Understanding The Performance of Modified Asphalt Binders in Mixtures: Low-Temperature Properties

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Foreword

This report documents the effects of polymer-modified asphalt binders on the low-temperature cracking resistances of asphalt mixtures. An emphasis was placed on evaluating the performances of mixtures containing polymer-modified asphalt binders with identical Superpave performance grades, but varied modification chemistries. This study is part of a larger study titled "Understanding the Performance of Modified Asphalt Binders in Mixtures," which is partially funded through the National Cooperative Highway Research Program (NCHRP) Project 90-07. The objective of NCHRP Project 90-07 is to determine if asphalt binder performance is correctly captured by the Superpave asphalt binder specification developed under the 1987 through 1993 Strategic Highway Research Program and modified under subsequent studies. This report will be of interest to highway personnel who use polymer-modified asphalt binders and Superpave.

The recently developed Superpave critical cracking temperature (T_{cr}) for asphalt binders agreed with mixture performance, except for one asphalt binder that is currently not used in practice. Several aggregate types were included in the study. The addition of hydrated lime to one of the aggregates significantly affected the low-temperature properties of the mixture. The mechanism for this is not clearly understood and will be investigated.

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16. Abstract
The objective of this study was to determine if the Superpave low-temperature rheological properties of polymer-modified asphalt binders correlate to asphalt mixture low-temperature resistance as measured by the Thermal Stress Restrained Specimen Test (TSRST). An emphasis was placed on evaluating polymer-modified asphalt binders with identical (as close as possible) low-temperature grades. This would indicate what types of modification provide properties that are, or are not, correctly captured by the current Superpave asphalt binder specification. Eleven asphalt binders were obtained for this study: two unmodified asphalt binders, an air-blown asphalt binder, and eight polymer-modified asphalt binders. All asphalt binders were tested with a diabase aggregate. Four asphalt binders were also tested using a limestone aggregate, a granite aggregate, and the granite aggregate treated with hydrated lime. Four asphalt binders were used in a study to determine the effect of the mixture short-term oven aging (STOA) period on low-temperature cracking resistance.
The correlations between the TSRST fracture temperatures and asphalt binder cracking resistance based on the critical cracking temperature (Tcr), bending beam rheometer (BBR) creep stiffness, BBR m-value, and the BBR limiting temperature, were poor to weak. However, the correlation using Tcr was good after eliminating the data for ESI. The r-squared increased from 0.54 to 0.85.
Aggregate type generally had no significant effect on the average TSRST fracture temperature. The effect was only significant in three cases involving hydrated lime. Elvaloy with granite had a significantly higher (poorer) fracture temperature compared to Elvaloy with diabase, limestone,

and the granite aggregate treated with hydrated lime. This means that adding hydrated lime to the granite aggregate was beneficial. Based on the average fracture temperatures, the inclusion of lime provided no benefit for the mixtures with the three other asphalt binders used in this part of the study. In fact, it increased the average fracture temperatures of two mixtures. The variability of the TSRST fracture temperatures from replicate to replicate specimen was generally higher for the granite aggregate compared to diabase and limestone, but the addition of hydrated lime to the granite aggregate tended to reduce this variability.
Initially, mixtures with ESI, Elvaloy, and SBS Radial Grafted had lower TSRST fracture temperatures than the mixture with the unmodified PG 70-22 asphalt binder. However, increasing the STOA period from 2 hours to 24 hours aged the polymer-modified asphalt binders, but not the PG 70-22 asphalt binder. After 24 hours, all four mixtures had fracture temperatures that were not significantly different. The use of softer asphalt binders when formulating the polymer-modified asphalt binders may have led to hardening from a loss of volatiles during STOA, while volatilization for the PG 70-22 asphalt binder was low.

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Objective

The objective of this study was to evaluate the cracking temperatures for asphalt binders provided by the Bending Beam Rheometer (BBR) and Thermal Stress Analysis Routine (TSAR™). Low-temperature mixture properties provided by the Thermal Stress Restrained Specimen Test (TSRST) were used to validate these asphalt binder tests. An emphasis was placed on evaluating the performances of mixtures containing polymer-modified asphalt binders with identical Superpave performance grades (PG's) and similar base asphalts, but varied modification chemistries. This would indicate what types of modification provide properties that are, or are not, correctly captured by the current Superpave asphalt binder specification.

BBR and TSAR™

The BBR provides two cracking temperatures. One temperature is based on creep stiffness (S); the other temperature is based on the m-value. The BBR test is performed in accordance with American Association of State Highway and Transportation Officials (AASHTO) TP1, titled "Method for Determining the Flexural Creep Stiffness of Asphalt Binders Using the Bending Beam Rheometer (BBR)."(1) TSAR™ is a computer program from Abatech, Inc., Doylestown, PA, that performs AASHTO PP42-01, "Standard Practice for Determination of Low-Temperature Performance Grade (PG) of Asphalt Binders."(2) A critical cracking temperature (T_{cr}) is computed using data from both the BBR and the direct tension. The standard test method for the direct tension is AASHTO TP3, titled "Determining the Fracture Properties of Asphalt Binder in Direct Tension (DT)."(2)

TSRST

The TSRST cools a beam of asphalt mixture at a rate of 10°Celsius/hour (C/h) while restraining it from contracting. Stress builds up in the beam until it breaks. The resistance to low-temperature cracking increases as the temperature needed for fracture decreases. The stress at failure can also be analyzed. Additional information on the TSRST is given in AASHTO TP10-93, titled "Method for Thermal Stress Restrained Specimen Tensile Strength."(2) (Note: This test is commonly called the "Thermal Stress Restrained Specimen Test.")

