sinδ of 2200 Pa used by the Superpave asphalt binder specification after RTFO aging because a DSR frequency of 0.9 rad/s was used to represent the speed of the French PRT. Plots like figures 2 and 3 are useful for determining whether an asphalt binder parameter correlates to mixture rutting under a set of conditions that roughly mimic average pavement loadings for a certain class of highway, such as Interstate highways. However, they should not be used to determine pass/fail criteria for asphalt binder tests unless it is known what the wheel-tracking device represents in terms of vehicle speed and ESAL's, and a DSR frequency that matches the speed of the wheel-tracking device can be established.

G. Conclusions

- High-temperature PG agreed with mixture rutting resistance based on both the cumulative permanent shear strain from RSCH at 50°C and the rut depths from the French PRT at 70°C . The data provided no reason to change the Superpave high-temperature asphalt binder specification.
- An increase in high-temperature PG from 70 to 76 decreased the cumulative permanent shear strain at 50°C .
- All mixtures with a PG of 70 or greater passed the French PRT. Even so, it could not be concluded that an increase in PG from 70 to 76 would not be beneficial because of the empirical nature of the device and its pass/fail specification.
- The cumulative permanent shear strains from RSCH showed that the G*/sinδ for Elvaloy at 50°C was low. G*/sinδ underpredicted the relative rutting resistance provided by Elvaloy. However, Elvaloy's high-temperature PG agreed with the strains from RSCH. Furthermore, the asphalt binder properties of Elvaloy agreed with the rut depths from the French PRT at 70°C . The data provided no reason to change the Superpave asphalt binder specification.
- The French PRT indicated that the G*/sinδ for EVA at 0.9 rad/s and 70°C was low. This anomaly is discussed in phase 2 of this report.

Table 3. DSR data and French PRT rut depths at 6,000 wheel passes.

Asphalt Binder or Mixture Designation	DSR After RTFO Aging		French PRT After 2.0 h of STOA		
	High-Temp. PG	G*/sinδ , 0.9 rad/s at 70°C (Pa)	Rut Depth at 70°C and 6,000 Wheel Passes (percent)		
			Diabase at 4.85% AC[1]	Limestone	Diabase at 4.55% AC[1]
Elvaloy	77	753	6.5	3.6	3.9
EVA Grafted	74	394	7.5	4.7	Not Tested
SBS Linear	72	309	8.5	5.4	5.7
PG 64-28	67	151	12.1	7.5	8.6
Range	10	602	5.6	3.9	4.7
Asphalt Binders From the FHWA 1993 to 2001 Superpave Validation Study					
Styrelf	88	2360	4.8	5.6	NT
AC-10	65	118	10.7	8.1	NT
AC-5	59	61	>11.7	14.3	NT

[1]AC = Asphalt content by total mass of the mixture.

Table 4. Percent rut depth from the French PRT at 70°C and 6,000 wheel passes.

Asphalt Binder	Diabase Aggregate With 4.85-Percent Asphalt Binder				Limestone Aggregate				Diabase Aggregate With 4.55-Percent Asphalt Binder			
	Test #1	Test #2	Avg.	CV[1]	Test #1	Test #2	Avg.	CV[1]	Test #1	Test #2	Avg.	CV[1]
Elvaloy	5.94	6.97	6.5	12.0	3.52	3.77	3.6	5.8	4.26	3.60	3.9	12.6
EVA Grafted	6.96	8.10	7.5	10.4	5.07	4.39	4.7	10.4	Not Tested			
SBS Linear	8.55	8.42	8.5	1.6	6.25	4.61	5.4	20.9	5.38	6.04	5.7	7.4
PG 64-28	11.73	12.42	12.1	4.0	8.71	6.22	7.5	23.6	9.13	8.05	8.6	9.1
Styrelf	4.32	5.19	4.8	13.3	5.07	6.20	5.6	13.9	Not Tested			
AC-10	10.59	10.79	10.7	1.3	8.35	7.83	8.1	5.2	Not Tested			
AC-5	12.39	11.02	11.7	8.5	16.31	12.58	14.3	18.3	Not Tested			

[1]CV = Coefficient of Variation, percent = (standard deviation ÷ average)*100.

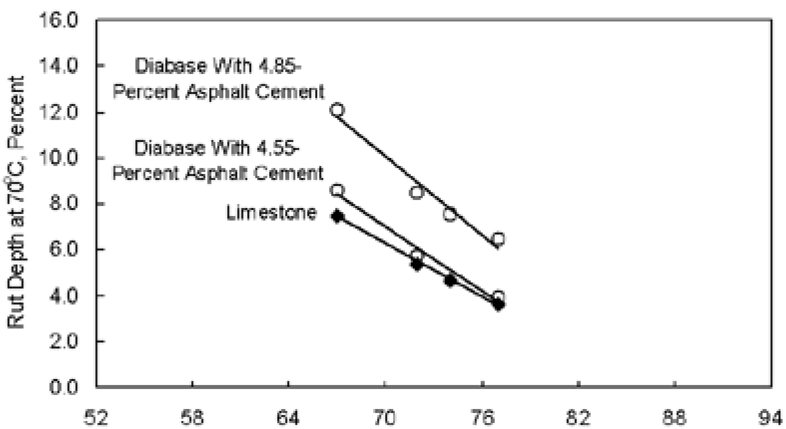

Figure 1. French PRT rut depth at 70°C vs. high-temperature PG.

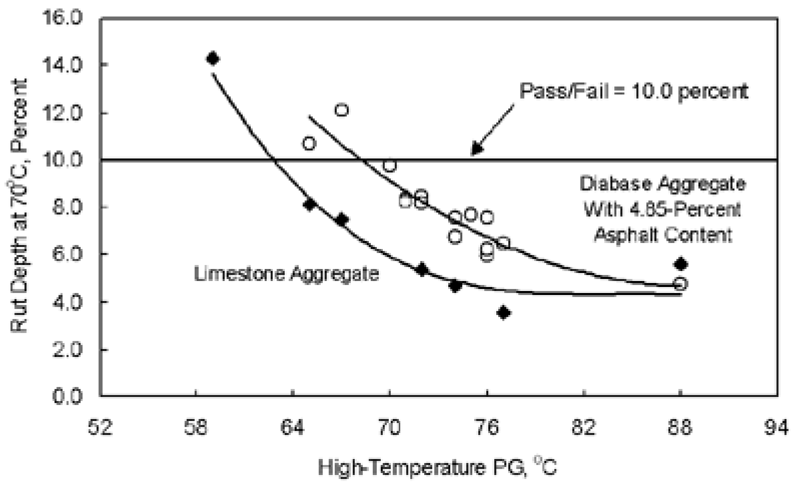

Figure 2. French PRT rut depth at 70°C vs. high-temperature PG for all asphalt binders.

Table 5. DSR data and French PRT rut depths at 20,000 wheel passes.

