



EVALUATION OF RUTTING SUSCEPTIBILITY OF MODIFIED ASPHALT BINDER

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Abstract: This study presents experimental investigation results on evaluation of rutting resistance characteristics of asphalt binder containing two types of Styrene-Butadiene-Styrene (SBS). In the present study, pure asphalt binder (40-50 PEN) typically used in the middle and southern regions in Iraq was obtained from two sources and blended with different amounts of SBS, 3, 6, 9%, based on the total weight of the asphalt binder. The Dynamic Shear Rheometer (DSR) was used to evaluate the modifier asphalt binders at various temperatures, i.e., 25, 35, 50 and 60 °C. Good multiple linear relationships between log transformation of rheological properties and the amount of SBS asphalt modifier were obtained from this study. The SBS contents, temperatures and applied frequency are significant variables. It was found that the addition of SBS modifier generally increases the asphalt binder resistance against rutting. It was observed that an increase in SBS content causes an increase in $G^*/\sin\delta$ and enhanced the viscosity at high temperature by increasing the values of low and zero shear viscosity.

Keywords: *Rutting criteria, zero shear viscosity, low shear viscosity, frequency sweep, Styrene-Butadiene-Styrene.*

تقييم حساسية الرابطة الأسفلتي المحسن للتخدد

الخلاصة: تقدم هذه الدراسة نتائج التحري التجريبية على تقييم خصائص مقاومة التخدد للرابطة الأسفلتي التي تحتوي على نوعين من الستايرين البيوتادين الستايرين (SBS). في هذه الدراسة، تم الحصول على الرابطة الأسفلتي النقي (PEN 50-40) المتستخدم عادة في المناطق الوسطى والجنوبية من العراق من مصدرين والمخلوط مع كميات مختلفة من SBS، 3، 6، 9٪، على أساس الوزن الكلي للرابطة الأسفلتي. تم استخدام جهاز Dynamic Shear Rheometer (DSR) لتقييم المضافات على خصائص الرابطة الأسفلتي و في درجات حرارة مختلفة 25، 35، 50 و 60 درجة مئوية. وقد تم الحصول على علاقات خطية متعددة جيدة بين الخصائص الريولوجية للرابطة الأسفلتي ومقدار SBS المضاف من هذه الدراسة نلاحظ بان كمية SBS المضاف ، ودرجات الحرارة و تكرار الحمل المسلط هي متغيرات هامة. وقد وجد أن إضافة SBS بشكل عام تزيد من مقاومة الرابطة الأسفلتي للتخدد. ولوحظ أن زيادة محتوى SBS تسبب زيادة في معامل التخدد $G^*/\sin\delta$ وتحسن لزوجة الرابطة الأسفلتي في درجات الحرارة العالية بزيادة قيم اللزوجة عند قيم القص القليلة .

1. Introduction

The central and southern regions of Iraq are tropical areas where temperatures during the summer rise to more than 50 C°. Summer lasts a long time, ranging from 5 to 6 months, and therefore all roads located in this area suffer from the phenomenon of rutting in addition to the lack of control of the high axial loads in previous years.

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The most widely material used in road construction in the central and southern regions of Iraq is asphalt, with usage 5 to 7 percent ranging from the total weight of the asphalt mixture.

One of the most important parameters that affect the performance of flexible pavement is selection of a suitable asphalt binder. While choosing the most suitable binder for a particular location, due attention is given to expected traffic loading condition and pavement temperature. As overloading and high pavement temperatures are most common on many highways in Iraq, modified binders have been used for construction of top surface courses of the flexible pavement for quite some time to achieve improved pavement performance. However, it has been observed that premature pavement distresses still persist in spite of the use of modifier binders in addition to stringent quality control exercised during construction. To improve the quality of asphalt binders, it is necessary to identify the proper parameter of the asphalt binder that controls the rutting failures in the flexible pavement and may be considered for introduction into the binder specifications.

Bitumen is a viscoelastic material and exhibits both elastic and viscous behaviour. Dynamic Shear Rheometer (DSR) is capable of quantifying elastic and viscous properties of the asphalt binder (ASTM D7175 – 08, 2008 and BS EN 14770:2012). Complex shear modulus (G^*) and phase angle (δ) are capable of explaining the behaviour of the bitumen. Total resistance of a binder to deformation when subjected to repeated pulses of shear stress that consists of both a storage modulus (G') and non-recoverable loss modulus (G'') is measured in terms of complex modulus (G^*); whereas phase angle (δ) is the ratio of loss over storage modulus (elastic property) and indicates level of viscous component present in the binder. Phase angles of zero and 90° indicate pure elastic and viscous material respectively. High values of G^* and low values of δ are desirable for rut resistance.

When the asphalt binder samples are cold, they can behave like an elastic solid where the stress follows the input strain. At elevated temperatures, the material behaves like a Newtonian fluid where the stress lags behind the strain and maximum stress will occur when the rate of strain is the greatest, which is 90° out of phase with the peak strain. In between the two extremes, the material behaviour is viscoelastic and peak stress lags behind peak strain anywhere between 0 and 90° , the phase shift δ , as shown in Figure 1. Thus, the δ is an indicator of the relative amounts of elastic (recoverable) and viscous (non-recoverable) deformation.

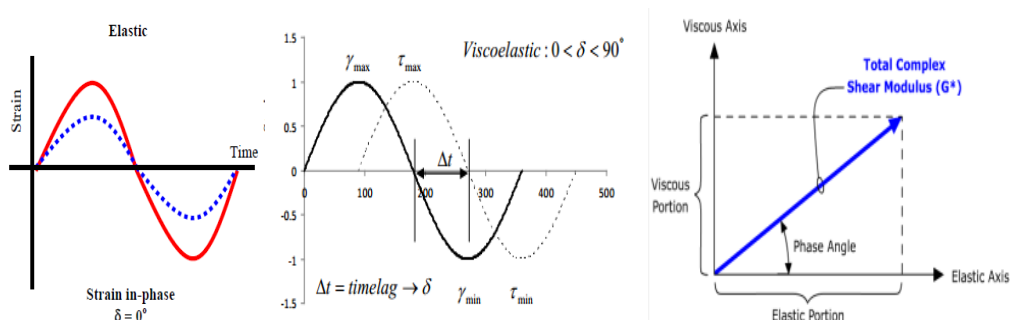


Figure 1. Definition of the phase angle (δ).

