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Superpave Shear Tester as a Simple Standardized Measure to Evaluate Aggregate-Asphalt Mixture Performance

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Abstract

The present work provides a standardized method by which various mixtures can be compared and their expected performance can be assessed in a uniform manner using the Superpave shear tester. Based on the present findings, it is evident that complete mixture evaluation can be done through the frequency sweep at constant height (FSCH) data from the Superpave shear tester (SST), without the need to generate the repeated shear at constant height (RSCH) data. This would reduce the experimental time without compromising the information obtained.

FSCH and RSCH data at different temperatures are generated on the SST for a number of aggregate-asphalt mixture combinations. The shear moduli versus frequency data from the FSCH at different temperatures are unified to form a single curve for each mixture so that a specification parameter T_S (°C) can be determined.

Each unified curve is fitted with a constitutive equation from which model parameters are evaluated. The slope B_1 in the low frequency region of the unified curve, when normalized with the term (T/ T_S), results in a parameter that relates to the permanent strain after 5000 cycles in RSCH at any temperature T. There is a good possibility that the slope B_2 in the high frequency region of the unified curve may relate to distresses in the intermediate temperature range, such as, fatigue. If this is proven true through future research, then the Superpave shear tester could earn the distinction of being a 'Simple Performance Tester'.

Keywords: Superpave shear tester, frequency sweep, repeated shear, performance-related specifications, aggregate-asphalt combinations, mixture evaluation

Introduction

Superpave Shear Tester

The Superpave shear tester (SST) was developed as a means to characterize asphalt mixture properties during the Strategic Highway Research Program – (SHRP), a five-year $150 million dollar United States research effort established and funded in 1987. The SST is a servo-hydraulic machine that can apply both axial and shear loads at constant temperatures using closed-loop control.

The current SST protocols consist of three different modes of operation: (1) simple shear at constant height (SSCH), (2) frequency sweep at constant height (FSCH), and (3) repeated shear at constant height (RSCH). In each mode, different types of information are available. This paper deals with the last two modes.

The FSCH test involves the application of a sinusoidal shear strain with a certain peak amplitude (e.g. 0.4 μm/mm) at a fixed temperature of interest at each of the following frequencies: 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz. The response of the material at these frequencies to the applied strain is analyzed easily through existing software. The generated response parameters are the complex shear modulus (G^*), the phase angle (δ), the recoverable shear modulus (G'), and the loss shear modulus (G'').

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 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.

The information obtained from the SST using different modes of operation is utilized conventionally by researchers to compare generated data for any proposed mixture of unknown performance with another mixture with known performance under the same conditions at identical temperatures. This practice is certainly useful but it is limited to those specific sets where there is available information on mixtures with known performance for comparison.

For example, recent studies [1-5] have demonstrated that certain stiffness parameters obtained from the FSCH test can be used to rank mixtures in a manner consistent with their field performance. More studies of this type will probably help in establishing a relationship between FSCH data and field performance. However, the information is confined to the specific systems of study. In cases where such data for comparison are not available, it becomes imperative to establish fresh databases. In fact, presently, there is no universally accepted criterion that can be used to discern a good performing asphalt mixture from a bad one. Hence, SST information is under-utilized and restricted to specific systems.

Study Objectives

The objectives of the present study are three-fold. Firstly, it is to establish uniformity in data analyses / interpretation within the asphalt paving community, and help in data sharing among practitioners from different locations, which is presently missing. Secondly, it is to find a method to cut down experimental time without sacrificing the information obtained. Thirdly, it is to demonstrate that the Superpave shear tester using the suggested data analyses has the potential of being designated as the Simple Performance Tester that the asphalt community has been seeking for so long.

Experimental Plan

The experimental plan involved the generation of FSCH and RSCH data from the SST on various laboratory- prepared samples. Laboratory specimens were prepared at the Turner-Fairbank Highway Research Center (TFHRC) Bituminous Materials Laboratory using the Superpave Gyratory Compactor.

Three sets of aggregate-asphalt mixture systems were used. The first set consisted of nine different binders with a gradation having a maximum nominal aggregate size of 19 mm. The nine binders included a PG64-22 (unmodified base), a PG70-22 (unmodified high grade), a PG70-28 (air-blown), and six PG70-28, which consisted of the following polymer-modified systems: Elvaloy, Styrene-Butadiene-Styrene_Linear-Grafted [SBS_L-G], Styrene-Butadiene-Styrene_Linear [SBS_L], Styrene-Butadiene-Styrene_Radial-Grafted [SBS_R-G], Ethylene-Vinyl Acetate [EVA] and Ethylene-Vinyl-Acetate_Grafted [EVA_G].

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 (PG70-28) was obtained by noncatalytic air-blowing of a PG52-28 (flux). The polymer-modified grades were obtained by addition of various amounts of different polymers to the PG64-22 (base) or the PG52-28 (flux) or mixture of the PG64-22 (base) and the PG52-28 (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 the Turner-Fairbank Highway Research Center.

In the second set, the selected systems were those that used binders and aggregate gradations that were previously utilized in the Superpave binder validation study using the Accelerated Loading Facility (ALF) [6] at the Federal Highway Administration (FHWA). Four laboratory-prepared samples used two unmodified binders – a PG58-34 (AC-5) and a PG64-22 (AC-20), and two modified binders – a PG82-22 (Styrelf) and a PG76-22 (Novophalt) with a diabase aggregate and a gradation having a nominal maximum aggregate size of 19 mm.

In the third set, the same four binders as in the second set were used, but with rounded river gravel from Westminster, MD having a nominal maximum aggregate size of 12.5 mm.

Specification Temperature T_S (°C)

A new specification parameter was recently introduced [7] through a systematic analysis of the FSCH data generated from the SST. The procedure involved unification of frequency sweep data and then determination of the specification parameter. The salient features of the approach [7] are outlined here briefly in order to maintain continuity of the thought process when carrying the ideas forward in order to relate FSCH data with RSCH data.

FSCH Data

FSCH data from the SST are obtained at three different temperatures chosen from the following four (25^{o}C, 33^{o}C, 40^{o}C, and 50^{o}C). At each temperature, three individual tests are performed and the average value is used for representing the data in the form shown in Figures 1 (a) - (e) for a select group of the laboratory-prepared samples from Set 1.

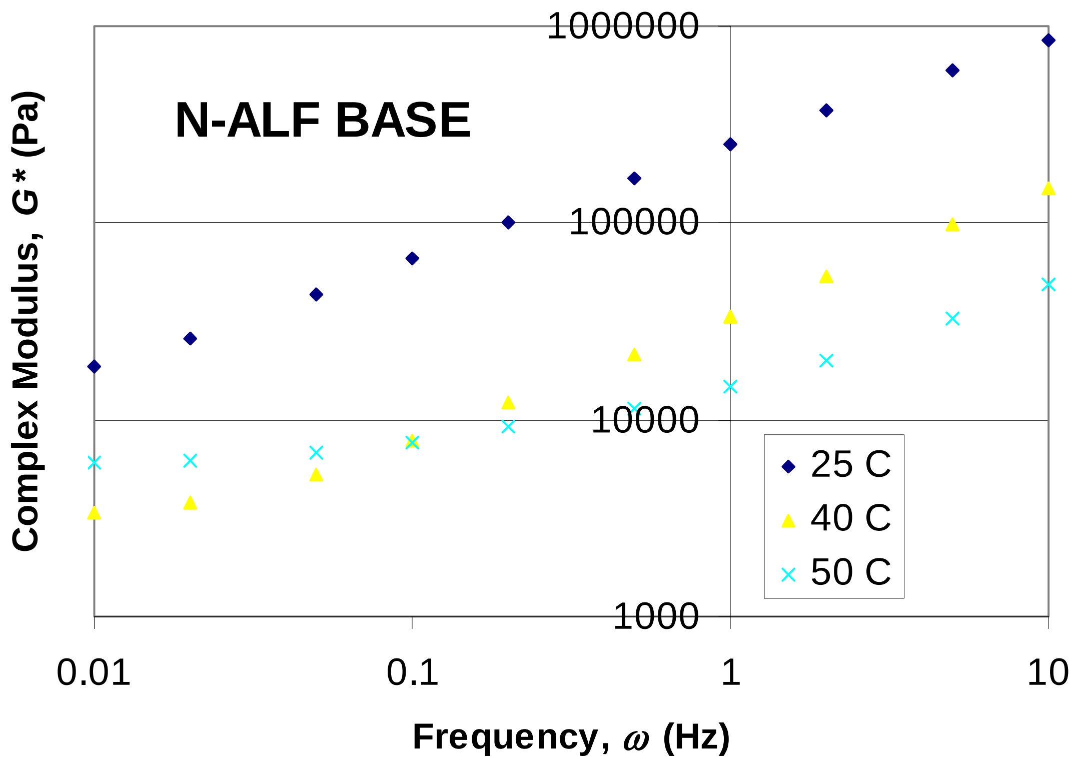

Figure 1 (a): Complex shear modulus G^* with frequency ω at three different temperatures of 25℃, 40℃ and 50℃ for N_ALF BASE mixture samples