Asphalt Binders

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 eight polymer-modified asphalt binders include elastomeric and plastomeric modifiers, some with the same modifier but different geometries (linear vs. radial geometries). The term "grafted" 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.

Experiment Using Diabase Aggregate

The mixtures consisted of diabase aggregate and the 11 asphalt binders. A minimum of three replicate beams at 7.0 ± 0.5-percent air voids were tested by the TSRST. The mixtures were subjected to 2 h of short-term oven aging (STOA) at 135°C before compaction. Two hours of STOA was found to provide the average amount of aging for pavements constructed in 1993 for a Federal Highway Administration (FHWA) Superpave validation study.[3] It was based on pavement samples taken 3 months after construction. Mixture tests that measure low-temperature cracking resistance are often performed on specimens that have been subjected to long-term oven aging (LTOA), such as at 85°C for 120 h.[4] In this study, it was decided to use 2 h of STOA and then determine from the data whether LTOA was needed. The asphalt binders were subjected to both rolling thin-film oven (RTFO) aging and pressure aging vessel (PAV) aging before testing, which is considered LTOA.

The data are given in tables 1 and 2. These tables provide the same data. The mixtures in table 1 are ranked according to the average TSRST fracture temperature, while the mixtures in table 2 are ranked according to the average TSRST fracture stress. An analysis of variance and Fisher's least squares difference (LSD) were used to rank the mixtures at a 5-percent level of significance. The capital letters in the tables are the statistical rankings. All mixtures with the same letter have averages that are not significantly different from one another. They are in the same group. All groups are designated by a single letter. However, the groups can overlap. An average with more than one letter indicates that it falls into more than one group. For example, if an average has the designation "A B," it falls into two groups, both A and B.

Fisher's LSD showed that the average TSRST fracture temperatures for the mixtures in table 1 must differ by at least 4.0°C for them to be significantly different at a 5-percent level of significance. The average TSRST fracture stresses must differ by approximately 500 kilopascals (kPa) for them to be significantly different. The data for individual beams are given in tables 3 and 4. (Note: The standard deviation [σ] and coefficient of variation [CV] for fracture temperature depend on what unit is used [Celsius, Fahrenheit, or Kelvin]. Celsius was used in this study.)

Table 1. Low-temperature asphalt binder properties vs. TSRST with the materials ranked according to mixture fracture temperature.

Asphalt Binder and Mixture Designation

	Asphalt Binder Cracking Temperature After RTFO/PAV (°C)			Mixture Property After 2 h of STOA at 135°C							
	T_{cr}	BBR S	BBR m	TSRST Fracture Temperature and Ranking (°C)							TSRST Fracture Stress (kPa)
ESI	-29	-31	-31	-33	A						2320
Elvaloy	-34	-31	-34	-33	A	B					2240
SBS Linear Grafted	-34	-33	-34	-33	A	B	C				2310
EVA Grafted	-33	-32	-31	-31	A	B	C	D			1860
SBS Linear	-33	-32	-31	-30	A	B	C	D	E		2110
SBS Radial Grafted	-34	-32	-32	-30	A	B	C	D	E		2300
EVA	-31	-31	-31	-29		B	C	D	E		2790
CMCRA	-29	-29	-29	-29			C	D	E		1095
Air-Blown	-28	-30	-28	-27				D	E	F	1960
PG 64-28	-28	-28	-30	-26					E	F	1680
PG 70-22	-27	-28	-29	-24						F	2120

T_{cr} = Critical Cracking Temperature.
S = Creep Stiffness.
m = m-value.

Table 2. Low-temperature asphalt binder properties vs. TSRST with the materials ranked according to mixture fracture stress.

Asphalt Binder and Mixture Designation

	Asphalt Binder Cracking Temperature After RTFO/PAV (°C)			Mixture Property After 2 h of STOA at 135°C						
	T_{cr}	BBR S	BBR m	TSRST Fracture Temperature (°C)	TSRST Fracture Stress and Ranking (kPa)					
EVA	-31	-31	-31	-29	2790	A				
ESI	-29	-31	-31	-33	2320	A	B			
SBS Linear Grafted	-34	-33	-34	-33	2310	A	B			
SBS Radial Grafted	-34	-32	-32	-30	2300	A	B			
Elvaloy	-34	-31	-34	-33	2240	A	B			
PG 70-22	-27	-28	-29	-24	2120		B			
SBS Linear	-33	-32	-31	-30	2110		B	C		
Air-Blown	-28	-30	-28	-27	1960		B	C		
EVA Grafted	-33	-32	-31	-31	1860		B	C		
PG 64-28	-28	-28	-30	-26	1680			C		
CMCRA	-29	-29	-29	-29	1095				D	

T_{cr} = Critical Cracking Temperature.
S = Creep Stiffness.
m = m-value.

Table 3. TSRST fracture temperatures for individual beams with diabase.

