

Full Length Research Paper

Fatigue evaluation of Iraqi asphalt binders based on the dissipated energy and viscoelastic continuum damage (VECD) approaches

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Received 29 January, 2015; Accepted 25 March, 2015

Bituminous materials in roads are subjected to short-term loading each time a vehicle passes. If sufficiently high, the loading results in a loss of rigidity of the material and can, by accumulation in the long term, lead to failure. The resulting fatigue deterioration is of great importance in pavement construction and must be correctly understood in order to ensure adequate structural design. The binder property plays a major role in determining the mechanical characteristics in asphalt pavement to resist distress. This paper presents results of an investigation to evaluate the effects of fume silica, ground slug and two types of styrene-butadiene-styrene (SBS) on the fatigue performance of local bituminous binders. These additives were incorporated into asphalt binder from two different sources, namely Nasiriyah and Durah refinery in the middle and southern regions of Iraq. This study adopts a time sweep (TS) test method to study the fatigue phenomenon under controlled strain and stress modes using a dynamic shear rheometer (DSR). Fatigue life of the asphalt binder is defined using the traditional approach based on number of cycles required to cause to failure and reduction in initial stiffness. To accurately predict the fatigue life of modified and unmodified binders, the viscoelastic continuum damage (VECD) approach and energy approach have been also adopted. It was found that additives had a superior performance in terms of fatigue life. However, the energy approach has been shown to be more realistic in predicting the fatigue life of modified binders than the VECD approach as the latter did not correlate well with traditional and energy approaches. It can be concluded that the fatigue performance of Durah asphalt binder is better than that of Nasiriyah in all cases with or without adding additives. Adding 2% silica fume and 6% SBS 1184 enhanced the fatigue performance of local asphalt.

Key words: Asphalt binder, fatigue performance, time sweep test, viscoelastic continuum damage (VECD), dissipated energy, plateau value, energy ratio, and energy stiffness ratio.

INTRODUCTION

Flexible pavements are designed to resist rutting, fatigue, low temperature cracking and other distresses. The most

serious distresses associated with flexible pavement are cracking, which occurs at intermediate and low

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temperatures, and permanent deformation, which occurs at high temperatures. These distresses reduce the service life of the pavement and increase the maintenance costs. Bituminous binder plays an important role in the behaviour of pavement structures. It influences various deterioration modes. It has been reported that binder influences asphalt distress by approximately 60% in terms of fatigue crack (Harvey and Cebon, 2003). In fact, fatigue is one of the main types of asphalt pavement deterioration. In reality, fatigue life is defined as the number of standard axles passing until mechanical failure while, in the laboratory, it is defined as the number of stress or strain cycles to failure of a sample predicted by fatigue criteria. Asphalt cement binds the aggregate particles together, enhancing the stability of the mixture and providing resistance to deformation under induced tensile, compressive and shear stresses. Bitumen materials are viscoelastic and their mechanical behaviour is dependent on both the temperature and rate of loading. At low temperatures and short loading times, asphalt cements behave as elastic solids, while at high temperatures and long loading times they behave as simple viscous liquids. At intermediate temperatures and loading times, the behaviour is more complex. A medium temperature range from 15 to 30°C is most suitable for fatigue cracking analysis and pavement fatigue life prediction (Deacon et al., 1994).

Several papers have been published that used a dynamic shear rheometer (DSR) to investigate binder fatigue properties (Bahia et al., 1999; Sybilski et al., 2013). In these papers fatigue is measured by continuing load cycles until a decrease in the evolution of the complex shear modulus G^* versus loading time occurs. Bahia et al. (1999) used the plate-plate set-up, while Phillips (1998) used cone-plate geometry. Bahia et al. (1999) conducted tests in the linear and also in the nonlinear range of viscoelasticity with a fixed number of load cycles (5,000 or 11,000 with strains of 1, 10, 20 and 50%). Material failure was defined by the amount of the reduction of G^* . In these studies, estimation and measurement of asphalt healing was also considered. It was shown that both strain dependency and fatigue are highly sensitive to the composition of the binders, the type of additives, the temperature, the heating rate, the aging process and the interaction of these factors. A significant improvement of fatigue properties can be achieved through binder modification with polymers. The papers indicate that high strain testing and determination of nonlinear properties are essential for understanding the mechanical role of binders in asphalt mixtures.

Within the last decade many research centres have started studies on binder fatigue phenomena (Bahia et al., 2001; Bonnetti et al., 2002; Anderson et al., 2001; Nicholls, 2006; Airey et al., 2004).

The goals are multiple, e.g.:

1. Understand the binder component affecting the

Fatigue of the asphalt binder,

2. Be able to measure fatigue behavior of the binder itself, and
3. Evaluate the influence of binder modifications or additives.

NCHRP Project 9-10 (Superpave Protocols for Modified Asphalt Binders) identified the general lack of correlation between mixture fatigue performance and $[G^* \sin \delta]$; therefore, the development of improved binder fatigue testing procedures has been pursued. During NCHRP 9-10, the time-sweep (TS) test was introduced as a binder-specific fatigue test performed in the DSR, where the specimen is subjected to repeated cyclic shear loading in either controlled-stress or controlled-strain mode at constant amplitude to measure the fatigue life of asphalt binders (Bahia et al., 2000; Bonnetti et al., 2002). The TS test allowed for the binder to go beyond linear viscoelastic behavior and into the damage accumulation range. Results from this testing gave a much higher correlation with mixture fatigue performance ($R^2 = 0.84$), indicating that the TS test was a promising procedure for evaluating binder fatigue characteristics.

Fatigue cracking and permanent deformation are considered to be the most serious distresses associated with flexible pavements. To reduce the pavement distresses, there are different solutions such as adopting a new mix design or by using asphalt additives. Use of asphalt additives in highway construction is known to give the conventional bitumen better engineering properties as well as being helpful to extend the lifespan of asphalt concrete pavement.

Polymer is a common method used to modify bitumen and addition of polymers has gained popularity in recent years. This is because modification provides the diversified properties needed to build better-performing roads. Polymeric modifiers have been introduced as a potential source of specific improvements in the characteristics of asphalt binder and mixtures. The main reasons that asphalt modification has become more accepted are the traffic factors, which have increased, including heavier loads, higher volumes and higher tyre pressures. Zhu et al. (2014) defined asphalt modifier as a material that, would normally be added to the binder or the mixtures to improve its properties. The choice of modifier for a particular project can depend on many factors including construction ability, availability, cost, and expected performance. Khodary (2010) described that the technical reasons for using modifiers in asphalt concrete mixtures are to produce stiffer mixes at high service temperature to resist rutting as well as to obtain softer mixtures at low temperature to minimise thermal crack and improve fatigue resistance of asphalt pavement. Improvement in the performance of asphalt concrete mixtures that contain polymer is largely due to the improvement in the rheological properties of the asphalt binder. The rheological properties of a binder that

Table 1. Properties of the asphalt binder.

Property	Nasiriyah	Durah
Penetration (0.1 mm, 100 g and 5 s)- 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. Chemical properties of GG.

Parameter	Principal oxides (%)				
	CaO	SiO ₂	Al ₂ O ₃	MgO	Fe ₂ O ₃
Regen company*	40	35	12	10	0.2
Portland cement	65	20	5	1	2

Regen Ground Granulated Blast furnace Slag (GGBS) is a cement substitute, manufactured from a by-product of the iron-making industry. The use of Regen in concrete reduces embodied CO₂ emissions by over 900kg per tonne of cement, and also increases its durability. http://www.heidelbergcement.com/uk/en/hanson/products/cements/ggbs_and_related_products/regen_ggbs.htm

allow flexibility under load control resistance to fatigue. The modified mixtures are less brittle at lower temperatures and have higher stiffness at higher temperatures compared to normal mixtures. This makes polymer modification extremely attractive for pavement designers and highway agencies.

Asphalt is exposed to a wide range of load and weather conditions; however, it does not have good engineering properties, because it is soft in a hot environment and brittle in cold weather. Therefore, asphalt is usually reinforced by polymers to improve its mechanical properties. The main advantage of using modified bitumen is the effect on the pavement performance in terms of permanent deformation. In the previous studies, it was recorded that 2 to 6 wt. % of SBS in bitumen should be used to improve the properties of base bitumen significantly (Isacsson and Lu, 1995). In this investigation, 3 and 6 wt. % SBS in bitumen were used for bitumen modification.

Objectives of the study

The objectives of this study were to:

1. To assess the fatigue behavior for the local asphalt and modify it using polymers.
2. To predict fatigue life of local asphalt binder in order to use it in pavement design.

EXPERIMENT

Materials

In this research, an investigation was made into the fundamental studies of modified asphalt binder and mixtures in order to

understand the influence of modifiers on the rheological properties and fatigue resistance with the aim of preventing fatigue cracking in asphalt pavement. The conventional bitumen samples were acquired from two sources (Nasiriyah and Durah refineries) which are commonly used in the middle and south of Iraq, with (40-50) penetration grade and which are expected to have different fatigue life capacities, modified with microsilica (s), ground granulated blast furnace slag (GG) and two types of styrene-butadiene-styrene (SBS) at three different modification levels, namely 3, 6 and 9% by weight of the bitumen. It is worth noting that, for the purpose of identifying fundamental fatigue performance of modified bituminous binder, an original modified binder with no ageing effect was considered in this study. The properties of asphalt binders and additives are shown in Tables 1 to 4.

Sample preparation and test conditions

The asphalt binder was preheated in an oven to the recommended temperature ($160 \pm 5^\circ\text{C}$) for the unmodified binders and ($160 \pm 5^\circ\text{C}$) for the modified binders, but one should note that binders were just heated up for a certain time to soften them to prevent ageing. Samples should be stirred before pouring into a silicon mould (stirring may be done manually) as the received sample must be homogenised when it is poured in the mould. Moulds should be left at room temperature (from 18 to 24°C) to cool the sample. Silicon moulds are then used to prepare samples for amplitude sweep and fatigue tests, as seen in Figure 1a to e. Both amplitude sweep and fatigue tests were conducted with the 8 mm plate-plate set-up. All tests were conducted at a frequency of 10 Hz, using 2 mm gap settings and the test temperature was 25°C.

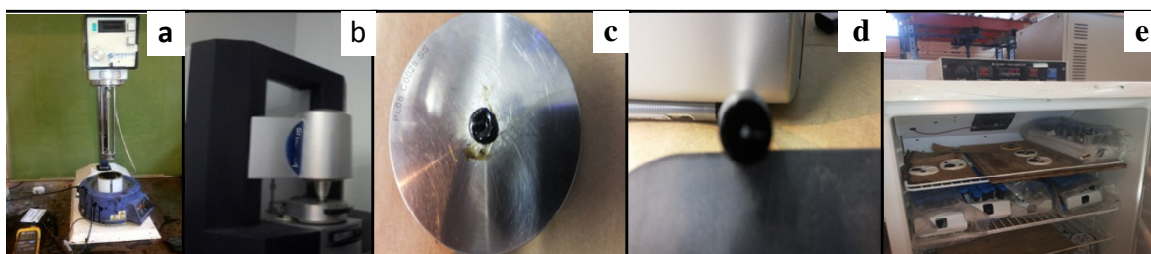
The sample is loaded into the rheometer within 60 min of moulding. The temperature of the rheometer plates during loading should be high enough in order to assure good adhesion to the plates. In the case of unmodified binders, a 60°C temperature is recommended. In any case, the sample should start flowing to get good adhesion to both plates (the gap is first decreased to 2.05 mm). The sample is cooled to the test temperature (25°C is recommended in this work) 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 fatigue tests, the sample should

Table 3. 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

Table 4. Properties of Elkem Microsilica Grade 940.

Chemical and physical requirements	Specification (characteristic values)
SiO ₂ (%)	> 90
H ₂ O (moisture content when packed, %)	> 90
Loss on Ignition, LOI (%)	< 3.0
Retained on 45 micron sieve (tested on Undensified, %)	< 1.5
Bulk density - undensified (when packed, kg/m ³).	200 - 350
Bulk density - densified (when packed, kg/m ³).	500 - 700

**Figure 1.** (a) Shear mixer (b) Kinexus Pro⁺ DSR (c) steel plate, (d) spindle after failure (e) silicon moulds in fridge.

achieve the correct temperature, and this period is referred to as the equilibration period. An equilibration period of 30 min is recommended at the test temperature of 25°C. During the equilibration period the sample modulus can be tested at a very low strain level every 3 min (at least 10 measuring points should be obtained before starting the fatigue test).

Mechanical testing

Stress-strain amplitude determination

The stress or strain levels for the experimental work were selected from the experimental results of amplitude sweep stress and strain used in establishing the linear viscoelastic regions of the asphalt binders. It was defined that the LVER (Linear Visco Elastic Regain) limit is the point at which the modulus decreased to 95% of the initial shear modulus.

A single stress and strain level for asphalt binders were chosen respectively within in the LVER limit in order to reduce the testing time of fatigue test. Tests were conducted at 25°C and three replicates were performed for each condition. Figure 2 illustrates an example of sweep strain and stress for Nasiriyah asphalt binder. It should be mentioned that sweep stress and strain were just

conducted on pure asphalt binders, and then the selected strain and stress values were implanted on all bitumen samples (pure and modified) so that comparison could be made with the control binder. Table 5 summarises the selected controlled strain and stress values for both binder grades.