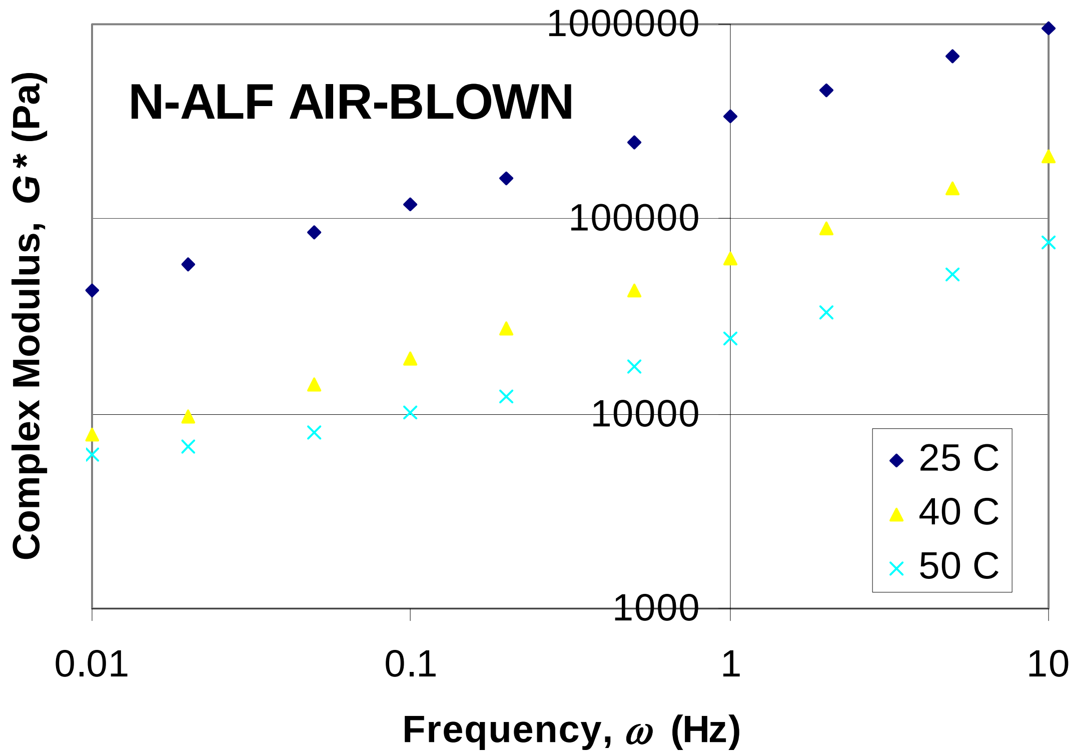

Figure 1 (b): Complex shear modulus *G** with frequency *ω* at three different temperatures of 25℃, 40℃ and 50℃ for N_ALF AIR-BLOWN mixture samples

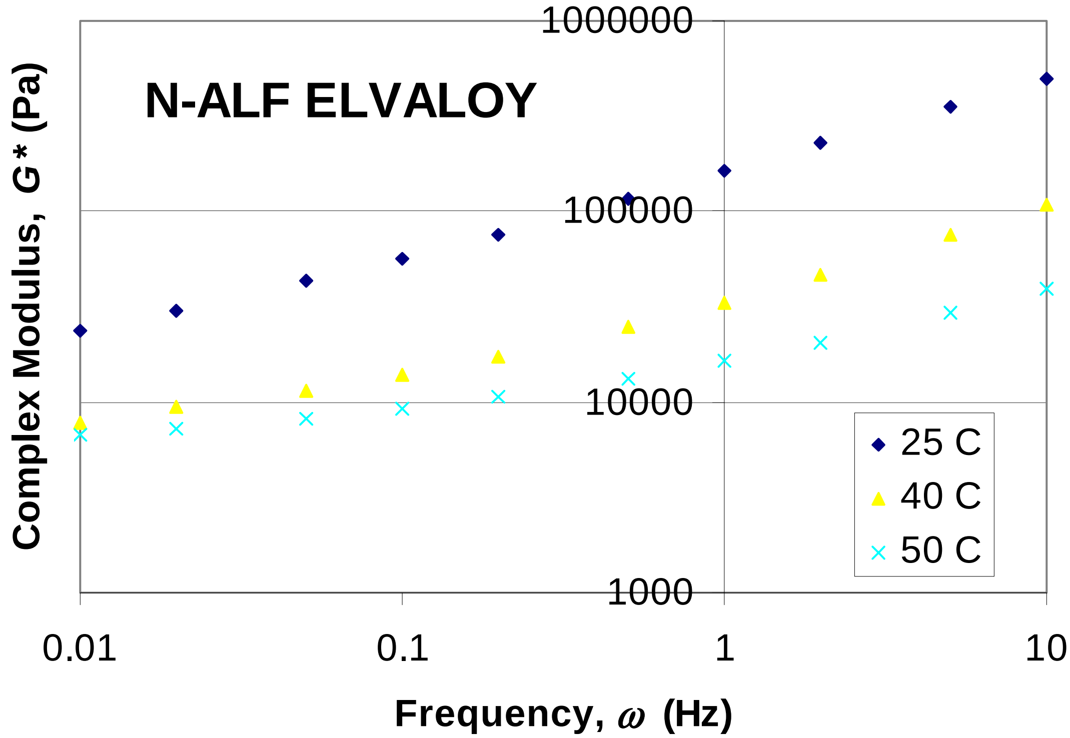

Figure 1 (c): Complex shear modulus *G** with frequency *ω* at three different temperatures of 25℃, 40℃ and 50℃ for N_ALF ELVALOY mixture samples

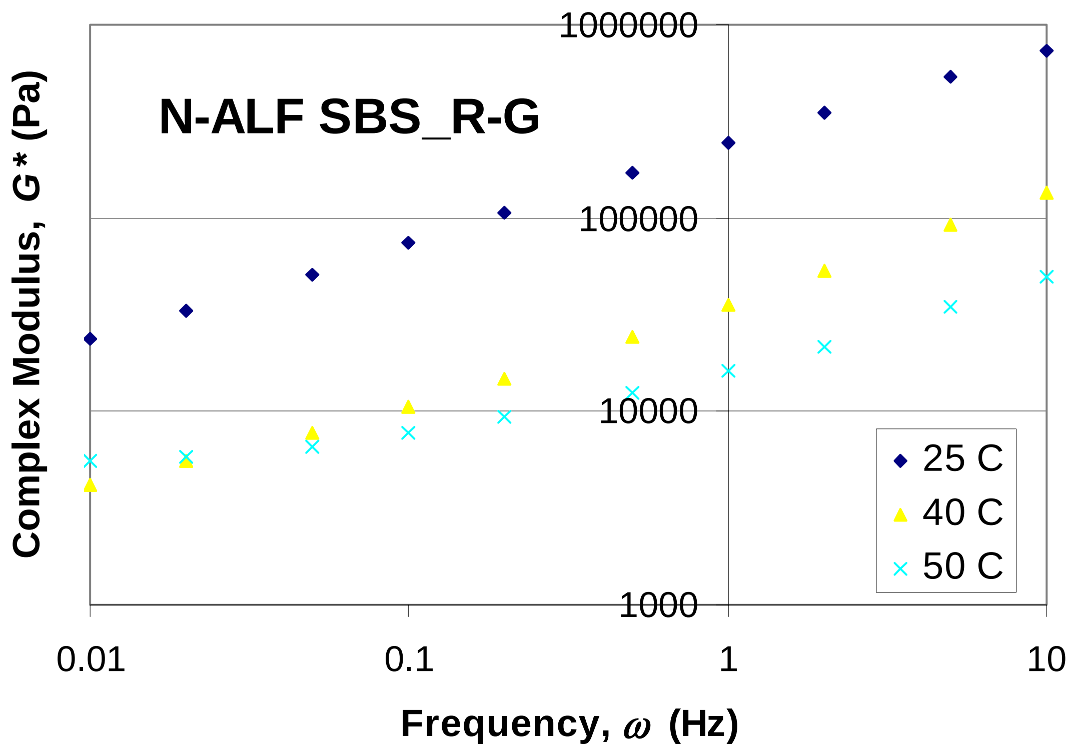

Figure 1 (d): Complex shear modulus *G** with frequency *ω* at three different temperatures of 25℃, 40℃ and 50℃ for N_ALF SBS_R-G mixture samples