Asphalt Binder or Mixture Designation	DSR After RTFO Aging		French PRT After 2.0 h of STOA		
	High-Temp. PG	G*/sinδ , 0.9 rad/s at 70°C (Pa)	Rut Depth at 70°C and 20,000 Wheel Passes (percent)		
			Diabase at 4.85% AC[1]	Limestone	Diabase at 4.55% AC[1]
Elvaloy	77	753	7.9	4.7	5.3
EVA Grafted	74	394	9.2	6.2	Not Tested
SBS Linear	72	309	10.5	7.8	8.7
PG 64-28	67	151	16.0	13.9	14.1

[1]AC = Asphalt content by total mass of the mixture.

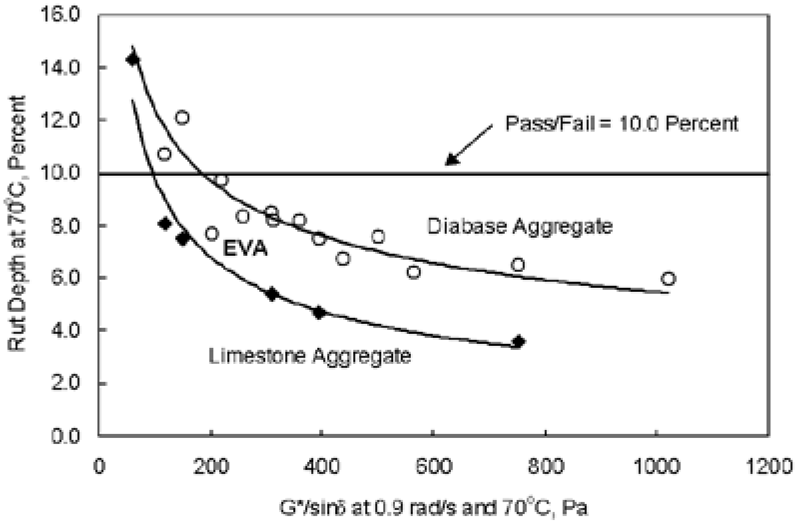

Figure 3. French PRT rut depth at 70°C vs. G*/sinδ at 70oC for all asphalt binders.

Phase 2--Evaluation of High-Temperature Asphalt Binder Tests Using the RSCH and French PRT Mixture Tests at 70°C

A. Background

The polymer-modified asphalt binders used in this study had continuous high-temperature PG's ranging from 71 to 77. The mixtures were tested by the French PRT at 70°C . This was the highest temperature that can be applied by this tester. The mixtures were tested for cumulative permanent shear strain at 50°C because of testing problems encountered at higher temperatures in previous studies. However, most of the problems were provided by the Frequency Sweep at Constant Height (FSCH) mode of loading. RSCH and FSCH are both applied by the Superpave Shear Tester. It was recommended that the diabase mixtures be retested using RSCH at a temperature closer to the PG's of the asphalt binders.

B. Objective

The objective of phase 2 was to retest the diabase mixtures at 70°C using RSCH to determine which asphalt binders provide high-temperature properties that do not agree with mixture rutting resistance.

C. Materials

All 11 asphalt binders were used. Information on the asphalt binders, aggregates, and mixture design are given elsewhere.[1-2] The reduced asphalt binder content of 4.55 percent by mixture mass was used so that the mixture met the 4.0-percent design air-void level as recommended by Superpave. Prior problems with testing mixtures at temperatures above 50°C contributed to the decision to lower the asphalt binder content. However, it confounded the analysis of the data because the mixtures tested by the French PRT had a 4.85-percent asphalt binder content.

D. Tests

High-temperature asphalt binder properties were measured by a DSR after RTFO aging.[3] Mixture rutting resistance was based on the cumulative permanent shear strains from RSCH and the rut depths from the French PRT.[4-5] All mixtures were subjected to 2 h of STOA at 135°C . Specimens were tested 48 h after compaction.

E. Cumulative Permanent Shear Strain

Cumulative permanent shear strain from RSCH was measured at 7.0-percent air voids, 70°C, and 5,000 cycles. The applied shear stress was 69 ±5 kPa. The loading time was 0.1 s and the rest time was 0.6 s. A minimum of three replicate specimens were tested per mixture. Lower cumulative permanent shear strains indicate more resistance to rutting.

The data at both 50°C and 70°C are given in table 6 and figure 4. The two regression lines suggest that mixtures containing asphalt binders with the highest PG's tended to be highly resistant to rutting at both test temperatures. While this seems reasonable, the difference in asphalt binder content probably decreased the vertical differences between the two lines.

Table 6 shows that the rankings are not the same at 50°C and 70°C . The only certain difference in ranking is that the mixture with PG 70-22 performed relatively worse at 70°C compared to 50°C . Figure 5 shows that the data point for this mixture was furthest from the regression line. Being above the line, this mixture performed worse than expected at 70°C , or better than expected at 50°C . Because of the change in asphalt binder content, no firm conclusions could be made for the other asphalt binders.

The cumulative permanent shear strains in table 6 indicate that grafting did not improve the rutting resistance of EVA at either temperature at a 5 percent level of significance. Grafting and geometry had no significant effect on the rutting resistance of SBS at 50°C . All three SBS mixtures fell into group D. SBS Radial Grafted did perform significantly better than SBS Linear at 70°C . The shear strain for SBS Linear Grafted at 70°C was not significantly different from the shear strains for SBS Radial Grafted or SBS Linear at 70°C .

The coefficients of variation (CV) for cumulative permanent shear strain at 5,000 cycles ranged from 1.7 percent to 36.7 percent. (See table 7.) Several data points were found to be outliers. These outliers were not used when evaluating asphalt binder properties. However, all of the replicate data are included in table 7 because the variability of the data in table 7 is a good representation of the variability typically provided by RSCH. The averages and CV's in the parentheses include the outliers. At 50°C , the CV's ranged from 8.2 to 24.1.[1] Variability appeared to be greater at 70°C , but a paired t-test indicated that it was not greater.

For the tests at 50°C , the cumulative permanent shear strains were correlated to the G*/sinδ 's of the asphalt binders at three DSR frequencies: 10.0, 2.0, and 0.125 rad/s.[1] The G*/sinδ 's are given in table 8. These three frequencies provided r^2's of 0.06, 0.55, and 0.89, respectively, using log-log transformations. The correlation depended on DSR frequency. The correlation to high-temperature PG was 0.68 without transformation. (Note: A log-log transformation was used if it provided a higher r^2. Relationships between asphalt binder and mixture high-temperature properties are normally curvilinear. Thus, a log-log or power law transformation usually provides a higher r^2.)

Table 6. DSR data and RSCH data at 70°C and 50°C.