Binder fatigue test

In general, there are two different approaches for studying the fatigue behavior of the asphalt binder. These can be broadly classified into phenomenological (empirical) approaches and mechanistic approaches. The phenomenological approaches are completely based on experimental data and are popular among engineering communities due to their simplistic nature. On the other hand, mechanistic approaches are based on fundamental energy, mechanics-based principles, and are complex but applicable to a wide range of loading and environmental conditions. The phenomenological models relate the fatigue performance to the properties of asphalt concrete in an undamaged state. However, damage evolution in asphalt concrete is complicated due to interaction among viscoelastic effects, relaxation, healing and the heterogeneous nature of the mix.

In this study, binder fatigue tests were conducted using the

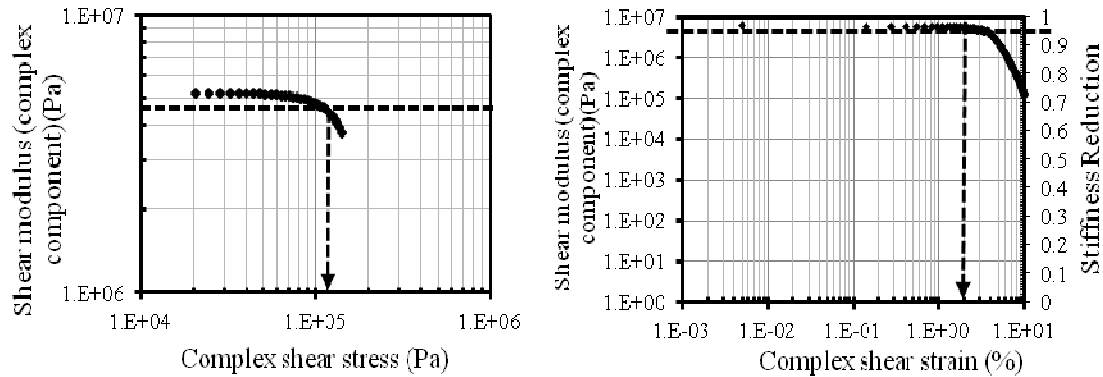


Figure 2. Sweep stress and sweep strain for Nasiriyah asphalt binder.

Table 5. Levels of stress and strain used in fatigue tests.

Binder source	Stress level, Pa	Strain, %
Nasiriyah refinery	120000-150000	2.0
Durah refinery	100000-120000	2.5

Kinexus Pro⁺ DSR developed by the Malvern Instrument Company, as shown in Figure 1b. The details of test conditions are as follows:

1. Both controlled stress and strain mode were conducted,
2. A high frequency 10 Hz is recommended to reduce testing time and number of load cycles,
3. It is recommended to perform the test at stress and strain levels within the LVER.

It is recommended that the fatigue test is performed:

1. Until the binder stiffness modulus G^* reaches 20 and 50% of the initial value,
2. Due to differences in fatigue behavior of modified and unmodified bitumen, it is recommended to gather test results allowing for the analysis of the results with a conventional as well as a dissipated energy approach (energy ratio (ER); reduced dissipated energy change (RDEC), plateau value (PV) and energy stiffness ratio (ESR)),
3. Applied viscoelastic continuum damage to assessment damage in asphalt binder,
4. Previous researchers recommended conducting fatigue tests using DSR at relatively low temperature in order to minimise the edge effect in the parallel plate of the DSR as a heterogeneous flow (plastic flow) may accrue at high temperature. In fact, the sophisticated Kinexus Pro⁺ DSR has the ability to overcome this issue because of machine capacity. This DSR incorporates controlled hood temperature which keeps a uniform temperature during the test. The test temperature used in this work was chosen as 25°C, as this is similar to the middle and southern regions of Iraq,
5. After performing the fatigue test, it is strongly recommended to check the bottom and the upper plate; if the test is performed correctly, both plates should be covered with bitumen when the fatigue test is finished. If this is not the case, the adhesion between the plate and the binder was probably not sufficient, and the test needs to be repeated, and the temperature at which the binder is loaded into the DSR can be increased, as shown in Figure 1b.

RESULTS AND DISCUSSION

Conventional approach

Conventional fatigue criteria defining fatigue life of the asphalt binder are arbitrary criteria which consider only stiffness modulus instead of the overall material properties. It is also worth noting that, for higher temperatures and loads, a decrease of stiffness modulus at the beginning of the test is significant and not always exclusively connected to the fatigue phenomenon. Conventional fatigue criteria, define failure of a material as a situation when its stiffness modulus decreases to 50% of its initial value for strain mode operation, whereas, in the controlled stress mode, it is defined as a reduction of stiffness modulus of the sample to 10% of its initial value (Artamendi and Khalid, 2005) or a complete fracture of the sample (Ghuzlan and Carpenter, 2006). In this study, for strain mode, failure criteria of 20 and 50% reduction in stiffness modulus of initial value and 10% for stress mode were adopted. Increased Fatigue Life Ratio (IFLR) parameters are calculated for each case as ratio of number of cycles caused to required failure criteria (50, 20 and 10%) between modified and unmodified (pure) asphalt in order to compare the results. The coefficient of variance on number of cycles at 20 and 50% reduction in shear modulus (strain mode) and to 10% reduction in shear modulus (stress mode) was also calculated. In all cases it can be said that it is acceptable, as shown in Figure 3 and Table 6.

In all cases in Figures A1, 5, 9 and 13 in the Appendix; it can be seen that:

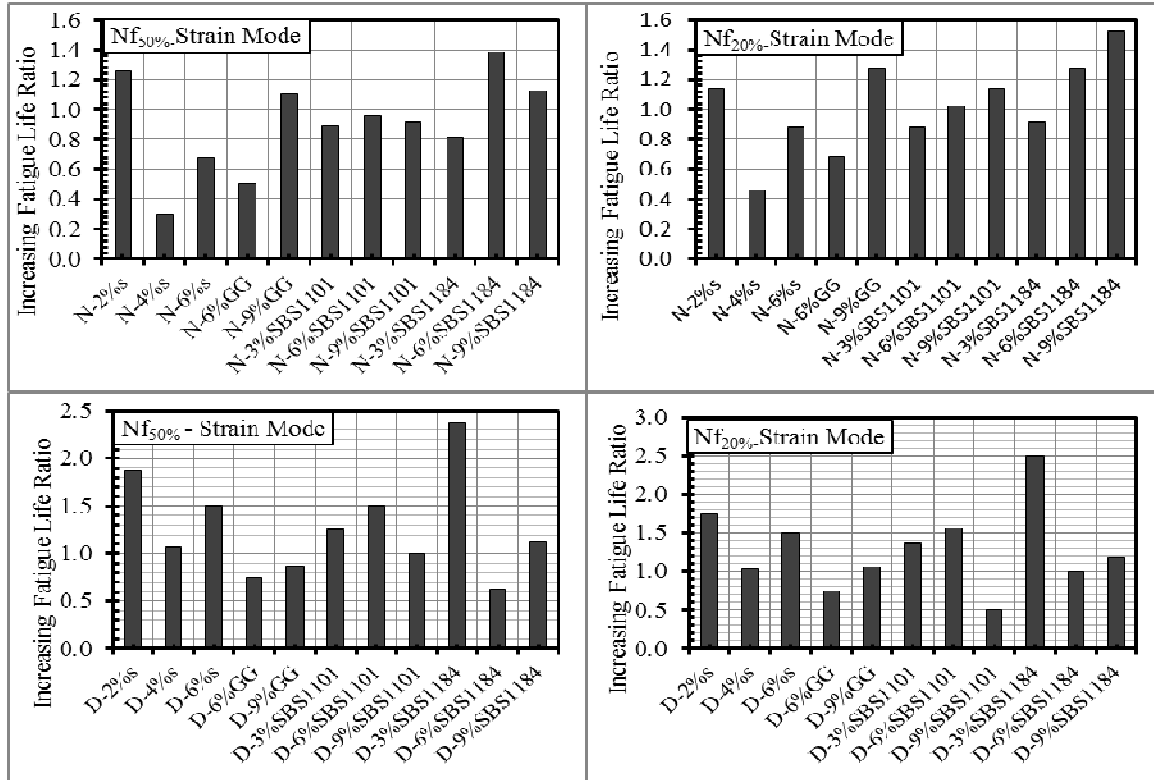


Figure 3. IFLR for the conventional approach.

Table 6. Conventional fatigue approach result

Parameter	Av. Increased fatigue life ratio (IFLR) with standard division											
	Nasiriyah Asphalt						Durah Asphalt					
	Strain mode		Stress mode		Strain mode		Stress mode		Strain mode		Stress mode	
	Nf _{50%}	σ	Nf _{20%}	σ	Nf _{10%}	σ	Nf _{50%}	σ	Nf _{20%}	σ	Nf _{10%}	σ
2% <i>s</i>	1.255	1.725	1.136	1.454	5.500	1.799	1.875	1.121	1.750	1.350	1.870	2.471
4% <i>s</i>	0.298	1.020	0.455	0.859	0.875	1.063	1.063	0.517	1.031	0.623	3.304	1.140
6% <i>s</i>	0.681	1.686	0.886	1.421	3.938	1.927	1.500	0.862	1.500	1.038	3.957	1.900
6%GG	0.502	1.137	0.682	0.958	0.375	1.299	0.750	0.690	0.750	0.831	0.609	1.520
9%GG	1.106	1.176	1.273	0.991	0.250	1.344	0.875	1.155	1.063	2.547	1.391	2.547
3%SBS1101	0.894	1.255	0.886	1.057	0.875	1.434	1.250	1.000	1.375	2.205	1.870	2.205
6%SBS1101	0.957	1.608	1.023	1.355	1.313	1.837	1.500	1.034	1.563	2.281	3.304	2.281
9%SBS1101	0.915	0.314	1.136	0.264	2.750	0.358	1.000	1.207	0.500	3.385	3.957	2.661
3%SBS1184	0.809	2.510	0.909	2.115	1.500	2.867	2.375	1.034	2.500	2.901	5.435	2.281
6%SBS1184	1.383	1.294	1.273	1.090	1.563	1.608	0.625	1.207	1.000	3.385	1.739	2.661
9%SBS1184	1.128	1.412	1.523	1.189	1.000	1.754	1.125	1.466	1.188	4.110	1.522	3.231

1. Micro silica significantly increases the fatigue life of asphalt binder regardless of binder sources and test mode. According to Table 1, adding 2% silica is a suitable amount to enhance fatigue performance for both sources of asphalt binder,
 2. The IFLR increased when the percentage of GG

additives increased,
 3. The IFLR increased with increased percentage of additives until 6% and then reduced for both types of SBS. Adding SBS 1184 increased the ability of the asphalt binder to resist fatigue more than adding SBS1101,

4. In more cases, fatigue performance of Durah asphalt binder is better than that of Nasiriyah.

However, in the conventional approach, the fatigue performance is assessed on the number of cycles against the reduction in the shear modulus without taking in account other variables such stress, strain, phase angle. Therefore, within this study, dissipated energy ratio (ER) and viscoelastic continuum damage are adopted (VECD) were adopted which both of them are advanced criteria to assess the fatigue life of bituminous.

Energy approach

Energy ratio method

Once the load is applied to the material, the resulting stress will induce strain and the area under the stress-strain curve is used to calculate the amount of energy being input into the material. In perfect elastic materials, all the energy going into the material is recovered during unloading. In contrast, for viscoelastic material, not all the applied energy can be recovered; therefore, in this case a retained part of the energy is related to mechanical fatigue of the material and can therefore be interpreted as dissipated energy.

In this regard, Van Dijk (1975) proposed an approach related to the dissipated energy to characterise the fatigue performance of asphalt mixture. Generally, in the fatigue process two stages are distinguished: initiation of micro-cracks and propagation of micro and macro-cracks leading to specimen and material failure. In both stages some energy is dissipated during a single load cycle and can be calculated as explained in Equation (1):

$$W_n = \pi \cdot \sigma_n \cdot \epsilon_n \cdot \sin \theta_n \tag{1}$$

Where: n = number of load cycle; ε = strain amplitude; σ = stress amplitude; θ = phase angle.

Based on this concept and Van Dijk’s work, Hopman et al. (1989) proposed the use of an energy ratio to define the number of cycles (N_{fi}) in a controlled strain mode to a point where cracks are considered to initiate, which is calculated as Equation (2):

$$R_i = \frac{n \cdot w_0}{w_i} \tag{2}$$

Where n = number of load cycles, w_0 = dissipated energy at the first cycle and w_i = dissipated energy at the i^{th} cycle. However, in 1993, Rowe simplified the equation proposed by Hopman to identify the number of cycles (N_{fi}) when cracks are conceded to initiate and, more accurately, it is a point where the micro-cracks coalesce to form a sharp crack (Rowe, 1993; Rowe and Bouldin, 2000).

In controlled strain mode, the equation of energy ratio

can be written as following:

$$R_i^E = \frac{n}{G_i^*} \tag{3}$$

Where R_i^E is energy ratio at controlled strain mode and G_i^* is the complex shear modulus at the i^{th} cycle.

N_{fi} can be defined in this mode as the point at which the slope of the dissipated energy ratio as a function of load cycles diverts from a straight line; whereas, for the controlled stress mode, N_{fi} corresponds to the peak value when the energy ratio is plotted against number of load cycle and the simplified equation of calculation energy ratio as:

$$R_i^E = n \cdot E_i^* \tag{4}$$

Where E_i^* is the energy ratio at controlled stress mode.