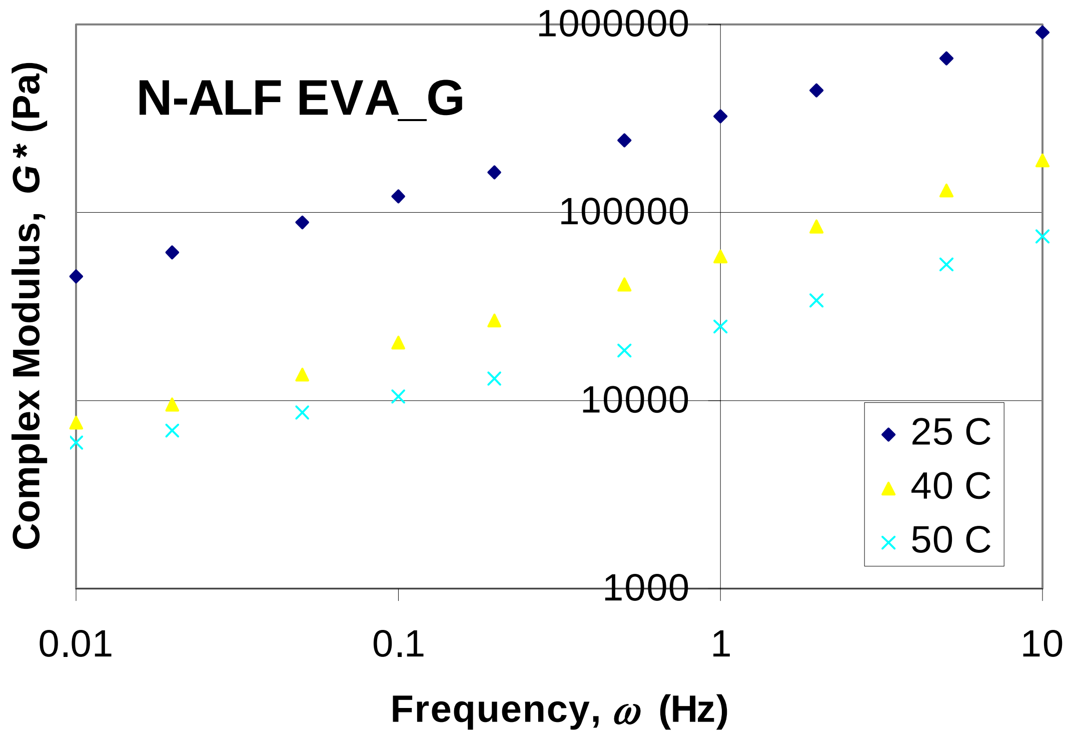

Figure 1 (e): Complex shear modulus G^* with frequency ω at three different temperatures of 25℃, 40℃ and 50℃ for N_ALF EVA_G mixture samples

In accordance with the procedure given in the earlier work [7], a normalizing frequency parameter ω_0 is determined corresponding to a particular reference modulus value G_0^*= 75,000 Pa in order to unify the curves in Figure 1. The choice of the reference modulus was arbitrary [7]. It was based on convenience, aptness, simplicity, and personal preference due to prior successes on similar curve sets in other areas [8, 9].

The value of G_0*= 75,000 Pa does not affect the unification technique. It only shifts the unified curve to a different position. In other words, the choice of G_0* value only fixes the base position of the unified curve. It was indicated in the earlier work [7] that, as more data become available, a new value of G_0* may be selected in order to increase the sensitivity of T_S. During the course of the present work, it was found that a value of G_0*= 18,500 Pa was more appropriate as it resulted in values of T_S with a wider spread and in a more familiar range. Hence G_0*= 18,500 Pa was chosen in this study and is recommended for future data analyses. The value of ω_0 corresponding to the reference modulus G_0* = 18,500 Pa is estimated using the following equation.

$$\ln \omega_0 = \ln \omega_1 + \ln\left(\frac{\omega_1}{\omega_2}\right) * \left((\ln \frac{G_0 *}{G_1 *}) / (\ln \frac{G_1 *}{G_2 *}) \right) \qquad (1)$$

where the normalizing frequency parameter ω_0 corresponds to the reference complex modulus G_0* =18,500. G_1*, ω_1 and G_2*, ω_2 are two sets of data corresponding to (a) one value of $G^* >$ 18,500 and (b) another value of $G^* <$ 18,500. In cases where the data do not include the range covering the value of G_0* = 18,500, Equation (1) is used for extrapolation. The various values of ω_0 for each of the curves in Figures 1 (a)-(e), as well as those that are not shown in the paper are given in Table 1.

TABLE 1 -- Values of the normalizing frequency parameter, ω_0 (Hz) using G^*_0=18,500

Binder	ω_0 @25°C	@33°C	@40°C	@50°C
19 mm nom.dia. aggregates				
N-ALF BASE	0.0097	_	0.3899	1.6534
N-ALF HIGH	0.0018*	_	0.1011	0.9114
N-ALF AIR-BLOWN	0.0014*	_	0.0917	0.5549
N-ALF ELVALOY	0.0049*	_	0.2339	1.4680
N-ALF SBS_L-G	0.0092*	_	0.3691	1.7984
N-ALF SBS_L	0.0086*	_	0.4968	2.0481
N-ALF SBS_R-G	0.0062*	_	0.3064	1.3608
N-ALF EVA	0.0011*	_	0.0961	0.5200
N-ALF EVA-G	0.0012*	_	0.0853	0.4945
19 mm nom.dia. aggregates				
ALF AC-5	0.0181	0.1408	0.9226	3.5680
ALF AC-20	0.0047*	0.0376	0.1862	1.2518
ALF Styrelf	_	0.0024*	0.0072*	0.1272
ALF Novophalt	_	0.0006*	0.0033*	0.0207
12.5 mm nom.dia. rounded aggregates				
WM AC-5	0.0920	0.5823	2.6796	_
WM AC-20	_	0.0483	0.2747	1.3722
WM Styrelf	_	0.0053*	0.0353	0.2744
WM Novophalt	_	0.0086*	0.0453	0.3453

* Values estimated by *extrapolation* using Eq. (1)

Note: N_ALF (New Accelerated Loading Facility); ALF (Accelerated Loading Facility); WM(Westminster)

Using these values, the original data are replotted as *G** versus ω / ω_0, combining the data for all temperatures for each mix on one graph but plotting each mix separately as shown in Figures 2 (a) - (e).

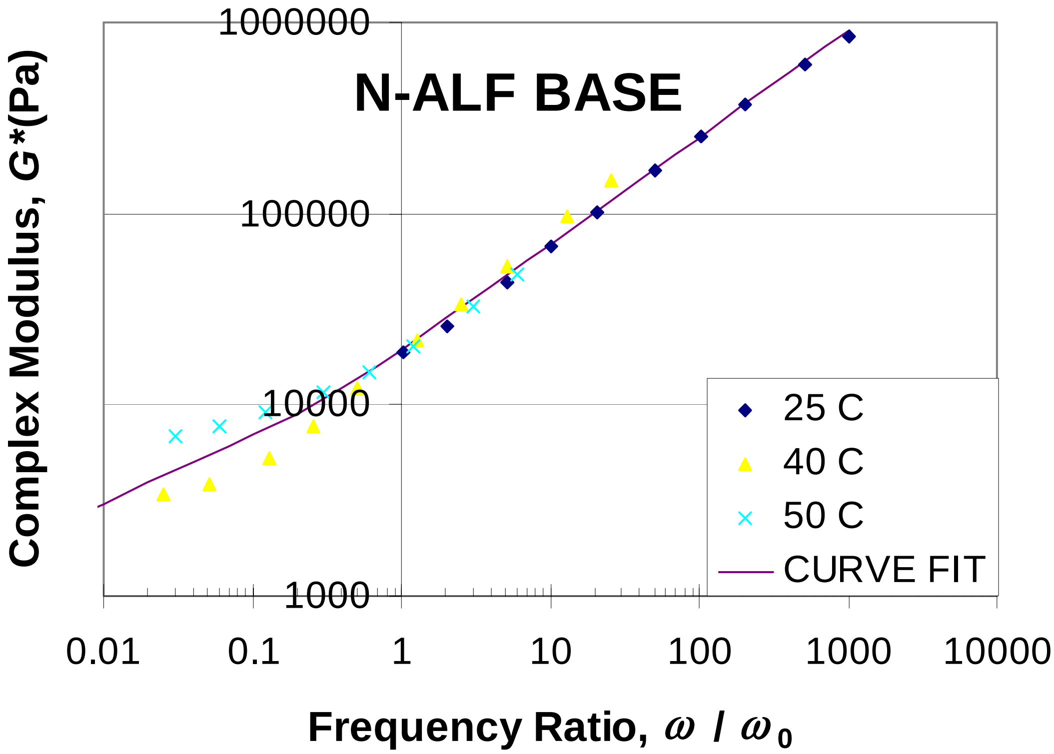

Figure 2 (a): Unified curve of the complex shear modulus *G** with modified frequency ω / ω_0 covering a range of 25℃ - 50℃ for N_ALF BASE mixture samples

