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Model-fitting the Master Curves of the Dynamic Shear Rheometer Data to Extract a Rut-Controlling Term for Asphalt Pavements

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Abstract

The dynamic shear rheometer (DSR) is currently being used by the asphalt community for determination of the viscoelastic properties of asphalts following the recommendations of the Strategic Highway Research Program (SHRP). The Superpave specification parameter $|G^*|/\sin\delta$ was identified as the term to be used for high temperature performance grading of paving asphalts in rating the binders for their rutting resistance. However, this term was found to be inadequate in describing the rutting performance of certain binders, particularly, the polymer-modified ones. A refinement of the Superpave specification parameter for performance grading of asphalt led to the evolution of the term $|G^*| / (1 - (1/\tan\delta\sin\delta))$. This performance-based specification (PBS) term was shown to be more sensitive to the variations in the phase angle δ than the Superpave specification parameter and thus was found to describe the unrecovered strain in the binders more accurately, especially in the case of polymer-modified asphalts.

The high specification temperature T_{HS} (°C) is specified as the temperature at which the term $|G^*| / (1 - (1/\tan\delta\sin\delta))$ takes a value of 1 kPa for the original unaged binder and a value of 2.2 kPa for the RTFOT aged binder. Though this refinement of the Superpave specification parameter has led to a better discrimination between the rutting resistances of various asphalts, it is found that not all asphalts that have been performance-graded as being the same, behave identically in their rutting performance. Thus, there is a need to create a rut-controlling term that would distinguish between asphalts that are graded the same but prepared by different modification routes. Such a rut-controlling term can then be used as a performance-related specification (PRS).

The present work extracts the rut-controlling term by model-fitting the master curve formed from the $|G^*| / (1 - (1/\tan\delta\sin\delta))$ or $|G^*| / (\sin\delta)^9$ versus frequency data at various temperatures for each binder. Each master curve is fitted with a constitutive equation from which model parameters are evaluated. The slope B_1 in the low frequency region of the master curve is normalized with the term (T / T_{HS}), resulting in the rut-controlling term that relates to the permanent strain after 5000 cycles in the repeated shear at constant height (RSCH) experiment on the Superpave shear tester (SST) at temperature T.

Keywords: dynamic shear rheometer, Superpave specification parameter, frequency sweep, master curve, rheological model, performance-related specifications, polymer-modified asphalts

Introduction

The dynamic shear rheometer (DSR) was suggested as a means to characterize asphalts' viscoelastic properties during the Strategic Highway Research Program (SHRP), a five-year $150 million United States research effort established and funded in 1987. The DSR is a conventional rotational rheometer that applies oscillatory shear to asphalt and assesses its rheological behavior through the response of the material to the imposed stresses or deformations. The viscoelastic characteristics of the asphalt are interpreted in terms of various material functions, such as the complex modulus $|G^*|$, storage modulus G', loss modulus G'', phase angle δ, or meaningful combinations of these functions.

The term $|G^*|/\sin\delta$ derived directly from the definition of the loss compliance J'' was recommended as the Superpave specification parameter to give a measure of the rutting resistance of asphalts. This parameter, which was found to work well for unmodified asphalts, does not perform effectively for polymer-modified asphalts. The ineffectiveness of $|G^*|/\sin\delta$ in capturing the high temperature performance of paving asphalts for rating their rutting resistance became a matter of significant concern [1-9] as more and more polymer-modified asphalts were tested for their performance. The failure of this parameter was demonstrated through field data during the Accelerated Loading Facility (ALF) testing at the Turner-Fairbank Highway Research Center, Federal Highway Administration, McLean, VA [2] and also through laboratory testing during the National Cooperative Highway Research Program (NCHRP) Project 9-10 [3].

The repeated creep and recovery test for binders (RCRB) was suggested [3] as a possible means to estimate the rate of accumulation of permanent strain in the binders. The RCRB test protocol consists of applying a creep load of 0.3 kPa for a 1 s duration (loading time) followed by a 9 s recovery period (rest period) for 100 cycles in the DSR. The results of the accumulated strain under repeated creep testing for three binders with the same high temperature performance grade of 82 showed [10] that the elastomeric binder had the least accumulated strain while the oxidized binder had the most. This is understandable since the elastomeric binder has the ability to recover a major portion of the strain while the oxidized binder cannot. The Superpave specification parameter $|G^*|/\sin\delta$ did not predict the expected trend, as can be seen from Figure 1. Though the RCRB test gives realistic information, the procedure is time-consuming and not attractive from a specification standpoint.

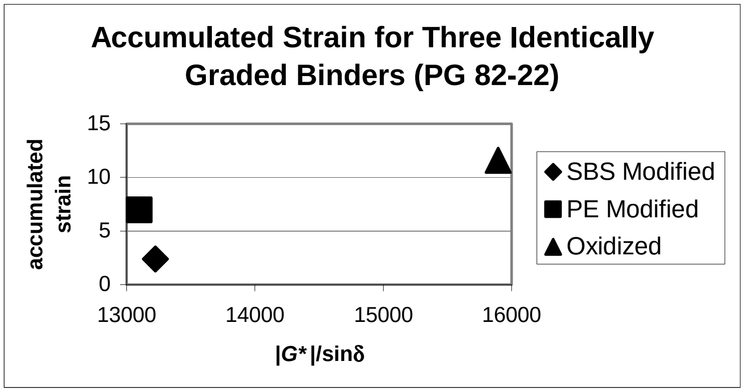

Figure 1: Plot of the accumulated strain versus the Superpave specification parameter at 70°C for three binders identically graded as PG 82-22 (Data taken from Ref.10)