The results of this approach are shown in Table 7. It can be noticed from Table 3 and Figure 4 that:

1. Increase IFLR parameter with increase the proportion of micro silica added to the extent of 2% and then decreases with increasing percentage of micro silica,
2. The IFLR increased when the percentage of GG increased in the strain mode and reduced in the stress mode,
3. The ILFR parameter increased with increased percentage of SBS1101 additives until 3% and then reduced,
4. Adding 6% of SBS1184 significantly improved the fatigue life of bitumen,
5. In strain mode cases, fatigue performance of Nasiriyah asphalt binder is better than Durah and vice versa in stress mode. Examples of the N_{fi} and how it is calculated are provided in Figures A2, 6, 10 and 14 in the Appendix.

Ratio of dissipated energy change (RDEC)

The ratio of dissipated energy change (RDEC) approach was introduced by Carpenter and Jansen (1997). The RDEC approach is perhaps the most refined energy method, which can be used to extrapolate fatigue life. The RDEC is defined as the difference in dissipated energy between two loading cycles which contributes to damage. In other words, the area found inside a hysteresis loop (created during cyclic loading and unloading of asphalt binder) is the dissipated energy. The difference in area of each loop indicates the damage produced by dissipated energy (Shen and Carpenter, 2007). This RDEC can be calculated based on Equation (1). The typical cycle count between a and b for RDEC calculation is 100, that is, b-a=100. Larger numbers such as 1000 or 10000 can be used when the DE change between every 100 cycles is too small to recognise. Such

Table 7. Energy ratio method.

Parameter	Av. Increased Fatigue Life Ratio (IFLR) with standard division (σ)							
	Nasiriyah Asphalt				Durah Asphalt			
	Strain mode		Stress mode		Strain mode		Stress mode	
	Nf _{50%}	σ	Nf _{10%}	σ	Nf _{50%}	σ	Nf _{10%}	σ
2% _s	0.783	1.27134783	5.500	1.581 85	1.136	1.861	3.421	1.248
4% _s	0.674	1.09477174	0.875	0.864 36	0.864	1.414	1.842	0.672
6% _s	0.522	0.84756522	3.938	3.888 63	0.818	1.340	2.895	1.056
6%GG	0.478	0.77693478	0.188	0.185 51	1.364	2.233	1.263	1.724
9%GG	0.565	0.91819565	2.875	2.839	1.273	2.084	0.526	0.718
3%SBS1101	0.674	1.09477174	0.875	0.864	0.545	1.439	6.053	3.661
6%SBS1101	0.609	1.59752174	1.375	1.351	0.409	1.079	3.684	2.228
9%SBS1101	0.370	0.96992391	2.938	2.903	0.273	0.719	6.184	3.740
3%SBS1184	0.696	1.82573913	1.688	1.635	0.773	2.038	6.579	3.979
6%SBS1184	0.935	2.45333696	1.781	1.751	0.727	1.918	2.368	1.432
9%SBS1184	0.739	1.93984783	1.125	1.104	0.477	1.259	1.842	1.114

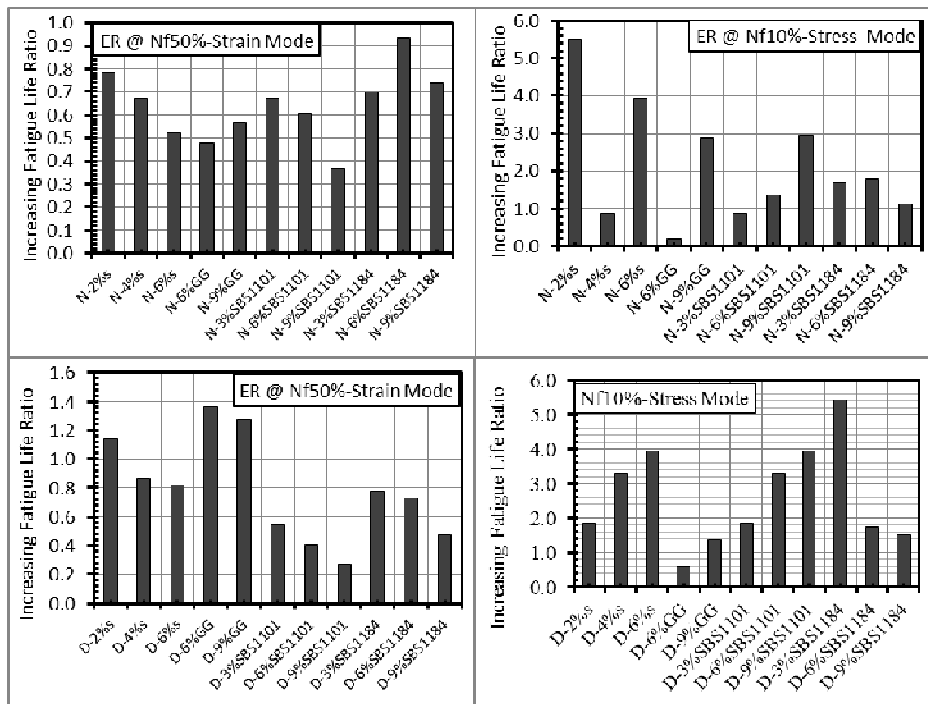


Figure 4. IFLR for the energy ratio method approach.

definition of RDEC provides a true indication of the damage being done to the mixture from one cycle to another by comparing the previous cycle's energy level and determining how much of it contributed to the damage (Shen and Carpenter, 2007):

$$RDEC_a = \frac{DE_a - DE_b}{DE_a * (b - a)} \tag{5}$$

where: a and b = loading cycle at points a and b, respectively; $RDEC_a$ = the average ratio of dissipated energy change at cycle a, compare to cycle b; and DE_a and DE_b = dissipated energy at cycle a and b, respectively, which were calculated directly by fatigue testing.

Previous studies by Ghuzlan (2001) and Carpenter et al. (2003) described the damage curve using the RDEC versus loading cycles shown in Figure 5. It can be seen

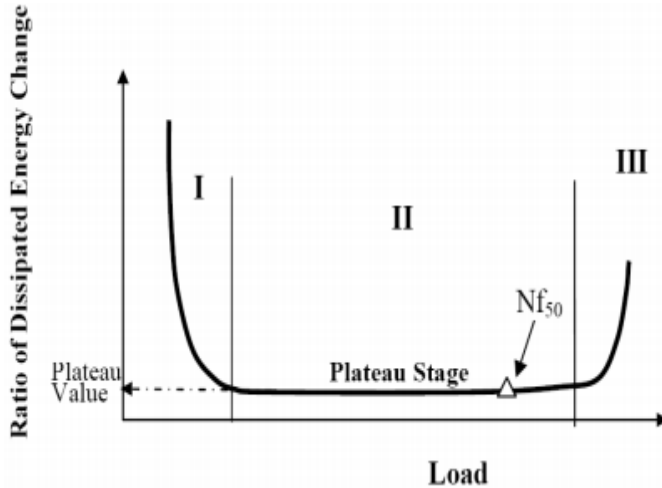


Figure 5. Plateau value calculation (Carpenter et al., 2003).

that the damage curve is separated into three stages: The initial period (Stage I), the plateau period (Stage II), and the failure period (Stage III). Stage I shows a rapidly decreasing dissipated energy ratio which indicates 'settling' of sample. The average dissipated energy ratio in Stage II is known as plateau value. The plateau stage is when a constant percentage of dissipated energy produces damage. This behavior continues until an increase in dissipated energy ratio occurs which signifies fatigue failure and unstable crack propagation (Stage III). From the plateau stage (Stage II), a value can be determined which indicates fatigue failure in a sample. This is called the Plateau Value and is defined as the RDEC value at the number of cycles equal to the failure point ($N_{f=50\%}$). Failure is defined as a 50% reduction in initial stiffness, with the initial stiffness being determined at the 50th loading cycle. Lower PVs correspond to longer fatigue lives (Ghuzlan and Carpenter, 2000). According to Carpenter and Shen (2005, 2006, 2009), the PV- $N_{f=50\%}$ relationship is not mixture-specific and is supposedly independent of temperature, mode of loading, frequency, and healing capacity (rest periods). Ghuzlan and Carpenter (2000) showed that the plateau value relates precisely to the true fatigue failure (Stage III).

They also proposed a simplified RDEC approach where the dissipated energy must be fitted by a power law relationship with the number of load cycles to obtain the slope (b) of the model as follows:

$$PV = a(N_{f50})^b \quad (6)$$

The slopes (b) of power law model and plateau value were calculated and are presented in Table 8 and Figure 6. The analysis of Figure 6 allows us to state that the plateau value calculated can be used to predict the fatigue life of asphalt binder.

From Table 5, the $N_{f(50 \text{ or } 10\%)}$ to starting Stage III (failure point) can be seen for different cases:

1. Adding 2 to 4% silica reduced the PV and so that increased the required cycle number to propagate the crack,
2. The PV reduced when percentage of GG increased,
3. Adding SBS1184 reduced the PV and increased the ability of the asphalt binder to resist fatigue,
4. In strain mode cases, fatigue performance of Nasiriyah asphalt binder is better than Durah asphalt binder.

Energy stiffness ratio (ESR)

By applying Abojaradeh's method (Abojaradeh et al., 2007), a new rational fatigue failure criterion was developed based on the Rowe and Bouldin failure definition (Rowe and Bouldin, 2000) by normalising the Rowe and Bouldin energy ratio ($N_i * S_i$) by dividing it by the initial stiffness (S_0), as follows:

$$ESR = \frac{N_i * S_i}{S_0} \quad (7)$$

where ESR is energy stiffness ratio, N_i is the cycle number, S_i is the stiffness at i^{th} cycle and S_0 is the initial stiffness taken at cycle number 50. In this study, using complex shear modulus and plotting the energy stiffness ratio value ($N_i * G_i / G_0$) versus the number of loading cycles, a peak value can be obtained, as shown in the example in Figures A3, 7, 11 and 15 in the Appendix.

The reason that the energy stiffness ratio increases before it reaches its peak is that the value of N_i continuously increases during the test, whereas the G_0 value is constant. The value of G_i during this time might be lightly decreasing. After reaching its peak, the energy stiffness ratio decreases suddenly because of the sudden decrease in the stiffness of the material even with the increase of the N_i value. Thus, failure is defined as the number of load repetitions at the peak value of the curve for either constant strain or constant stress mode, as shown in Figure A3. The ESR value at failure, when plotted versus the corresponding number of cycles at failure for all specimens on a log-log scale, results in a straight line relationship with high coefficients of determination, as shown in Figure 7. The results also show that there is little to no significant difference between separate curves for constant stress and constant strain. Excellent fit was obtained for the two modes of loading separately as well as the two modes combined, as shown in Figure 7. Also, the determination of the number of load cycles to failure was straightforward. The regression equation developed in Figure 8 is tabulated in Table 9 and the IFLR for all cases in Table 10.

It can be seen from Table 10 and Figure 9 that:

Table 8. Average of plateau value with number of load cycle caused to failure.

Parameter	Nasiriyah asphalt				Durah asphalt			
	Strain mode		Stress mode		Strain mode		Stress mode	
	N _{f50%}	PV	N _{f10%}	PV	N _{f50%}	PV	N _{f10%}	PV
Pure	23500	6.00E-06	8000	1.30E-05	8000	7.00E-05	4600	1.80E-04
2% <i>s</i>	29500	8.00E-06	44000	2.00E-06	15000	9.00E-06	8600	2.50E-04
4% <i>s</i>	7000	1.50E-06	7000	1.50E-05	8500	4.00E-05	15200	6.00E-04
6% <i>s</i>	16000	3.00E-06	31500	4.00E-06	12000	2.00E-05	18200	4.00E-04
6%GG	11800	2.00E-06	3000	9.00E-05	6000	6.00E-05	2800	1.00E-04
9%GG	26000	6.00E-06	2000	9.00E-05	7000	7.00E-05	6400	3.00E-04
3%SBS1101	21000	6.00E-06	7000	1.00E-05	10000	2.00E-05	8600	3.00E-04
6%SBS1101	22500	6.00E-06	10500	9.00E-06	12000	3.00E-05	15200	4.00E-04
9%SBS1101	21500	4.50E-06	22000	8.00E-06	8000	7.00E-05	18200	6.00E-04
3%SBS1184	19000	4.50E-06	12000	8.00E-06	19000	1.00E-05	25000	8.00E-04
6%SBS1184	32500	5.00E-06	12500	7.00E-06	5000	8.00E-05	8000	4.00E-04
9%SBS1184	26500	4.80E-06	8000	3.00E-05	9000	5.00E-05	7000	3.00E-04

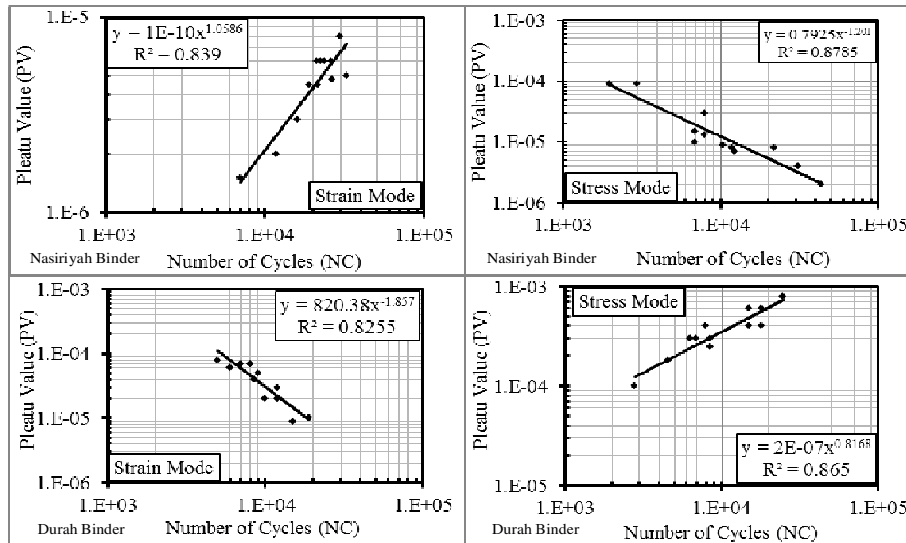


Figure 6. Result of RDEC and calculated plateau value.