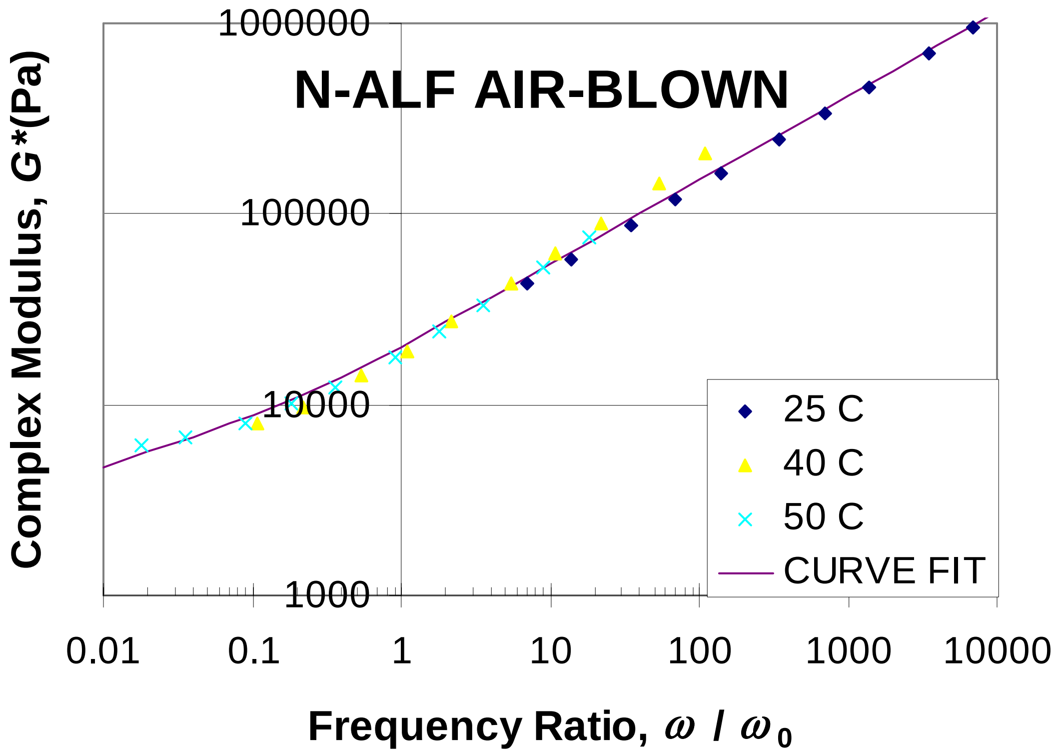

Figure 2 (b): Unified curve of the complex shear modulus G^* with modified frequency ω / ω_0 covering a range of 25℃ - 50℃ for N_ALF AIR-BLOWN mixture samples

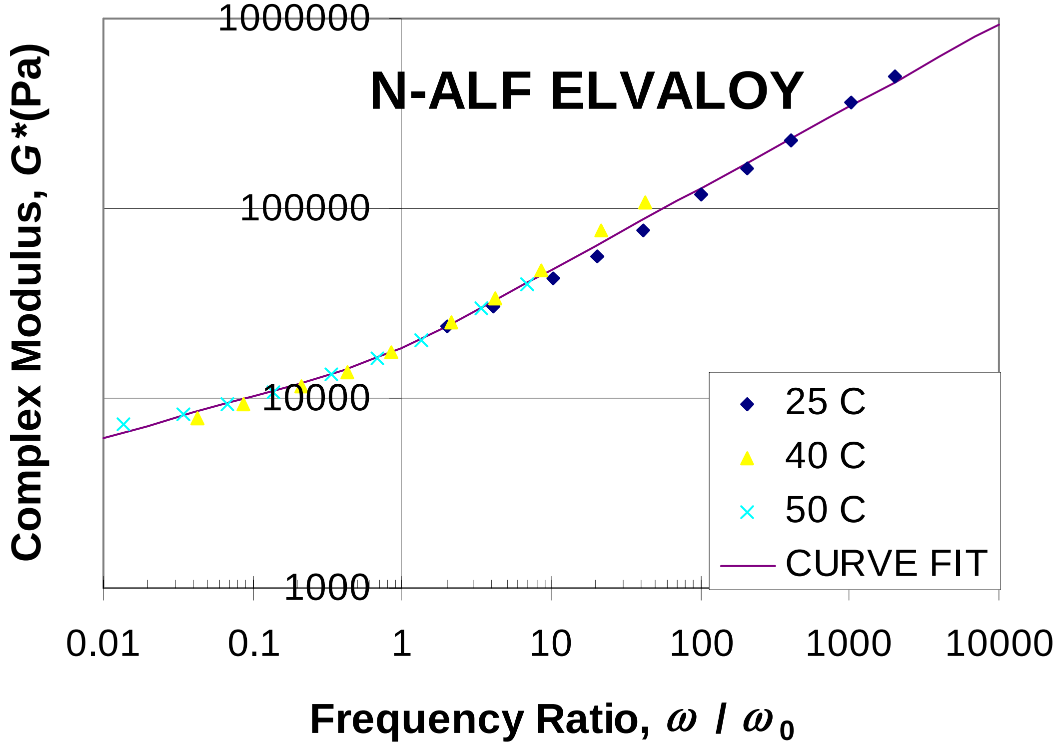

Figure 2 (c): Unified curve of the complex shear modulus G^* with modified frequency ω / ω_0 covering a range of 25℃ - 50℃ for N_ALF ELVALOY mixture samples

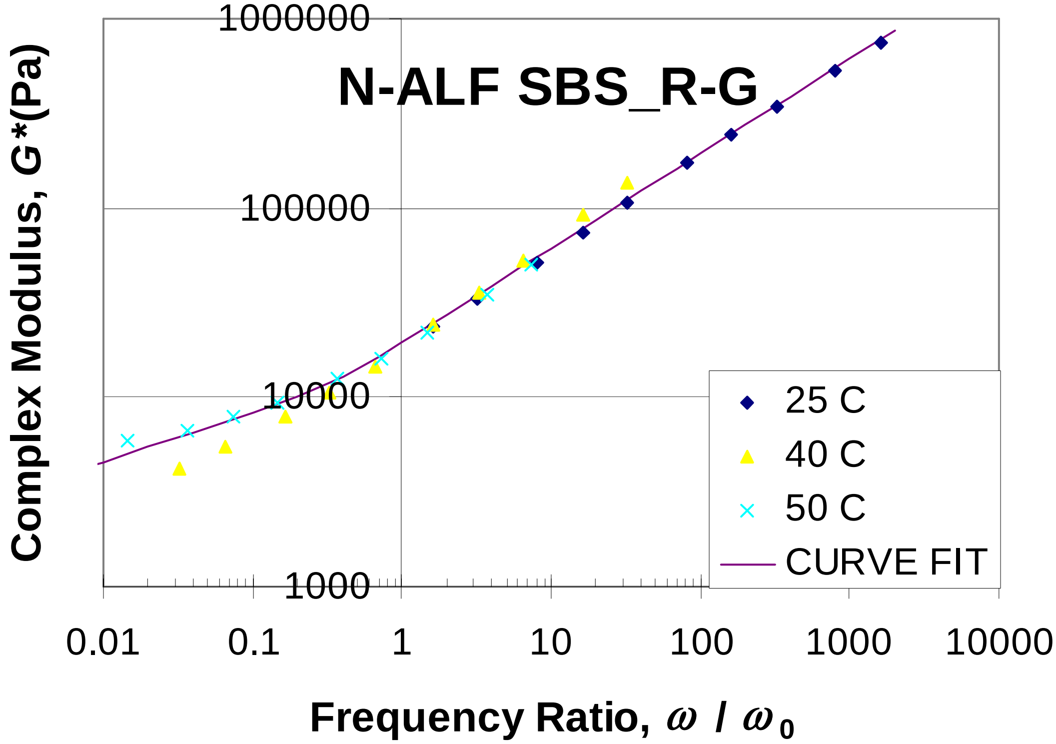

Figure 2 (d): Unified curve of the complex shear modulus G^* with modified frequency ω / ω_0 covering a range of 25℃ - 50℃ for N_ALF SBS_R-G mixture samples