Asphalt Mixture Designation	TSRST Fracture Temperature (°C)					
	Test #1	Test #2	Test #3	Test #4	σ	CV
STOA = 2 h						
ESI	-32.7	-31.9	-33.2	-37.3	2.4	7.3
Elvaloy	-31.3	-35.4	-34.3		2.1	6.4
SBS Linear Grafted	-29.6	-34.0	-35.5		3.1	9.4
EVA Grafted	-31.1	-25.8	-36.3	-31.2	4.3	13.9
SBS Linear	-32.2	-30.1	-29.1		1.6	5.3
SBS Radial Grafted	-31.3	-26.1	-33.0		3.6	12.0
EVA	-29.6	-29.0	-30.4		0.7	2.4
CMCRA	-28.6	-29.7	-28.4		0.7	2.4
Air-Blown	-26.3	-27.8	-27.3		0.8	3.0

PG 64-28	-25.0	-27.1	-27.0		1.2	4.6
PG 70-22	-24.0	-24.0	-26.7	-23.0	1.6	6.7
STOA = 8 h						
ESI	-35.0	-30.7	-32.5		2.2	6.9
Elvaloy	-29.0	-27.6	-30.2		1.3	4.6
SBS Radial Grafted	-28.3	-30.9	-28.4		1.5	5.0
PG 70-22	-20.4	-20.2	-22.4		1.2	5.7
STOA = 24 h						
ESI	-23.4	-23.7	-24.5		0.7	2.3
Elvaloy	-25.8	-27.1	-26.8		0.7	2.6
SBS Radial Grafted	-22.9	-23.5	-25.1		1.1	4.8
PG 70-22	-19.3	-26.7	-21.4		3.8	16.9

σ = Standard Deviation of Fracture Temperature, C.
CV = Coefficient of Variation, percent = (σ ÷ average)*100.

Table 4. TSRST fracture stresses for individual beams with diabase.

Asphalt Mixture Designation	**TSRST Fracture Stress (kPa) (STOA = 2 h)**					
	Test #1	**Test #2**	**Test #3**	**Test #4**	**σ**	**CV**
EVA	2830	2650	2890		120	4.3
ESI	2260	2370	2480	2170	130	5.6
SBS Linear Grafted	2450	2210	2270		120	5.2
SBS Radial Grafted	2940	2080	1870		570	24.8
Elvaloy	2670	2000	2050		370	16.5
PG 70-22	2070	1910	2470	2030	240	11.3
SBS Linear	840[1]	2020	2210		120	5.7
Air-Blown	1770	1920	2190		210	10.7
EVA Grafted	1920	2440	1220		610	32.9
PG 64-28	1540	1940	1560		230	13.7
CMCRA	1290	1050	940		180	16.4

[1]Outlier.
σ = Standard Deviation of Fracture Temperature, C.
CV = Coefficient of Variation, percent = (σ ÷ average)*100.

Tables 1 and 2 show that the ranges in the TSRST fracture temperatures and stresses provided by the polymer-modified asphalt binders were narrow. Table 1 shows that most of the polymer-modified binders provided relatively close fracture temperatures, and six of these binders fell into group A. Furthermore, the fracture temperature for SBS Linear and SBS Radial Grafted are not significantly different from the temperature for any other mixture except for the mixture with the unmodified PG 70-22 asphalt binder. The closeness of the fracture temperatures was expected because the asphalt binders were produced to have close low-temperature PG's. Table 2 shows that the TSRST fracture stresses for 8 of the 11 mixtures were not significantly different. Most mixtures fell into group B. The TSRST tests on the mixtures with EVA and SBS showed that grafting and polymer geometry generally had no significant effect on fracture temperature or stress. The only exception is that the mixture with EVA Grafted had a significantly lower fracture stress than the mixture with EVA.

The correlation between TSRST fracture temperature and T_{cr} is shown in figure 1. The r-squared (r^2) was low at 0.54, but it increased to 0.85 after eliminating the data from ESI. Table 3 shows that the individual TSRST fracture temperatures for ESI were not highly variable. High variability could decrease the confidence in the average temperature. Tables 3 and 4 show that EVA Grafted and SBS Radial Grafted provided the highest variability using 2 h of STOA. The slope for the regression line without ESI is 0.96 and the offset is 2°C, with T_{cr} providing the lower temperature. Therefore, the TSRST fracture temperature is equal to T_{cr} plus 2°C when the mixture STOA period is 2 h. This difference in temperature may be related to differences in age-hardening or to the absorption of asphalt light ends into the aggregate. LTOA would increase the fracture temperatures of the mixtures, which would increase the offset.

Figure 2 shows that the correlation between the TSRST fracture temperatures and the cracking temperatures provided by creep stiffness was poor, although the trend is correct. The r^2 was 0.66. The slope is 1.5. The data point for ESI is not an obvious outlier as in figure 1. Therefore, creep stiffness alone cannot explain why ESI is an outlier based on T_{cr}. Furthermore, the polymer in ESI is not prone to separate from the base asphalt during use.

Figure 3 shows that the correlation between the TSRST fracture temperatures and the cracking temperatures provided by the m-value was poor, although the trend is correct. The r^2 was 0.59. The slope is 1.2.