Asphalt Binder or Mixture	DSR After RTFO Aging				RSCH After 2 h of STOA											
	High-Temp. PG	G*/sinδ at 70°C and Three DSR Frequencies (Pa)			Cumulative Permanent Shear Strain at 70°C (μm/m)						Cumulative Permanent Shear Strain, at 50°C (μm/m)					
		10.0 rad/s	2.0 rad/s	0.125 rad/s												
Elvaloy	77	4 110	1 330	166	13 100	A					14 600	A				
EVA	75	1 910	434	36	22 220	A	B				13 600	A				
SBS RG	71	2 680	657	49	23 720		B				21 300		B	C	D	
SBS LG	72	2 880	746	62	27 600		B	C			23 200			C	D	
EVA G	74	3 440	823	61	28 200		B	C			15 400	A	B			
CMCRA	76	4 510	1 150	93	28 900		B	C			19 100	A	B	C		
ESI	76	4 030	1 040	76	30 400		B	C			22 700			C	D	
Air-Blown	74	3 870	920	66	33 340			C			21 300		B	C	D	
SBS L	72	2 710	655	50	35 800			C			26 500				D	
PG 70-22	71	2 640	568	37	50 850				D		23 900			C	D	
PG 64-28	67	1 570	330	21	62 700					E	38 600					E

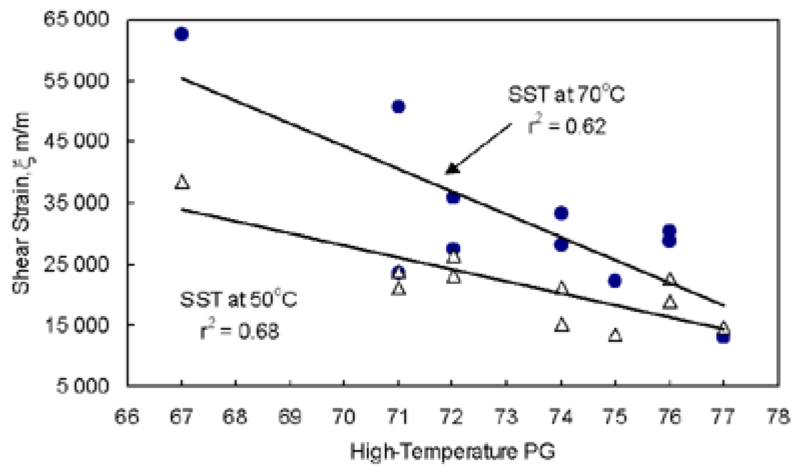

Figure 4. RSCH cumulative permanent shear strain vs. high-temperature PG of the asphalt binder.

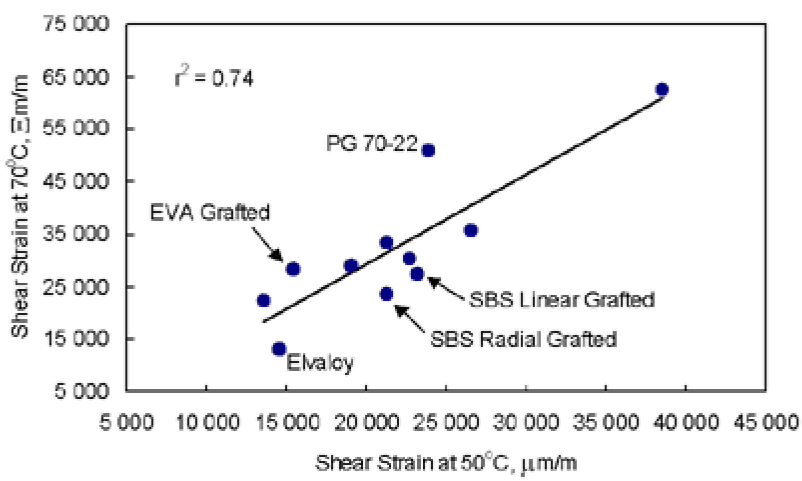

Figure 5. RSCH cumulative permanent shear strain at 70°C vs. RSCH cumulative permanent shear strain at 50°C.

Table 7. Replicate cumulative permanent shear strains at 70°C.

Mixture	Sample Number	2,500 Cycles			5,000 Cycles		
		Strain (μm/m)	Average Strain	CV[1]	Strain (μm/m)	Average Strain	CV[1]
PG 70-22	1	41 980	35 820	17.9	64 000	50 850	28.0
	2	29 490			36 000		
	3	40 620			62 000		
	4	31 170			41 400		
Elvaloy	1	8 990	11 400	18.3	10 290	13 100	18.4
	2	12 740			14 570		
	3	12 470			14 330		
ESI	1	27 230	24 800	11.1	34 560	30 400	15.2
	2	21 820			25 410		
	3	25 400			31 260		
EVA	1	(10 260)[2]	19 110 (18 620)	17.9 (31.9)	(11 470)[2]	22 220 (22 140)	20.2 (36.7)
	2	15 210			17 280		
	3	21 540			26 080		
	4	20 590			23 290		
	5	(25 490)[2]			(32 590)[2]		
SBS LG	1	19 570	22 800	13.2	23 130	27 600	14.2
	2	23 400			29 420		
	3	25 560			30 320		
AB	1	(41 510)[2]	26 740 (29 690)	6.3 (22.8)	(57 680)[2]	33 340 (38 200)	8.6 (29.2)
	2	27 930			34 600		
	3	28 330			36 670		
	4	24 790			30 190		
	5	25 900			31 880		
SBS L	1	39 930	31 100	27.4	42 500	35 800	22.2
	2	22 970			27 030		
	3	30 280			37 990		
EVA G	1	23 710	23 700	17.1	27 880	28 200	19.7
	2	19 620			22 750		
	3	27 700			33 850		
SBS RG	1	23 750	20 300 (23 450)	12.7 (31.5)	27 860	23 720 (26 800)	12.4 (27.4)
	2	20 610			23 660		
	3	(36 060)[2]			(39 120)[2]		
	4	17 800			21 170		
	5	19 050			22 170		
CMCRA	1	24 160	24 900	12.8	28 050	28 900	13.0
	2	22 150			25 610		
	3	28 380			32 960		
PG 64-28	1	52 300	51 400	4.0	62 850	62 700	1.7
	2	52 810			61 600		
	3	49 010			63 700		

[1]CV = Coefficient of Variation, percent = (standard deviation ÷ average)*100.
[2]Outlier.

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Table 8. G*/sinδ 's of the asphalt binders at 10.0, 2.0, and 0.125 rad/s with the asphalt binders listed from highest to lowest G*/sinδ based on 0.125 rad/s.

Asphalt Binder	G*/sinδ at 50°C After RTFO Aging (Pa)		
	10.0 rad/s	2.0 rad/s	0.125 rad/s
EVA	26 300	12 100	2 740
EVA Grafted	35 800	14 300	2 310
Elvaloy	28 700	10 000	1 600
CMCRA	44 300	13 900	1 540
Air-Blown	49 100	14 200	1 390
SBS Linear Grafted	25 600	8 000	920
ESI	32 300	8 900	870
SBS Linear	25 400	7 700	810
PG 70-22	40 700	10 200	810
SBS Radial Grafted	25 100	7 600	800
PG 64-28	22 200	5 400	400

Table 6 gives the G*/sinδ 's at 70°C . When correlated against cumulative permanent shear strain, frequencies of 10.0, 2.0, and 0.125 rad/s provided r^2's of 0.22, 0.37, and 0.59, respectively, using log-log transformations. This correlation also depended on DSR frequency. The correlation to high-temperature PG was 0.63 without transformation. All of the r^2's are given in table 9.