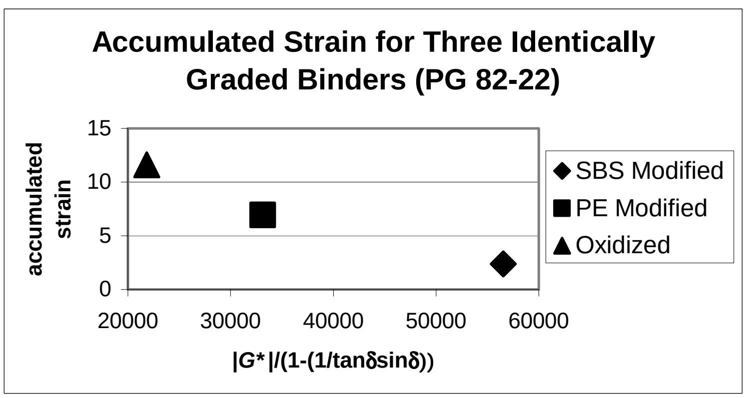

Figure 2: Plot of the accumulated strain versus the refined specification parameter at 70°C for three binders identically graded as PG 82-22 (Data taken from Ref.10)

Shenoy [11] showed that the information obtained during RCRB on the unrecovered strain in a binder that is periodically subjected to an applied stress could be estimated effectively directly from the frequency sweep test data. The term $|G^*| / (1-(1/\tan\delta\sin\delta))$ was suggested [11] as a refinement to the Superpave specification parameter for performance grading of asphalts.

The performance-based specification (PBS) term $|G^*| / (1-(1/\tan\delta\sin\delta))$ was shown [11] to be more sensitive to the variations in the phase angle δ than the Superpave specification parameter $|G^*| / \sin\delta$ and thus was found to describe the unrecovered strain in the binders more accurately, especially in the case of polymer-modified asphalts. In fact, when the RCRB data [10] at the temperature of 70°C for the three binders with the same high temperature performance grade of 82 are compared with the term $|G^*| / (1-(1/\tan\delta\sin\delta))$, the correct trend is obtained as shown in Figure 2.

The high specification temperature T_{HS} (°C) is specified as that temperature at which the term $|G^*| / (1 - (1/\tan\delta\sin\delta))$ takes a value of 1 kPa for the original unaged binder and a value of 2.2 kPa for the RTFOT aged binder. The refinement of the Superpave specification parameter has led to a better discrimination among the rutting resistances of various asphalts.

Despite this, the question is whether asphalts that have been performance-graded as the same, behave identically in their rutting performance. This question has been raised in the past [10, 12] and also has been the focus of the on-going polymer research program at the Turner-Fairbank Highway Research Center (TFHRC), Federal Highway Administration, McLean, VA, where eight different PG 70-28s (each modified by different means) are being evaluated.

In laboratory studies [10], the three binders graded as PG 82-22 based on the Superpave specification parameter were shown to give different accumulated strains. In the Kentucky field trials [12], though all the asphalts were graded as PG 70-22 based on the Superpave specification parameter, they were found to perform differently. The preliminary results at the TFHRC also indicate that all the asphalts graded as PG 70-28 using the Superpave specification parameter behave differently in their ability to resist rutting. Instead of using the Superpave specification parameter, using the parameter $|G^*| / (1 - (1/\tan\delta\sin\delta))$ helps to discriminate the asphalts better, but does not change the fact that identically-graded asphalts do not behave the same.

The present work seeks an answer as to why identically-graded asphalts do not behave the same. It is shown that the master curves of the $|G^*| / (1 - (1/\tan\delta\sin\delta))$ versus frequency ω data reflect the differences in the rheological behavior of the asphalts that have been graded as the same. Each master curve is fitted with a constitutive equation from which model parameters are evaluated. The slope B_1 in the low frequency region of the master curve is normalized with the term (T / T_{HS}), resulting in the rut-controlling term that relates to the permanent strain after 5000 cycles in the repeated shear at constant height (RSCH) experiment on the Superpave shear tester (SST) at temperature T. Thus, the rut-controlling term distinguishes between asphalts that are graded the same but prepared by different modification routes. Such a rut controlling term can therefore be used as a performance-related specification (PRS).

Experimental Plan

Binders

The experimental plan involved the use of three sets of binders. The first set consisted of nine binders that included a PG 64-28 (unmodified base B6225), a PG 70-28 (unmodified high grade B6226), a PG 70-28 (air-blown B6227), and six PG 70-28s, which consisted of the following polymer-modified systems: Elvaloy (B6228), Styrene-Butadiene-Styrene Linear-Grafted (B6229), Styrene-Butadiene-Styrene Linear (B6230), Styrene-Butadiene-Styrene Radial-Grafted (B6231), Ethylene-Vinyl Acetate (B6232) and Ethylene-Vinyl Acetate Grafted (B6233).

The PG numbers shown are based on the Superpave system description. All the asphalts were from the same source, namely, Venezuelan crude (blend of Boscan and Bachaquero). The air-blown grade (PG 70-28) was obtained by noncatalytic air-blowing of a PG 52-28 (flux). The polymer-modified grades were obtained by addition of various amounts of different polymers to the PG 64-28 (base) or the PG 52-28 (flux) or mixture of the PG 64-28 (base) and the PG 52-28 (flux) in different proportions so as to achieve the same performance grading. All these asphalts are part of the extensive ongoing polymer research program being carried out at the Pavement Testing Facility located at TFHRC.

In the second set, the binders were those that were previously utilized in the Superpave binder validation study using the Accelerated Loading Facility (ALF) [13] at the TFHRC. These included two unmodified binders – a PG 58-34 (AC-5) and a PG 64-22 (AC-20), and one modified binder – a PG 82-22 (Styrelf).

In the third set, the binders were those that were used in the Nevada I-80 project, namely, one unmodified binder 64-22 graded as a PG 67 and a modified binder AC20P graded as a PG 63 on a continuous grading scale. Thus, the unmodified binder should have performed better than the modified because it was stiffer as per the grading. However, rutting performance in the field was reverse of that which was expected, since the modified binder outperformed the unmodified binder despite the fact that it was less stiff than the unmodified binder.