For a given asphalt binder, the BBR provides two temperatures. One temperature is based on creep stiffness while the other temperature is based on the m-value. The higher of the two temperatures is the limiting cracking temperature. Figure 4 shows that the correlation between the TSRST fracture temperatures and the limiting cracking temperatures was weak. The r^2 was 0.71. The slope is 1.5, which means that when the temperature based on the BBR changes by 6°C (one PG), the change in TSRST fracture temperature is 9°C. A 9°C change in fracture temperature is large. This suggests that the increment between PG's should be less than 6°C.

Figure 5 shows that the relationship between T_{cr} and the limiting cracking temperature from the BBR was fair. The r^2's were 0.77 and 0.89, with and without ESI, respectively. Although the two tests may correlate to each other, they are not identical. They provided different slopes when correlated to the TSRST fracture temperature.

There was no correlation between the TSRST fracture temperature and the TSRST fracture stress. A linear regression provided an r^2 of 0.09. There was no correlation between the TSRST fracture stress and T_{cr}, creep stiffness, m-value, or the limiting cracking temperature based on both creep stiffness and m-value. The r^2's were 0.13, 0.24, 0.23, and 0.23, respectively. The relationship using creep stiffness is shown in figure 6.

Experiment Using Diabase, Granite, and Limestone Aggregates

The ESI, Elvaloy, SBS Radial Grafted, and air-blown asphalt binders were tested with granite and limestone aggregates to determine the effect of aggregate type on TSRST fracture temperature. Table 5 shows that the effect of aggregate type was relatively small, except for the mixtures with Elvaloy. The fracture temperature of -24°C for Elvaloy with granite is high compared to the temperature of -33°C for Elvaloy with either diabase or limestone. It was hypothesized that the adhesive strength between Elvaloy and granite may be relatively poor. Therefore, 1.0-percent hydrated lime was added to the granite aggregate to determine if this would decrease (improve) the fracture temperature. The average temperature did decrease from -24°C to -36°C, although the fractured surfaces of the beams showed no visual differences. Granite with hydrated lime was then evaluated as a fourth aggregate type.

Table 5 shows that creep stiffness provided cracking temperatures closest to the average TSRST fracture temperatures. However, most of the temperatures are very close to each other, so a firm conclusion regarding which asphalt binder test correlates the best with TSRST fracture temperature cannot be made. Note that 2 h of STOA were used for the mixtures.

The effect of aggregate type on the fracture temperature of each asphalt binder is shown in table 6. Aggregate type had no significant effect on the mixture with the air-blown asphalt binder. Although the hydrated lime decreased the fracture temperature for Elvaloy with granite, it did not decrease the fracture temperatures for the other three asphalt binders. In fact, the hydrated lime significantly increased the fracture temperatures for ESI and SBS Radial Grafted with granite.

Table 7 presents the same data grouped to show the effect of asphalt binder. Elvaloy provided a significantly higher fracture temperature of -24°C in combination with granite and a significantly lower fracture temperature of -36°C in combination with granite and hydrated lime. The air-blown asphalt binder provided the highest fracture temperature using diabase and limestone.

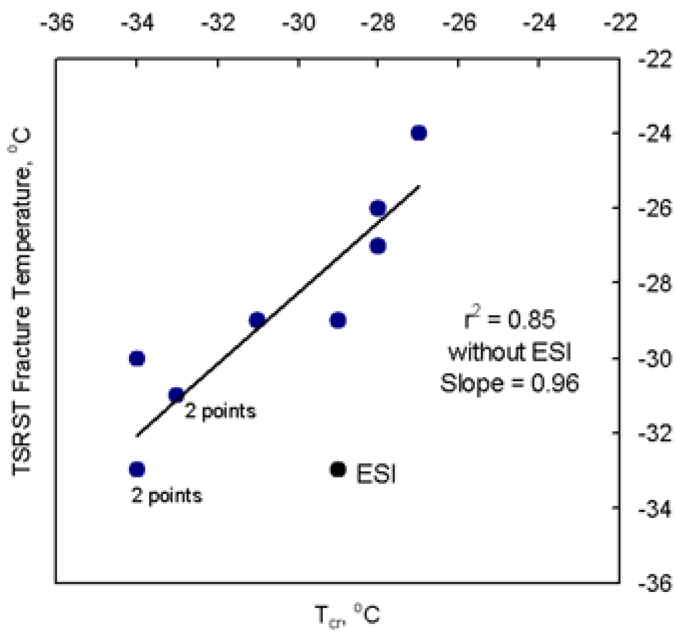

Figure 1. TSRST vs. T$_{cr}$.

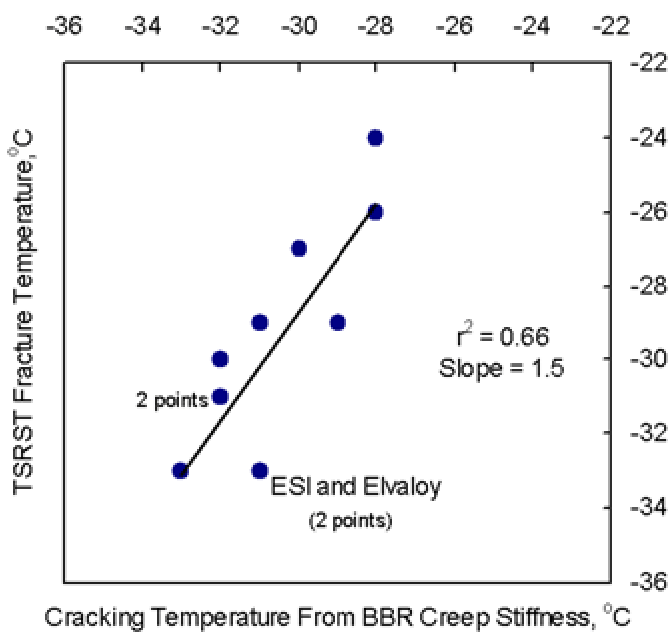

Figure 2. TSRST vs. BBR creep stiffness.