The correlations to G*/sinδ at 50°C and 70°C using a DSR frequency of 0.125 rad/s are shown in figures 6 and 7, respectively. The correlation at 50°C is very good. The largest deviation was provided by Elvaloy, followed by SBS Radial Grafted. Figure 7 shows that the G*/sinδ 's for EVA and SBS Radial Grafted are low at 70°C . G*/sinδ underpredicted their resistances to rutting. Because the data for EVA significantly affected the position of the trend line, the trend line in figure 7 was drawn without the data for EVA. The data point for SBS Radial Grafted did not significantly affect the position of the trend line.

Figures 8 and 9 show the data at 70°C using DSR frequencies of 2.0 and 10.0 rad/s, respectively. Both figures show that the G*/sinδ for PG 70-22 is high, while the G*/sinδ 's for EVA and Elvaloy are low. The G*/sinδ for SBS Radial Grafted is low at 2.0 rad/s, but not at 10.0 rad/s based on 95-percent confidence bands.

Figure 10 shows that the correlation using high-temperature PG is poor, although the r^2 increased from 0.63 to 0.79 after excluding the data for SBS Radial Grafted. The 95-percent confidence band for cumulative permanent shear strain at the mean PG of 74 is 22 000 to 36 000 μm/m with SBS Radial Grafted and 25 000 to 36 000 μm/m without SBS Radial Grafted.

The higher r^2 using G*/sinδ at 0.125 rad/s compared to G*/sinδ at 10.0 rad/s suggests that, according to cumulative permanent shear strain, a low DSR frequency might provide a better grading system. If the frequency is changed, then the criterion, which is currently 2200 Pa after RTFO, must also be changed. Figure 11 shows the relationship between cumulative permanent shear strain and temperature if the frequency is changed to 0.125 rad/s, but the criterion is not changed. The temperatures are very low and the correlation is poor. The lack of a known correlation between cumulative permanent shear strain and pavement rutting makes it difficult to choose a criterion. A preliminary recommendation based on the ranking in table 6 is to use a maximum allowable shear strain of around 30 000 μm/m to 40 000 μm/m. Figure 7 shows that a shear strain of 30 000 μm/m (log 30 000 = 4.477) provides a criterion of around 60

Pa (log 60 1.8), although the scatter in figure 7 shows that this will not provide a perfect grading system. Furthermore, the relationship based on 0.125 rad/s in figure 7 is not better than the relationship based on high-temperature PG in figure 10.

Table 10 and figure 12 provide the cumulative permanent shear strains for the asphalt mixtures at 70°C and 5,000 cycles vs. the cumulative permanent shear strains for the asphalt binders from repeated creep at 70°C and 100 cycles. The correlation is poor, having an r^2 of 0.58. If the data for the PG 64-28 materials are removed, the r^2 drops to 0.21. Based on the mixture test results, the cumulative permanent shear strains for the Elvaloy and EVA Grafted asphalt binders are high, while they are low for the PG 70-22 asphalt binder. The relationship should start at the zero-zero origin, but it does not. Therefore, the relationship must be curvilinear. Figure 13 provides a log-log relationship. This did not improve the correlation. The r^2 of 0.38 is poor. The repeated creep is a new asphalt binder test and it is not known if the protocols are the optimal protocols.

F. French PRT

The rut depths from the French PRT at 70°C are given in tables 11 and 12.[1] Table 12 shows that the mixture with SBS Radial Grafted had a high coefficient of variation. Tests on the mixtures with EVA and SBS Radial Grafted were repeated. The range in the replicate rut depths for these mixtures is relatively large compared to the range in average rut depth for all modified asphalt binders. The statistical ranking in table 11 shows that the rut depths for all mixtures, except for the mixture with PG 64-28, had rut depths that were not different at a 5-percent level of significance.

Figures 14 and 15 show the relationships between rut depth and $G^*/\sin\delta$ using DSR frequencies of 0.9 and 10.0 rad/s, respectively. The $G^*/\sin\delta$'s for EVA may be low. If so, $G^*/\sin\delta$ underpredicted the relative rutting resistance provided by EVA. Without EVA, frequencies of 0.9 and 10.0 rad/s provided r^2's of 0.83 and 0.91, respectively, compared to 0.54 and 0.56 with EVA. Without both EVA and PG 64-28, frequencies of 0.9 and 10.0 rad/s provided r^2's of 0.69 and 0.67, respectively. The data point for PG 64-28 increases the upward curvature of the relationship, while the data point for EVA tends to flatten the relationship. If the 9.9-percent rut depth for SBS Radial Grafted in table 12 were to be eliminated, $G^*/\sin\delta$ would also underpredict the relative rutting resistance of this asphalt binder.

Figure 16 provides the correlation with high-temperature PG. The PG of EVA agrees with mixture performance. This means that the $G^*/\sin\delta$ for EVA is not increasing as rapidly as it should at temperatures immediately below its high-temperature PG. EVA was found to have the lowest slope ($G^*/\sin\delta$ divided by temperature) around the grading temperatures. The r^2 of 0.89 drops to 0.57 without the data for PG 64-28. Even so, no data point is more than 1.5°C away from the regression line.

Unlike cumulative permanent shear strain, low and high DSR frequencies provided approximately the same degree of correlation with rut depth, even though a cursory review of the $G^*/\sin\delta$'s in table 11 showed that the two frequencies did not provide identical rankings for the asphalt binders. To examine this in more detail, the $G^*/\sin\delta$'s were linearly regressed. The r^2 of 0.81 in figure 17 shows that the relationship was good. Without Elvaloy, the r^2 is 0.97. Based on the rut depths in table 11, the $G^*/\sin\delta$ of 4110 Pa for Elvaloy at 10 rad/s is low relative to the other asphalt binders. It should have the highest $G^*/\sin\delta$.

Table 9. Coefficients of determination between RSCH and DSR properties.