2. Rutting Parameters of Asphalt Binders

2.1 Superpave Rutting Criteria of the Asphalt Binder ($G^*/\sin\delta$ parameter)

The Superpave binder specification assumed rutting to be a stress-controlled cyclic loading phenomenon. A parameter, $G^*/\sin\delta$, was proposed to specify binders according to rutting susceptibility at high pavement temperatures. Superpave used this parameter to rank the rutting susceptibility of flexible pavements.

This parameter is measured using a DSR, which subjects a sample of asphalt binder between two parallel plates to oscillatory shear. The parameter, $G^*/\sin\delta$, is based on the dissipated energy approach: with each cycle of loading, the work done in deforming an asphalt at high temperatures is partially recovered by the elastic component of the strain and partially dissipated by the viscous component of the strain and any associated generation of heat. The energy dissipated by the viscous component per cycle of loading can be calculated:

$$\Delta U = \int \tau * d\gamma = \int_0^{2\pi} \tau * d\gamma \quad (1)$$

The following relationship is obtained for a sine wave loading upon integrating equation 1 from 0 to 2π .

$$\Delta U = \pi * \tau_{max} * \gamma_{max} * \sin \delta \quad (2)$$

The asphalt binder will be subjected to the same maximum stress or set of stresses during the test. Therefore, the τ_{max} is a constant along with π , and

$$|G^*| = \frac{\tau_{max}}{\gamma_{max}} \text{ and } \gamma_{max} = \frac{\tau_{max}}{|G^*|} \quad (3)$$

$$\text{So; } \Delta U = \pi * \tau_{max}^2 * \frac{\sin \delta}{|G^*|} \quad (4)$$

Two changes were made in equation 4 when developing the binder specification. First, the absolute value symbols for $|G^*|$ were dropped. G^* is the complex shear modulus, that is a vector containing an imaginary element, while $|G^*|$ is the dynamic shear modulus, that is a scalar containing no imaginary element. In Superpave, only the absolute value symbols were dropped for simplification purposes. Second, because most asphalt paving technologists have some understanding of the term modulus the parameter $\sin\delta/G^*$ was inverted to $G^*/\sin\delta$ for convenience. Based on dissipated energy, $G^*/\sin\delta$ is inversely proportional to the energy dissipated by the viscous flow component of the strain; therefore, as $G^*/\sin\delta$ increases, rutting susceptibility should decrease. However, $G^*/\sin\delta$ specifications were derived mostly from the testing of unmodified binders in the linear viscoelastic range, so $G^*/\sin\delta$ may not predict the rutting performance of modified binders (Bahia et al, 2001 and D'Angelo et al, 2007) whose performance is highly stress dependent.

2.2 Zero Shear Viscosity (ZSV) of Bitumen

In Europe, Zero Shear Viscosity (ZSV), which is the viscosity at very low frequencies, is measured when the dynamic viscosity approaches the ordinary steady flow viscosity. ZSV is considered as the high service temperature performance parameter for the European PMB specification which is currently under development (CEN/TR 15325, 2008). This parameter was also widely used for predicting the rutting performance of unmodified and modified binders (Anderson et al, 2002; Morea, et al. 2014).

Generally, angular frequency of 0.1 rad/s at high test temperature is used to measure the dynamic viscosity that represents zero shear viscosity (Kakade, et al. 2013). ZSV (η_o) can be estimated by the following equation.

$$\eta_o \cong \eta' \cong \frac{G''}{\omega} \cong \frac{G^*}{\omega} \quad (5)$$

Where: G'' = loss modulus; G^* = complex shear modulus; η' = in-phase component of the dynamic viscosity; ω = angular frequency (rad/s)

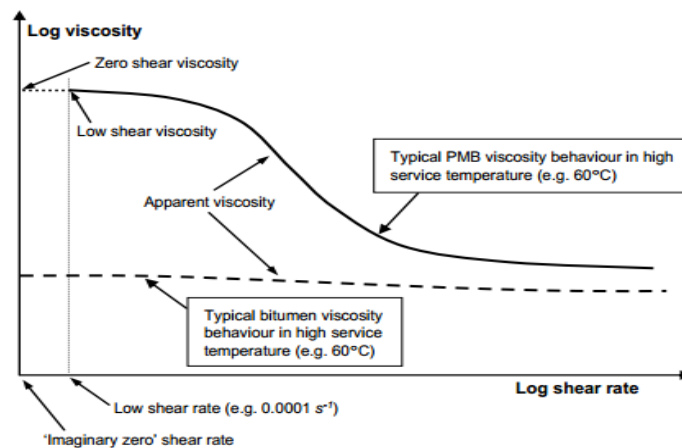


Figure 2. Concept of ZSV and LSV (Choi, 2010)

The term ZSV is still considered plausible when a binder demonstrates a plateau on the viscosity vs. shear rate curve (see Figure 2). The plateau indicates that the viscosity will remain the same (i.e. shear rate independent) from this point to the extreme end of zero shear rates; this condition does not exist in practice. However, it was found that some of the highly modified bitumen did not display the plateau even at a very low shear rate. Therefore, the term 'Low Shear Viscosity' (LSV) is often used as an approximation of ZSV limited to a certain low shear rate (e.g. 0.0001 s^{-1}), regardless of the existence of a plateau. It should also be noted from Figure 2 that the viscosity of typical bitumen is generally insensitive to varying shear rates. Thus, for bitumen, the ZSV (or LSV) can be approximated to 'viscosity'.

3. Objectives of the Study

The main objectives of this study are:

- Determine rheological properties of local asphalt binders.
- Determine LSV and ZSV based on the data obtained from the frequency sweeps test and using a Log model.
- Investigate the relationship between rheological property of pure and modified asphalt binder for evaluation of the permanent deformation (rutting susceptibility characteristics).

4. Experimental Methods

4.1 Materials

The conventional bitumen samples were acquired from two sources (Nasiriyah and Durah refineries) in the middle and south of Iraq, where they are commonly used; they have (40-50) penetration grade. Styrene-Butadiene-Styrene (SBS) significantly increases strength at higher temperatures as well as flexibility at lower temperatures. Two types of SBS at three different modification levels, namely 3%, 6% and 9%, by weight of the bitumen are used to modify the rheological properties of asphalt binder. The properties of asphalt binders are shown in Tables 1 and 2.