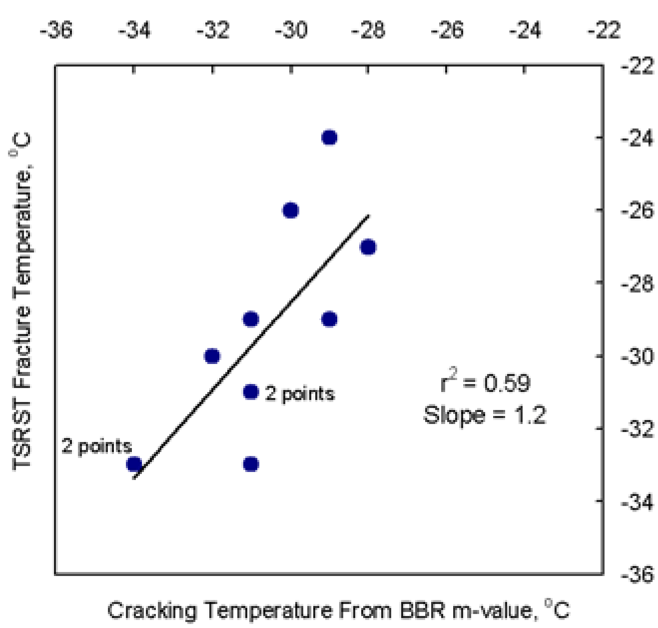

Figure 3. TSRST vs. BBR m-value.

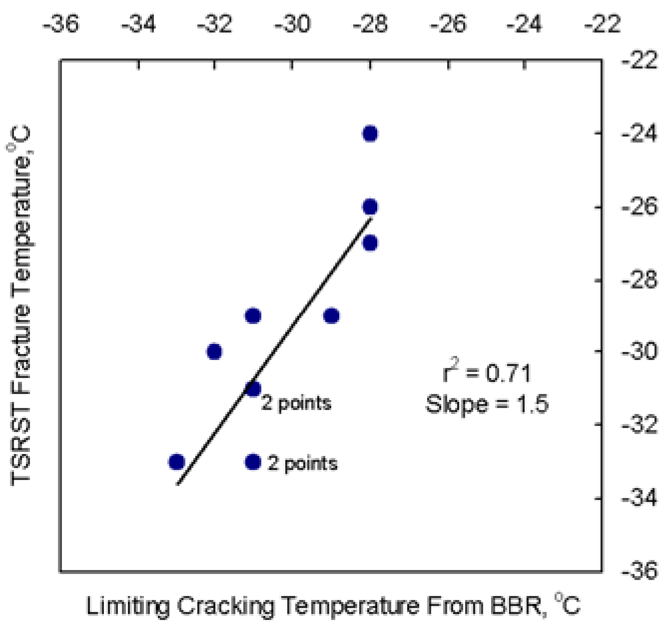

Figure 4. TSRST vs. limiting cracking temperature based on both BBR creep stiffness and BBR m-value.

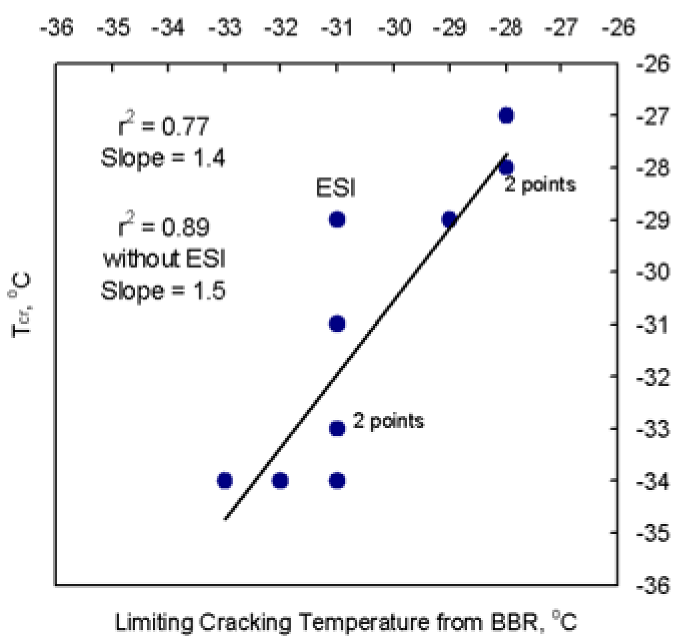

Figure 5. Tcr vs. limiting cracking temperature from BBR.