1. Adding 2% silica increased fatigue life for the asphalt binder.
2. Increased percentage of GG enhanced the ability of the asphalt binder to resist fatigue.
3. Adding 6% SBS 1184 increased fatigue performance in comparison to SBS 1101.
4. The fatigue performance of Durah asphalt binder is better than that of Nasiriyah asphalt binder.

Viscoelastic continuum damage approach (pseudo-strain approach)

In order to be able to accurately predict the fatigue

performance of asphalt binder, advanced mathematical model such as viscoelastic continuum damage (VECD) offers great potential for better understanding of fatigue behavior (Kutay et al., 2008b; Kutay et al., 2008a) and also for modelling the fatigue behavior of modified bitumen.

Kim (2008) successfully applied the elastic-viscoelastic correspondence principle for modelling sand-asphalt mixture behavior under multi-level cyclic loading. With the elastic-viscoelastic correspondence principle, the physical strain (ϵ) in the elastic theory is replaced with a pseudo-strain, (ϵ^R). A pseudo-strain is similar to a physical strain, except that it is independent of time or loading history. The pseudo-strain accounts for the linear

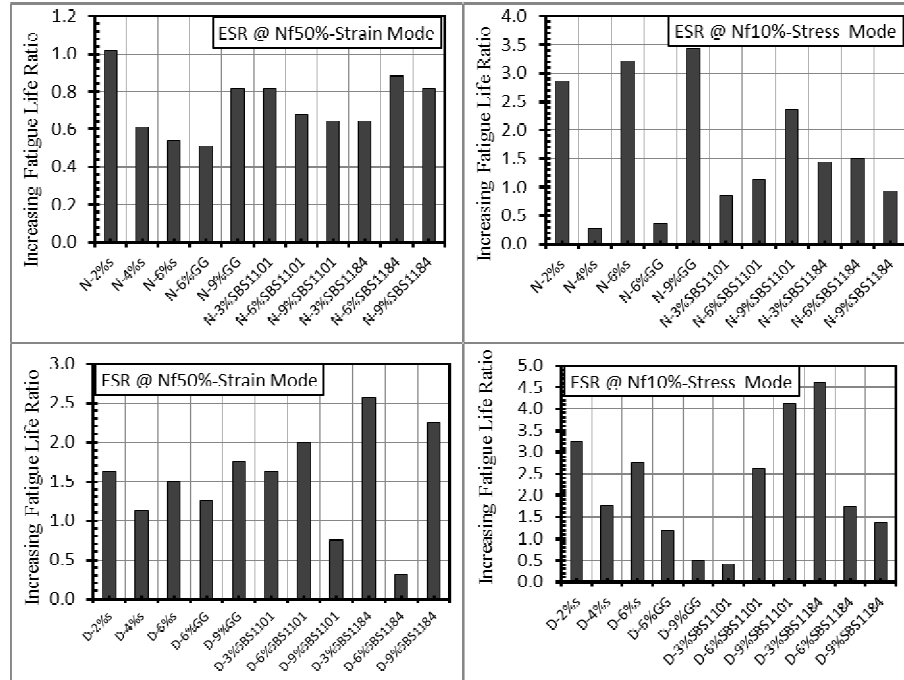


Figure 7. Results of ESR approach.

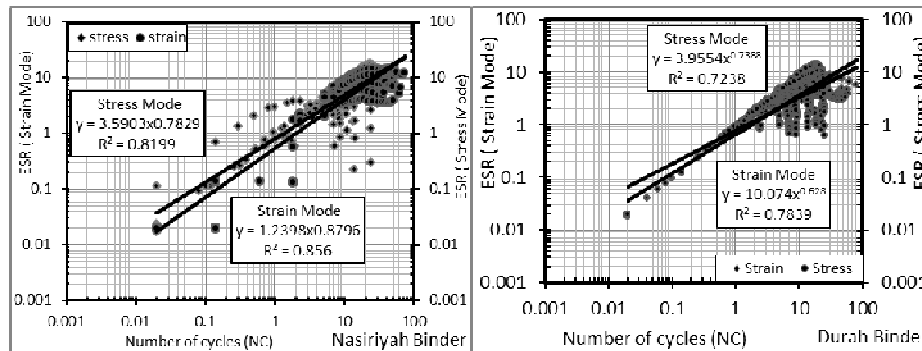


Figure 8. Regression equation for the ESR approach.

viscoelastic hereditary effects of the material through the convolution integral. Thus, damage may be evaluated separately from viscoelastic effects. Without this substitution, identifying damage during cyclic loading is very difficult as there may only be a slight difference in hysteresis loops.

VECD has been successfully used by a number of researchers (Kutay et al., 2008b; Kutay et al., 2008a; Kim and Little, 1990; Kim et al., 1995; Daniel, 2001; Lundstrom and Isacson, 2003; Christensen Jr and Bonaquist, 2005). Therefore, it would be great to use this approach to rank the performance of modified bitumen. Fatigue can be identified based on the curve of C-S. The (C) parameter is pseudo-stiffness, which is defined as the loss of material stiffness due to loss of material integrity

caused by damage, while (S) is a single parameter which is used to quantify the damage growth (Kutay et al., 2008a).

Damage parameter (S) is calculated as:

$$S_{\epsilon}^{N+\Delta N} = S_{\epsilon}^N + (\Delta N/f)^{\frac{1}{1+R}} \left[-0.5/\sigma_N^R (C_{N+\Delta N} - C_N) \right]^{\frac{R}{1+R}} \quad (8)$$

$$S_{\sigma}^{N+\Delta N} = S_{\sigma}^N + (\Delta N/f)^{\frac{1}{1+R}} \left[0.5/\sigma_N^R \left(\frac{1}{C_{N-\Delta N}} - \frac{1}{C_N} \right) \right]^{\frac{R}{1+R}} \quad (9)$$

Where (ϵ^R) is pseudo-strain, (σ^R) is pseudo-stress, l is initial stiffness parameter, C is pseudo-stiffness, f is a

Table 9. Regression equation for ESR approach.

Parameter	Nasiriyah Asphalt		Durah Asphalt	
	Predicted equation	R ²	Predicted equation	R ²
Strain	ESR = 1.2398(NC) ^{0.8796}	0.8560	ESR = 10.074(NC) ^{0.628}	0.784
Stress	ESR = 3.5903(NC) ^{0.7829}	0.820	ESR = 3.9554(NC) ^{0.7388}	0.724

Table 10. Results for ESR approach for all cases.

Parameter	Av. Increased fatigue life ratio (IFLR) and standard division (σ)							
	Nasiriyah Asphalt				Durah Asphalt			
	Strain mode		Stress mode		Strain mode		Stress mode	
	Nf _{50%}	σ	Nf _{10%}	σ	Nf _{50%}	σ	Nf _{10%}	σ
2%S	1.017	3.252	2.857	3.330	1.625	1.271	3.250	2.122
4%S	0.610	2.252	0.286	3.195	1.125	0.763	1.775	0.212
6%S	0.542	1.502	3.214	2.051	1.500	0.678	2.750	2.174
6%GG	0.508	1.252	0.357	2.160	1.250	0.636	1.200	0.353
9%GG	0.814	1.752	3.429	0.900	1.750	1.017	0.500	3.186
3%SBS1101	0.814	1.627	0.857	0.765	1.625	1.017	0.425	0.646
6%SBS1101	0.678	2.628	1.143	2.726	2.000	0.848	2.625	1.129
9%SBS1101	0.644	0.986	2.357	1.227	0.750	0.805	4.125	3.128
3%SBS1184	0.644	3.367	1.429	3.739	2.563	0.805	4.625	1.911
6%SBS1184	0.881	0.625	1.500	1.793	0.313	1.102	1.750	2.481
9%SBS1184	0.814	4.053	0.929	1.409	2.250	1.017	1.375	1.917

constant frequency, (S_e) is the damage parameter when (ϵ^R) is used in the analysis (strain mode), (S_e) is the damage parameter when (σ^R) is used (stress mode), N is number of cycles, and α is a material constant related to the rate of damage.

α is calculated based on undamaged rheological properties using the slope of relaxation modulus (Hintz et al., 2011a, b). Lee and Kim suggested that ($\alpha = 1 + 1/m$) is more suitable for strain controlled tests, whereas ($\alpha = 1/m$) is suitable for stress mode tests (Kutay et al., 2008a; Lee and Kim, 1998).

m is the maximum slope of the relaxation modulus plotted against time in a log-log scale. In this study, it was difficult to run a relaxation test; therefore, it was decided to use a method developed by Scharpery and Park (1999) to convert sweep frequency test data to the relaxation data, as can be seen in Figure 9:

Where G^* is the complex shear modulus and $G^*(t)$ is the relaxation modulus. The sweep frequency (for each control and modified bitumen) was conducted within the LVER at 25°C.

As previously noted, data were analysed based on the stress mode because, according to VECD theory, a single damage characteristic curve (C-S) should exist

independently of loading frequency, temperature and mode of loading and (C-S) curves calculated at different temperatures, and at different loading modes should collapse on a single curve (Kutay et al., 2008a).

The main advantages of the VECD approach is that it is based on a constitutive model and the characteristic curve can be utilised to model the behavior of the material under any load history and temperature can be assessed (Kutay et al., 2008a; Kutay et al., 2008b; Daniel, 2001).

Once the damage characteristics of C-S curves were obtained, an exponential best-fit line was fitted to the curves, as in the following equation:

$$C = \exp(\alpha S^b) \quad (10)$$

Where (a and b) are constant parameters defining the best fit. Those parameters with other equations (Kutay et al., 2008a) could be used to predicate the response of the material to a given loading history. The characteristic curves of Figures A4, 8, 12 and 16 in the Appendix, and Tables 11 and 12 describe how the internal damage changes with additive types and content. The internal damage parameter can be used to represent the degradation of the bitumen. All additive types increased the complex shear modulus of bitumen and also delayed the deterioration (development of micro-cracks) and

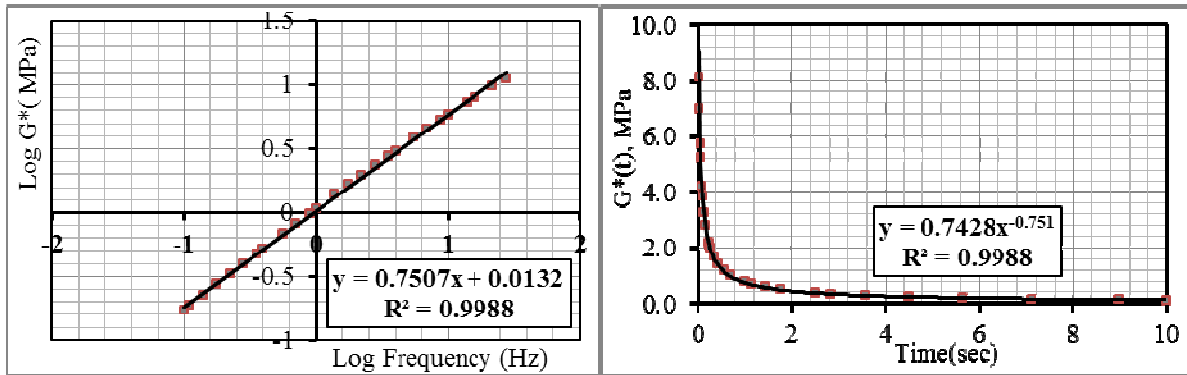


Figure 9. An example of conversion of the sweep frequency data to relaxation data (a) Sweep frequency data (b) Relaxation data.

Table 11. Exponential fit coefficient and a parameter of damage characteristics curves of modified bitumen.