Table 1. Properties of the asphalt binder.

Property	Nasiriyah	Durah
Penetration (0.1 mm, 100 g and 5 sec)- ASTM D5	41	43
Softening point (°C) - ASTM D36	52	53
Penetration Index(PI)	-1.0	-0.35
Viscosity cP, 135 (°C) -ASTM D 4402	500	481.3

Table 2. Summary properties of elastomer used (Kraton Polymers, 2006).

Property	D 1101 K SBS	D 1184 K SBS
Tensile Strength, (PSI).	4,600	4,000
Elongation (%)	880	820
Specific Gravity	0.94	0.94
Brookfield Viscosity (cps at 77 °F)	4,000	20,000
Diblock (%)	16 %	16 %
300% Modulus (PSI)	400	800
Molecular structure	Linear	Radial

4.2 Sample Preparation and Test Conditions

The asphalt binder was preheated in an oven to the recommended temperature (140 °C \pm 5 °C) for the unmodified binders and (160 °C \pm 5 °C) for the modified binders. Samples should be stirred before being poured into a silicon mould as the received sample must be homogenised when it is poured in. The silicon moulds are then used to prepare samples for amplitude sweep, as seen in Figure 3-b. The Dynamic Shear

Rheometer (DSR) was chosen to evaluate permanent deformation by measuring the properties of asphalt binder at high temperatures. Frequency sweep tests were conducted with the 25 mm diameter plate with a 1 mm testing gap. The sample is loaded into the rheometer within 60 min of moulding. The temperature of the rheometer plates during loading should be high enough in order to assure good adhesion to the plates. In the case of unmodified binders, a 60 °C temperature is recommended. In any case, the sample should start flowing to get good adhesion to both plates (the gap is first decreased to 2.05 mm). The sample is cooled to the test temperature at a rate of 2 °C/min. Then it is trimmed using a heated spatula. Afterwards, the gap is decreased to exactly 2.0 mm. Before starting the test, the sample should achieve the correct temperature, and this period is referred to as the equilibration period (30 min).

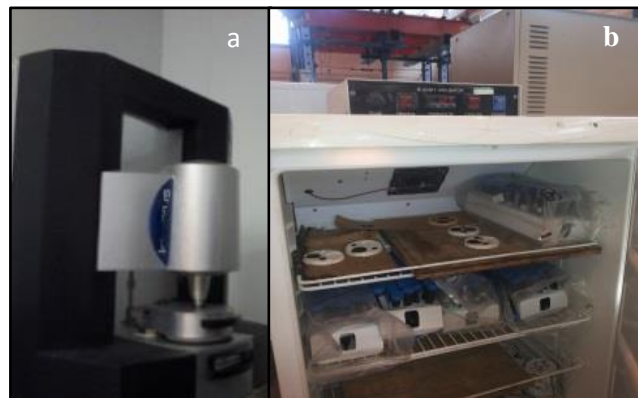


Figure 3. a) Kinexus Pro⁺ DSR b) Silicon moulds in fridge

(Structure and material Lab. /school of engineering/ Liverpool University)

According to CEN/TS 15324, 2008 and CEN/TS 15325, 2008, the procedure involves:

- Test temperature range 25-60 °C.
- Frequency sweep range 0.1–10 Hz (it is recommended to do the temp. sweep at a frequency of 0.01 Hz. This corresponds to a shear rate of 0.0063 s⁻¹).
- Sample geometry = 25 mm diameter with 1 mm gap.
- Strain amplitude = 0.1%.

EquiViscous Temperature (EVT) method based on LSV in DSR is used to measure the ZSV.DSR testing; it is carried out to identify a temperature which displays a complex shear viscosity (η^*) of 2.0 kPa (under frequency of 0.01 Hz). At the identified temperature (i.e. EVT), a further frequency sweep test is carried out (e.g. 0.003 – 1 Hz). The data are then used to extrapolate the viscosity (i.e. LSV) to an even lower frequency sweep (i.e. 0.0001 Hz). The EVT is then further adjusted using the LSV. Thus, the alternative methods for estimating ZSV used in this study are:

- 1) Extrapolation of the dynamic viscosity to zero frequency.
- 2) Measurement of the dynamic viscosity by using Cross model or Log model.

The EVT-based method defines the LVS as the complex shear viscosity (η^*) measured at a frequency of 0.0001 Hz. The test is typically carried out as low as 0.1 Hz and the data are then used to extrapolate the complex shear viscosity (η^*) to 0.0001 Hz

using the Log model. This target low frequency (where LSV was obtained) was chosen according to the European method.

5. Analysis and Discussion

5.1 Superpave Rutting Criteria of the Asphalt Binder

The frequency sweep tests were also performed at 25, 35, 50 and 60 °C with frequencies varying from 0.1 to 10 Hz with measurements taken at 21 different intervals between the two frequencies. The tests were performed on five specimens and the average value is presented in this study. The DSR test results (rutting parameter, $G^*/\sin\delta$) of asphalt binder containing SBS have been plotted for comparative analysis purposes (Figures 4, 5 and 6). It may be noted that:

- The rutting parameter (y-axis) is in a log scale. This is the scale recommended by the Asphalt Institute to find the viscosity of blends of new and recovered asphalt. The log scale was used for easier presentation and better interpretation.
- The rutting parameter increased with increasing applied frequency (viscosity of asphalt binder reduced when increased frequency).
- The rutting parameter reduced with increased test temperature (viscosity of asphalt binder reduced with increased temp.)
- Adding SBS enhanced the rutting performance of asphalt binder due to increased recoverable part in complex viscosity (increased elastic part).
- The rutting parameter increased with increased percentage of SBS.
- Adding SBS1184 is better than SBS1101 to increase rutting performance of asphalt binder.
- From the experimental results, it can be seen that the Durah asphalt binder is better at resisting rutting than the Nasiriyah.