Mixtures

The asphalt-aggregate mixtures were prepared using the first two sets of binders with a diabase aggregate of gradation having a nominal aggregate size of 19 mm. Laboratory specimens were prepared at the TFHRC Bituminous Materials Laboratory using the Superpave Gyratory Compactor (SGC).

Equipment

The Rheometrics dynamic shear rheometer (DSR) was used for generating dynamic data at nine different temperatures ranging from 7°C to 82°C with a set of parallel plates following the procedure given in the AASHTO provisional specifications TP5. The samples for the test were prefabricated using a silicone rubber mold. The data were generated using a frequency sweep covering a range from 1 to 100 radians/s. All data were generated within the linear viscoelastic range of response.

The Superpave shear tester (SST) was used for characterization of the asphalt-aggregate mixture properties. The mode of operation that was used was the repeated shear at constant height (RSCH). The RSCH test consists of applying 5000 cycles of a haversine shear load with a shear stress level of 68 ± 5 kPa while the axial load is varied automatically during each cycle to maintain constant height of the specimen to within 0.0013 mm. The test involves the repeated use of a 0.1 s load pulse followed by a 0.6 s rest period during which the permanent deformation is recorded as a function of the number of cycles and used for comparisons. The protocol followed is in accordance with the American Association of State and Highway Transportation Officials (AASHTO) Provisional Standard TP7-94 that contains a detailed description of the SST test in the different modes of operation.

Results and Discussion

Using the refined specification parameter $|G^*| / (1 - (1/\tan\delta\sin\delta))$, the high specification temperatures were determined for all the binders from set 1 as shown in Table 1. The RSCH data at 50°C are also given alongside each specification temperature.

TABLE 1 – Comparison of the high specification temperature T_{HS}(°C) based on the parameter $|G^*|/(1-(1/\tan\delta\sin\delta))$ from the DSR frequency sweep data with the percentage permanent strain from the SST RSCH data at 50°C

Binder Code	Binder Type	Grade (Superpave Spec.)	High Spec. Temperature (Refined Spec.) (°C)	% Permanent Strain (RSCH Data @ 50°C)
Set 1				
B6225	BASE	PG 64-28	68.0	2.73
B6226	HIGH	PG 70-28	71.9	2.39
B6227	AIR-BLOWN	PG 70-28	74.6	2.13
B6228	ELVALOY	PG 70-28	82.2	1.46
B6229	SBS_L-G	PG 70-28	77.8	2.32
B6230	SBS_L	PG 70-28	73.2	2.65
B6231	SBS_R-G	PG 70-28	76.5	2.13
B6232	EVA	PG 70-28	76.0	1.36
B6233	EVA-G	PG 70-28	75.5	1.54

It can be seen from Table 1 that, though the modified binders were designed to have the same high temperature performance grading (PG 70-28) using the Superpave specification parameter, their mixture response at 50°C in the RSCH experiment is not the same. If the RSCH results are assumed to reflect the rutting behavior in the field, then in all likelihood, these modified binders would behave differently in actual field performance. The refined specification parameter helps to discriminate the binders better because of its enhanced sensitivity to changes in the phase angle. However, it can be seen that B6231, B6232, and B6233, which have nearly identical high specification temperatures of 76.5°C, 76°C, and 75.5°C, respectively, depict differences in their percent permanent deformation of 2.13, 1.36 and 1.54, respectively, in the RSCH experiment at 50°C in the SST.

The variation of $|G^*|/(1-(1/\tan\delta\sin\delta))$ versus frequency ω for the two modified binders B6231 and B6233 at their respective high specification temperatures T_{HS} of 76.5°C and 75.5°C is shown in Figure 3. The data were not actually generated at these two temperatures. They were obtained by interpolation of the frequency sweep data at 70°C and 82°C in each case. As expected, the plot shows minimal differences in the rheological behavior between the two modified binders B6231 and B6233 at their respective T_{HS} of 76.5°C and 75.5°C. The values of $|G^*|/(1-(1/\tan\delta\sin\delta))$ are identical at the frequency of ω=10 radians/s, while at other frequencies they could be considered to be relatively close. The deviations are evident at the low frequency range implying that at temperatures greater than 76°C, the rheological behavior would not be identical. What might happen at lower temperatures is not obvious from Figure 3 because the data at the higher frequencies almost superimpose.

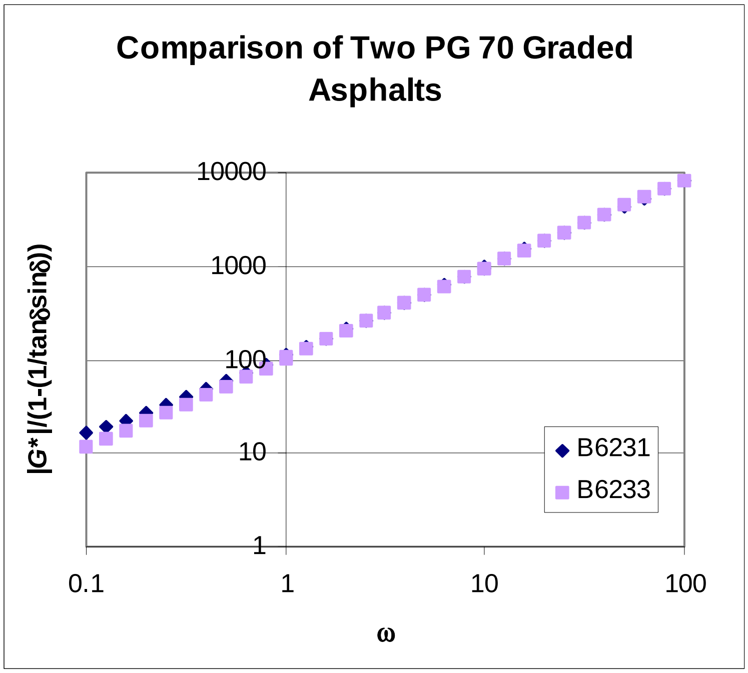

Figure 3: Plot of |G*|/(1-(1/tanδsinδ)) versus frequency ω for binders B6231 and B6233 at their respective high specification temperatures T_{HS} of 76.5°C and 75.5°C.