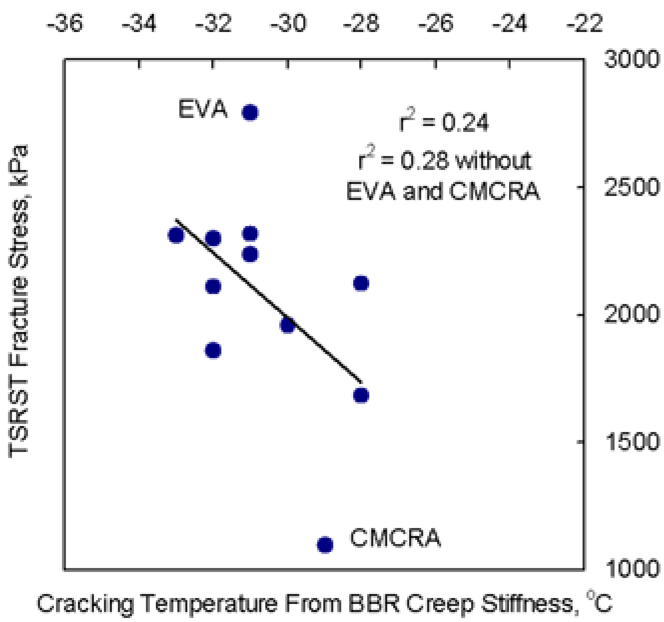

Figure 6. TSRST fracture stress vs. BBR creep stiffness.

Table 5. Low-temperature binder properties vs. TSRST using four aggregates.

Asphalt Binder	Asphalt Binder Cracking Temperature After RTFO/PAV (°C)			TSRST Fracture Temperature After 2 h of STOA at 135°C (°C)				
	T_{cr}	BBR S	BBR m	Average of Four Mixes	Granite	Granite With Lime	Diabase	Limestone
ESI	-29	-32	-31	-33	-34	-29	-33	-36
Elvaloy	-34	-32	-34	-31	-24	-36	-33	-33
SBS Radial Grafted	-34	-32	-32	-30	-34	-26	-30	-32
Air-Blown	-28	-30	-29	-28	-29	-28	-27	-30

T_{cr} = Critical Cracking Temperature.
S = Creep Stiffness.
m = m-value.

Table 6. Effect of aggregate type on TSRST fracture temperature after 2 h of STOA at 135°C.

Aggregate Type	Fracture Temperatures for Each Asphalt Binder (°C)											
	ESI			Elvaloy			SBS Radial Grafted			Air-Blown		
Granite	-34	A		-24		B	-34	A		-29	A	
Granite With Lime	-29		B	-36	A		-26		B	-28	A	
Diabase	-33	A		-33	A		-30	A	B	-27	A	
Limestone	-36	A		-33	A		-32	A		-30	A	
Range in Temperature	7			12			8			3		

Table 7. Effect of asphalt binder on TSRST fracture temperature after 2 h of STOA at 135°C.

Aggregate Binder	Fracture Temperatures for Each Aggregate Type (°C)											
	Granite			Granite With Lime			Diabase			Limestone		
ESI	-34	A		-29		B	-33	A		-36	A	
Elvaloy	-24		B	-36	A		-33	A		-33	A	
SBS Radial Grafted	-34	A		-26		B	-30	A	B	-32	A	B
Air-Blown	-29	A		-28		B	-27		B	-30		B
Range in Temperature	10			10			6			6		

The replicate data for the granite and limestone mixtures are given in table 8, while the replicate data for the diabase mixtures are given in table 3. The fracture temperatures were generally more variable using the granite aggregate. The addition of hydrated lime decreased the variability of the temperatures for the mixtures with Elvaloy, SBS Radial Grafted, and the air-blown asphalt binder.

Experiment Using 2, 8, and 24 h of STOA

Table 9 provides the data for the ESI, Elvaloy, SBS Radial Grafted, and PG 70-22 asphalt binders in combination with the diabase aggregate where STOA periods of 2, 8, and 24 h were used. The STOA temperature was fixed at 135°C. These tests were conducted to determine how aging time affects the TSRST fracture temperatures of asphalt binders having the same crude source. The replicate data are given in table 3. Table 9 shows that a STOA period of 2 h provided TSRST fracture temperatures that were closest to the temperatures for the asphalt binders. If it is desirable to have the binder and mixture tests provide cracking temperatures that are close to each other, either LTOA is not needed for these mixtures, or the asphalt binders need to be aged to a greater degree. (Note: It is possible that the binder and mixture data would correlate better to each other if LTOA were to be applied to both materials, and the resulting cracking temperatures from the binder and mixture tests are not close to each other. This was not checked in this study.)

The effect of the STOA period on TSRST fracture temperature is shown in table 10. The STOA period had no effect on the fracture temperature of the mixture with the unmodified PG 70-22 asphalt binder. It did increase the fracture temperatures of the mixtures with the polymer-modified asphalt binders, although an aging period greater than 8 h was needed to show a significant effect for ESI and SBS Radial Grafted.

Table 11 presents the same data grouped according to asphalt mixture. The mixture with the PG 70-22 asphalt binder had the highest (poorest) fracture temperatures at 2 h and 8 h, but not at 24 h. The fracture temperature for this mixture was not affected by the length of the STOA period. The other mixtures performed similarly after each STOA period.