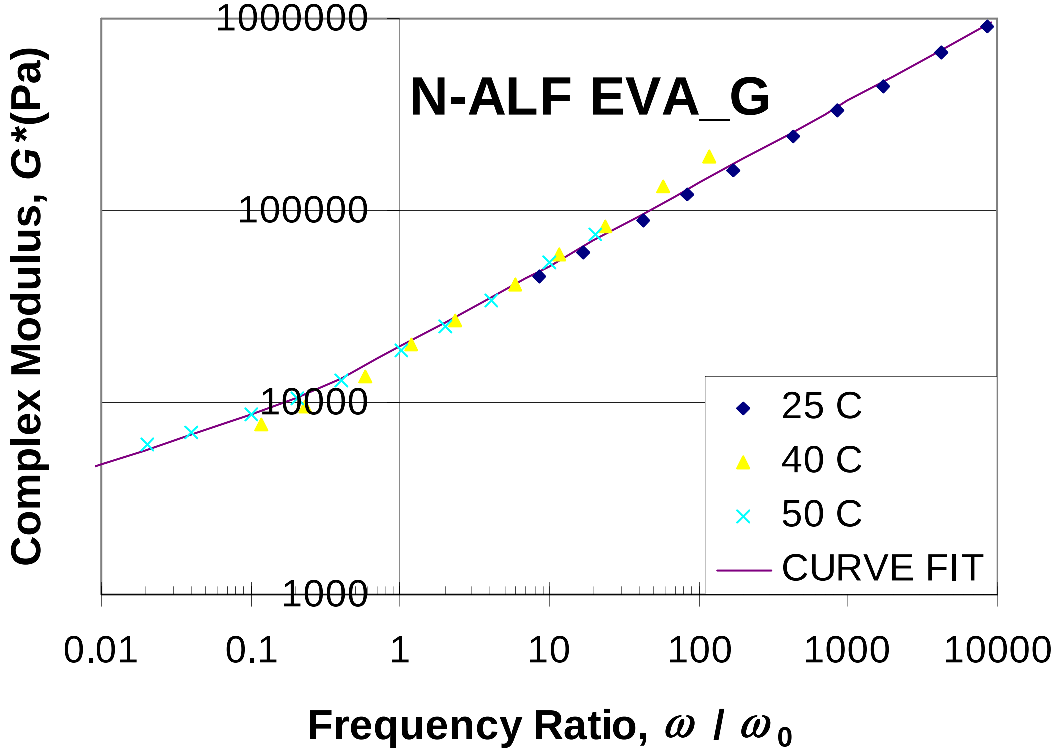

Figure 2 (e): Unified curve of the complex shear modulus G^* with modified frequency ω / ω_0 covering a range of 25℃ - 50℃ for N_ALF EVA_G mixture samples

It can be seen that unified curves are obtained in all cases. The best-fit curves through the data points in Figures 2 (a) - (e) are obtained using the following equation.

$$G^* = \left(\frac{A_1(\omega/\omega_0)^{B_1}}{[1+\{(A_1/A_2)^{2/(B_1-B_2)}(\omega/\omega_0)^2\}]^{(B_1-B_2)/2}} \right) \quad (2)$$

where the values of A_1, B_1, A_2, and B_2 for each of the curves, as well as for those that are not shown, are given in Table 2.

TABLE 2 -- Values of the coefficients and power indices in Equation (2)

Binder	A_1	B_1	A_2	B_2
19 mm nom.dia. aggregates				
N-ALF BASE	15636	0.3547	18940	0.5604
N-ALF HIGH	15933	0.2685	17504	0.5234
N-ALF AIR-BLOWN	16198	0.2702	19877	0.4406
N-ALF ELVALOY	16980	0.2204	17409	0.4319
N-ALF SBS_L-G	15209	0.2882	18984	0.5183
N-ALF SBS_L	15614	0.3345	19446	0.5161
N-ALF SBS_R-G	14812	0.2562	19125	0.5028
N-ALF EVA	16144	0.2692	19260	0.4261
N-ALF EVA-G	15191	0.2515	19314	0.4274
19 mm nom.dia. aggregates				
ALF AC-5	16246	0.3527	18492	0.5135
ALF AC-20	14812	0.3102	18679	0.5493
ALF Styrelf	17945	0.2406	17185	0.3643
ALF Novophalt	18513	0.2164	15520	0.3465
12.5 mm nom.dia. rounded aggregates				
WM AC-5	15480	0.4205	18431	0.5885
WM AC-20	18570	0.5340	18646	0.5571
WM Styrelf	17168	0.2417	17543	0.4164
WM Novophalt	16600	0.2575	18254	0.4519

Note: N_ALF (New Accelerated Loading Facility); ALF (Accelerated Loading Facility); WM(Westminster)

The variation of the normalizing frequency parameter with temperature is expressed through a semi-logarithmic plot of ω_0 versus $1/T$ (where T is the temperature in Kelvin) [7]. The data points are fitted with the best line using an equation of the following form [7].

$$\omega_0 = \exp\left(A_0(1 - \frac{T_0}{T})\right) \tag{3}$$

TABLE 3 -- Values of A_0, T_0(K) and T_S(°C) from Equation (3)

Binder	A_0	T_0**(K)**	T_S**(°C)**
19 mm nom.dia. aggregates			
N-ALF BASE	62.86	319.35	46.35
N-ALF HIGH	74.50	323.10	50.10
N-ALF AIR-BLOWN	71.46	324.80	51.80
N-ALF ELVALOY	69.11	320.60	47.60
N-ALF SBS_L-G	64.40	319.19	46.19
N-ALF SBS_L	67.52	318.27	45.27
N-ALF SBS_R-G	65.85	320.37	47.37
N-ALF EVA	73.92	324.71	51.71
N-ALF EVA-G	72.57	325.15	52.15
19 mm nom.dia. aggregates			
ALF AC-5	65.50	315.38	42.38
ALF AC-20	66.80	321.42	48.42
ALF Styrelf	80.64	331.11	58.11
ALF Novophalt	73.50	338.64	65.64
12.5 mm nom.dia. rounded aggregates			
WM AC-5	67.97	308.45	35.45
WM AC-20	63.88	320.57	47.57
WM Styrelf	68.68	328.82	55.82
WM Novophalt	65.32	328.13	55.13

Note: N_ALF (New Accelerated Loading Facility); ALF (Accelerated Loading Facility); WM(Westminster)

The values of A_0 and T_0 for all sets of data as determined from Equation (3) are given in Table 3.

The specification temperature parameter is determined as T_S (°C) = T_0 (K) - 273. This is in essence the temperature at which the mixture has a stiffness of 18,500 Pa at a loading frequency of 1 Hz.

Specific Deformation D_{TS}

The specification parameter in terms of the specific deformation D_{TS} is now introduced. The conventional practice of estimating the ability of a mixture to resist deformation has been through the analysis of RSCH data. However, the temperature at which the tests are run is normally chosen arbitrarily, as the maximum temperature recorded at a site, or as an effective temperature determined based on seasonal variations. Hence, there is no uniformity in the information accumulated in different laboratories. It is proposed that the specific deformation D_{TS} be defined as the percent permanent strain experienced by a mixture at its specification temperature of T_S when subjected to RSCH test for 5000 cycles.

RSCH Data

It would have now been apt to simply generate RSCH data from the SST at the specification temperature T_S (°C) corresponding to each of the laboratory-prepared samples and show that a relation exists between the FSCH data and the RSCH data. Instead the RSCH data in this work are generated at various temperatures that are different from the specification temperature T_S. This has been done in order to establish a general correlation between the FSCH and RSCH data at any temperature T rather than at the specification temperature T_S. It can then be demonstrated that the specific deformation is a specialized case of the general equation, recommended for future use as a simplified approach for getting reliable information. RSCH data obtained at various temperatures from 30°C to 50°C for different samples are shown in Table 4. At each temperature, three individual tests are performed and the average value is used in the tabulation.