RSCH at 5,000 Cycles	Coefficient of Determination, r^2			
	High-Temp. PG	G*/sinδ at the RSCH Test Temperature and Three Frequencies		
		10.0 rad/s	2.0 rad/s	0.125 rad/s
Cumulative Permanent Shear Strain at 50°C	0.68	0.06	0.55	0.89
Cumulative Permanent Shear Strain at 70°C	0.63	0.22	0.37	0.59

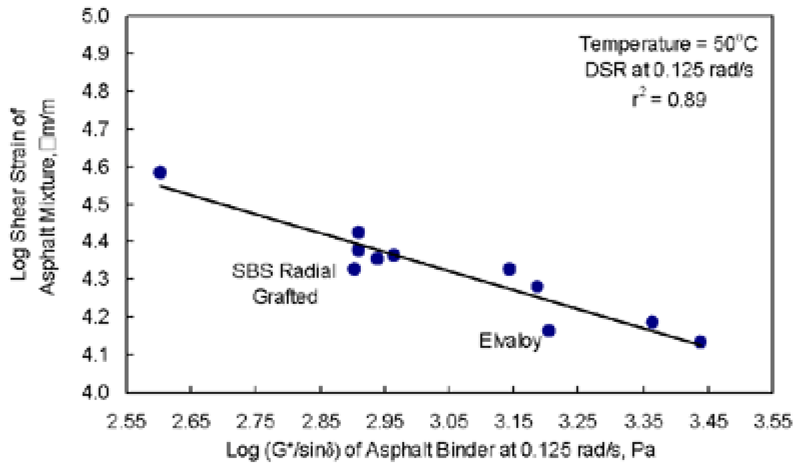

Figure 6. Log RSCH cumulative permanent shear strain at 50°C vs. log (G*/sinδ) of the asphalt binder at 50°C and 0.125 rad/s.

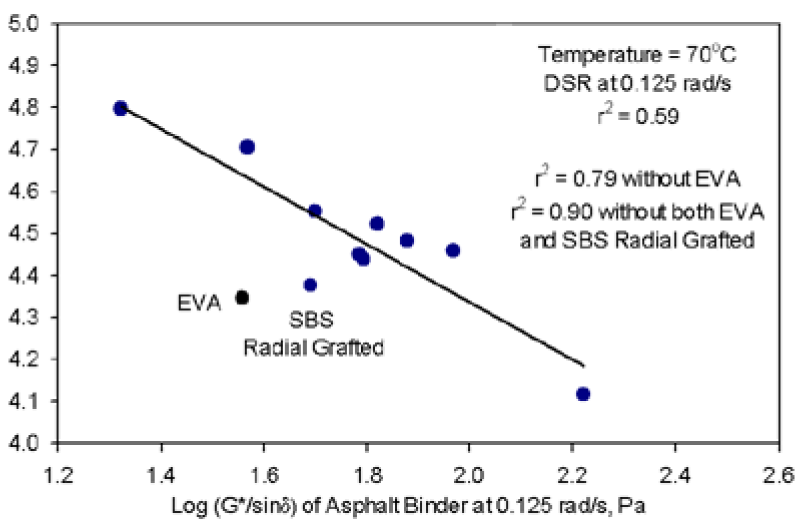

Figure 7. Log RSCH cumulative permanent shear strain at 70°C vs. log (G*/sinδ) of the asphalt binder at 70°C and 0.125 rad/s.

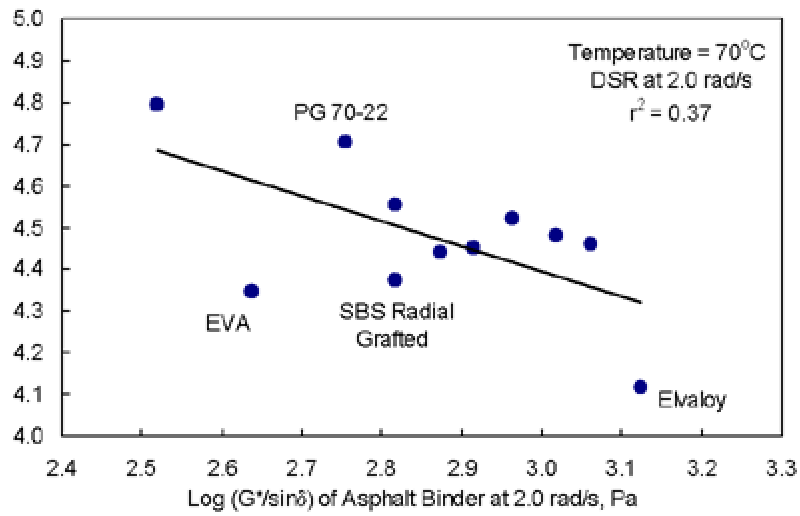

Figure 8. Log RSCH cumulative permanent shear strain at 70°C vs. log (G*/sinδ) of the asphalt binder at 70°C and 2.0 rad/s.

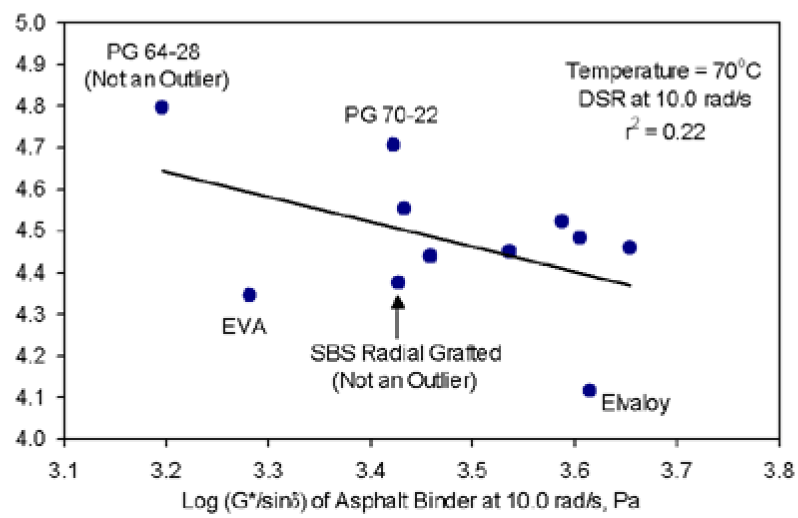

Figure 9. Log RSCH cumulative permanent shear strain at 70°C vs. log (G*/sinδ) of the asphalt binder at 70°C and 10.0 rad/s.

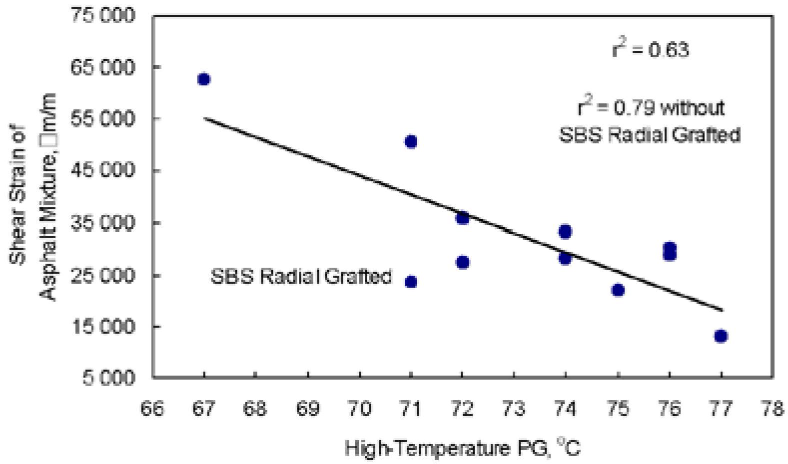

Figure 10. RSCH cumulative permanent shear strain at 70°C vs. high-temperature PG of the asphalt binder.