Anomaly Concerning the Definition of Fracture Temperature

Usually, the stress builds up in the TSRST beam until it breaks in half. Typical relationships between load and temperature are shown by the data for beams #2 and #3 in figure 7. However, the data from some tests have shown that the beam did not fail at the highest stress level. Data provided for beam #1 were obtained. The TSRST uses the readings from two linear variable differential transformers (LVDT) to keep the beam from contracting. The average of the two readings is kept constant over time. Quite often, the readings indicate that the beam is bending even though the average length of the beam does not change. The readings from one LVDT go in the positive direction, while the readings from the other LVDT go in the negative direction. A reason for this bending is not known, but it is probably related to the variability in mixture composition. It is also not clear why the stress in some beams starts to decrease after the peak stress is reached, but it could be due to eccentricities in bending when the beam is failing. All replicate specimens for a particular mixture generally do not show this phenomenon, so it is not related to the type of mixture alone. Because all replicates generally do not exhibit this phenomenon, the average temperatures based on complete fracture and on peak stress are usually very close to each other. The temperature based on complete fracture is rarely more than 1°C lower than the temperature based on peak stress. However, this phenomenon provided a difference of 4°C for the mixture with SBS Radial Grafted after 8 h of STOA, and a difference of 3°C for the mixture with PG 70-22 after 24 h of STOA. (See table 9.) The higher average temperatures based on peak stress are more reasonable than those based on complete failure when compared against the other TSRST fracture temperatures in table 9.

Conclusions: Diabase Mixture Study

The correlations between the TSRST fracture temperatures and the asphalt binder cracking temperatures based on T_{cr}, BBR creep stiffness, BBR m-value, and the BBR limiting temperature, were poor to weak. However, the correlation using T_{cr} was good after eliminating the data for ESI. The r^2 increased from 0.54 to 0.85.

The relationship between the TSRST fracture temperature and T_{cr} had a slope of 1.0 and an offset is 2°C after excluding the data for ESI. T_{cr} provided the lower temperature. These two tests agreed with each other very well except for ESI.

The relationship between the TSRST fracture temperature and BBR limiting temperature provided a slope of 1.5. This means that a 6°C change in limiting temperature (1 PG) would provide a relatively large change of 9°C in TSRST fracture temperature. This suggests that the specification increment between the low-temperature PG's should be less than 6°C.

Grafting and polymer geometry of the EVA and SBS asphalt binders had no significant effect on their TSRST fracture temperature.

TSRST fracture stress did not correlate to TSRST fracture temperature, T_{cr} , creep stiffness, m-value, or the limiting temperature. A higher TSRST fracture stress does not necessarily lead to a lower TSRST fracture temperature.

Table 8. TSRST fracture temperatures for individual beams with granite and limestone.

Asphalt Mixture Designation	TSRST Fracture Temperature (°C)					
	Test #1	Test #2	Test #3	Test #4	σ	CV
Granite Aggregate						
ESI	-33.1	-33.8	-36.0		1.5	4.4
Elvaloy (nine tests)[1]	-33.0	-21.0	-23.7	-22.2	5.4	22.5
	-28.3	-21.7	-16.5	-23.0		
	-31.8					
SBS Radial Grafted[2]	-36.9	-23.6	-34.0	-31.8	5.7	18.4
Air-Blown (six tests)[3]	-43.8	-35.1	-25.9	-30.2	6.6	21.3
	-27.1	-29.4				
Granite Aggregate With Hydrated Lime						
ESI	-28.8	-26.8	-32.8		3.1	10.4
Elvaloy	-34.2	-39.4	-35.9		2.6	7.3
SBS Radial Grafted	-26.7	-26.0	-25.3		0.7	2.4
Air-Blown	-28.2	-27.8	-27.6		0.3	1.2
Limestone Aggregate						
ESI	-36.8	-35.2	-36.0		0.8	2.2
Elvaloy	-30.6	-34.2	-34.1		2.1	6.4
SBS Radial Grafted	-32.1	-33.4	-32.1		0.8	2.5
Air-Blown	-30.0	-29.2	-30.8		0.8	2.7

[1]If the highest and lowest temperatures are eliminated, the CV is 16.3 percent.
[2]If the high temperature of -23.6°C is eliminated, the CV is 12.2 percent.
[3]If the low temperature of -43.8°C is eliminated, the CV is 7.4 percent.

σ = Standard Deviation of Fracture Temperature, °C.
CV = Coefficient of Variation, percent = (σ ÷ average)*100.

Table 9. Low-temperature binder properties vs. TSRST using three STOA periods.

Asphalt Binder and Mixture Designation	Asphalt Binder Cracking Temperature After RTFO/PAV (°C)			Mixture Property: TSRST Fracture Temperature (°C)			Mixture Property: Temp.
	T_{cr}	BBR S	BBR m	2-h STOA	8-h STOA	24-h STOA	2 h to 24 h
ESI	-29	-32	-31	-33	-32	-24	+9
Elvaloy	-34	-32	-34	-33	-28	-26	+7
SBS Radial Grafted	-34	-32	-32	-30	-29[a]	-24	+6
PG 70-22	-27	-29	-30	-24	-21	-22[b]	+2

[a]Based on peak stress. The temperature based on complete fracture was -33°C.
[b]Based on peak stress. The temperature based on complete fracture was -25°C.

T_{cr} = Critical Cracking Temperature.
S = Creep Stiffness.
m = m-value.

Table 10. Effect of STOA period on the TSRST fracture temperature of each mixture.