TABLE 4 – RSCH data on % permanent strain after 5000 cycles at different temperatures

Binder	**@ 30°C**	**@ 37°C**	**@ 40°C**	**@ 42°C**	**@ 50°C**
19 mm nom.dia. aggregates					
N-ALF BASE	_	_	_	_	2.73
N-ALF HIGH	_	_	_	_	2.39
N-ALF AIR-BLOWN	_	_	_	_	2.13
N-ALF ELVALOY	_	_	_	_	1.46
N-ALF SBS_L-G	_	_	_	_	2.32
N-ALF SBS_L	_	_	_	_	2.65
N-ALF SBS_R-G	_	_	_	_	2.13
N-ALF EVA	_	_	_	_	1.36
N-ALF EVA-G	_	_	_	_	1.54
19 mm nom.dia. aggregates					
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
ALF Novophalt	_	_	0.26	_	_
12.5 mm nom.dia. rounded aggregates					
WM AC-5	_	_	_	_	_
WM AC-20	1.65	_	4.02	_	6.17
WM Styrelf	_	_	0.75	_	1.69
WM Novophalt	0.72	_	1.03	_	_

Note: N_ALF (New Accelerated Loading Facility); ALF (Accelerated Loading Facility); WM(Westminster)

Results and Discussion

The development of the unified curves for FSCH data in the manner done herein has a number of distinct advantages. The unified curve helps to extend the range of the data and can be used for predicting the dynamic mechanical behavior of the mixture at temperatures outside the measured values. For example, though the temperatures of measurement are between 25℃ and 50℃, the values of ω_0 at temperatures outside this range can be predicted using Equation (3) and values of A_0 and T_S from Table 3. These values of ω_0, in turn, when used in Equation (2) with values of coefficients A_1, A_2 and power indices B_1, B_2 help to give the variation of G^* versus ω at the temperature of interest, for example, 58℃ as shown in Figure 3. Measured data from the FSCH at this high temperature are normally not possible because they fall outside the sensitive range of the some SST equipment due to lower stiffness of the samples, especially those that have a lower performance grade binder.

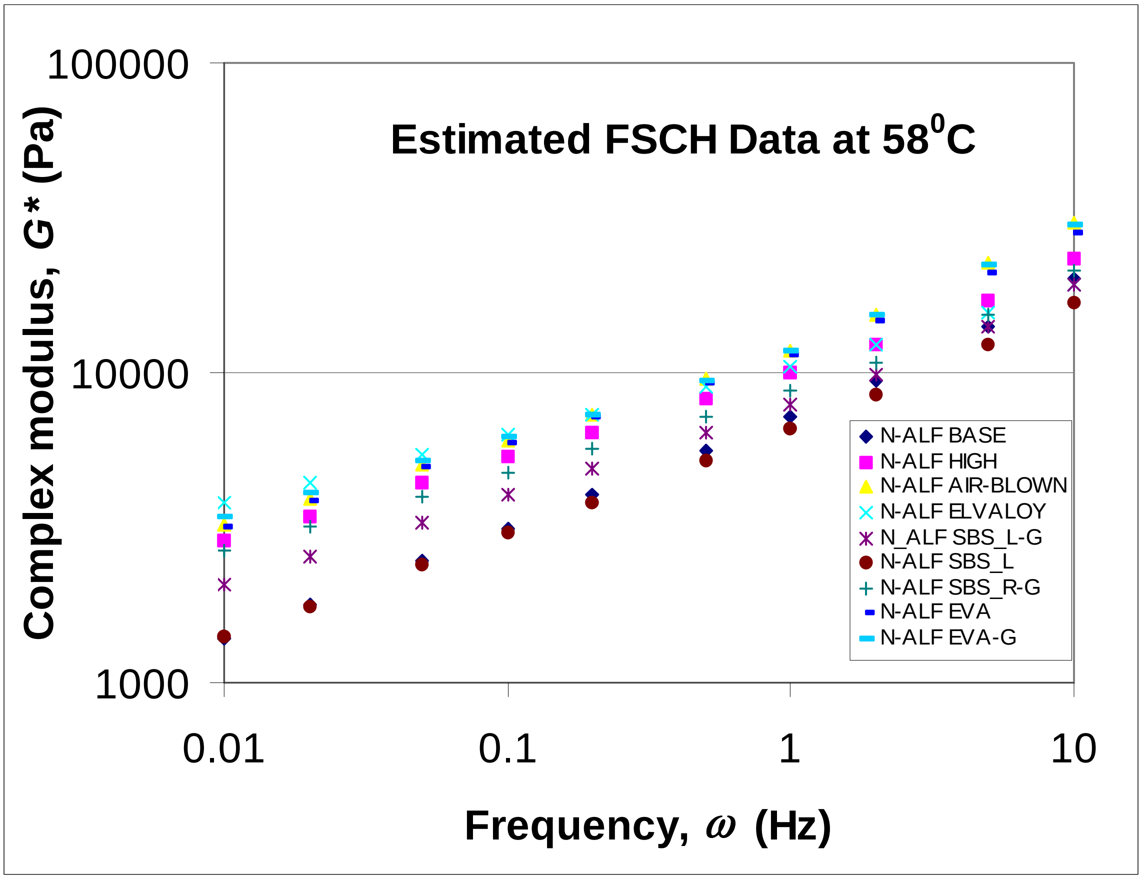

Figure 3: Variation of complex shear modulus G^* with frequency ω at the temperature of 58℃ estimated through Equations (2) and (3) for various mixture samples

The model described by Equation (2) that is used for fitting the data points on the unified curve is a combination of two equations [7], one for the lower frequency region and the other for the higher frequency region.

$$G^* = A_1(\omega/\omega_0)^{B_1} \text{ for } 0.0001 < \omega/\omega_0 < 1 \quad (4a)$$

$$G^* = A_2(\omega/\omega_0)^{B_2} \text{ for } 1 < \omega/\omega_0 < 1000 \quad (4b)$$

This automatically marks the two portions of the unified curve that are of significance. The portion of the unified curve in the low frequency region describes the rheological behavior of the mixture at higher temperatures applicable to rutting, while the other portion of the unified curve in the higher frequency region describes the rheological behavior at lower temperatures applicable to intermediate temperature distresses. This is because the unification forces the data at higher temperatures to lie in the lower region of the normalized frequency while aligning the data at intermediate temperatures to fall within the higher region of normalized frequency.

The RSCH data 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 (4a). The stiffness of the mixture 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 stiffness at $\omega/\omega_0 = 1$, and is again an expression of the rheological behavior under one specific condition. On the other hand, the power index B_1 being the slope of G^* versus ω/ω_0 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 in the first instance to establish the relationship between the FSCH and RSCH data.

The lower the power index B_1, the greater is the resistance of the mixture to rutting. Similarly, the higher the value of T_S, the greater is the resistance of the mixture to rutting. This implies that the permanent deformation D_T at temperature T would essentially be a function of T, T_S, and B_1. The form $(T/T_S)^* B_1$ 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 4 shows a plot of the rutting control term $C_R = (T/T_S)^* B_1$ with D_T which is the percent permanent strain after 5000 cycles recorded from the RSCH measurement at temperature T°C. It can be seen that 26 samples were used, of which 14 were tested at 50°C, 1 at 42°C, 7 at 40°C, 1 at 37°C, and 3 at 30°C. The 26 samples comprised 13 different binders and 2 different aggregate types. Figure 4 shows that the correlation coefficient $R^2 = 0.9$ for such a wide spectrum of data encompassing diverse set of mixtures is quite good.