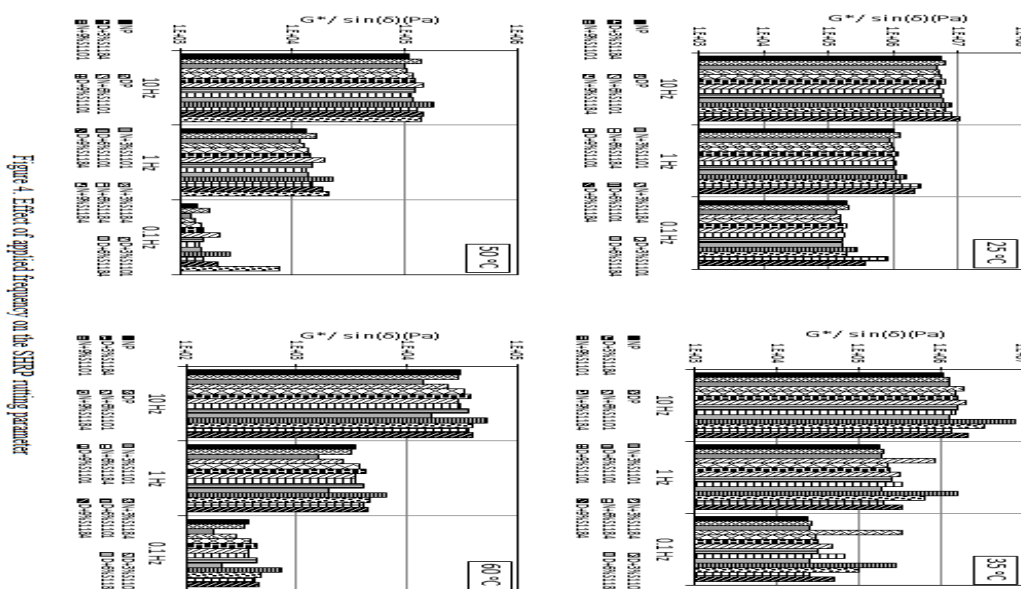


Figure 4. Effect of applied frequency on the rutting parameter

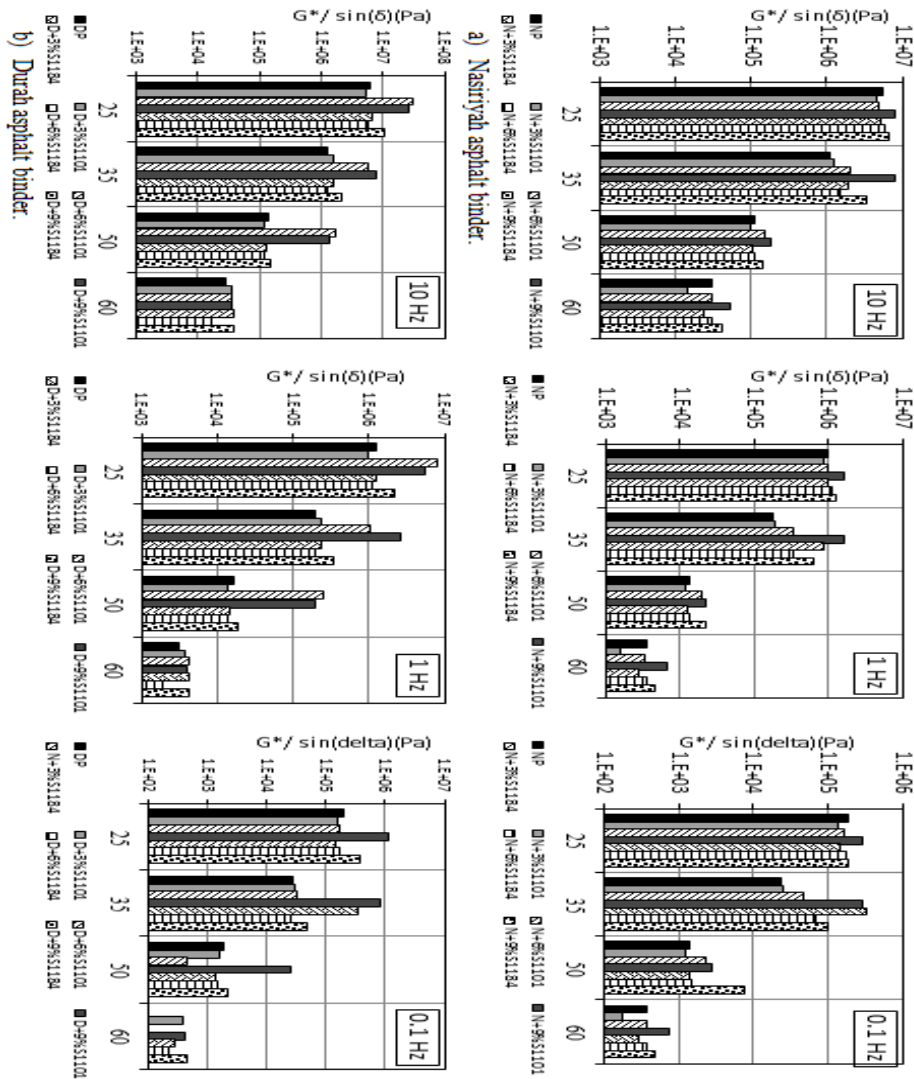


Figure 5. Effect of test temperature on the SHRP rutting parameter

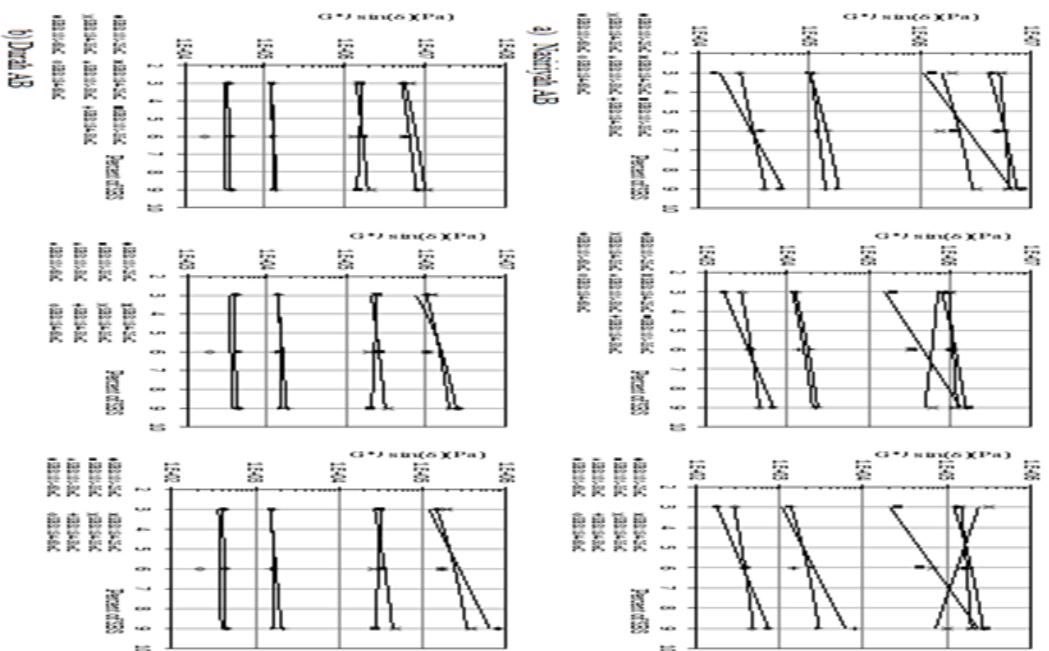


Figure 6. Effect of increased percentage of SSF modifier on the SHRP rutting parameter

5.2 LSV and ZSV of the Asphalt Binder

In previous research efforts, it has been identified that the rutting parameters that are currently being used, $G^*/\sin\delta$, for PG specifications do not accurately predict the rutting potential, especially when modifiers are used (Morea, et al. (2011); Morea, et al. (2010)). Other parameters being investigated include zero shear viscosity and low shear viscosity. Zero shear viscosity (ZSV), used as a specification criterion for asphalt binders, was implemented when the inability of the Superpave criterion $G^*/\sin\delta$ was identified (Anderson, et al., 2002). ZSV has the ability to capture the contribution to rutting resistance afforded by polymer modification:

a) Determine LSV.

According to the CEN/TS 15324:2008, the procedure for calculating LSV is performed in two steps:

