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The Effect of Extended Aging, Modification, Strain Level and Temperature on the Fatigue Behavior of Asphalt Binders

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ABSTRACT

Fatigue cracking is considered one of the major distresses that occur in asphalt pavements, which can decrease the expected service life of this type of pavements. This study aimed at investigating the effect of aging, strain level, modification and temperature on the fatigue behavior of asphalt binders. To achieve the objectives of this study, a 60/70-penetration grade asphalt binder having a superpave performance grade of PG 64–16 and 4% Styrene-Butadiene-Styrene (SBS) modification was used in this study. Unmodified and modified asphalt binders were aged using the rolling thin-film oven (RTFO) test and pressure aging vessel (PAV). The PAV aging was conducted for four periods: 0, 20, 40 and 60 hrs, providing four PAV-aged asphalt binders named as: PAV0, PAV20, PAV40 and PAV60, respectively. Asphalt binders were tested using the dynamic shear rheometer (DSR) at a single loading frequency (10 Hz), four different temperatures (22, 25, 28 and 31°C) and four strain levels (5, 10, 15 and 20%). Findings of the study showed that increasing the aging period generally decreased the fatigue life of unmodified asphalt binders, particularly at lower temperatures (22 and 25°C). However, at higher temperatures (28 and 31°C), the fatigue life for 60-hr aging period was higher than that for 40-hr aging. The SBS modification increased the fatigue life of asphalt binders and showed an opposite trend to that of the unmodified asphalt binders at low temperatures. The strain level increase decreased the fatigue life for both unmodified and SBS-modified asphalt binders. However, the fatigue life reduction was higher at low strain levels. The effect of temperature on the fatigue life agreed with literature; the increase in the temperature resulted in a decrease in the fatigue life of asphalt binders for all aging periods and strain levels.

KEYWORDS: Asphalt binder, Fatigue, Strain level, Extended aging, Modification.

INTRODUCTION

Flexible pavements are commonly used around the world for their low cost and ease of construction. One of the major distresses occurring in these pavements is fatigue cracking, which is caused by the repeated load of traffic on a stiff layer of pavement mix. Aging of pavement mix during the service life of the road results in stiffening the mix and making it highly affected by fatigue cracking. As the aging process only affects the asphalt binder of the mix, the aging effect on the fatigue behavior of asphalt binders is to be considered in the design of flexible pavements.

There are several studies that have been conducted to investigate the behavior of fatigue cracking, the effect of aging on asphalt binders and the development of new testing methods in the Dynamic Shear Rheometer (DSR) regarding the fatigue behavior of asphalt binders. Furthermore, the effect of adding modifiers like Styrene-Butadiene-Styrene (SBS) on extending the fatigue life of pavements is taken into consideration.

Bahia et al. (1998) studied the non-linear fatigue behavior of asphalt binders accommodating large strains above the 20% used in linear analysis. The paper showed a parametric study of factors affecting the fatigue

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behavior of asphalt binders in non-linear state. The results showed that even in strains below 20%, non-linear analysis could be justified, as thin films used in DSR test showed non-linear behavior under 20% strains. Asphalt binder fatigue behavior was noticed to be highly sensitive to change in temperature, strain level and aging.

Zhou et al. (2012) evaluated fatigue behaviour of binders by using a ductility test machine based on the delayed elastic response of binders tested empirically or fundamentally by using the multiple stress creep recovery (MSCR) test using the DSR.

Abojaradeh (2013) developed a fundamental energy-based fatigue failure criteria methodology for hot mix asphalt using the dissipated energy approach, which is independent of the type of load control, temperature, mix and binder type.

Bergh and Ven (2012) studied the influence of aging on asphalt mixtures. A new test method was used by the DSR; this new method maintained a controlled stress loading. A 10-Hz frequency and a minimum temperature of 15ºC were used. The failure criterion was set to be the highest point in the curve of the complex modulus (G*) multiplied by the number of cycles *versus* the number of cycles. Based on their test, aged asphalt samples required more cycles to fail than those for unaged samples in the controlled stress test.

Lu et al. (2004) evaluated the fatigue characteristics of aged and unaged asphalt binders using the DSR in controlled strain setup. In their study, several types of asphalt binders were tested in both controlled stress and controlled strain modes. A 50% reduction of the initial complex modulus (G*) value was used as a failure criterion. The results showed that the aged asphalt binder had an increase in the slope of plotted log-log relation between the complex modulus and the number of load cycles; this indicated a higher probability of fatigue failure.