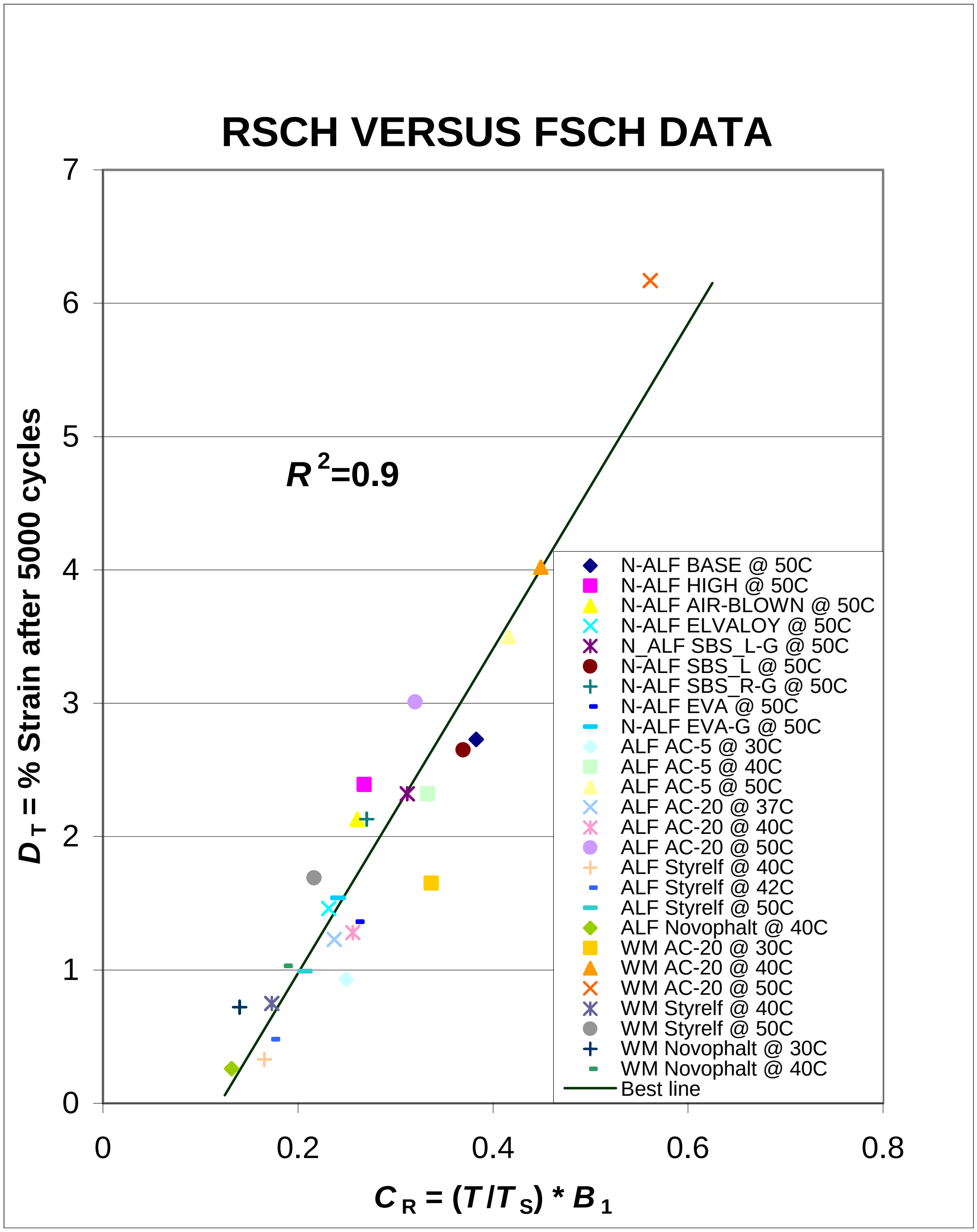

Figure 4: Variation of deformation D_T with the controlling term C_R for all mixture samples

The equation of the best line for this group of data is

$$D_T = a_0 C_R - b_0 \tag{5}$$

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

$$C_R = (T / T_S) B_1 \tag{6}$$

and the coefficients a_0 = 12.2 and b_0 = 1.5. The values of the coefficient a_0, b_0 are specific to the sets of data analyzed and could change for different mixture sets. 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:

$$D_{TS} = a_0 B_1 - b_0 \tag{7}$$

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_S) 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.

Table 5 gives the values of the (B_1/ T_S) ratio for the mixtures analyzed in this work. The ranking is confined to individual sets rather than an overall ranking for all mixtures. This was done because there was field performance ranking available for only one set, namely, the previous binder validation study [6]. The present method of grading mixtures based on the (B_1/ T_S) ratio gave identical rankings to those observed in the previous binder validation study as can be seen from Set 2. The mixtures in Set 1 are part of the ongoing research program on polymer-modified asphalts with intent for field validation. The present ranking in Set 1 gives an indication of what to expect and could be strengthened by field validation whenever that work is undertaken and completed. It is interesting, however, to note that the current Superpave specification of PG70-28 for these binders implies that all these binders should have fallen within the same performance category. The present ranking system identifies four clear groups whose performances would be different. A comparison with the results of RSCH data in Table 4 for this Set 1 confirms that the performances are indeed different. This indicates that the suggested method of using the slope of the unified curve is more effective in predicting the performance of the mixtures than the single-point value of the Superpave performance grading parameter.

TABLE 5 – Performance ranking for resistance to distress at high temperatures

Binder	T_s	B_1	B_1 / T_s	Ranking Lab-Predicted	Ranking Field-Performance
19 mm nom.dia. aggregates					
N-ALF ELVALOY	47.60	0.2204	0.0043	1	_
N-ALF EVA-G	52.15	0.2515	0.0048	2	_
N-ALF EVA	51.71	0.2692	0.0052	3	_
N-ALF AIR-BLOWN	51.80	0.2702	0.0052	3	_
N-ALF HIGH	50.10	0.2685	0.0054	3	_
N-ALF SBS_R-G	47.37	0.2562	0.0054	3	_
N-ALF SBS_L-G	46.19	0.2882	0.0062	4	_
N-ALF SBS_L	45.27	0.3345	0.0074	5	_
N-ALF BASE	46.35	0.3547	0.0077	6	_
19 mm nom.dia. aggregates					
ALF Novophalt	65.64	0.2164	0.0033	1	1
ALF Styrelf	58.11	0.2406	0.0041	2	2
ALF AC-20	48.42	0.3102	0.0064	3	3
ALF AC-5	42.38	0.3527	0.0083	4	4
12.5 mm nom.dia. rounded aggregates					
WM Styrelf	55.82	0.2417	0.0043	1	_
WM Novophalt	55.13	0.2575	0.0046	2	_
WM AC-20	47.57	0.5340	0.0112	3	_
WM AC-5	35.45	0.4205	0.0119	4	_

Note: N_ALF (New Accelerated Loading Facility); ALF (Accelerated Loading Facility); WM(Westminster)

As indicated earlier, the portion of the unified curve in the higher frequency region would describe the rheological behavior at lower temperatures applicable to other distress modes. The power index representing the behavior in that portion of the curve is B_2. The structural design of the pavement would dictate whether a higher stiffness material or a lower stiffness material would mitigate the distresses in the intermediate temperature region. As an example, we could consider a pavement structure wherein a material with lower stiffness would provide better resistance to the distress such as fatigue cracking. In such a circumstance, the lower the power index B_2, the greater would be the resistance of the mixture to the distress in the intermediate temperatures. Similarly, the lower the value of T_S, the greater would be the resistance of the mixture to the distress in the intermediate temperatures. This implies that the resistance to intermediate temperature distress F_T at temperature T would essentially be a function of T, T_S, and B_2. The form $(T_S / T) * B_2$ would give an adequate description of this function and could be considered as the control term C_F, giving a measure of the resistance of a mixture to intermediate temperature distress. The lower the value of C_F, the better would be the resistance.

If the temperatures of interest were equal to the specification temperature, then the variations in the control term C_F would be simply given by the variations in B_2. 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_2 values to ascertain that the one with the lower value would show lower distress in the intermediate temperatures.

TABLE 6 – Performance ranking for resistance to distress at intermediate temperatures

Binder	T_s	B_2	$T_s * B_2$	Lab-Predicted Ranking
19 mm nom.dia. aggregates				
N-ALF ELVALOY	47.60	0.4319	20.56	1
N-ALF EVA	51.71	0.4261	22.04	2
N-ALF EVA-G	52.15	0.4274	22.29	2
N-ALF AIR-BLOWN	51.80	0.4406	22.82	3
N-ALF SBS_L	45.27	0.5161	23.36	3
N-ALF SBS_R-G	47.37	0.5028	23.82	4
N-ALF SBS_L-G	46.19	0.5182	23.94	4
N-ALF BASE	46.35	0.5604	25.98	5
N-ALF HIGH	50.10	0.5234	26.22	5
19 mm nom.dia. aggregates				
ALF Styrelf	58.11	0.3642	21.17	1
ALF AC-5	42.38	0.5135	21.76	1
ALF Novophalt	65.64	0.3465	22.75	2
ALF AC-20	48.42	0.5493	26.60	3
12.5 mm nom.dia. rounded aggregates				
WM AC-5	35.45	0.5885	20.86	1
WM Styrelf	55.82	0.4164	23.24	2
WM Novophalt	55.13	0.4519	24.91	3
WM AC-20	47.57	0.5571	26.50	4

Note: N_ALF (New Accelerated Loading Facility); ALF (Accelerated Loading Facility); WM(Westminster)

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 ($T_S * B_2$) product. As a matter of fact, it would be this product that could be used for ranking mixtures, assuming that a comparison of the performance of the mixtures in their resistance to distress in the intermediate temperature region is being sought at a constant temperature of T for all mixtures.