Parameter	Strain mode				Stress mode			
	S at C _{50%}	a	b	R ²	S at C _{10%}	a	b	R ²
Nasiriyah asphalt binder								
Pure	120	1.1632	-0.008	0.9538	460	1.6838	-0.012	0.8395
2% <i>s</i>	305	1.1136	-0.003	0.9642	515	1.2532	-0.004	0.7605
4% <i>s</i>	110	1.0698	-0.008	0.9895	240	1.5458	-0.018	0.6394
6% <i>s</i>	380	0.9751	-0.002	0.9984	315	1.2031	-0.007	0.9673
6%GG	160	1.1496	-0.005	0.9714	240	1.6188	-0.017	0.8286
9%GG	480	1.0045	-0.002	0.994	660	1.8355	-0.006	0.7661
3%SBS1101	270	1.1748	-0.004	0.9647	340	1.8242	-0.011	0.8677
6%SBS1101	240	1.1026	-0.004	0.9726	480	1.9819	-0.009	0.8036
9%SBS1101	340	1.2168	-0.005	0.9065	680	1.5766	-0.005	0.8986
3%SBS1184	145	1.1320	-0.007	0.9667	510	1.9539	-0.009	0.8562
6%SBS1185	275	1.1035	-0.004	0.9581	480	1.6479	-0.007	0.8903
9%SBS1186	325	1.0608	-0.003	0.9887	380	1.999	-0.01	0.872
Durah asphalt binder								
Pure	200	1.4309	-0.006	0.9771	380	1.7761	-0.01	0.8916
2% <i>s</i>	175	1.5431	-0.008	0.955	600	2.2455	-0.007	0.8892
4% <i>s</i>	225	1.3953	-0.005	0.9763	300	3.6239	-0.013	0.9333
6% <i>s</i>	235	1.4649	-0.004	0.9764	580	2.3507	-0.007	0.8842
6%GG	110	1.3737	-0.01	0.9625	340	3.2109	-0.0015	0.9098
9%GG	120	1.3708	-0.009	0.9783	285	2.2658	-0.017	0.9246
3%SBS1101	205	1.6715	-0.006	0.9562	640	2.1761	-0.006	0.8895
6%SBS1101	215	1.3377	-0.005	0.9683	460	2.8246	-0.008	0.8836
9%SBS1101	260	1.359	-0.004	0.9782	390	2.468	-0.01	0.6098
3%SBS1184	165	1.4565	-0.007	0.9782	640	3.2566	-0.007	0.8873
6%SBS1185	110	1.2638	-0.009	0.9804	480	2.4656	-0.009	0.895
9%SBS1186	180	1.1551	-0.005	0.9808	400	2.1863	-0.009	0.8945

reduced internal damage. Therefore, the performance of this additive should further increase the performance of asphalt binder in terms of fatigue life.

It can be noticed that:

1. Micro silica significantly slowed degradation (internal damage),
2. Adding 6% GG increased the ability of the asphalt binder to resist fatigue and reduced internal damage,

Table 12. Internal damage parameter at 50% stiffness reduction.

Parameter	Av. Internal damage parameter (SP) with standard division (σ)							
	Nasiriyah Asphalt				Durah Asphalt			
	Strain mode		Stress mode		Strain mode		Stress mode	
	$C_{50\%}$	σ	$C_{10\%}$	σ	$C_{50\%}$	σ	$C_{10\%}$	σ
2% <i>s</i>	2.542	1.374	1.120	2.684	0.875	2.871	1.579	4.045
4% <i>s</i>	0.917	1.320	0.522	3.311	1.125	3.096	0.789	3.629
6% <i>s</i>	3.167	1.203	0.685	2.577	1.175	2.800	1.526	2.354
6%GG	1.333	2.223	0.522	3.467	0.550	2.939	0.895	3.215
9%GG	4.000	1.943	1.435	3.932	0.600	3.948	0.750	2.032
3%SBS1101	2.250	2.272	0.739	3.907	1.025	3.940	1.684	1.952
6%SBS1101	2.000	2.463	1.043	2.263	1.075	4.804	1.211	2.534
9%SBS1101	2.833	2.718	1.478	1.800	1.300	3.845	1.026	4.230
3%SBS1184	1.208	2.529	1.109	2.231	0.825	1.367	1.684	3.302
6%SBS1184	2.292	1.362	1.043	1.882	0.550	1.465	1.263	4.226
9%SBS1184	2.708	1.309	0.826	2.283	0.900	1.272	1.053	3.747

3. Adding SBS1184 is better than SBS 1101 to decrease the internal damage in increased fatigue life of the asphalt binder,

4. The fatigue performance of Durah asphalt binder is better than Nasiriyah.

Summary

The above discussion has provided a review of a number of energy-based fatigue failure criteria which have been used by different researchers to assess the fatigue behavior of asphalt binders or mixtures. These criteria appear to be successful under different conditions. However, these criteria usually refer to different stages of failure, crack initiation, propagation, or catastrophic failure. Selecting any one of the failure definitions without fully understanding what stage the failure criteria are referring to can be misleading for the pavement design. The total results are explained in Figure 10.

Conclusions

This paper has presented a comprehensive review of four dissipated energy-based fatigue failure criteria and compared them with the traditional 50 and 20% initial modulus deduction failure criteria (N_{f50} and N_{f20}). Fatigue-testing data for asphalt binders under strain-controlled and stress-controlled conditions were analysed using different approaches. Based on the review and evaluation, the following findings and conclusions are drawn the fatigue data used in this paper are mainly based on DSR testing for binders:

1. The energy ratio approach provides a means by which

to determine the number of cycles to crack initiation, N_f . It can be used for asphalt binders under strain-controlled and stress-controlled conditions. However, it should be noted that N_f is hard to determine practically and it generally has a low correlation with other failure criteria,

2. N_{f20} is more suitable for assessing the fatigue performance in a strain-controlled test. It can be used to refer to the start of micro-crack propagation, and corresponds to the beginning of the plateau stage as defined in the RDEC approach,

3. The dissipated energy approach provides comprehensive information on the internal deformation mechanisms of asphalt binder and can be adopted for evaluating the degradation resistance. The dissipated energy approach provides a reliable estimation method for performance ranking of the asphalt binder,

4. The number of cycles to failure determined from VECD and DE approaches are highly correlated there is only a difference in the definition of when the failure occurs,

5. The RDEC principles are very interesting because they focus the attention on the change of DE. The fatigue life based on the RDEC (true failure) approach is longer than the fatigue lives based on the other approach,

6. Adding 2% silica works to improve the efficiency of local asphalt to resist fatigue cracks due to decreasing the proportion of internal damage and increasing viscosity and thus increasing the fatigue life,

7. Whenever a growing proportion of GG over 6% increases the viscosity of the asphalt binder reduced the amount of internal deformation and less than the amount of dissipated energy and thus increasing its ability to resist fatigue cracks,

8. Adding both types of polymer improves the performance of the asphalt binder to resist fatigue cracks but using 6% SBS 1184 is the best way to increase the viscosity of the asphalt and reduce the amount of internal

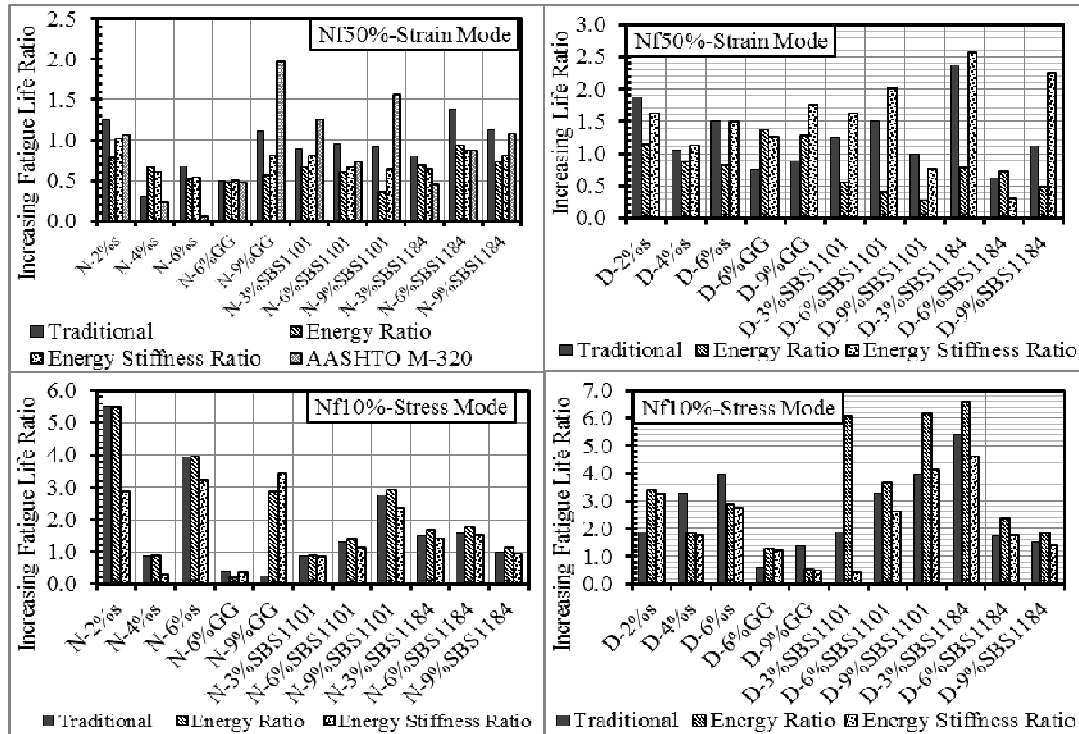


Figure 10. Comparison with different fatigue approaches.

deformation and dissipated energy during each cycles, 7. Performance of the asphalt product from Durah to resist fatigue cracks is better than the asphalt product from the Nasiriyah refinery, so it is advised to use the former in flexible pavements in the middle and southern regions of Iraq with the use of proposed proportions of additives, referred to previously, 8. The fatigue life can be predicted from plateau value. When the plateau values decreased (the dissipated energy per each cycle will be reduced) the number of load cycles required to propagate the crack.

Conflict of Interest

The author has not declared any conflict of interest.

ACKNOWLEDGMENTS

The writer sincerely thanks Dr Hussain A. Khalid at the University of Liverpool for allowing the use of DSR to evaluate the local asphalt binders.

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APPENDIX

Nasiriyah asphalt binder

Control strain mode

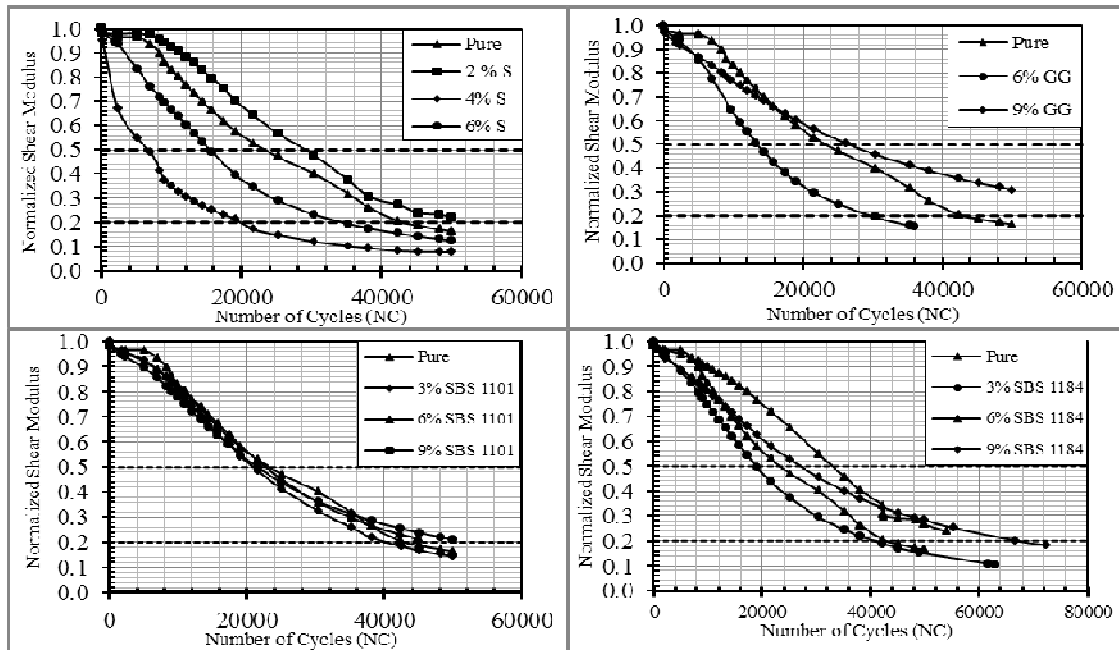


Figure A1. Normalised shear modulus against number of cycles at traditional approach.