Al-Khateeb and Alqudah (2018) investigated the influence of laboratory aging on the fatigue performance of asphalt mixtures prepared using the superpave method. One type of asphalt binder (PG64-10) and one type of aggregate (limestone) were used. Loose mixtures were short-term aged (STA) in a draft oven at 135 C for 2 hours, 3 hours and 4 hours. A half of the tested samples were long-term aged (LTA) in a draft oven at 85ºC for time periods of 3 days, 5 days and 7 days. Fatigue test was performed on the test specimens using the Indirect Tensile Test (IDT). It was found that STA led to an increase in fatigue life at both test temperatures under stress-controlled mode in the Indirect Tensile Test (IDT) test. Nevertheless, the fatigue life increased as the LTA period increased from 3 to 5 days, but then it was reduced for 7-day long-term aging. Findings of the study also showed that the fatigue life increased as the temperature increased from 20 to 40º C.

Raad et al. (2001) assessed the effect of field aging on asphalt binder fatigue behavior and compared the results to laboratory aging. In this study, field-aged samples from ten years old pavements were used and tested at low temperatures. A simulation of longer aging than that described in AASHTO was also used to check for the behavior of over-aged asphalt. The results showed that aging increased the stiffness by 30%, which led to a higher chance of fatigue failure. Finally, a predictive model was constructed for new pavements that can predict the fatigue behavior of such asphalt during the service life of this pavement.

Dave et al. (2009) investigated the effect of temperature and aging on the graded viscoelastic model. This model replaced the layered model used in pavement design. This model assumed that the top layer of the pavement endures long-term aging, while the bottom layer endures short-term aging. Also, this model showed superiority over the other models in predicting the behavior of viscoelastic materials that have been aged at different temperatures.

Lu et al. (2009) evaluated the characteristics of aged polymer-modified asphalt binders. In their study, the effect of aging on SBS-modified asphalt binder was investigated. Samples of aged asphalt in the laboratory were compared to samples extracted from aged asphalt pavements. A validation between aging in the lab using the PAV and aging in the roads was conducted. The results showed that extending the aging process in the lab for 40 hours could duplicate severe aging in the real life. The study also showed that during the mixing and laydown of the asphalt mix, degradation of SBS occurred and reduced the effectiveness of this additive.

Mollenhauer et al. (2010) compared the laboratory aging of asphalt mixes with natural aging in the field. Four aging procedures were used in their study to simulate aging in the field to assess the durability and fatigue resistance of aged asphalt. The results showed that aging asphalt mixtures in conditions similar to aging asphalt binder using the PAV was the most appropriate way to simulate field aging. The results also assured that PAV aging of asphalt binder could be used to predict the fatigue behavior of asphalt mixes in the field.

Mitchell et al. (2009) investigated the effect of long-term aging of asphalt binder on rubberized asphalt binders. In their study, four aging methods were used, including PAV for 20 and 40 hours. A fatigue life of rubberized asphalt binder was carried out to check the effects of aging on these asphalt binders. The results showed that adding rubber to the asphalt increased its fatigue resistance after aging. The results of PG 64-22 asphalt binder with rubber of 10% were similar to those of PG 76-22 in terms of fatigue resistance.

Wright et al. (2011) assessed the effect of oxidization aging on asphalt binder. The study aimed to verify the current standards used by the superpave (RTFO and PAV) and their applicability in field aging. Asphalt samples were extracted from different aged sections of the same environmental conditions and compared with different aged samples prepared in the laboratory. The results showed that the current methods for aging are good enough for poor fatigue-resisting asphalts. However, modified asphalts need an extended PAV aging time (40 hours) to simulate field aging.

Objectives

The main objectives of this study are to:

1. Study the fatigue behavior of aged asphalt binders.
2. Investigate the fatigue behavior for different PAV aging periods at different strain levels.
3. Assess the combined effect of strain level and temperature on the fatigue behavior of asphalt binders.
4. Compare the fatigue behavior of unmodified asphalt binders with that of the modified asphalt binders at different testing temperatures.

Materials

Asphalt Binders

To achieve the objectives of this study, two types of asphalt binders were used; the first one is a fresh asphalt binder without any modification having a penetration grade of 60/70 and superpave grade of PG 64-16, while the second one is a modified asphalt binder using 4% Styrene-Butadiene-Styrene (SBS).

The Styrene-Butadiene-Styrene (SBS) is a compound used to improve the behavior of asphalt binder during the service life of the pavement. In the literature, it was shown that SBS can improve the superpave grading of poorly graded asphalt. The effect of SBS enhances both the high and low temperature performances of asphalt binders. Motamed et al. (2013) also showed that a 4% SBS is the optimum percentage that can improve the behavior of asphalt binder.