STOA Period at 135°C	Fracture Temperatures for Each Asphalt Mixture (°C): ESI			Elvaloy			SBS Radial Grafted			PG 70-22		
2 h	-33	A		-33	A		-30	A		-24	A	
8 h	-32	A		-28		B	-29	A		-21	A	
24 h	-24		B	-26		B	-24		B	-22	A	

Table 11. Effect of asphalt mixture on TSRST fracture temperature.

Asphalt Mixture	Fracture Temperatures at Each STOA Period (°C): 2 h, 135°C			8 h, 135°C			24 h, 135°C		
ESI	-33	A		-32	A		-24	A	
Elvaloy	-33	A		-28	A		-26	A	
SBS Radial Grafted	-30	A		-29	A		-24	A	
PG 70-22	-24		B	-21		B	-22	A	

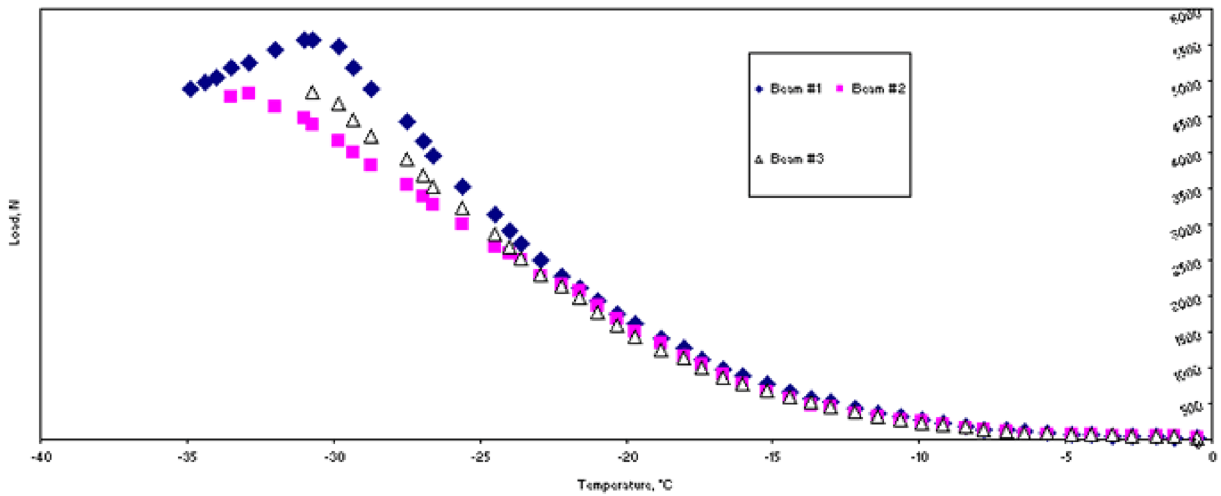

Figure 7. Sample of data from the TSRST.

Conclusions: Aggregate Type Study

Aggregate type, and the associated changes in mixture composition, generally had no effect on the TSRST fracture temperature. The effect was only significant in three cases involving hydrated lime. Four asphalt binders were used in this part of the study: Elvaloy, ESI, SBS Radial Grafted, and an air-blown asphalt. Elvaloy with granite had a significantly higher (poorer) fracture temperature compared to the same Elvaloy asphalt binder with diabase, limestone, and granite treated with hydrated lime. This means that adding hydrated lime to the granite aggregate was beneficial. No benefit was obtained for the other three asphalt binders. The fracture temperatures of the granite mixture with and without hydrated lime were not significantly different when combined with the air-blown asphalt binder. The addition of hydrated lime increased the fracture temperatures of the mixtures with ESI and SBS Radial Grafted.

The TSRST fracture temperatures for three of the four asphalt binders used in combination with the granite aggregate were more variable from replicate to replicate specimen compared to the other aggregates. Adding hydrated lime to the granite aggregate decreased the variability of the data.

Conclusions: STOA Study

Initially, mixtures with ESI, Elvaloy, and SBS Radial Grafted had lower TSRST fracture temperatures than the mixture with the unmodified PG 70-22 asphalt binder. However, increasing the STOA period from 2 h to 24 h aged the polymer-modified asphalt binders, but not the PG 70-22 asphalt binder. The length of the STOA period had no significant effect on the latter binder. After 24 h, all four mixtures had fracture temperatures that were not significantly different. The base asphalt for each polymer-modified asphalt binder was a blend of PG 67-28 and PG 54-33. The use of these softer asphalt binders may have led to more hardening from a loss of volatiles and/or and the absorption of asphalt light ends during STOA compared to the PG 70-22 asphalt binder.

The data suggested that LTOA was not needed for the mixtures even though the asphalt binders were subjected to LTOA. A STOA period of 2 h was sufficient.

Recommendations

Determine why ESI was an outlier for the correlation between TSRST fracture temperature and T_{cr}. This asphalt binder was retested several times, but it remained an outlier. ESI is not currently used in practice; however, an evaluation of it may provide some insight that can be applied to other modified asphalt binders.

Evaluate the effect of hydrated lime on low-temperature mixture properties and the repeatability of the TSRST fracture temperature.

CMCRA provided one of the higher TSRST fracture temperatures. Determine whether this is related to the properties of the base asphalt. CMCRA was the only modified asphalt binder where the base asphalt was 100 percent PG 67-28. The base asphalt for all other modified asphalt binders consisted of at least 50 percent PG 54-33 asphalt binder, with the remainder being PG 67-28.

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