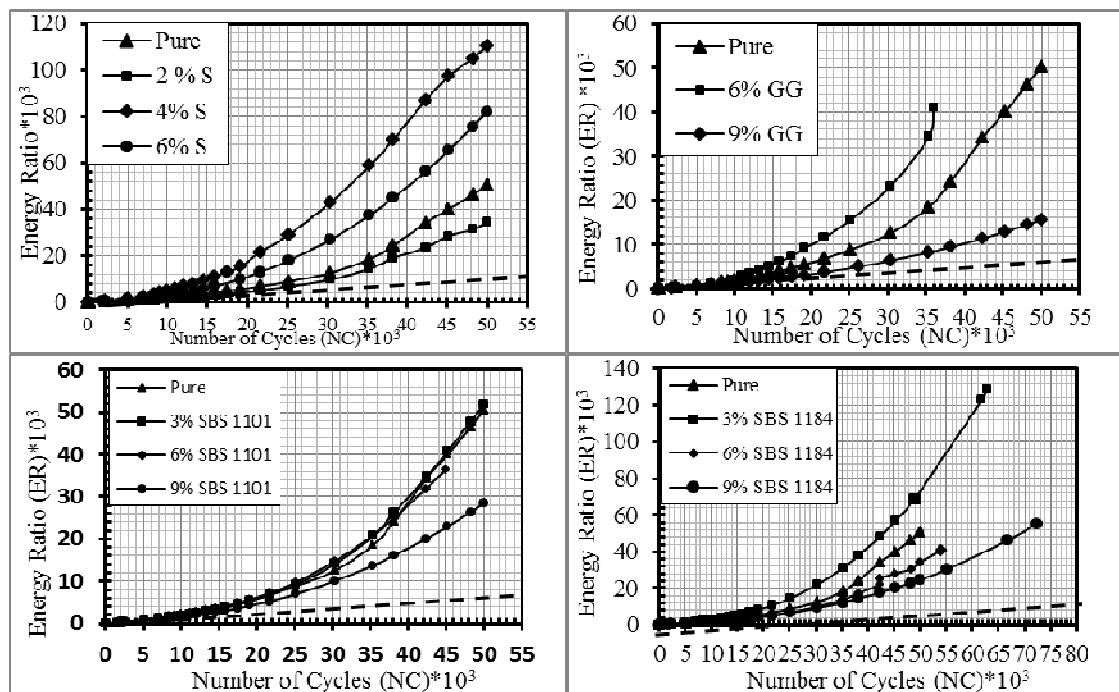


Figure A2. Energy Ratio against number of cycles at energy approach.

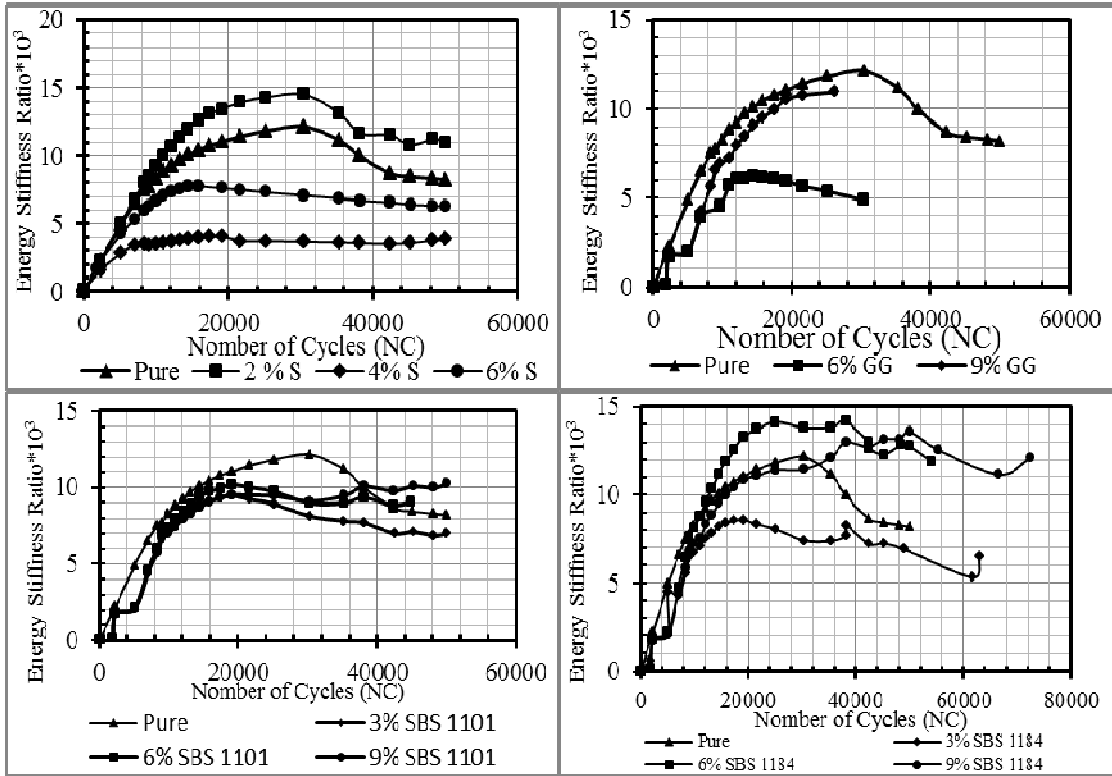


Figure A3. Energy stiffness ratio against number of cycles at energy stiffness approach.

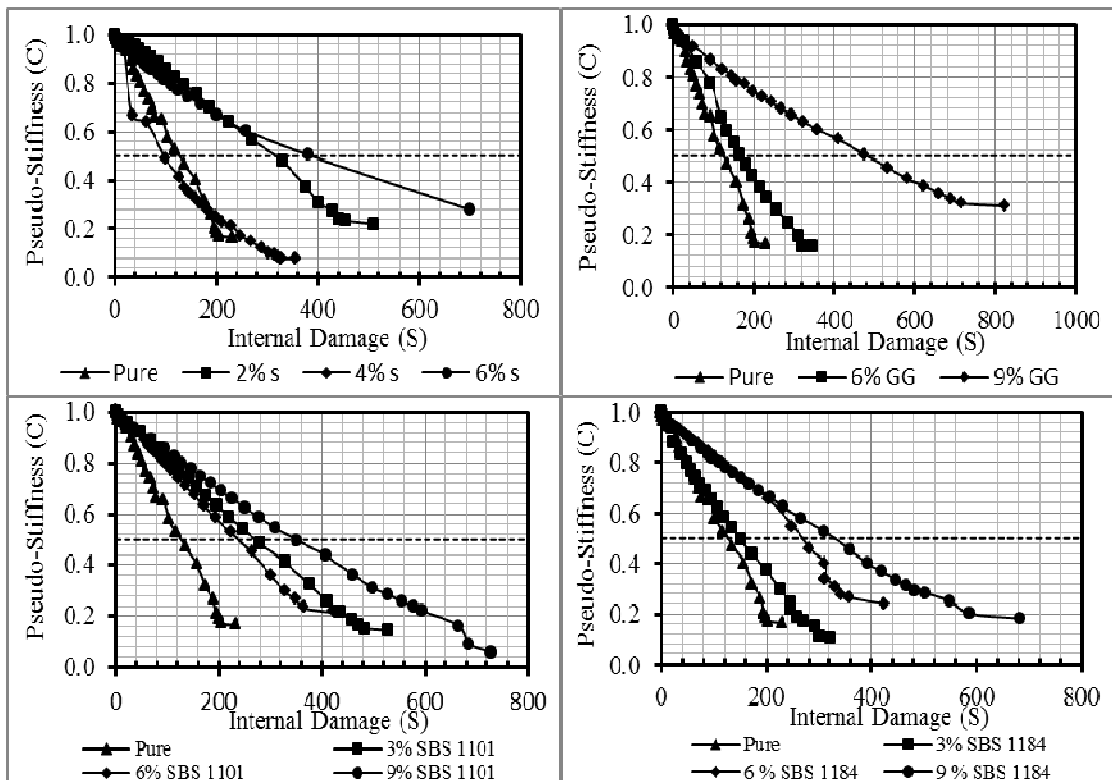


Figure A4. Pseudo-strain-based damage parameter of Nasirysh asphalt binder.

Control stress mode results

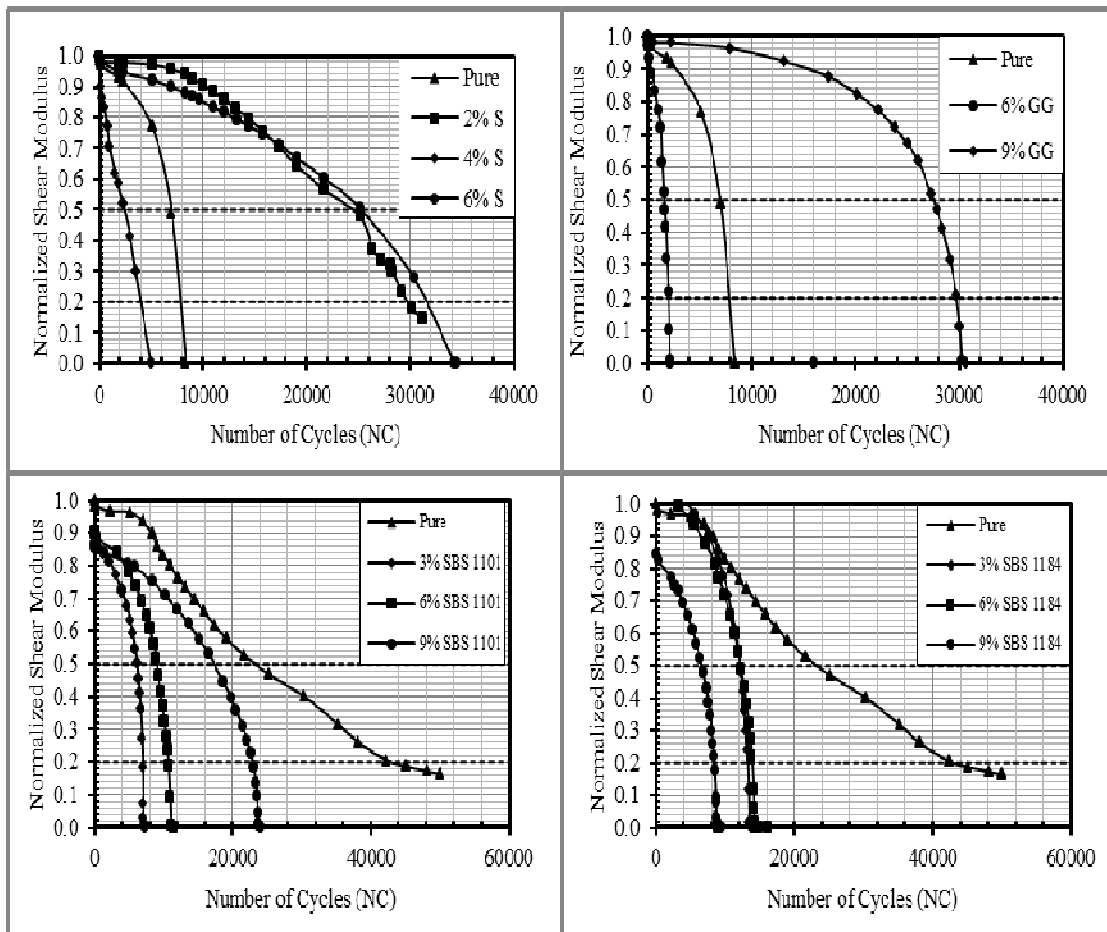


Figure A5. Normalised shear modulus against number of cycles at traditional approach.

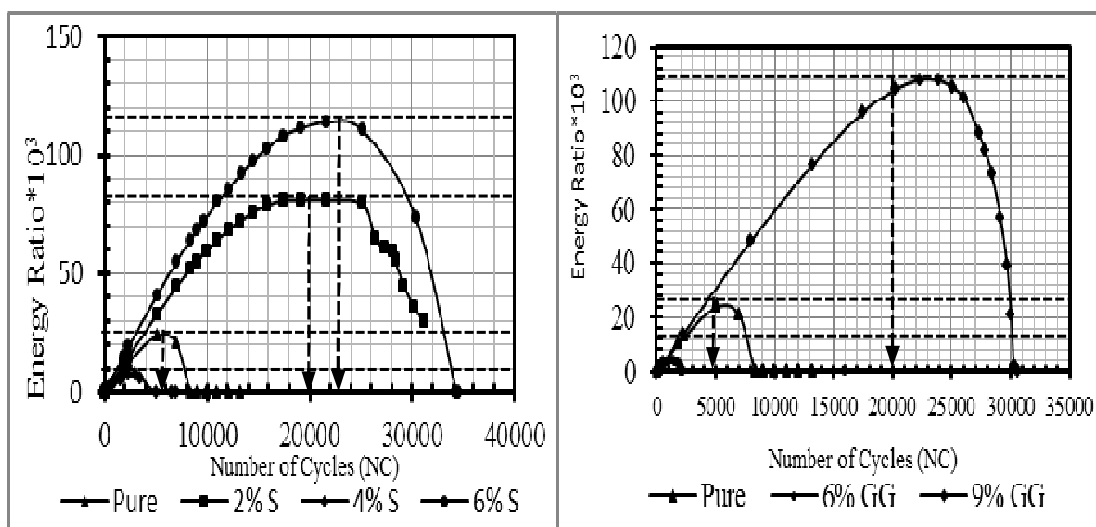


Figure A6. Energy ratio against number of cycles at energy approach.