The two asphalt binders were aged using the Rolling Thin-Film Oven (RTFO) test at the standard test temperature of 163°C for 75 minutes. This is the first part of aging; the test samples obtained at this stage, because they were not aged using the Pressure Aging Vessel (PAV), were named PAV0. The second part of the aging process is the PAV aging; asphalt binders were aged at 100°C and 300 psi for 20 hours. These samples were denoted as PAV20. The asphalt samples residues from the 20-hour PAV aging were used in the third stage, where they were aged again in the PAV for additional 20 hours at 100°C and 300 psi; the aged asphalt binders from this stage were denoted as PAV40. The residues from the 40-hour aging were aged in the PAV for additional 20 hours at 100°C; the asphalt binders from this last stage were denoted as PAV60. Table 1 shows a summary of these asphalt binders used in the study.

Table 1. Naming code for asphalt samples

Code	PAV Aging (hr)	Representation in life
PAV0	0 (RTFO only)	Pavement roads when open to traffic
PAV20	20	Pavement roads after 7-10 years of service
PAV40	40	Pavement roads after 14-20 years of service
PAV60	60	Pavement roads after 21-30 years of service

METHODOLOGY

PG Grading of Asphalt Binders

Four types of superpave tests were used and conducted according to the AASHTO standard test methods described in (AASHTO R 28 [2012], AASHTO T 240 [2013], AASHTO T 313 [2012] and AASHTO T 315 [2010]) to grade the asphalt binder according to the flow chart shown in Figure 1.

Table 2 summarizes the PG grading results for the unmodified asphalt binder and the SBS-modified asphalt binder after testing both binders using the required superpave tests at the specified temperatures according to the standard procedures mentioned above.

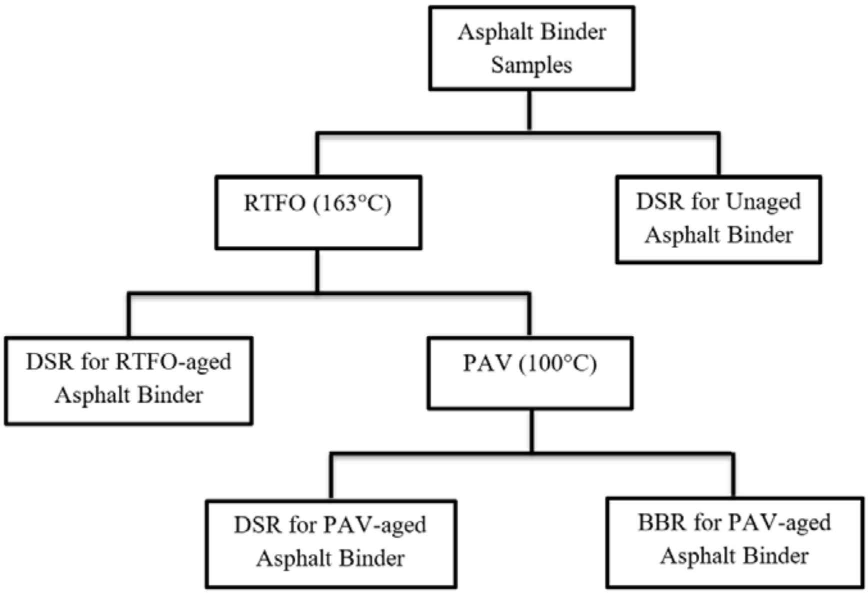

Figure (1): PG grading flowchart

Table 2. PG grading results for unmodified and SBS-modified asphalt binders

Test Type	Unmodified Asphalt Binder	SBS-modified Asphalt Binder	Superpave Criteria
Mass Loss	0.33%	0.68%	Mass Loss ≤ 1%
DSR for Unaged Binder	64°C	70°C	G*/sinδ ≥ 1 kPa
DSR for RTFO-aged Binder	64°C	76°C	G*/sinδ ≥ 2.2 kPa
DSR for PAV-aged Binder	25°C	25°C	G*sinδ ≤ 5000 kPa
BBR for PAV-aged Binder	-6°C	-12°C	m-value ≥ 0.3 and S ≤ 300 MPa
PG Grading	PG 64-16	PG 70-22	

DSR Testing of Asphalt Binders

PAV-aged asphalt binder samples were tested at four different intermediate temperatures: 22, 25, 28 and 31°C selected according to the superpave specifications of asphalt binder grading (classification) for PG 64. These temperatures represent the service temperatures that the pavement encounters during its service life. At each temperature, asphalt binder samples were also tested at four strain levels to investigate the effect of strain level on the failure criteria. The selected strain levels were: 5, 10, 15 and 20% representing strains in the linear range and can be linked to the design traffic during service life.