- 1) Temperature sweep for determination of equiviscous temperature value (EVT_1) related to a defined LSV (2.2 KPa.s) at a low frequency (e.g. 0.01Hz) and low strain amplitude (e.g.0.1%). The temperature sweep shall run from lower to higher temperature and calculate LSV for each cycle and then plot the average values of LSV in log scale versus the temperature, as shown in Figure 7, and determine a and b parameters to fit the equation .

$$\log \eta = -a * T(^{\circ}C) + b \quad (6)$$

Calculate EVT_1 from the following equation:

$$EVT_1 = \frac{\log \eta - b}{-a} \quad (7)$$

- 2) Frequency sweep for determination of EVT_2 and ΔT . A frequency sweep at test temperature EVT_1 is carried out from a higher frequency (e.g. 10 Hz) to a lower frequency (e.g. 0.1 Hz) with an additional extrapolation to 0.0001 Hz, as shown in Figure 8. The difference in temperature (EVT_1 and EVT_2) shall be calculated from the following equation:

$$\Delta T = \frac{\Delta \log(\eta)}{-a} = \frac{\log \eta_1 - \log \eta_2}{-a} = \frac{\log \frac{\eta_1}{\eta_2}}{-a} \quad (8)$$

$$EVT_2 = EVT_1 + \Delta T \quad (9)$$

b) Determine ZSV.

Extrapolate the experimental data using the log model as shown in Figure 8, to 0.00001 Hz ($\omega = 2\pi f = 0.000063 \text{ rad/s}$).

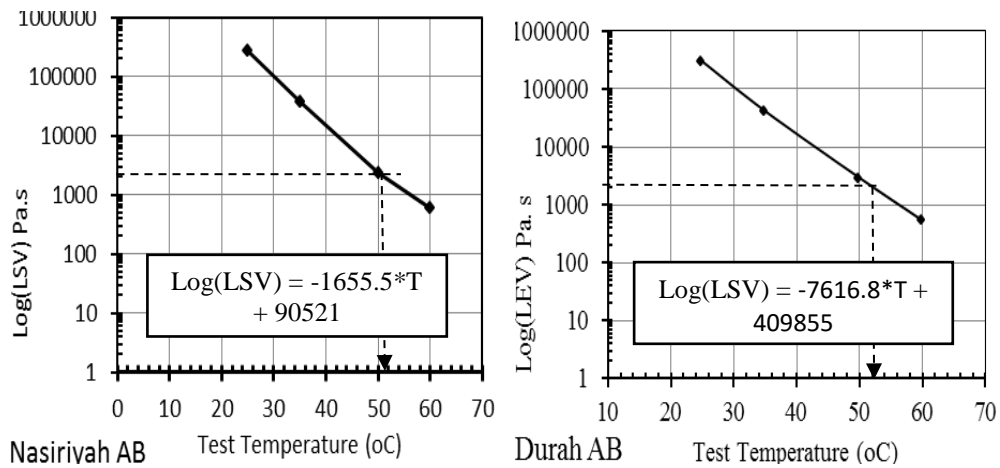


Figure 7. Example of Temperature frequency for determination of EVT_1 for $\eta=2.2$ KPa.s

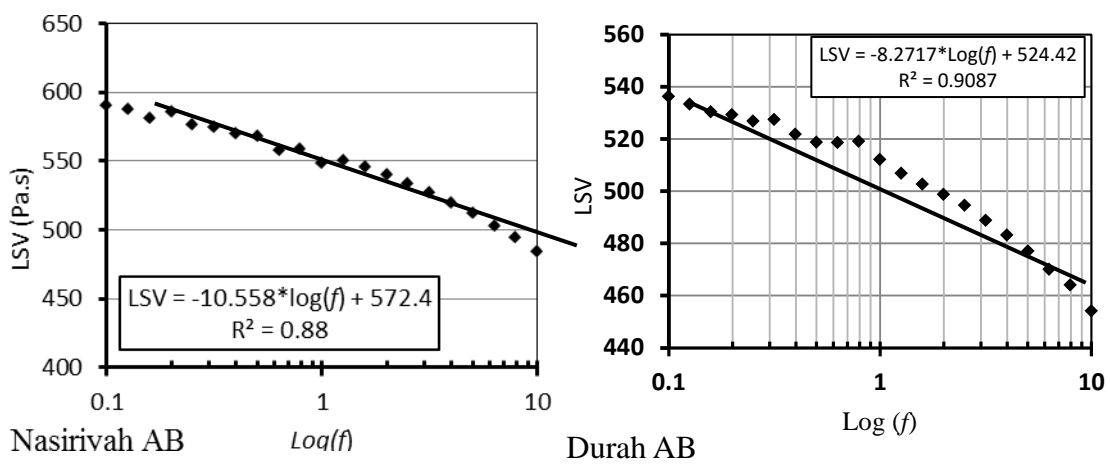


Figure 8. Example of frequency sweep for extrapolation to required frequency.