In order to get a better insight into how different the rheological behaviors of these two binders would be, it is best to look at the master curves for these binders B6231 and B6233. The master curve is formed by shifting the frequency sweep data for the specification parameter |G*|/(1-(1/tanδsinδ)) at temperatures 7°C, 19°C, 31°C, 40°C, 58°C, 70°C, and 82°C to the reference temperature of 25°C. Since the validity of the parameter |G*|/(1-(1/tanδsinδ)) is limited to a value of phase angle δ greater than 52° [11], the term $|G^*|/(\sin\delta)^9$ was used in the calculations of the y-axis during the formation of the master curve for the entire frequency range data at the temperature of 7°C and mostly, the higher frequency range data at the temperature of 19°C wherever the phase angle was less than 55° to be on the safe side. This is because it has been shown [11] that the term $|G^*|/(\sin\delta)^P$ follows closely the predictions of the term $|G^*|/(1-(1/\tan\delta\sin\delta))$ when P=9 and could be used as a good approximation. The master curves formed in this manner for the binders B6231 and B6233 are shown in Figure 4.

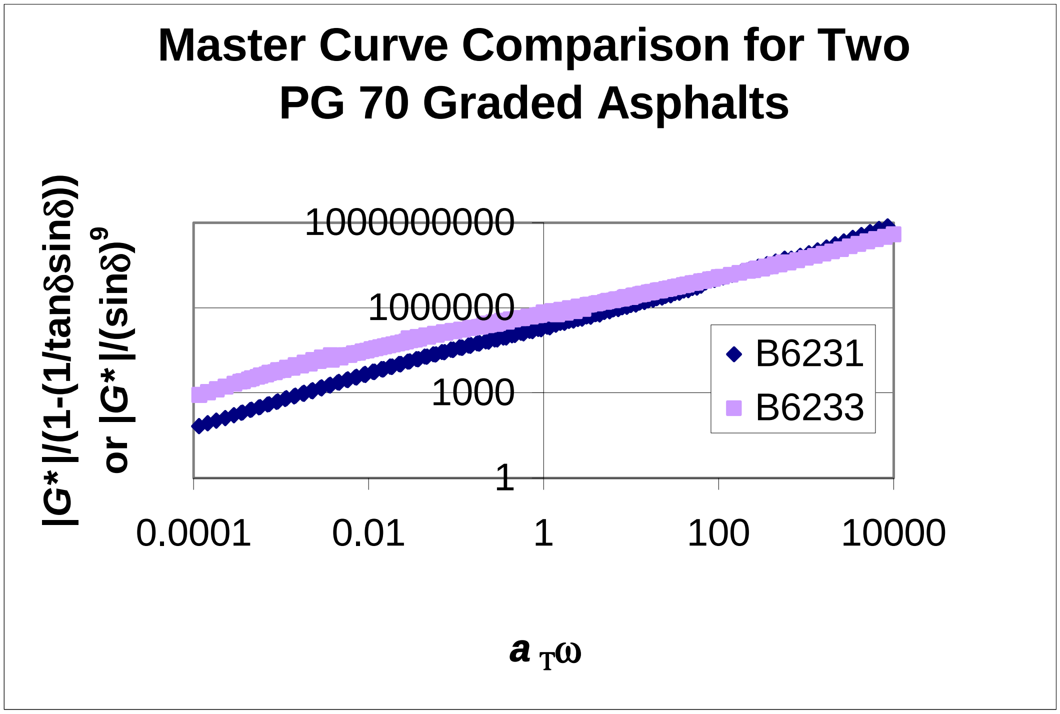

Figure 4: Master curves for binders B6231 and B6233 formed by shifting the data at nine temperatures from 7-82°C to the reference temperature of 25°C.

The variation of the shift factor a_T with temperature is expressed through a semilogarithmic plot of a_T versus $1/T$ (where T is the temperature in Kelvin). The data points are fitted with the best line using an equation of the following form

$$a_T = \exp\left(-A_0(1-\frac{T_0}{T})\right) \quad (1)$$

The values of A_0 and T_0 for the different binders used in this study are given in Table 2.

TABLE 2 -- Values of A_0, T_0(K) in Equation (1) and values of the coefficients A_1, A_2 and exponents B_1, B_2 in Equations (2)-(5)

Binder	A_0	T_0(K)	A_1	B_1	A_2	B_2
Set 1 (T_{ref}=25°C)						
B6225 BASE	64.26	299.36	177163	0.9570	130205	0.9912
B6226 HIGH	66.39	299.65	404841	0.9550	272996	1.0528
B6227 AIR-BLOWN	66.20	299.28	420264	0.9103	322592	0.8888
B6228 ELVALOY	63.05	299.54	179558	0.7650	129523	0.8302
B6229 SBS_L-G	63.28	299.77	219128	0.8523	142336	0.8875
B6230 SBS_L	64.24	299.59	250662	0.8603	163406	0.9057
B6231 SBS_R-G	64.71	299.76	251717	0.8803	160557	0.9165
B6232 EVA	98.77	299.91	550210	0.5236	256565	0.5369
B6233 EVA-G	77.35	298.37	941766	0.7651	504590	0.7016
Set 2 (T_{ref}=25°C)						
ALF AC-5	67.79	299.93	73176	0.9758	54568	0.7912
ALF AC-20	71.88	300.04	259174	0.9558	175061	0.8018
ALF Styrelf	97.38	299.00	15335099	0.6360	6982205	0.6075
Set 3 (T_{ref}=59°C)						
Nevada 64-22	50.38	332.24	1006	0.9952	1179	0.8977
Nevada AC-20P	47.11	332.28	587	0.8411	603	0.8366