A single frequency DSR test was used to evaluate the fatigue behavior of asphalt binders. The DSR test was conducted at the selected temperature using a controlled strain and constant frequency of 10 Hz. In the DSR test, the lower plate is fixed and the upper plate rotates to the right for a quarter of a cycle, then rotates back to its original location. Then, it rotates to the left a quarter of a cycle before going back to its original location. Each complete movement is considered as one cycle of testing. In this study, a constant loading frequency of 10 Hz was used. The complex modulus (G*) value and the phase angle (δ) were obtained from the test. 3000 points were noted to be sufficient to obtain the expected failure in each sample. This number was selected by a trial-and-error procedure to ensure reaching the failure criteria chosen for this study. Figure 2 shows the setting of the DSR test used in this study and Table 3 shows the final testing matrix used in this study. Full report of this research work can be found in Khader (2015).

ANALYSIS AND DISCUSSION OF RESULTS

For the purpose of this study, the fatigue failure criterion was set to be the number of cycles (Nf) to reach 50% reduction in the complex modulus (G*) value of the asphalt binder although dissipated energy concepts have been used for asphalt mixtures (Ghuzlan and Carpenter, 2006). The effect of aging, temperature, strain level and SBS modification on the fatigue failure is described in this part.

Data Obtained

The data obtained from the DSR needs to be reduced before it can be used in the analysis. The first step is to calculate the number of cycles using the following equation:

$$Number\ of\ Cycles = Time\ obtained\ from\ DSR \times\ frequency \quad (1)$$

Table 3. Testing matrix used to achieve the study objectives

Parameter	Number	Notes
Asphalt Binder Types	2	Unmodified and Modified (SBS)
Aging Periods (hr)	4	PAV0, PAV20, PAV40, PAV60
Testing Temperatures (°C)	4	22, 25, 28, 31
Strain Levels (%)	4	5, 10, 15, 20%
Total	2×4×4×4	128

The frequency used in this study was 10 Hz. The initial complex modulus was assumed to be the complex modulus value at 200 cycles to allow the asphalt sample to stabilize and start giving acceptable data. The final complex modulus value is simply 50 percent of the initial complex modulus value based on the criterion used in this study. From the final complex modulus value, the number of cycles to failure was determined.

Figure 3 shows the results and computations for an unmodified RTFO-aged asphalt binder sample at 28°C and 20% strain level.

In Figure 3, the initial complex modulus is 3.99 MPa. The final complex modulus is then 3.99/2 = 1.995 MPa. The corresponding number of cycles (447 cycles) is then set to be the number of cycles to fatigue failure (Nf) for this sample.

Data Analysis

The analysis of data is composed of three types:

The effect of aging on fatigue failure (Nf).

The effect of temperature on fatigue failure.

The effect of strain level on fatigue failure.

These three types of analysis were performed for both unmodified and SBS-modified asphalt binders.