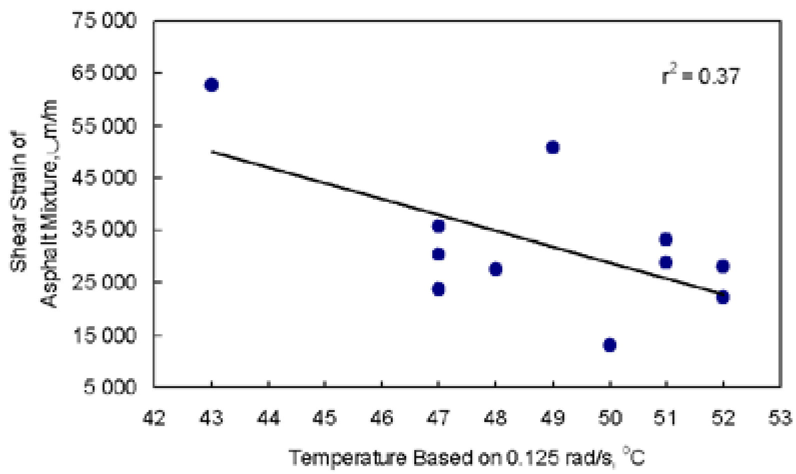

Figure 11. RSCH cumulative permanent shear strain at 70°C vs. PG temperature based on 0.125 rad/s.

Table 10. Cumulative permanent shear strain at 70°C.

Asphalt Binder or Mixture	Asphalt Binder Cumulative Permanent Shear Strain at 100 Cycles (µm/m)	Asphalt Mixture Cumulative Permanent Shear Strain at 5,000 Cycles (µm/m)
Elvaloy	3 418	13 100
EVA	3 667	22 220
SBS Linear Grafted	4 752	27 600
EVA Grafted	10 400	28 200
CMCRA	4 242	28 900
SBS Radial Grafted	4 948	23 720
ESI	1 751	30 400
SBS Linear	6 609	35 800
Air-Blown	5 051	33 340
PG 70-22	8 040	50 850
PG 64-28	20 082	62 700

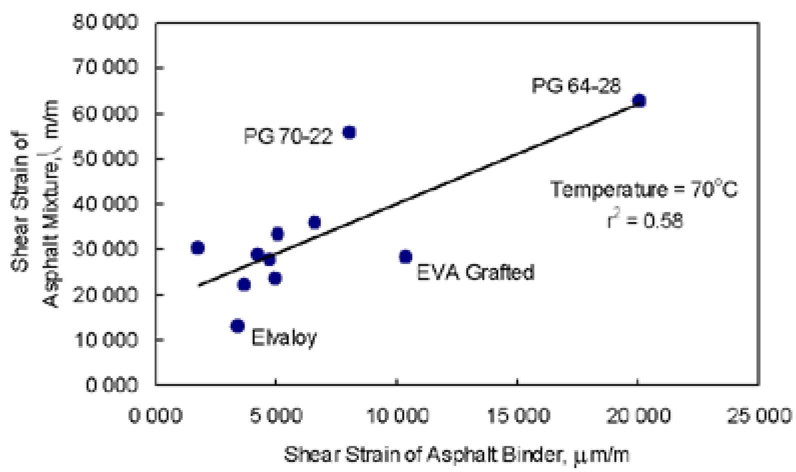

Figure 12. Asphalt mixture cumulative permanent shear strain vs. asphalt binder cumulative permanent shear strain.

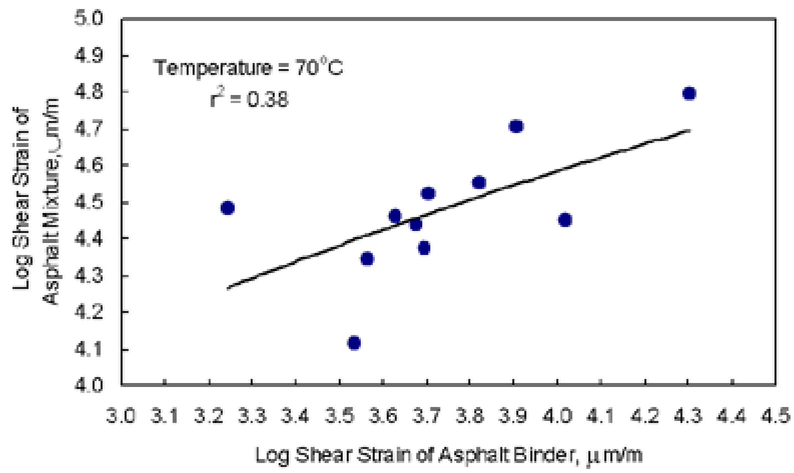

Figure 13. Comparison of cumulative permanent shear strain using a log-log transformation.

Table 11. DSR data and French PRT rut depths with the materials listed from lowest to highest rut depth at 6,000 wheel passes.

Asphalt Binder or Mixture Designation	DSR After RTFO Aging			French PRT After 2 h of STOA	
	High-Temp. PG	G*/sinδ at 70°C (Pa)		Rut Depth at 70°C (percent)	
		10.0 rad/s	0.9 rad/s	6,000 Passes	20,000 Passes
Elvaloy	77	4 110	753	6.5 A	7.9 A
Air-Blown	74	3 870	439	6.8 A	9.0 A
CMCRA	76	4 510	566	6.8 A	9.7 A
EVA	75	1 910	203	7.1 A	9.4 A
SBS Radial Grafted	71	2 680	312	7.4 A	8.9 A
EVA Grafted	74	3 440	394	7.5 A	10.4 A
ESI	76	4 030	500	7.6 A	9.2 A
SBS Linear Grafted	72	2 880	361	8.2 A	10.3 A
PG 70-22	71	2 640	260	8.3 A	10.6 A
SBS Linear	72	2 710	309	8.5 A	10.5 A
PG 64-28	67	1 570	151	12.1 B	16.0 B

Table 12. Replicate data for the French PRT at 6,000 wheel passes.

Asphalt Mixture	Rut Depth at 6,000 Wheel Passes and 70°C (percent)			CV[1]
	Specimen No. 1	Specimen No. 2	Average	
Elvaloy	5.9	7.0	6.5	12.1
Air-Blown	6.4	7.1	6.8	7.3
CMCRA	6.6	6.9	6.8	3.1
EVA	6.8	8.5	7.1	15.6
EVA (Repeat)	7.1	6.0		
SBS Radial Grafted	6.5	9.9	7.4	22.6
SBS Radial Grafted (Repeat)	6.3	7.0		
EVA Grafted	7.0	8.1	7.5	10.3
ESI	8.3	6.8	7.6	14.0
SBS Linear Grafted	8.6	7.7	8.2	7.8
PG 70-22	8.0	8.6	8.3	5.1
SBS Linear	8.6	8.4	8.5	1.7
PG 64-28	11.7	12.4	12.1	4.1

[1]CV = Coefficient of Variation, percent = (standard deviation ÷ average)*100.