Note: ALF (Accelerated Loading Facility)

In order to compare the rheological behavior of the binders based on their master curves, it is advantageous to fit the master curves with an appropriate rheological model. It can be seen that the data points in the master curves cover a very large range of modified frequency $a_T\omega$. Under such circumstances, it is beneficial to first split the modified frequency range into two parts, then fit appropriate constitutive equations to each part, and later combine these two equations to give a composite model covering the entire range of data. Such a model was found to be effective for unified curves of binders [14] and mixtures [15] in the past, and hence is being used for the master curves in the present case as well. The rheological model for fitting the master curves is derived through a combination of the following two equations.

$$\frac{|G^*|}{\left(1-\frac{1}{\tan\delta\sin\delta}\right)} \; or \; \frac{|G^*|}{(\sin\delta)^9} = A_1(a_T\omega)^{B_1} \qquad for \qquad 0.0001 < a_T\omega < 1 \qquad (2)$$

$$\frac{|G^*|}{\left(1-\frac{1}{\tan\delta\sin\delta}\right)} \; or \; \frac{|G^*|}{(\sin\delta)^9} = A_2(a_T\omega)^{B_2} \qquad for \qquad 1 < a_T\omega < 10000 \qquad (3)$$

The above forms presume that the data points of the master curve fit a power-law model in the two modified frequency ranges. The coefficients and exponents can be calculated by fitting the best line through the data points on the log-log plot of the master curve. In order to fit the entire range of data in the master curves, the two expressions in Equations (2) and (3) are combined through the following form.

$$\left[\frac{|G^*|}{\left(1-\frac{1}{\tan\delta\sin\delta}\right)}\right]^N or \left[\frac{|G^*|}{(\sin\delta)^9}\right]^N = \left[A_1(a_T\omega)^{B_1}\right]^N + \left[A_2(a_T\omega)^{B_2}\right]^N \quad (4)$$

The exponent N needs to be determined by trial and it was found that N=2/(B_2-B_1) was appropriate in the present case for all data sets. The simplified form of the Equation (4) is written as follows.

$$\frac{|G^*|}{\left(1-\frac{1}{\tan\delta\sin\delta}\right)} or \frac{|G^*|}{(\sin\delta)^9} = \frac{A_1(a_T\omega)^{B_1}}{[1+\{(A_1/A_2)^{2/(B_1-B_2)}(a_T\omega)^2\}]^{(B_1-B_2)/2}} \quad (5)$$

The curve fit based on Equation (5) was found to give a good agreement with the data points of the master curve shown in Figure 5 for illustration purposes, as well as for all other binders used in the present study.

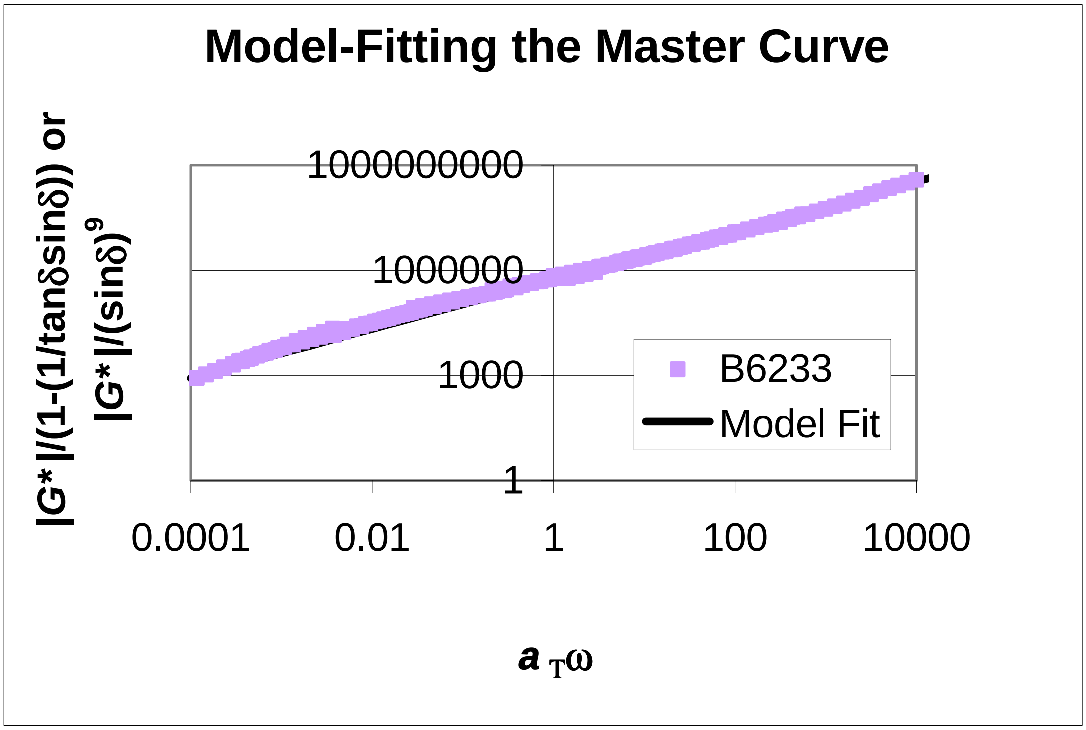

Figure 5: Model-fitting the master curve of the binder B6233.

The values of A_1, B_1, A_2, and B_2 for each of the master curves shown in Figure 4, as well as for those that are not shown, are given in Table 2. It is the differences in the values of these coefficients and exponents that truly mark the difference in behavior of the different binders even when they have identical high specification temperatures. In fact, it can be seen clearly from the master curves shown in Figure 4 that the binders B6231 and B6233 could never behave exactly in the same manner in their rutting performance even when their high specification temperatures are nearly the same. From among A_1, B_1, A_2, and B_2, it is important to determine which is truly significant in rut resistance.