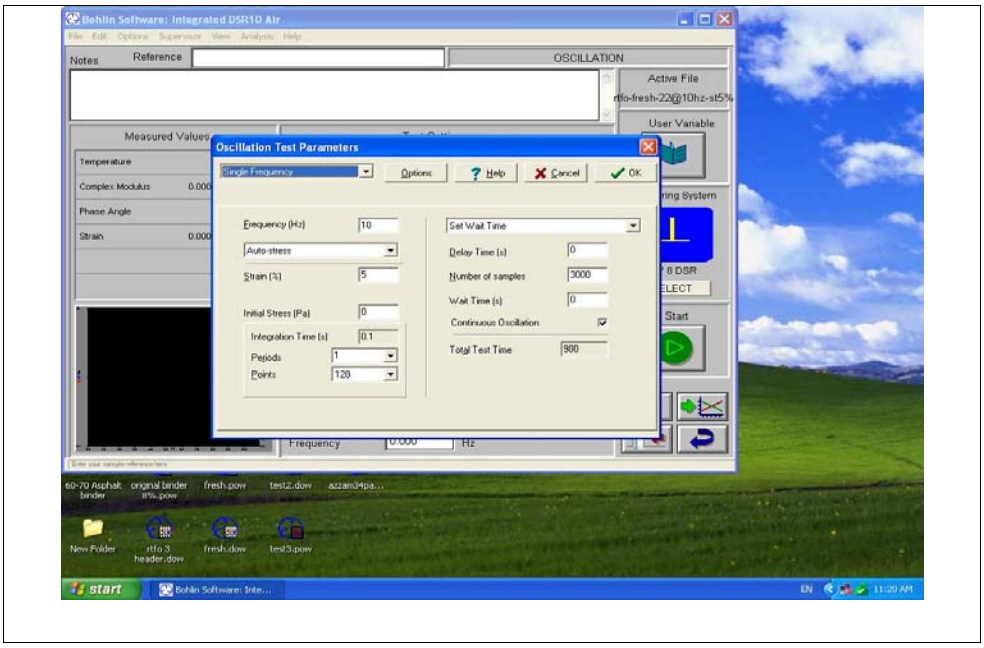

Figure (2): Setting parameters for the DSR test

	A	B	C	D	E	F	G
1							
2							
3	Point	Cycle Number	Time	Strain	Complex Modulus	Shear Stress	Phase Angle
4	1	10.35	1.035	7.68E-02	5.00E+06	9.95E+04	50.07
5	2	23.52	2.352	8.64E-02	4.99E+06	9.95E+04	52.41
6	3	36.57	3.657	9.16E-02	4.93E+06	9.96E+04	53.08
7	4	49.04	4.904	9.56E-02	4.93E+06	9.95E+04	53.48
8	5	62.15	6.215	9.93E-02	4.91E+06	9.95E+04	53.86
9	6	75.32	7.532	1.03E-01	4.79E+06	9.94E+04	54.11
10	7	88.48	8.848	1.06E-01	4.69E+06	9.95E+04	54.43
11	8	101.63	10.163	1.07E-01	4.64E+06	9.95E+04	54.61
12	9	114.68	11.468	1.09E-01	4.58E+06	9.95E+04	54.79
13	10	127.17	12.717	1.11E-01	4.51E+06	9.95E+04	54.97
14	11	139.67	13.967	1.14E-01	4.43E+06	9.94E+04	55.11
15	12	152.77	15.277	1.18E-01	4.42E+06	9.94E+04	55.33
16	13	165.94	16.594	1.24E-01	4.18E+06	9.95E+04	55.64
17	14	179.05	17.905	1.30E-01	4.13E+06	9.95E+04	56.01
18	15	192.19	19.219	1.38E-01	4.07E+06	9.95E+04	56.35
19	16	205.3	20.53	1.47E-01	4.06E+06	9.94E+04	56.69
20	17	218.48	21.848	1.60E-01	3.99E+06	9.95E+04	57.11
21	18	251.59	25.159	1.76E-01	3.27E+06	9.95E+04	57.46
22	19	337.3	33.73	1.93E-01	2.05E+06	9.95E+04	57.85
23	20	447.03	44.7	2.01E-01	1.97E+06	9.95E+04	58.04

Figure (3): Procedure to determine the number of cycles at failure (N_f)

Aging Effects on Fatigue Failure

The aging process used for this study simulates the oxidization process occurring in the field. As the asphalt binder ages, higher stiffness is reached and thus a sudden failure occurs. In this study, four aging periods were used to simulate the effect of extended field aging. The results for the effect of aging of unmodified asphalt samples are shown in Figure 4 (a, b, c and d) for different testing temperatures.

Results showed that the RTFO-aged asphalt binders (PAV0) have lower numbers of cycles to failure compared to the asphalt binders aged using other aging processes (PAV20, PAV40 and PAV60). This is due to the low initial complex modulus that the RTFO-aged asphalt binders have. RTFO-aged asphalt binders with very low stiffness cannot be tested using the DSR as seen in the literature; in other words, the asphalt binder will fail for fatigue quickly if aged only using the RTFO.

For the other aging periods, at low temperatures (22 and 25°C), the fatigue life decreases as the aging period increases due to the fact that the asphalt binder becomes stiffer (brittle) and as a result fails rapidly with extended aging periods.

Figure 4 represents the relationship between aging and fatigue resistance for unmodified asphalt binders. The relationship between aging and fatigue resistance seems to be clear at the lower temperature range (22 and 25°C). The fatigue life increases as the aging time increases up to an optimum value at the 20-hr aging time. However, this relationship was vague for the higher temperature range (28 and 31°C). In other words, the number of cycles to fatigue failure (fatigue life) for asphalt binders aged for 40 hrs was found to be less than that for asphalt binders aged for 60 hrs. This can be explained by the stiffening effect of the asphalt binder at higher aging time to the extent that the asphalt binder becomes too stiff to resist fatigue cracking. In general, the variability of the data becomes higher at higher temperatures and that could contribute to the unclear trend at these temperatures.