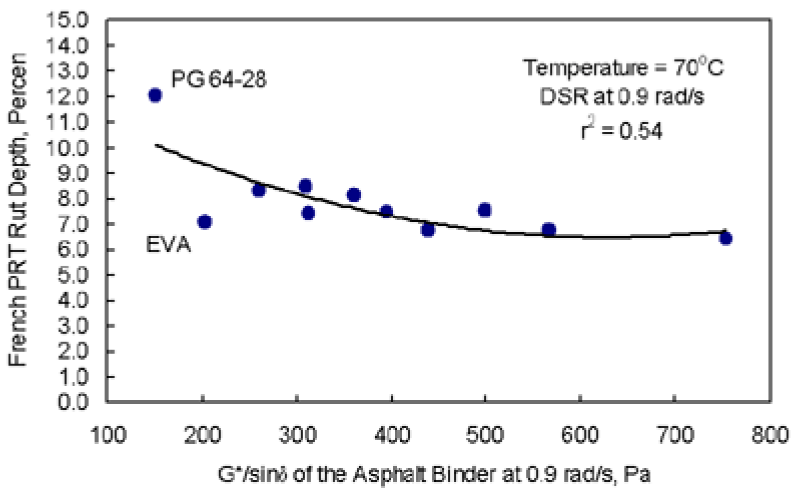

Figure 14. French PRT rut depth at 70°C vs. G*/sinδ of the asphalt binder at 70°C and 0.9 rad/s.

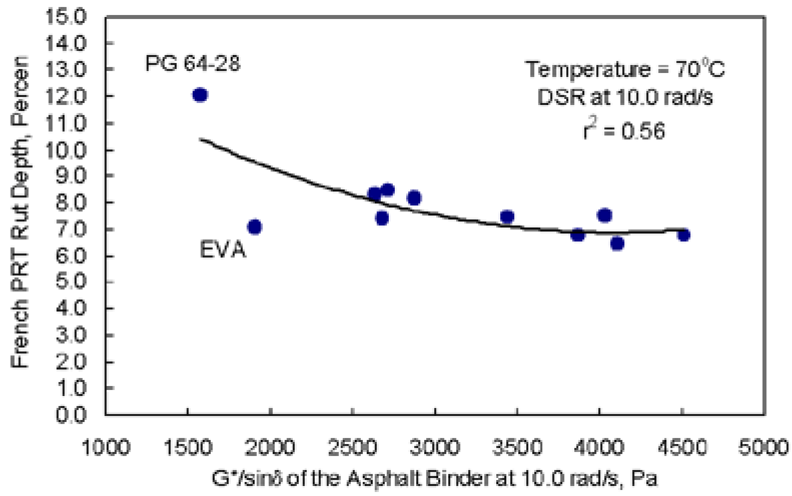

Figure 15. French PRT rut depth at 70°C vs. G*/sinδ of the asphalt binder at 70°C and 10.0 rad/s.

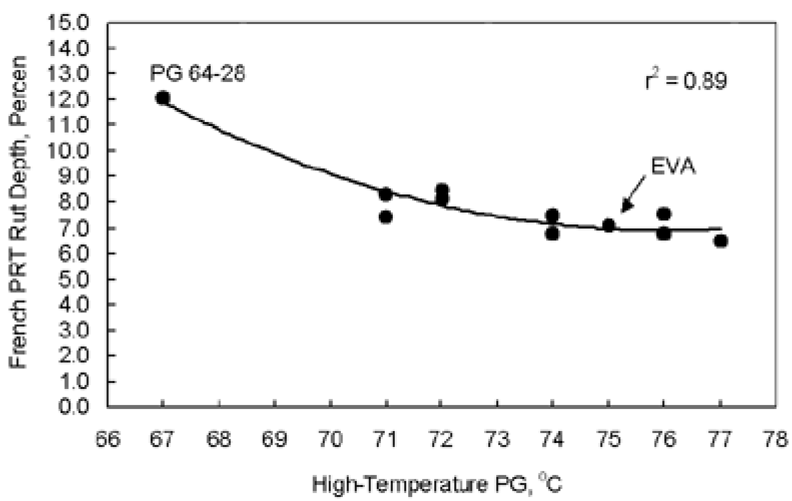

Figure 16. French PRT rut depth at 70°C vs. high-temperature PG.

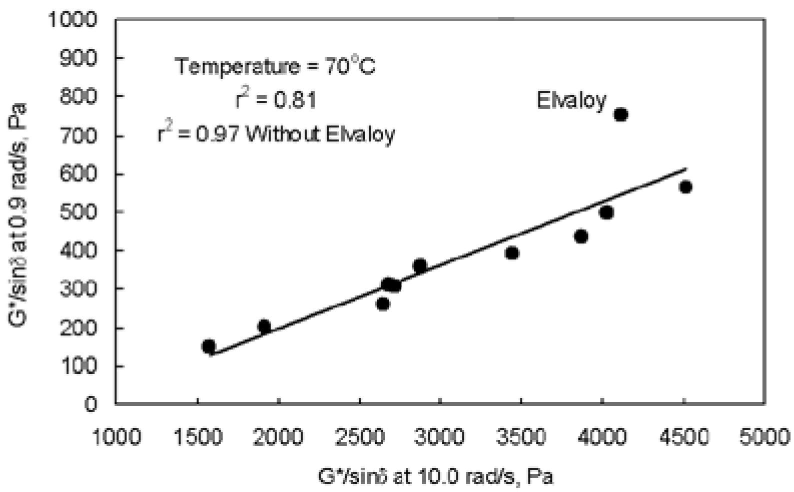

Figure 17. G*/sinδ at 0.9 rad/s vs. G*/sinδ at 10.0 rad/s.

Figure 18 provides the correlation with the cumulative permanent shear strains from the asphalt binder repeated creep test. The r^2 of 0.83 drops to 0.19 without the data for PG 64-28. The narrow range in rut depth provided by the French PRT makes it difficult to make a firm conclusion.

Figure 19 provides the relationship between the cumulative permanent shear strain from RSCH at 70°C and the French PRT rut depth at 70°C . If the data for the mixture with the PG 64-28 asphalt binder are excluded, the remaining data indicate that the French PRT provided a narrower range in performance compared to RSCH. The statistical rankings in tables 6 and 11 support this finding. Table 6 shows that shear strain provided five statistical groups (A through E), while table 11 shows that only the mixture with the PG 64-28 asphalt binder had a significantly different resistance to rutting according to the French PRT. In a previous FHWA study, both tests agreed with full-scale pavement rutting tests, although only five asphalt binders were evaluated and only two of these binders were polymer-modified asphalt binders.[5]

The mixtures with EVA, EVA Grafted, and SBS Linear at an asphalt binder content of 4.85 percent were tested using RSCH at 70°C to determine if the reduction in asphalt binder content contributed to the differences between RSCH and the French PRT. Table 13 shows that the cumulative permanent shear strains for EVA Grafted and SBS Linear at an asphalt binder content of 4.85 percent were not repeatable, so a conclusion could not be made.