Table 3. LSV and ZSV for different types of binders at 60 °C

Frequency Hz	Experimental Results			Log Model Results. See Figure 8				
	EVT1, °C	EVT2, °C	η , Pa.s	0.1	Percentage error	0.01	0.0001	0.00001
Parameter			η , Pa.s	η , Pa.s		η , Pa.s	LSV, Pa.s	ZSV, Pa.s
NP	53.79	53.79	590.9	582.96	0.013	593.52	614.63	625.19
N+3%SBS1101	54.08	54.08	280.3	271.10	0.033	276.06	285.97	290.92
N+6%SBS1101	54.69	54.69	586.6	575.24	0.019	585.40	605.72	615.88
N+9%SBS1101	53.92	53.92	686	684.66	0.002	696.13	719.06	730.53
N+3%SBS1184	57.37	57.37	461.5	451.96	0.021	459.07	473.28	480.39
N+6%SBS1184	54.82	54.82	584	582.92	0.002	592.97	613.07	623.12
N+9%SBS1184	58.28	58.28	776.9	769.68	0.009	782.40	807.83	820.54
DP	53.81	53.80	536.3	532.69	0.007	540.96	557.51	565.78
D+3%SBS1101	53.25	54.07	639.9	632.19	0.012	641.68	660.68	670.17
D+6%SBS1101	54.16	54.15	701.1	694.12	0.010	707.71	734.90	748.49
D+9%SBS1101	53.23	53.22	686	683.65	0.003	696.36	721.79	734.50
D+3%SBS1184	53.99	53.98	706	699.31	0.009	711.41	735.61	747.71
D+6%SBS1184	53.93	53.91	339.8	330.01	0.029	336.87	350.58	357.44
D+9%SBS1184	58.28	58.26	744.8	739.39	0.007	753.36	781.30	795.27

Table 3 shows the LSV and ZSV of local asphalt binders measured at 60 °C.

It can be noticed from the predicted results of ZSV that:

- 1) The viscosity at high temperature and very low frequency for Nasiriyah AB are greater than Durah AB. Thus, the rutting susceptibility of Nasiriyah AB is better than Durah AB.
- 2) Adding SBS to asphalt binder enhanced the viscosity at high temperature and increased its ability to resist rutting.
- 3) Increased percentage of SBS added to asphalt binder increased the viscosity of the asphalt binder and then increased its rutting performance.

Figure 9 shows the relation between experimental results obtained from DSR and results calculated from the log model.

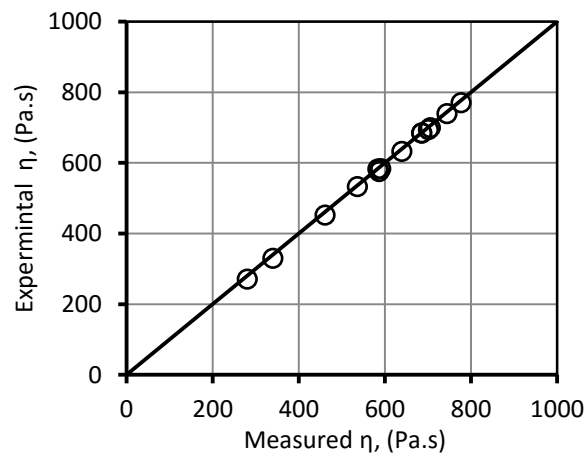


Figure 9. Experimental against predicted dynamic viscosity (η , Pa.s) for modified asphalt binder.

5.3 Predicted Model for SHRP parameter

Statistical analyses were used in this experimental study. A multiple linear regression analysis was applied in order to predict rutting performance of local asphalt binder based on more than one independent variable which is needed in the regression model. From the ANOVA analysis shown in Table 4, it can be seen that the regression was significant because a p-value was equal to zero. This indicated that there was a relationship between three independent variables (SBS contents, test temperatures and applied frequency) and the response values ($G^*/\sin\delta$). The regression equations and R^2 are shown in Table 5. In this case, we may conclude that this regression model is linear.

$$\frac{G^*}{\sin\delta} = 10^A \quad (10)$$

$$A = a + bX_1 + cX_2 + dX_3 \quad (11)$$

Where;

X_1 = independent variable representing temperature measured by $^{\circ}\text{C}$;

X_2 = independent variable representing frequency measured by Hz;

X_3 = independent variable representing percentage of SBS added;

a= constant, and

b, c and d= unknown parameters for independent variables.

More details about these unknown parameters are shown in Table 5.

Table 4 . Example of statistical analysis using SPSS ver.22

a) Correlations matrix of independent variables						
Pearson	Rutting Par	Temp	Freq	Add Percent	Add	
Rutting Par	1.000	-.775	.321	.063	-.005	
Temp	-.775	1.000	.000	.000	.000	
Freq	.321	.000	1.000	.000	.000	
Add Percent	.063	.000	.000	1.000	-.240	
Add Type	-.005	.000	.000	-.240	1.000	
b) Model Summary ^d						
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate		
1	.775 ^a	.601	.60121	.94272		
2	.839 ^b	.704	.70323	.81273		
3	.941 ^c	.885	.88548	.80771		
c) ANOVA ^a						
Model		Sum of square	df	Mean	F	Sig.
1	Regression	1178.013	1	1178.013	13.526	.000 ^b
	Residual	782.068	880	.889		
	Total	1960.081	881			
2	Regression	1379.471	2	689.736	24.208	.000 ^c
	Residual	580.610	879	.661		
	Total	1960.081	881			
3	Regression	1387.282	3	462.427	3.820	.000 ^d
	Residual	572.799	878	.652		
	Total	1960.081	881			
a. Dependent Variable: Rutting Par			b. Predictors: (Constant), Temp			
c. Predictors: (Constant), Temp, Freq			d. Predictors: (Constant), Temp, Freq,			