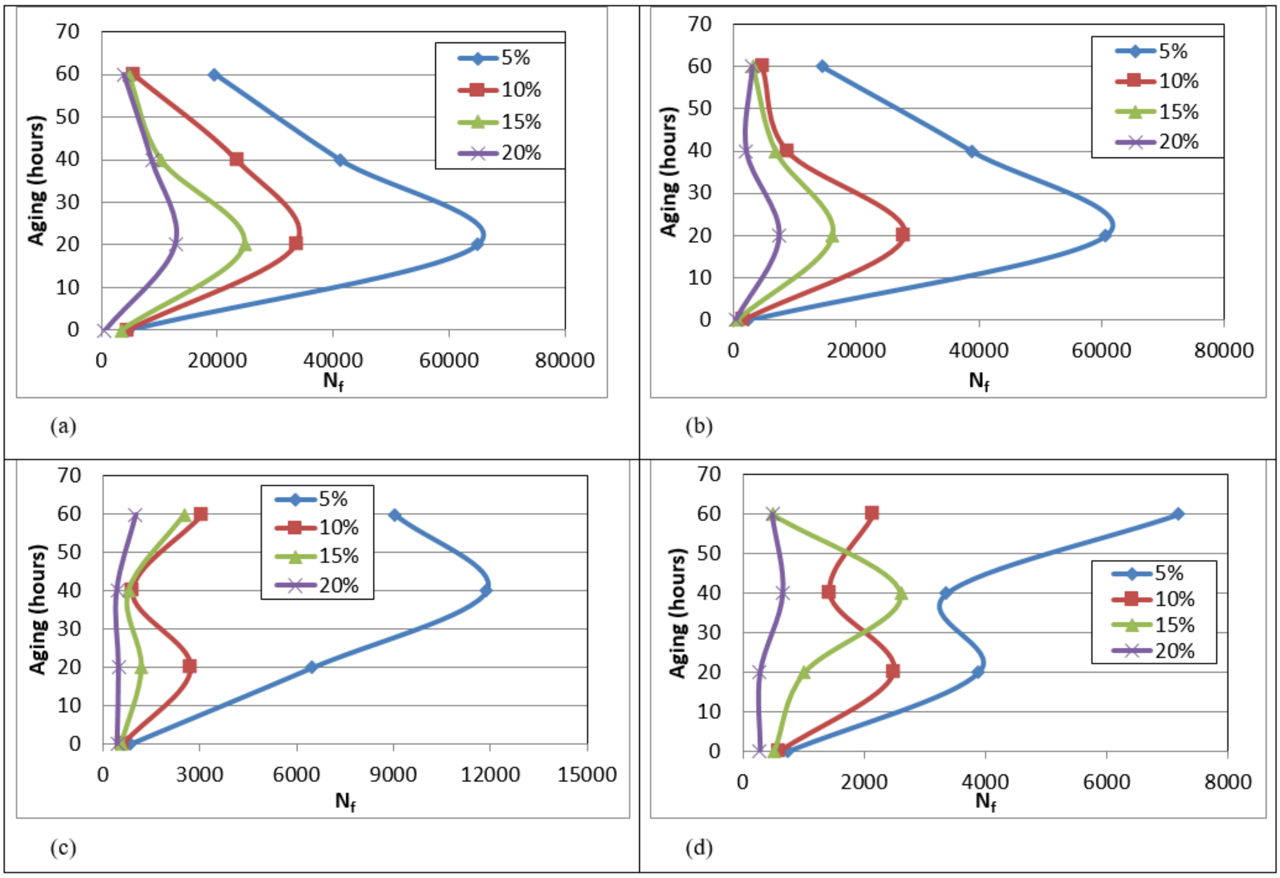

Figure (4): Effect of aging on fatigue failure for unmodified asphalt binder at a) 22°C, b) 25°C, c) 28°C and d) 31°C

The results of the effect of aging on fatigue failure for 4% SBS-modified asphalt binders are illustrated in Figure 5 (a, b, c and d). The results for SBS-modified asphalt binders showed an opposite trend to those of unmodified asphalt binders. At low temperatures (22 and 25°C), the number of cycles to failure for the 60-hr-aged asphalt binder is higher than that for the 40-hr-aged asphalt binder. This result is similar to the result at high temperatures for the unmodified asphalt binders. This is due to the improvement of the SBS modifier on the low PG grade that enhanced the fatigue resistance. Asphalt binders aged for 60 hrs have an extremely high stiffness at low temperatures and this high stiffness results in extending the number of cycles to fatigue failure. However, at higher temperatures (28 and 31°C), lower numbers of cycles to failure with increasing aging period can be obtained. This can be only explained by the interaction between the temperature, SBS modification and extended aging effects.

The above findings revealed that asphalt binders experiencing higher aging periods resist fatigue cracking more than asphalt binders aged less. The maximum limit set by the superpave for fatigue failure is 5,000 kPa for the G*Sin δ value; this limit only ensures lower stiffness than the failure stiffness obtained in the laboratory. However, this criterion neither takes into account the behavior during the life of asphalt pavement nor higher stiffness values that can resist fatigue without failure.