G. Conclusions

The cumulative permanent shear strains from RSCH at 70°C were correlated to the G*/sinδ 's of the asphalt binders at 70°C and three DSR frequencies: 10.0, 2.0, and 0.125 rad/s. The best correlation was provided by a frequency of 0.125 rad/s. At 0.125 rad/s, G*/sinδ underpredicted the relative rutting resistance provided by EVA and SBS Radial Grafted. G*/sinδ at the standard frequency of 10.0 rad/s underpredicted the rutting resistances provided by EVA and Elvaloy, and overpredicted the relative rutting resistance provided by the unmodified PG 70-22 asphalt binder. High-temperature PG underpredicted the relative rutting resistance provided by SBS Radial Grafted.

Based on the French PRT at 70°C , G*/sinδ underpredicted the relative rutting resistance provided by EVA at both high and low DSR frequencies. However, the high-temperature PG of EVA agreed with mixture performance. This means that the G*/sinδ for this asphalt binder did not increase as rapidly as it should have at temperatures immediately below its high-temperature PG of 75°C . The correlation between high-temperature PG and the French PRT provided no obvious outliers.

Grafting did not improve the rutting resistance of EVA. Grafting and geometry had no effect on the rutting resistances of the SBS-modified asphalt binders at 50°C . The effect at 70°C was marginal.

H. Recommendations

- The French PRT indicated that the current Superpave binder specification is valid. The G*/sinδ for one asphalt binder, EVA, was low at 70°C , but its high-temperature PG agreed with mixture rutting performance. No changes to the specification are recommended based on the French PRT results.

- The cumulative permanent shear strains from RSCH suggested that a low DSR frequency, such as 0.125 rad/s, might provided a better grading system than 10.0 rad/s. However, it is not known whether this finding applies to pavements or if it is related to the accelerated nature of the RSCH test. This requires full-scale validation. Furthermore, G*/sinδ at 0.125 rad/s and 70°C did not clearly provide a better correlation to RSCH than high-temperature PG.

- Based on the coefficients of variation in tables 2, 7, and 13, a minimum of five replicate specimens should be tested by RSCH per mixture.

- Additional research is needed to evaluate various protocols for the asphalt binder repeated creep test.

- For similar studies involving fewer asphalt binders, it is imperative that the high-temperature PG's of the asphalt binders be as close to each other as possible. If the performances of the asphalt binders at one particular temperature are of interest, then the most important property of the asphalt binders, such as their G*/sinδ 's, must be as close to each other as possible at this temperature. In this study, the high-temperature PG's of the polymer-modified asphalt binders varied from 71°C to 77°C . The G*/sinδ 's of the asphalt binders at the test temperature of 70°C also varied significantly. Regression and ranking statistical analyses were used to find which asphalt binders had properties that did not agree with the properties of the other asphalt binders based on mixture rutting resistance. For studies involving fewer asphalt binders, these analyses may not provide a valid conclusion because of insufficient data points. Therefore, the deviation in the high-temperature properties of the asphalt binders must be so small that they should not affect mixture rutting resistance. An alternative approach is to adjust the mixture test temperature according to the asphalt binder property so that all of the asphalt binders should provide the same resistance to rutting.

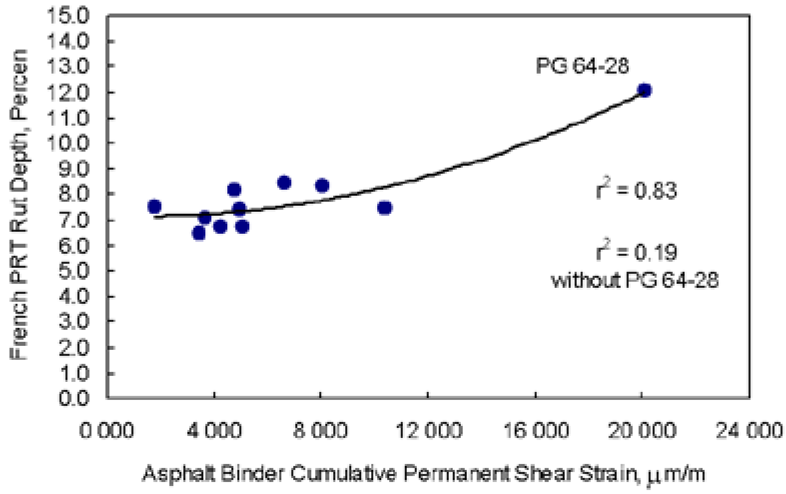

Figure 18. French PRT rut depth vs. asphalt binder cumulative permanent shear strain.

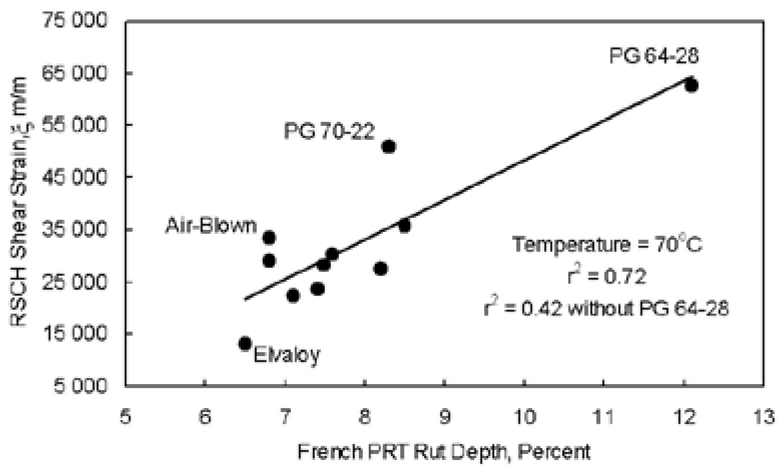

Figure 19. Cumulative permanent shear strain of the asphalt mixture vs. French PRT rut depth of the asphalt mixture.

Table 13. RSCH cumulative permanent strains at 70°C and 5,000 cycles using two asphalt binder contents.

Mixture	Sample Number	4.85-Percent Asphalt Binder Content			4.55-Percent Asphalt Binder Content		
		Strain (µm/m)	Average Strain	CV[1]	Strain (µm/m)	Average Strain	CV[1]
EVA	1	33 640	35 040	9.4	11 470	22 140	36.7
	2	38 800			17 280		
	3	32 680			26 080		
	4				23 290		
	5				32 590		
EVA G	1	37 860	25 040	44.8	27 880	28 200	19.7
	2	17 040			22 750		
	3	20 220			33 850		
SBS LG	1	30 280	44 000	33.2	23 130	27 600	14.2
	2	32 530			29 420		
	3	55 500			30 320		
	4	57 700					

[1]CV = Coefficient of Variation, percent = (standard deviation ÷ average)*100.

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3. AASHTO TP5, "Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer," *AASHTO Provisional Standards*, American Association of State Highway and Transportation Officials, Washington, D.C., April 2000 Edition.

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