Table 5. Predicted model of $G^*/\sin\delta$

Binder modifier	Multiple linear regression model				R ²
	Constant	Temp. (°C)	Freq. (Hz)	Additive (%)	
NSBS1101	7.0857	- 0.06707	0.16406	0.04352	0.885
NSBS1184	7.0924	- 0.06273	0.17350	- 0.03744	0.826
DSBS1101	6.7353	- 0.05031	0.17040	0.00246	0.904
DSBS1184	6.1200	- 0.02486	0.16770	- 0.04760	0.864

It can be shown from Table 5 that:

- 1) Temperature adversely affects the ability of asphalt binder to resist rutting: whenever the temperature increases, the asphalt is less viscous and the asphalt binder shows reduced performance to resist rutting. Vehicle speed affects the efficiency of the asphalt paving to resist rutting and reduces the service life. We can express vehicle speed by applied frequency; we note direct proportion between the ability of asphalt binder to resist rutting and applied frequency.
- 2) There is a direct relationship between adding SBS1101 and rutting parameter.
- 3) There is an inverse relationship when adding SBS1184 and rutting parameter.

The relation between the experimental and predicted rutting parameter by Multi-Linear Regression (MLR) is demonstrated in Figures 10 and 11 for Nasiriyah and Durah asphalt binder respectively. It is noticed from the value of R² that the MLR model is better at prediction.

Trend line for the results obtained from MLR for modified asphalt binder by SBS1101 is close to the equality line; that means the prediction data from this model are presenting real experimental results, but the trend line that is obtained from the adding of the SBS1184 result is further away from the equality line and gives less accuracy when predicting the value of $G^*/\sin\delta$.

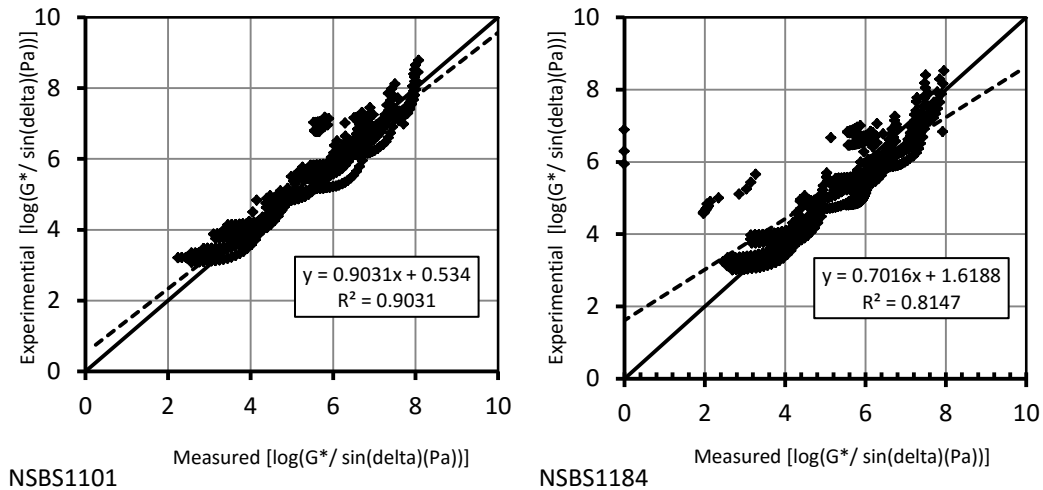


Figure 10. Experimental against predicated $G^*/\sin\delta$ for modified Nasiriyah asphalt binder.

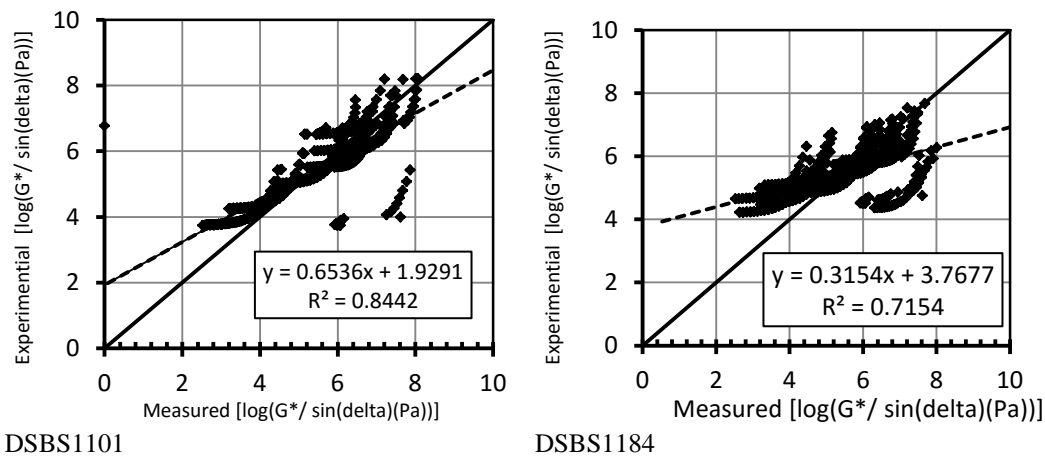


Figure 11. Experimental against predicated $G^*/\sin\delta$ for modified Durah asphalt binder.

5.4 Effect of aging

The Superpave binder specification requires the rutting factor, $G^*/\sin\delta$, to be a minimum 2.20 kPa for Rolling Thin Film Oven Test (RTFOT)-aged binder according to (AASHTO T 240-09 and ASTM D 2872-12e1). The rutting factor reflects the total resistance of a binder to deform under repeated loading (G^*), and the relative energy dissipated into non-recoverable deformation ($\sin\delta$) during the loading cycle. A higher value of $G^*/\sin\delta$ implies that the binder behaves more like an elastic material, which is desirable for rutting resistance. The rutting resistance was evaluated mainly by

examining $G^*/\sin\delta$ values of RTFOT-aged binder, because the aging simulates a short-term aging, including the hardening at the asphalt plant.

As expected, the values of $G^*/\sin\delta$ RTFOT-aged binder were increased as the content of SBS was increased at all temperatures and frequencies (Figure 11). It appeared that the addition of SBS would enhance the resistance against rutting.