The SBS modification increased the fatigue life of asphalt binders at all temperatures and strain levels. SBS modification and other additives were used in several studies of the literature (Motamed et al., 2013; Lu et al., 2009; Mitchell et al., 2009; Al-Khateeb et al., 2005) and the findings of these studies supported this finding.

Strain Level Effects on Fatigue Failure

Different strain levels were chosen in the linear range (below 20%) to evaluate the effect of aging of asphalt binder on fatigue failure. Four strain levels were chosen for each aging level and the results are shown in Figure 6 (a, b, c and d) for the unmodified asphalt binders.

Results showed a power relation between the applied strain level and the number of cycles to failure for all temperatures and aging levels.

The increase in the strain level resulted in a decrease in the number of cycles to fatigue failure (fatigue life reduction) following a power trend. In real world, this means that the strain level induced into the asphalt pavement is very crucial to control its fatigue life in all aging stages. For instance, at 20-hr aging, the fatigue life for the unmodified asphalt binder at 22°C decreased by about 53 percent when the strain level increased from 5 to 10%. Another example at 60-hr aging shows that the fatigue life for the unmodified asphalt binder at 28°C decreased by approximately 64 percent when the strain level increased from 5 to 10%. The fatigue life reduction results for the unmodified asphalt binders are presented in Table 4.

Table 4. Fatigue life reduction with strain level for unmodified asphalt binders

Aging Period (hr)	0				20				40				60			
	T = 22C															
Strain Level	k_1	k_2	N_f	Reduction (%)	k_1	k_2	N_f	Reduction (%)	k_1	k_2	N_f	Reduction (%)	k_1	k_2	N_f	Reduction (%)
0.05	179.46	-1.205	6633.0		2588.0	-1.095	68801		1270.7	-1.180	43577		518.62	-1.164	16953	
0.10			2877.2	56.6			32208	53.2			19233	55.9			7566	55.4
0.15			1765.1	38.7			20661	35.9			11919	38.0			4719	37.6
0.20			1248.0	29.3			15078	27.0			8488	28.8			3376	28.5

	T = 25C															
0.05	25.59	-1.597	3060.3		882.24	-1.445	66923		116.21	-1.940	38837		389.64	-1.167	12852	
0.10			1011.6	66.9			24580	63.3			10122	73.9			5724	55.5
0.15			529.4	47.7			13682	44.3			4609	54.5			3566	37.7
0.20			334.4	36.8			9028	34.0			2638	42.8			2549	28.5
	T = 28C															
0.05	236.66	-0.421	835.3		33.95	-1.802	7503		8.24	-2.330	8855		118.32	-1.453	9193	
0.10			623.9	25.3			2152	71.3			1761	80.1			3358	63.5
0.15			526.0	15.7			1036	51.8			685	61.1			1863	44.5
0.20			466.0	11.4			617	40.5			350	48.8			1227	34.2
	T = 31C															
0.05	137.27	-0.593	811.1		26.18	-1.770	5258		246.17	-0.878	3416		13.28	-2.112	7428	
0.10			537.7	33.7			1542	70.7			1859	45.6			1718	76.9
0.15			422.8	21.4			752	51.2			1302	30.0			730	57.5
0.20			356.5	15.7			452	39.9			1011	22.3			398	45.5

Generally, it can be noted that the reduction values in fatigue life for the unmodified asphalt binders as the strain value increased from one level to another level decreased continuously with the increase in the strain level. In other words, the fatigue life reduction values are smaller at higher strain levels. That is valid for all aging periods and temperatures. There is no specific trend for the fatigue life reduction values from temperature to another temperature or from aging period to another aging period for all strain levels.

The results for the effect of strain level on the SBS-modified asphalt binders with aging are shown in Figure 7 (a, b, c and d). These figures showed a fatigue behavior similar to that for the unmodified asphalt binder. This means that the same power relations are obtained for all aging levels and temperatures.