Since the master curve is a combination of the two Equations (2) and (3), it automatically marks the two portions of the master curve that are of significance. The portion of the master curve in the low frequency region describes the rheological behavior of the binder at higher temperatures applicable to rutting, while the other portion of the master curve in the higher frequency region describes the rheological behavior at lower temperatures applicable to intermediate temperature distresses. This is because, during the formation of the master curve, the data at temperatures higher than 25°C are forced to lie in the lower region of the normalized frequency while the data at temperatures lower than 25°C get aligned in the higher region of normalized frequency.

The RSCH data on the mixture that were taken at high temperatures give a measure of the permanent deformation and, in principle, should be linked to the portion of the unified curve in the lower frequency region, namely, Equation (2). The rheological behavior of the binder based on $|G^*|/(1-(1/\tan\delta\sin\delta))$ or $|G^*|/(\sin\delta)^9$ at the temperature of the RSCH measurement could be obtained from this equation at any desired frequency or frequencies. If a single frequency value is used, then the rheological behavior gets expressed at one specific condition only. The controlling parameter A_1 is actually the value of the parameter $|G^*|/(1-(1/\tan\delta\sin\delta))$ or $|G^*|/(\sin\delta)^9$ at $a_T\omega = 1$, and is again an expression of the rheological behavior under one specific condition. On the other hand, the exponent B_1, being the slope of $|G^*|/(1-(1/\tan\delta\sin\delta))$ or $|G^*|/(\sin\delta)^9$ versus $a_T\omega$ on a log-log plot, would capture the behavioral pattern through a range of temperatures and frequencies applicable to rutting. Hence, B_1 will be used for establishing a rut-controlling term.

The lower the exponent B_1, the greater is the resistance of the binder to rutting. Similarly, the higher the value of T_{HS}, the greater is the resistance of the binder to rutting. This implies that the permanent deformation D_T at temperature T would essentially be a function of T, T_{HS}, and B_1. The form $(T/ T_{HS})* B_1$ would give an adequate description of this function and could be considered as the rutting control term, C_R, for giving a measure of the rutting resistance. The lower the value of C_R, the better is the rutting resistance.

Figure 6 shows a plot of the rutting control term $C_R = (T/ T_{HS})* B_1$ versus D_T, which is the percent permanent strain after 5000 cycles recorded from the RSCH measurement at temperature T°C for the various binders as shown in Table 3.

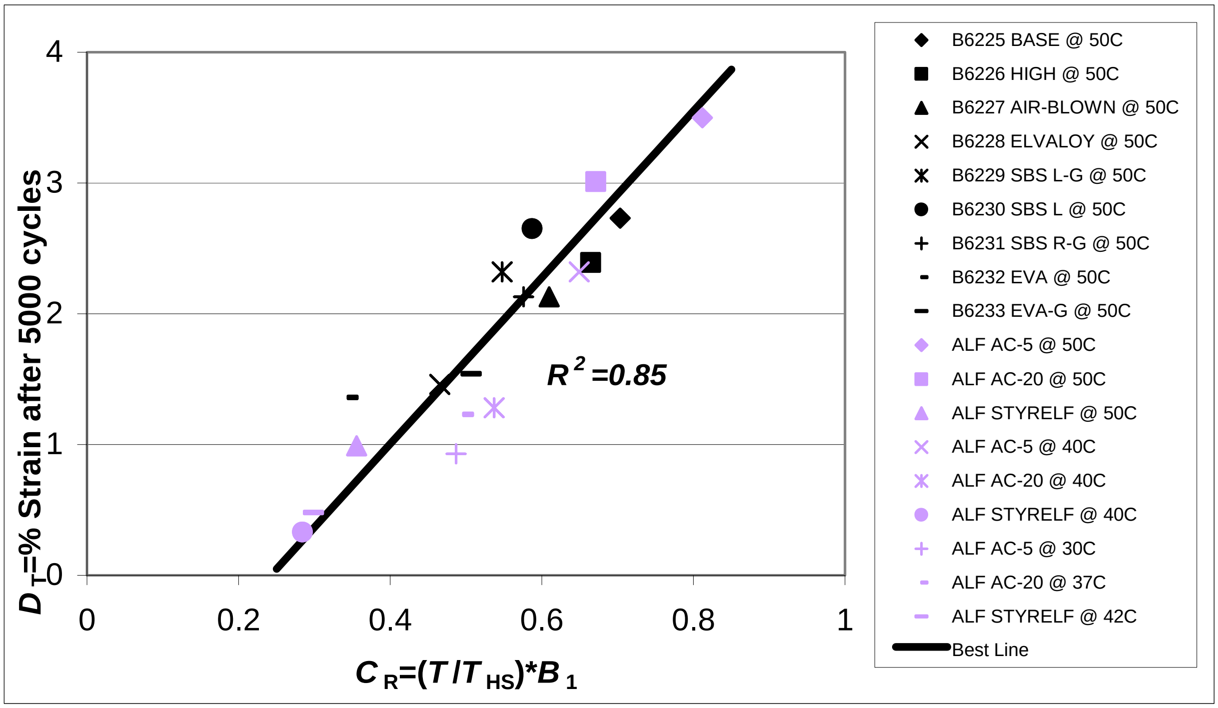

Figure 6: Plot of the deformation D_T measured with the SST on the mixtures versus the rut-controlling term C_R obtained from parameters measured with the DSR on the binders.