Table 6 gives the values of the (T_S *B_2) product for the mixtures analyzed in this work. The ranking is confined to individual sets rather than an overall ranking for all mixtures. The mixtures in Set 1 are part of the ongoing research program on polymer-modified asphalts with intent for field validation. The present ranking in Set 1 gives an indication of what to expect and could be strengthened by the field validation whenever that work is undertaken and completed.

Table 5 or 6 would be useful when the selection of the aggregate-asphalt system is made on the criterion of its resistance to either high or intermediate temperature, as the case may be. Depending on the geographical location of the pavement, it is often true that only one of the criteria assumes importance. But it should not be ruled out that there would be locations where the pavement could be prone to distresses at both high and intermediate temperatures. The pavement structural design will dictate whether a pavement that shows excellent resistance to distress at high temperature would fail in the intermediate temperatures, and vice versa.

In such circumstances, what one is looking for is a balance of properties such that the aggregate-asphalt system would perform reasonably well in its resistance to distresses at both high and intermediate temperatures. To develop a criterion for this, it is important to revisit the suggested two controlling terms C_R and C_F that were used for ranking the aggregate-asphalt systems in their resistance to distresses at high and intermediate temperatures, respectively.

A lower value of C_R provides a higher resistance to rutting. As an example, we again focus on the case when the structural design is such that a lower value of C_F gives a higher resistance to the distress at intermediate temperatures. The product of the two controlling terms would thus form a good criterion for adjudging the overall performance of the aggregate-asphalt system to resist distresses at both high and intermediate temperatures. This product can be seen to be essentially equal to the product of B_1 and B_2. Thus, the product $B_1 * B_2$ is used as the criterion for establishing the overall performance ranking as given in Table 7 for all the laboratory-prepared samples. The lower the value of the product, the better would be the expected resistance to distresses at the high and intermediate temperatures. This ranking will evaluate aggregate-asphalt systems for their performance in the intermediate to high temperature ranges. Conceptually, this ranking should match field performance provided the pavement structural design demands a material with lower stiffness as the preferred material to mitigate distresses in the intermediate temperatures. Presently, there are no data to validate these findings. It should be noted that the tests performed on the SST do not account for the effect of moisture; hence, the rankings obtained herein are also devoid of this effect on the performance.

TABLE 7 – Performance ranking for resistance to distresses at high and intermediate temperatures (for the special case of thin pavement structure)

Binder	B_1	B_2	$B_1 * B_2$	Lab-Predicted Ranking
19 mm nom.dia. aggregates				
N-ALF ELVALOY	0.2204	0.4319	0.0952	1
N-ALF EVA-G	0.2515	0.4274	0.1075	2
N-ALF EVA	0.2692	0.4261	0.1147	3
N-ALF AIR-BLOWN	0.2702	0.4406	0.1190	4
N-ALF SBS_R-G	0.2562	0.5028	0.1288	5
N-ALF HIGH	0.2685	0.5234	0.1405	6
N-ALF SBS_L-G	0.2882	0.5182	0.1494	7
N-ALF SBS_L	0.3345	0.5161	0.1726	8
N-ALF BASE	0.3547	0.5604	0.1988	9
19 mm nom.dia. aggregates				
ALF Novophalt	0.2163	0.3465	0.0750	1
ALF Styrelf	0.2406	0.3642	0.0876	2
ALF AC-20	0.3102	0.5493	0.1704	3
ALF AC-5	0.3527	0.5135	0.1811	4
12.5 mm nom.dia. rounded aggregates				
WM Styrelf	0.2417	0.4164	0.1006	1
WM Novophalt	0.2575	0.4519	0.1164	2
WM AC-5	0.4205	0.5885	0.2475	3
WM AC-20	0.5340	0.5571	0.2975	4

Note: N_ALF (New Accelerated Loading Facility); ALF (Accelerated Loading Facility); WM(Westminster)

Conclusions

The present work introduces certain mixture grading parameters (T_S, C_R, and C_F) that could be used as identification tags to grade mixtures and rank their expected field performance. This method of performance-related specification would help in streamlining the data analysis procedure from the SST. It would provide a uniform platform to compare data from different practitioners and project the expected performance of the mixtures. It would also be useful for targeting mixture grades when designing pavements for specific regions.

The suggested method is simple and straightforward. It involves the determination of a specification temperature T_S (°C) from the FSCH data. This is done by determining the normalizing parameter ω_0 corresponding to the value of G_0^* = 18,500 Pa using Equation (1). The values of ω_0 at two different temperatures are sufficient to determine the value of T_0 (K) from Equation (3), from which T_S (°C) is immediately obtained. In case ω_0 is available at more than two temperatures (as was the case in the present work), then a semi-logarithmic plot of ω_0 versus $1/T$ (K) is to be used to determine the value of T_0 (K) and, subsequently, T_S (°C).

The complex modulus G^* versus frequency ω data at different temperatures for each aggregate-asphalt mixture are unified by normalizing the frequency using corresponding values of ω_0. The unified data are then fitted with the rheological model given by Equation (2) and the values of the model parameters are determined. The slopes B_1 and B_2 of the two portions of the unified curve are used for determining the controlling terms for ranking the aggregate-asphalt mixtures by their expected performance to resist distresses in different temperature ranges. The product of slopes B_1 and B_2 is suggested as a measure for evaluating the overall performance of the mixture to resist distresses over the entire intermediate and high temperature ranges, for the special case of pavement structural design that warrants lower stiffness material to mitigate distresses at intermediate temperatures. If the structural design warrants higher stiffness instead, the ratio of the slopes B_1 and B_2 could evaluate the overall performance.

The reliability of the information generated from the slopes B_1 and B_2 is dependent on the authenticity of the generated data and the goodness of unification. The experimental data must be generated within the sensitive range of the equipment capabilities. In order to ensure that this is always the case, it is prudent to generate FSCH data on the SST for different binders not at some predetermined fixed temperatures but rather at temperatures where the stiffness of the material is within the sensitivity of SST measurement. For example, it would be better to take data at lower temperatures from 25℃ to 45℃ for low stiffness binders like AC-5 while at higher temperatures from 35℃ to 55℃ for high stiffness binders like Styrelf. This would result in data that will unify without scatter over the entire frequency range.

By generating the data within different temperatures but similar stiffness ranges, the other advantage is that the normalizing parameter will not need extrapolation in the manner done for some cases in Table 1. Using unextrapolated values of ω_0 would improve the goodness of unification. It is difficult to guess the stiffness of the aggregate-asphalt system before any measurements are performed on the SST. Hence, it may not always be easy to choose the temperature range for SST measurement such that the stiffness of the system lies within the sensitivity range of the equipment.

Based on the present work, a rough guideline is suggested that should help in making a reasonable choice of the measurement temperatures. The first temperature of measurement is chosen to be half the value of the high performance grade temperature of the binder used. The subsequent two temperatures are selected to be higher by increments of 6°C. Table 8 shows an example of how the temperatures could be chosen.

TABLE 8 – Examples of proper choice of temperatures for FSCH measurements

Binder (PGxx-xx)	**High PG Temperature**	**Choice of Three Measurement Temperatures**		
		(T_{PG}/2=)	**(T_1+6=)**	**(T_2+6=)**
	T_{PG}(°C)	**T_1 (°C)**	**T_2 (°C)**	**T_3 (°C)**
AC-5 (PG58-34)	58	(58/2=) 29	(29+6=) 35	(35+6=) 41
AC-20 (PG64-22)	64	(64/2=) 32	(32+6=) 38	(38+6=) 44
PMA (PG70-28)	70	(70/2=) 35	(35+6=) 41	(41+6=) 47
Styrelf (PG82-22)	82	(82/2=) 41	(41+6=) 47	(47+6=) 53

Note: PMA is polymer-modified asphalt

It is shown that the permanent deformation data from RSCH can be related to the rutting control term C_R that is obtained from FSCH data. Therefore, in the future, it would be sufficient to generate only FSCH data from the SST to derive performance-related specifications. The advantage is that FSCH is a nondestructive test. Thus, many tests can be run even when limited numbers of samples are available. Generation of FSCH data on the SST is very simple. Analysis of this data as outlined here is equally simple. The proposed method of data analyses gives a wealth of useful information, thereby creating the possibility of designating the SST as a "Simple Performance Tester".

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Disclaimer

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