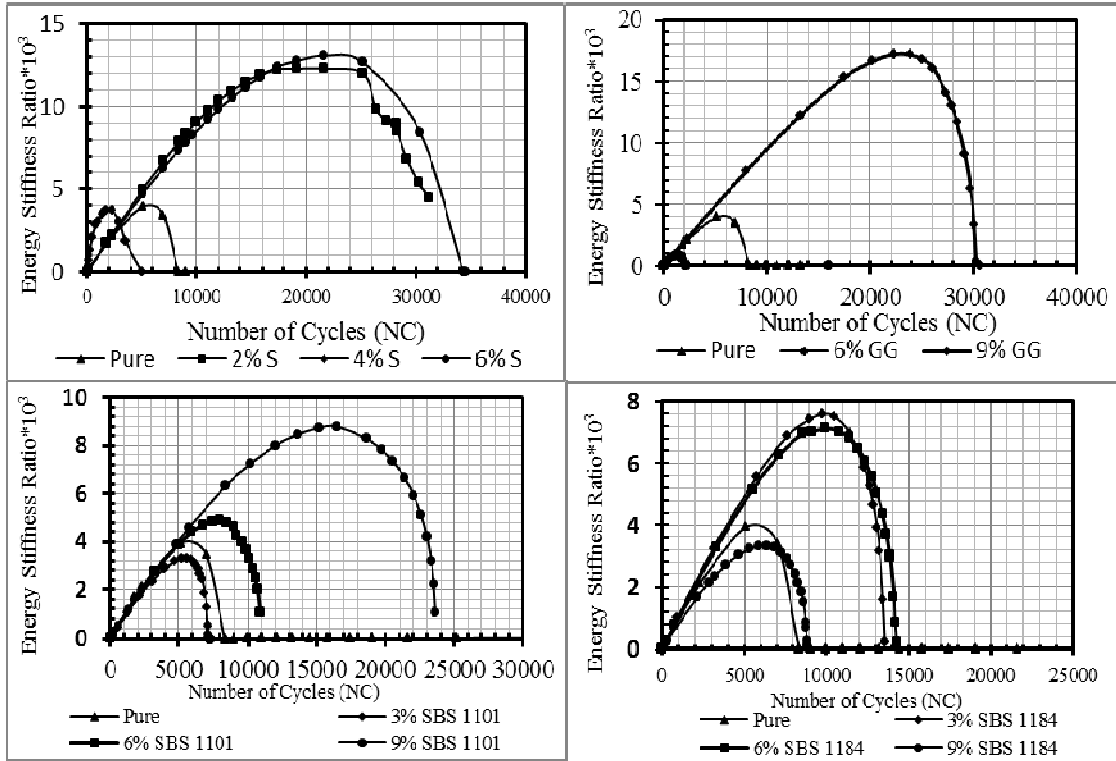


Figure A7. Energy stiffness ratio against number of cycles at energy stiffness approach.

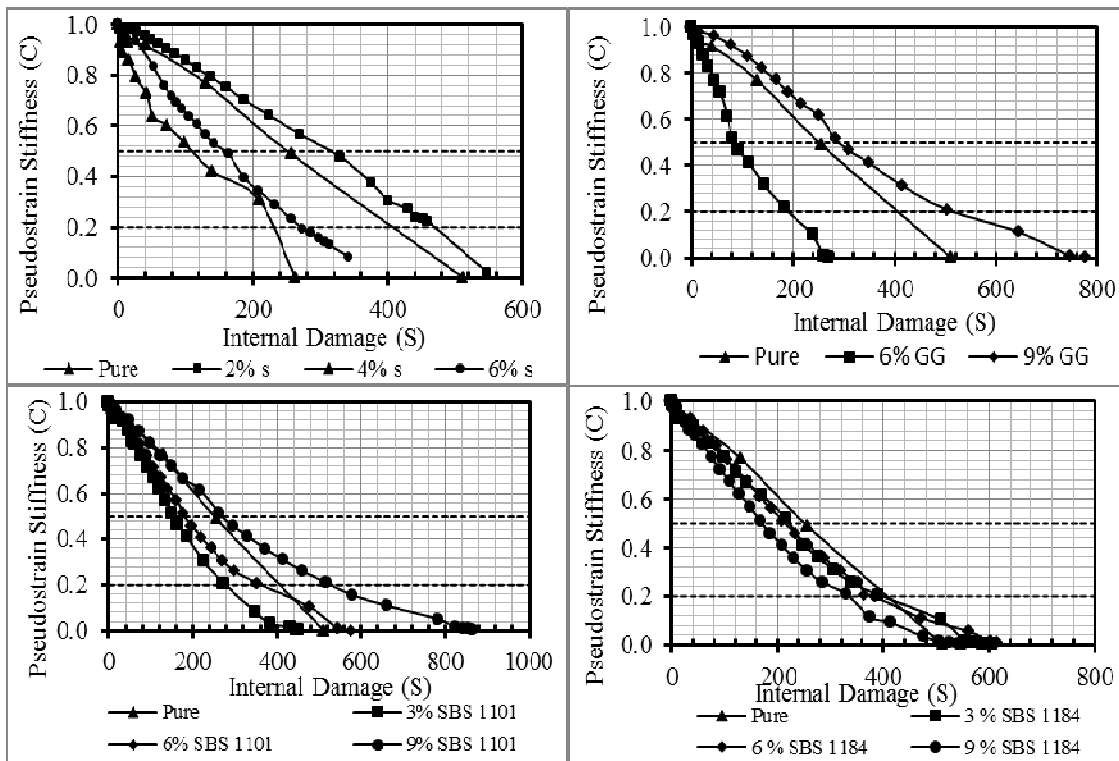


Figure A8. Pseudo-strain-based damage parameter of Nayisirh asphalt binder.

Durah asphalt binder

Control strain mode results

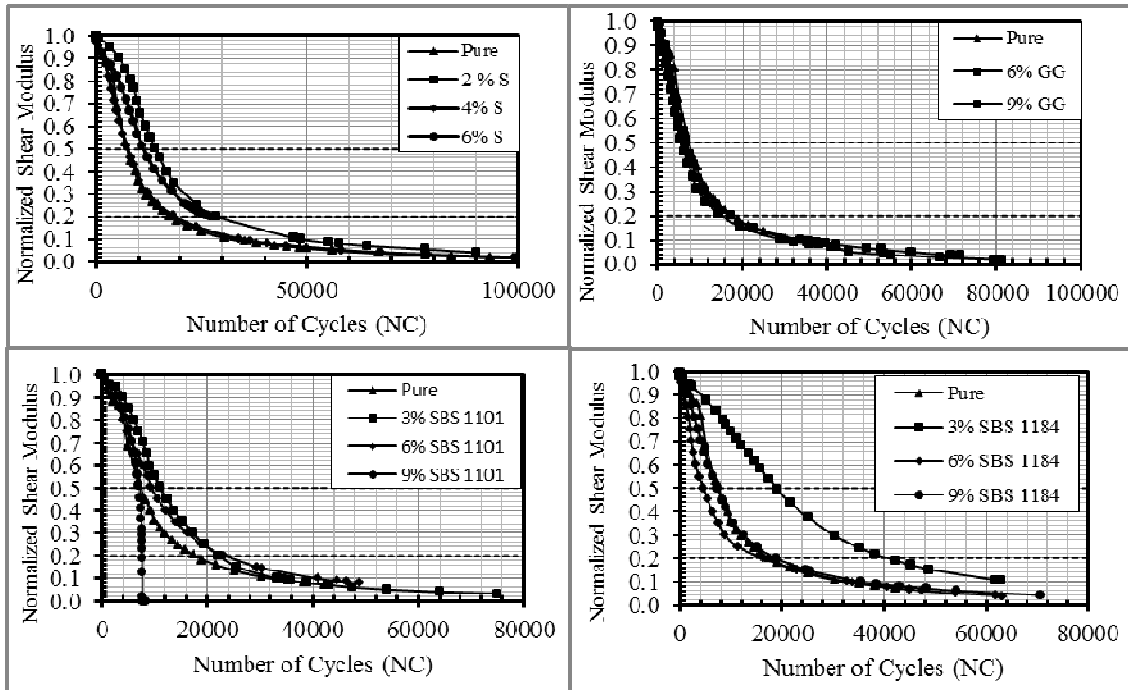


Figure A9. Normalised shear modulus against number of cycles at traditional approach.

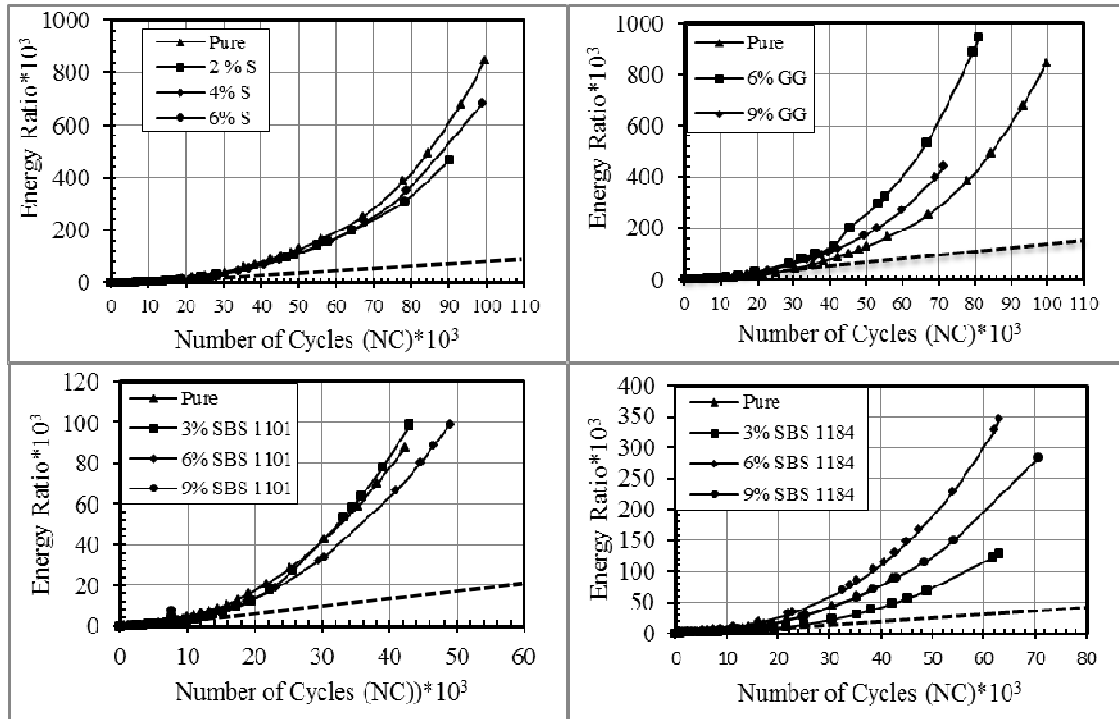


Figure A10. Energy ratio against number of cycles at energy approach.

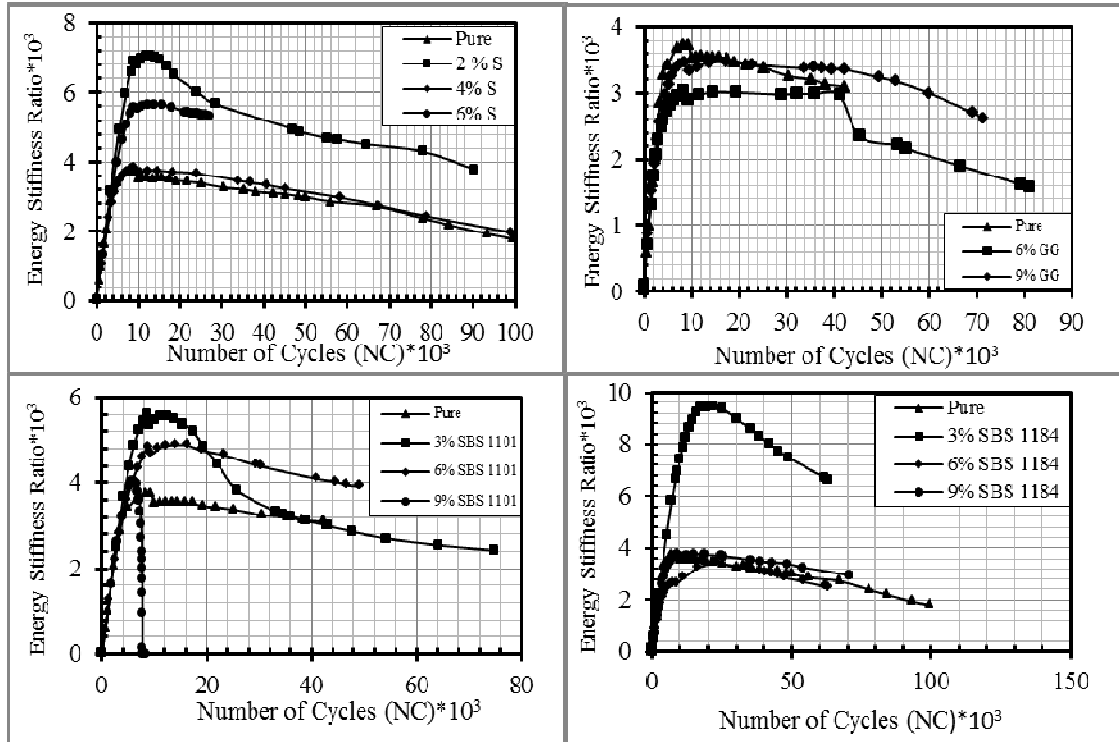


Figure A11. Energy stiffness ratio against number of cycles at energy stiffness approach.