The data presented in Figure 12 indicate that the aged asphalt binder exhibited lower values compared to unaged binder for $G^*/\sin\delta$ parameter. The relationships between $G^*/\sin\delta$ and, frequencies and temperatures for aged and unaged modified binders are shown in Figures 11 and 12, respectively. All of the binders behaved similarly before aging, with pure asphalt behaving slightly better than the other binders.

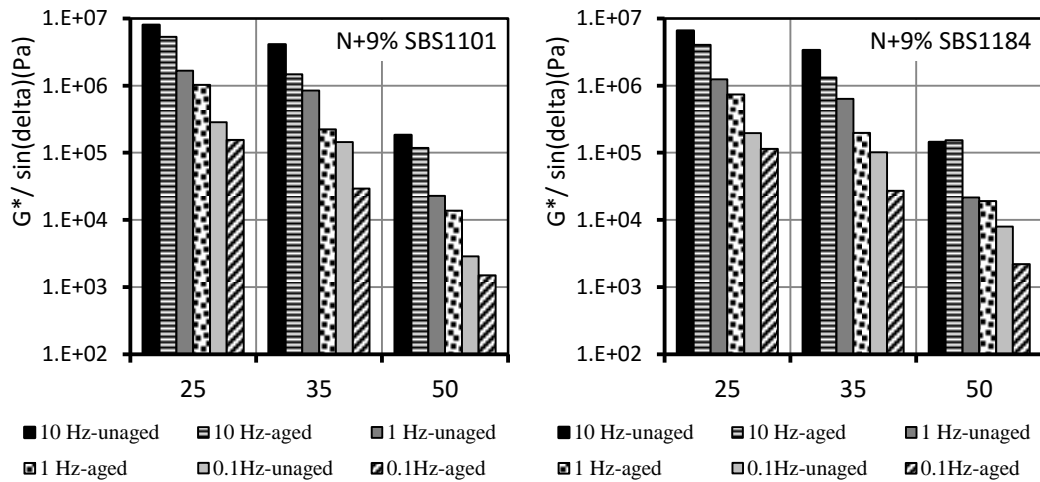


Figure 11. Example of test results to study effect of short-term aging.

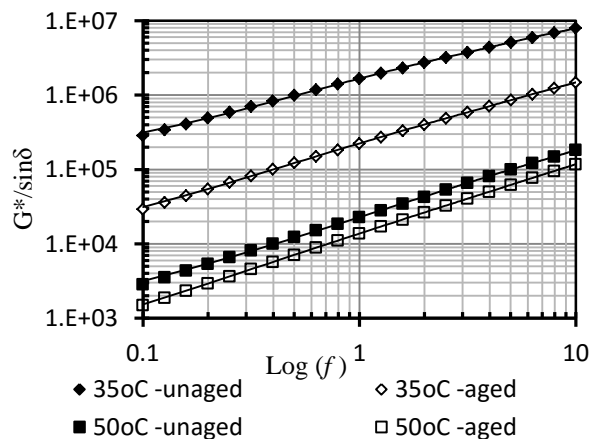


Figure 12. Example explaining effect of test temperature.

5.5 Correlation between $G^*/\sin\delta$ and accumulated strain

The relation between $G^*/\sin\delta$ and accumulated strain can be used to identify rutting potential of the asphalt binder; this relation is presented in Figure 13. It can be noticed that:

- 1) There is an inverse relationship between the SHRP rutting parameter and accumulated permanent deformation during the repeated test.
- 2) When SBS was added to modified asphalt binder, this enhanced viscosity and increased rutting parameter and so reduced amount of dissipated energy and then reduced the accumulated shear strain during the test.

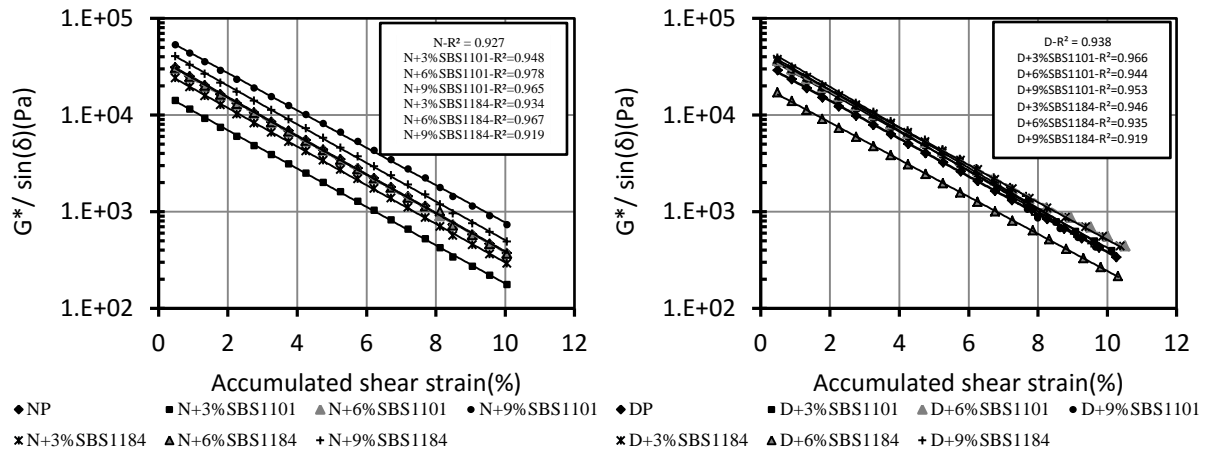


Figure 13. Example of correlation between $G^*/\sin\delta$ and accumulated strain @ 60°C.

6. Conclusions

The following conclusions can be drawn from the finding of the present investigation:

1. SBS contents, frequency and temperatures have a significant effect on the $\log G^*/\sin\delta$.
2. A multiple linear regression model was obtained for this experimental study. This indicated a good relationship between $\log G^*/\sin\delta$, SBS contents, applied frequency and temperatures.
3. The addition of SBS increased the values of $G^*/\sin\delta$ and could improve the resistance of asphalt binder against rutting.
4. To reduce the effect of rutting, $G^*/\sin\delta$ should be minimised. This means that $G^*/\sin\delta$ should be maximised to control permanent deformation.
5. Asphalt binder should be stiff and it should be elastic (it should be able to return to its original shape after load deformation), in order to increase rutting resistance.
6. The parameter $G^*/\sin\delta$ should be maximised to reduce the work dissipated during loading cycle and then increase rutting performance of asphalt binder.

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