TABLE 3 – RSCH data on % permanent strain after 5000 cycles at different temperatures

Binder	@ 30^0C	@ 37^0C	@ 40^0C	@ 42^0C	@ 50^0C
Set 1					
B6225 BASE	_	_	_	_	2.73
B6226 HIGH	_	_	_	_	2.39
B6227 AIR-BLOWN	_	_	_	_	2.13
B6228 ELVALOY	_	_	_	_	1.46
B6229 SBS_L-G	_	_	_	_	2.32
B6230 SBS_L	_	_	_	_	2.65
B6231 SBS_R-G	_	_	_	_	2.13
B6232 EVA	_	_	_	_	1.36
B6233 EVA-G	_	_	_	_	1.54
Set 2					
ALF AC-5	0.93	_	2.32	_	3.50
ALF AC-20	_	1.23	1.28	_	3.01
ALF Styrelf	_	_	0.33	0.48	0.99

Note: ALF (Accelerated Loading Facility)

It can be seen that 18 samples were used, of which 12 were tested at 50°C, 1 at 42°C, 3 at 40°C, 1 at 37°C, and 1 at 30°C. The 18 samples comprised 12 different binders and one aggregate type and gradation. Figure 6 shows that the correlation coefficient $R^2 = 0.85$. The equation of the best line for this group of data is

$$D_T = a_0 C_R - b_0 \qquad (6)$$

where D_T is the % permanent strain after 5000 cycles at any temperature T, and the rutting control term C_R is given by the following equation

$$C_R = (T / T_{HS}) B_1 \qquad (7)$$

and the coefficients $a_0 = 5.62$ and $b_0 = 1.17$. The values of the coefficient a_0, b_0 are specific to the sets of data analyzed and would change for different mixtures. In any case, they are mere constants and the permanent deformation after 5000 cycles could as well be tracked by observing the variation in the rutting control term C_R. If the temperatures of interest were equal to the specification temperature, then the variations in the rutting control term C_R would be given simply by the variations in B_1. Thus, if one were to compare the behavior of two mixtures at their respective specification temperatures, then it would be sufficient to compare their respective B_1 values to ascertain that the one with the lower value would show lower rutting. The equation for the specific deformation D_{TS} would be then given as follows:

$$D_{TS} = a_0 B_1 - b_0 \qquad (8)$$

On the other hand, if the temperature of interest were a particular average pavement temperature T, then to understand how two mixtures would perform under identical temperature conditions of T, it would be enough to compare their (B_1/ T_{HS}) ratio. As a matter of fact, it would be this ratio that could be used for ranking mixtures, assuming that a comparison of the performance of the mixtures in their resistance to rutting is being sought at a constant temperature of T for all mixtures.

In order to validate the efficacy of the proposed rut-controlling term, the Nevada I-80 project binders were considered in the study. The two binders used in the Nevada I-80 project were one unmodified binder 64-22 and the other a modified binder AC-20P. Both binders were graded under the Superpave grading as PG 64-22 and were expected to perform in the same manner, but the modified binder AC20P was found to outperform the unmodified binder 64-22. Based on the proposed methodology, the master curves for the two binders were prepared at the reference temperature of 59°C using the DSR frequency sweep data at temperatures of 47°C, 53°C, 59°C, 65°C, and 71°C. The master curves were fitted using Equation (5) and the model parameters were determined as shown in Table 2. The rut-controlling term C_R=(T/ T_{HS})*B_1 was used for ranking the expected performance of the two binders. It can be seen from Table 4 that only when this ratio is used for the comparison, is the ranking identical to that seen in the field. All other cases, namely, the conventional PG grading, the continuous grading, and the refined specification parameter do not predict that the modified binder would outperform the unmodified binder.

TABLE 4 – Performance ranking for the binders used in the Nevada I-80 project

	Nevada AC20P	**Nevada 64-22**
Actual field performance	Higher rut resistance	Lower rut resistance
Grade (Superpave Spec.)	PG64-22	PG64-22
Expected performance	Same	Same
Continuous PG (Superpave Spec.)	63	67
Expected performance	Lower rut resistance	Higher rut resistance
T_{HS} (°C) (Refined Spec.)	71.84	75.85
Expected performance	Lower rut resistance	Higher rut resistance
$C_R=(T/T_{HS})*B_1$ (for T=60°C)	0.703	0.763
Expected performance	Higher rut resistance	Lower rut resistance

Conclusions

The present work introduces a rut-controlling parameter C_R that could be used as an identification tag to grade binders and rank their expected field performance. This method of performance-related specification would help in matching the expected behavior of the binder with that of the mixture and thus would relate to field performance.

The suggested method is simple and straightforward. The first step involves the determination of a specification temperature T_{HS} (°C) using the frequency sweep data from the DSR measurements, based on the refined specification parameter $|G^*|/(1-(1/\tan\delta\sin\delta))$. This is done by calculating the temperature at which refined specification parameter $|G^*|/(1-(1/\tan\delta\sin\delta))$ takes a value of 1kPa at the frequency of 10 radians/s.

The second step involves plotting the variation of $|G^*|/(1-(1/\tan\delta\sin\delta))$ or $|G^*|/(\sin\delta)^9$ versus the frequency ω at various temperatures of DSR measurements and getting the master curve by shifting the data to a reference temperature.

The third step is to fit the master curve with the rheological model given by Equation (5) and then to determine the values of the model parameters. The slope B_1 for the lower frequency range of the master curve is used for determining the controlling term for ranking the binders by their expected performance to resist rutting.

It is shown that the permanent deformation data from RSCH measurement on the SST can be related to the rutting control term C_R that is obtained from frequency sweep data measured from the DSR. Generation of frequency sweep data on the DSR is relatively simple and the analysis of the data as outlined here is equally simple. The proposed method is effective as a performance-related specification.