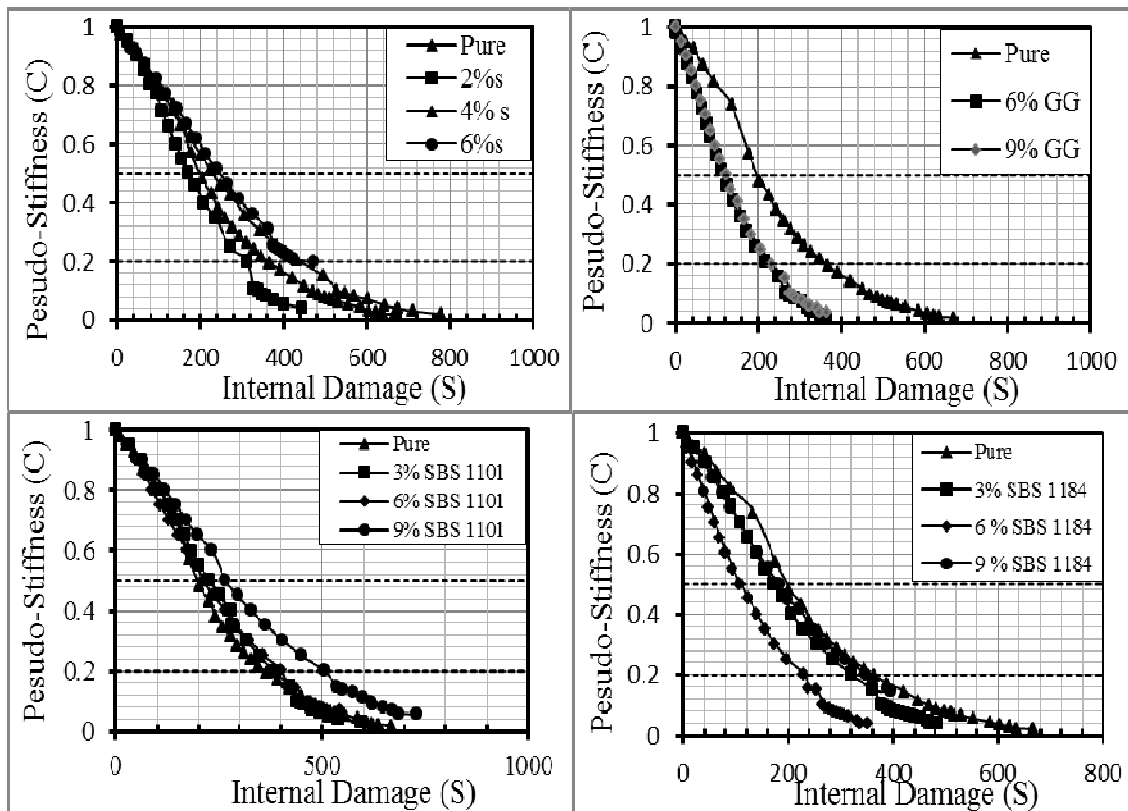


Figure A12. Pseudo-strain-based damage parameter of Durah asphalt binder.

Control stress mode

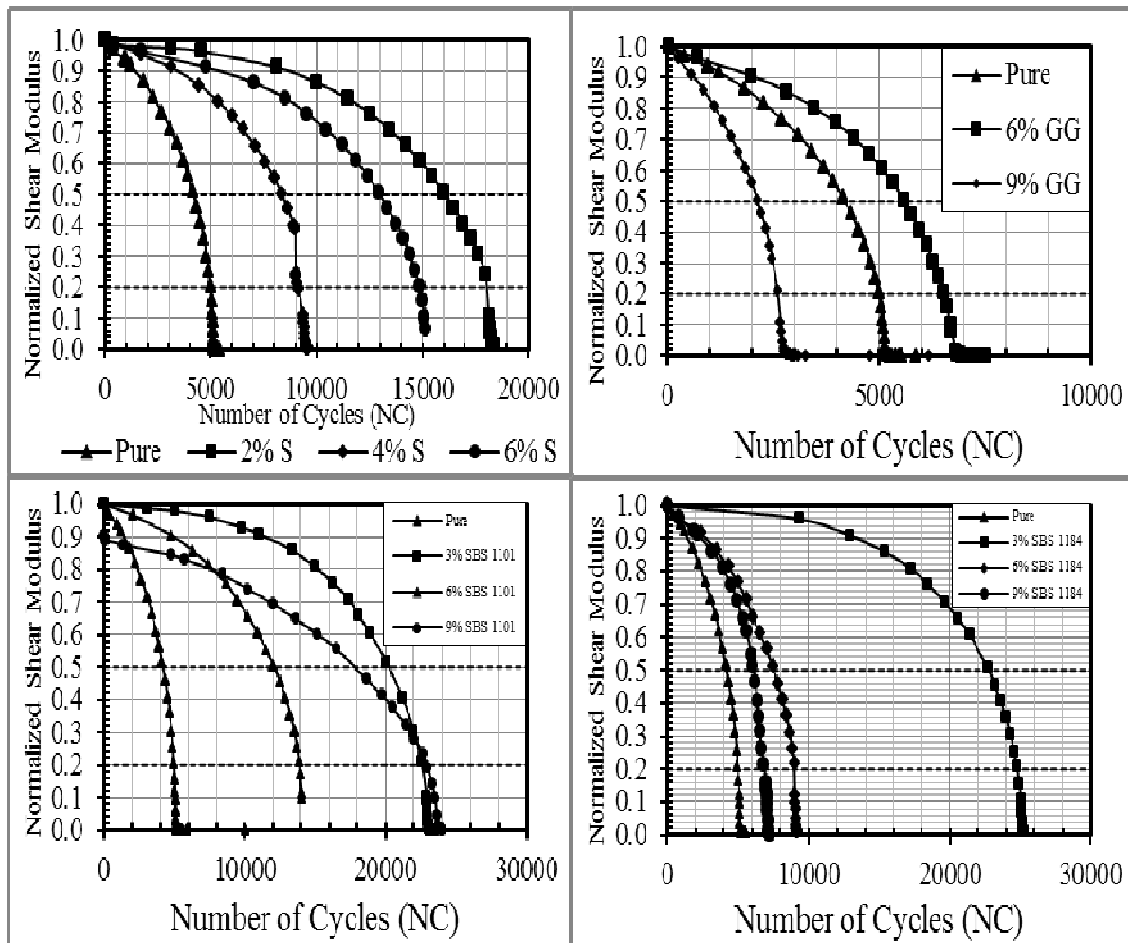


Figure A13. Normalised shear modulus against number of cycles at traditional approach.

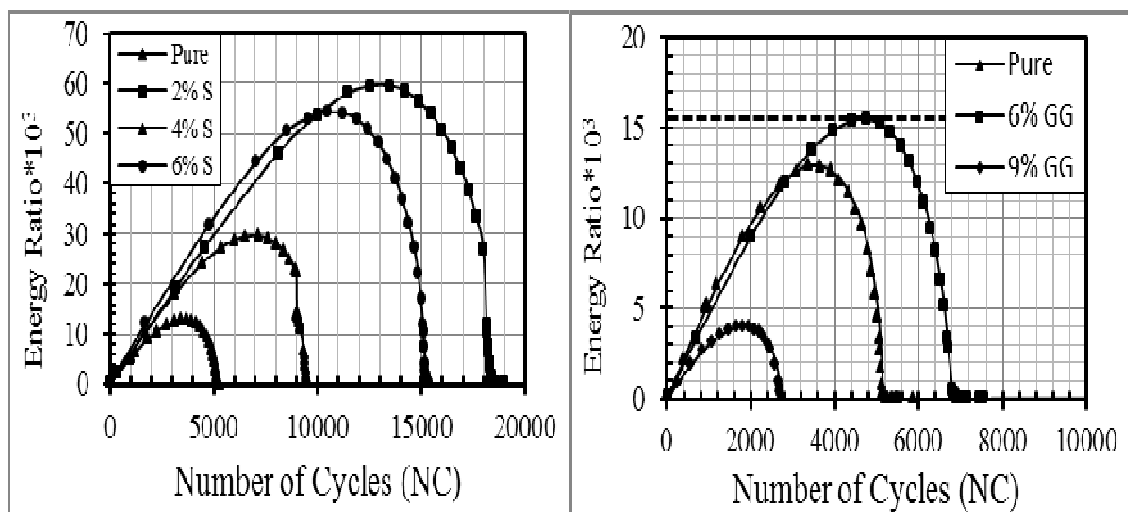


Figure A14. Energy ratio against number of cycles at energy approach.

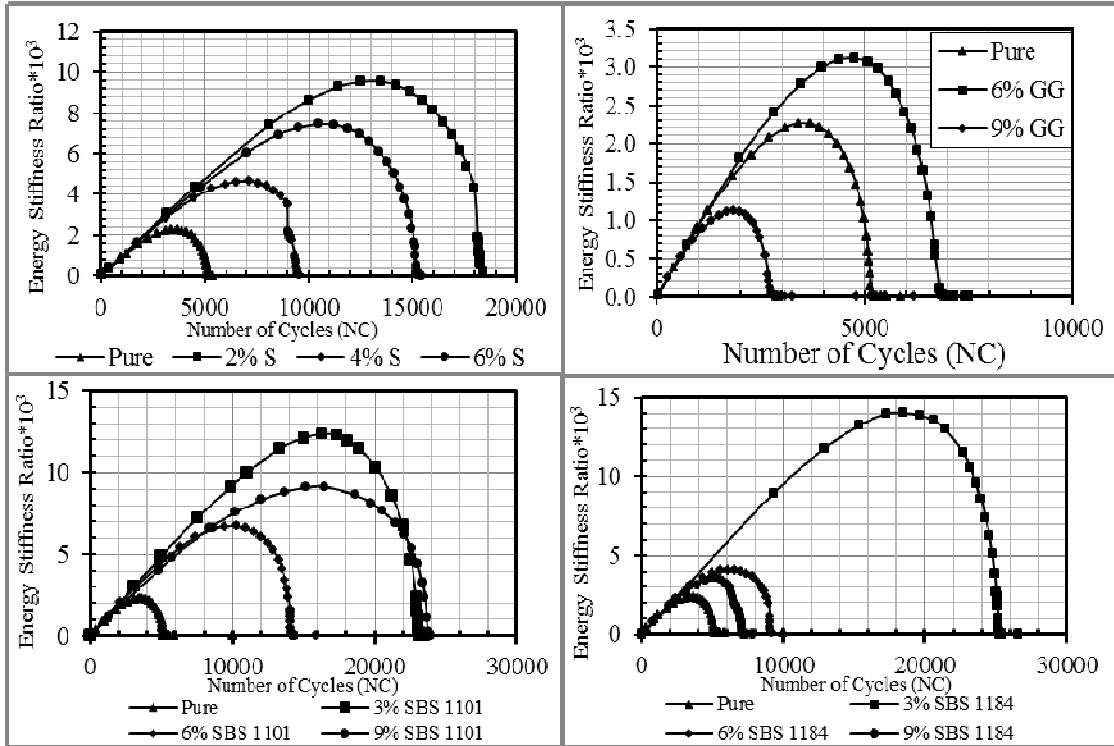


Figure A15. Energy Stiffness Ratio against number of cycles at energy stiffness approach.

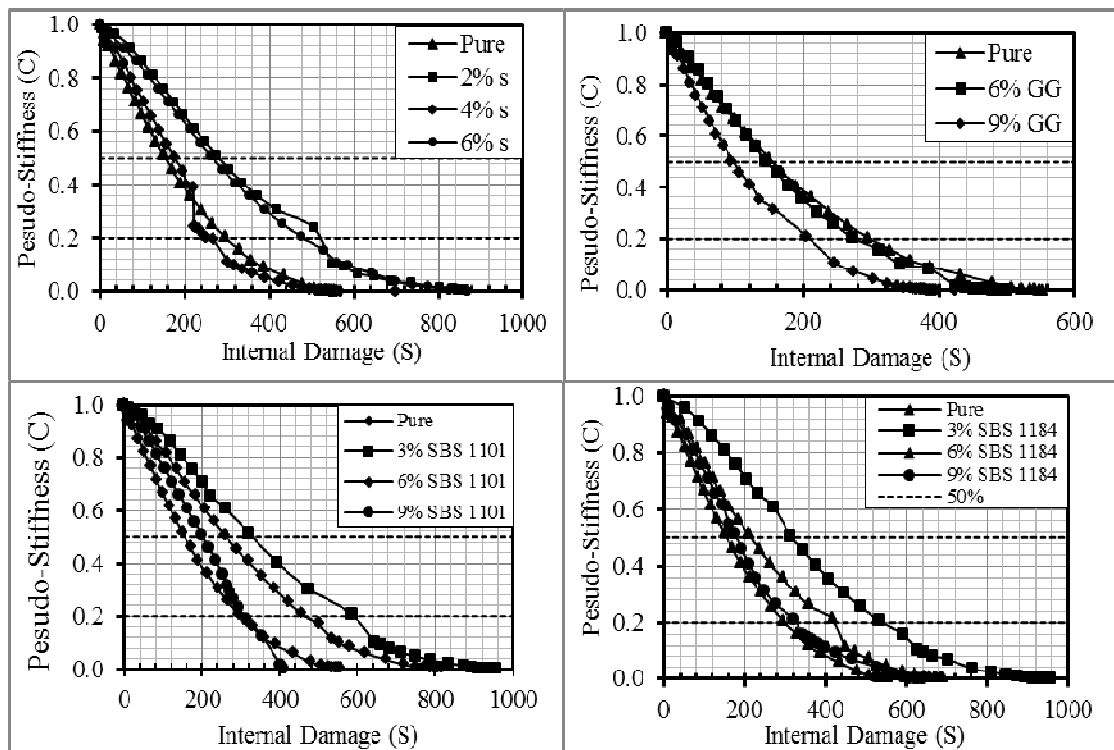


Figure A16. Pseudo-strain-based damage parameter of Durah asphalt binder.