While the rutting control term C_R is recommended for use as a performance-related specification since, in principle, it should work in all cases, the parameter $|G^*|/(1-(1/\tan\delta\sin\delta))$

could be used as a performance-based specification since it is effective in most cases in discriminating the rheological behavior. The parameter $|G^*|/(1-(1/\tan\delta\sin\delta))$ can be estimated [16] from the material's volumetric-flow rate (MVR) through the use of the unification technique [17-19], and hence the MVR can be used as an effective quality control / quality assurance tool for high temperature performance grading [20-21]. Thus, where precision is required, C_R should be used as the PRS while the T_{HS} based on the parameter $|G^*|/(1-(1/\tan\delta\sin\delta))$ should be used as the performance-based specification for purchase purposes and the MVR could be used routinely for verification purposes of performance-graded asphalts.

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Disclaimer

The opinions, findings, and conclusions expressed in this document are those of the author only and not necessarily of the Federal Highway Administration.

References

1. Phillips, M. C. and Robertus, C., “Binder Rheology and Asphaltic Pavement Permanent Deformation; The Zero-shear Viscosity”, *Presented at the Eurasphalt & Eurobitume Congress*, 1996.

2. Stuart, K. D. and Mogawer, W. S., “Validation of Asphalt Binder and Mixture Tests that Predict Rutting Susceptibility using FHWA Accelerated Loading Facility”, *Journal of the Association of Asphalt Paving Technologists*, Vol. 66, pp. 109-152 (1997).

3. Bahia, H. U., Zeng, M., Zhai, H. and Khatri, A., “Superpave Protocols for Modified Asphalt Binders”, *Fifteenth Quarterly Progress Report- NCHRP Project 9-10*, Washington D.C., 1999.

4. Chabert, D., Triquigneaux, J-P. and Vaniscote, J-C., “Rheology of Elastomer Binders and Rutting Resistance of Bituminous Mixes”, *Proceedings of the Eurobitume Workshop 99*, Paper No. 028, 1999.

5. Collop, A. C. and Khanzada, S., “Permanent Deformation in Idealised Bituminous Mixtures and Bitumen Properties”, *Proceedings of the Eurobitume Workshop 99*, Paper No. 124, 1999.

6. Mazé, M. and Brûlé, B., “Relationship between Rheological Properties of Modified Binders and Hot Mixtures Rutting”, *Proceedings of the Eurobitume Workshop 99*, Paper No. 044, 1999.

7. Desmazes, C., Lecomte, M., Lesueur, D. and Phillips, M. “A Protocol for Reliable Measurement of Zero-shear-viscosity in Order to Evaluate the Anti-rutting Performance of Binders”, *Proceedings of 2nd Eurasphalt & Eurobitume Congress, Barcelona, Spain*, Book 1, 202-211, 2000.

8. Bouldin, M. G., Dongré, R., Zanzotto, L. and Rowe, G. M., "The Application of Visco-elastic Models to Predict the Relative Performance of Binders for Grading Purposes", *Proceedings of 2nd Eurasphalt & Eurobitume Congress, Barcelona, Spain*, Book 1, 74-82, 2000.

9. Bouldin, M. G., Dongré, R. and D'Angelo, J., "Proposed Refinement to the Superpave High Temperature Specification Parameter for Performance Graded Binders", *Presented at the 80th Annual Meeting of the Transportation Research Board*, Washington D. C., 2001.

10. Bahia, H. U., Zhai, H., Zeng, M., Hu, Y. and Turner, P., "Development of Binder Specification Parameters based on Characterization of Damage Behavior", *Paper prepared for presentation at the 2001 Annual Meeting of the Association of Asphalt Paving Technologists*.

11. Shenoy, Aroon, "Refinement of the Superpave Specification Parameter for Performance Grading of Asphalt", *Journal of Transportation Engineering*, Vol. 127, pp. 357-362 (2001).

12. Blankenship, P. B., Walker, D. E., Myers, A. S., Clifford, A. S., Thomas, T. W., King, H. W. and King, G. N., "Are All PG 70-22's the Same? Lab Tests on KY I-64 Field Samples", *Journal of the Association of Asphalt Paving Technologists*, Vol. 67, pp. 493-552 (1998).

13. Stuart, K. D., Mogawer, W. S., and Romero, P., "Validation of Asphalt Binder and Mixture Tests that Measure Rutting Susceptibility using the Accelerated Loading Facility", *Report FHWA-RD-99-204*, 1999.

14. Shenoy, Aroon "Prediction of the High Temperature Rheological Properties of Aged Asphalts from the Flow Data of the Original Unaged Samples", *Construction and Building Materials*, submitted for possible publication, 2001.

15. Shenoy, A. and Romero, P., " Superpave Shear Tester as a Simple Standardized Measure to Evaluate Aggregate-Asphalt Mixture Performance", *Journal of Testing & Evaluation*, Vol. 29,

pp. 50-62 (2001).

16. Shenoy, Aroon, “Estimating the Unrecovered Strain during a Creep Recovery Test from the Material’s Volumetric-flow Rate”, *International Journal of Pavement Engineering*, Vol.3 (2002).

17. Shenoy, Aroon, “Unifying Asphalt Rheological Data using the Material’s Volumetric-flow Rate”, *Journal of Materials in Civil Engineering*, Vol. 13, pp. 260-273 (2001).

18. Shenoy, Aroon, “Validating the Generality and Predictive Ability of Unified Rheological Curves for Unmodified Paving Asphalts”, *Construction and Building Materials*, Vol. 14, pp. 325-339 (2000).

19. Shenoy, Aroon, “Developing Unified Rheological Curves for Polymer-modified Asphalts – Part I. Theoretical Analysis and Part II. Experimental Verification”, *Materials and Structures*, Vol. 33, pp. 425-437 (2000).

20. Shenoy, A., “High Temperature Performance Grade Specification of Asphalt Binder from the Material’s Volumetric-flow Rate”, *Materials and Structures*, Vol. 34, (2001).

21. Shenoy, Aroon, “Material’s Volumetric-flow Rate (MVR) as a Unification Parameter in Asphalt Rheology and Quality Control / Quality Assurance Tool for High Temperature Performance Grading”, *Applied Rheology*, Vol. 6, pp. 288-306 (2000)