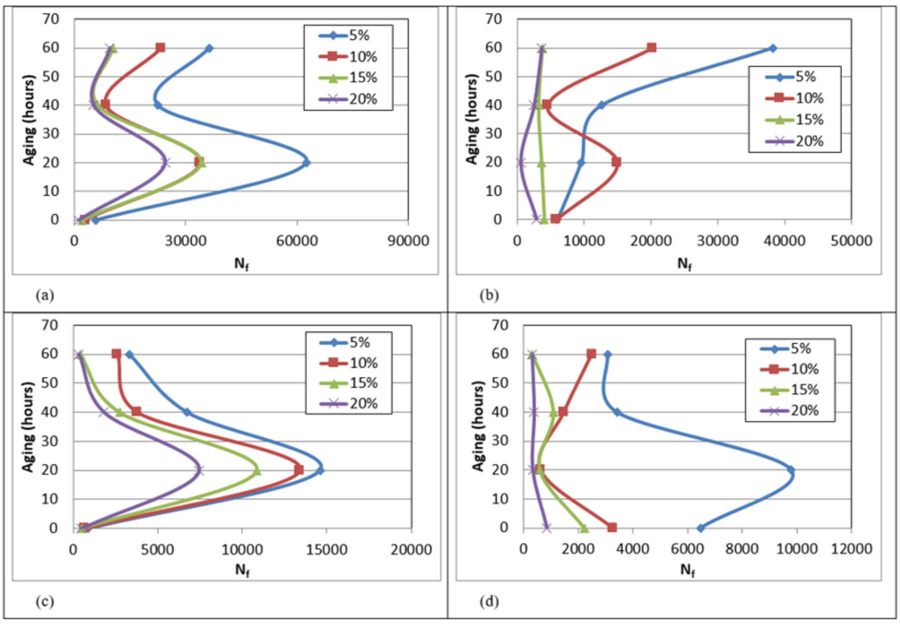

Figure (5): Effect of aging on fatigue failure for SBS-modified asphalt binder at a) 22°C, b) 25°C, c) 28°C and d) 31°C

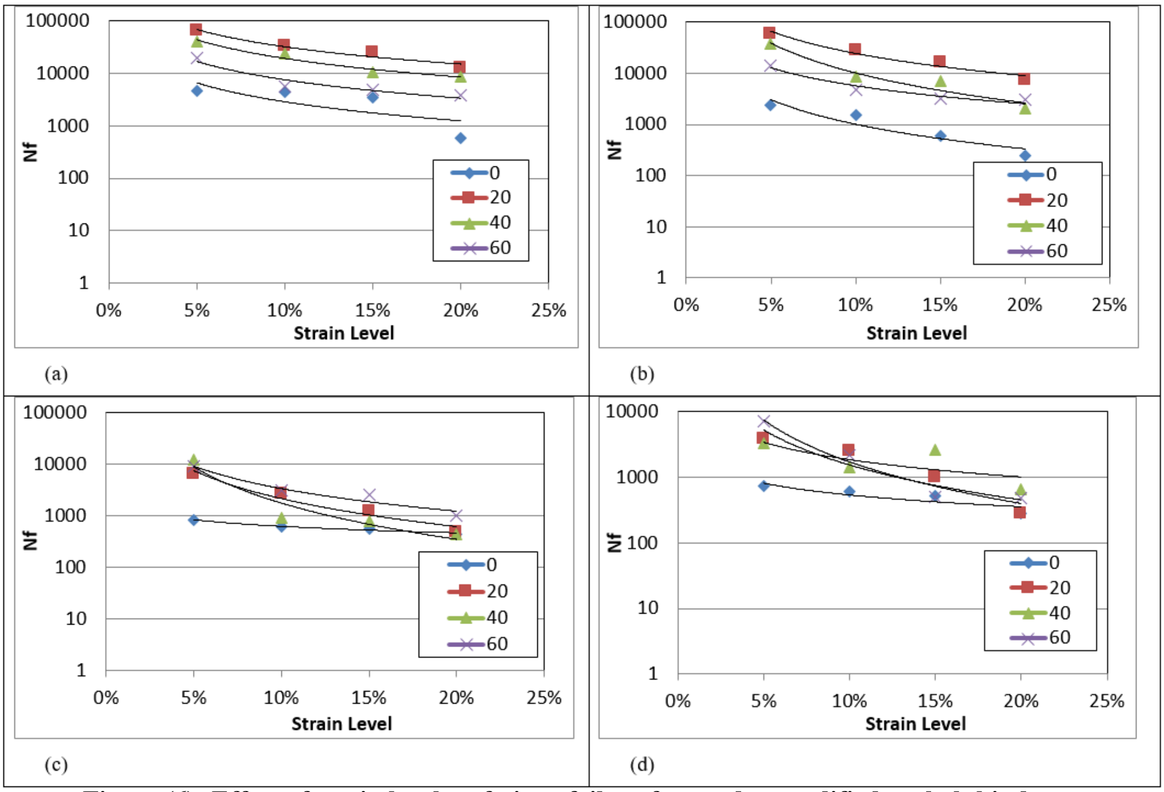

Figure (6): Effect of strain level on fatigue failure for aged unmodified asphalt binder at a) 22°C, b) 25°C, c) 28°C and d) 31°C

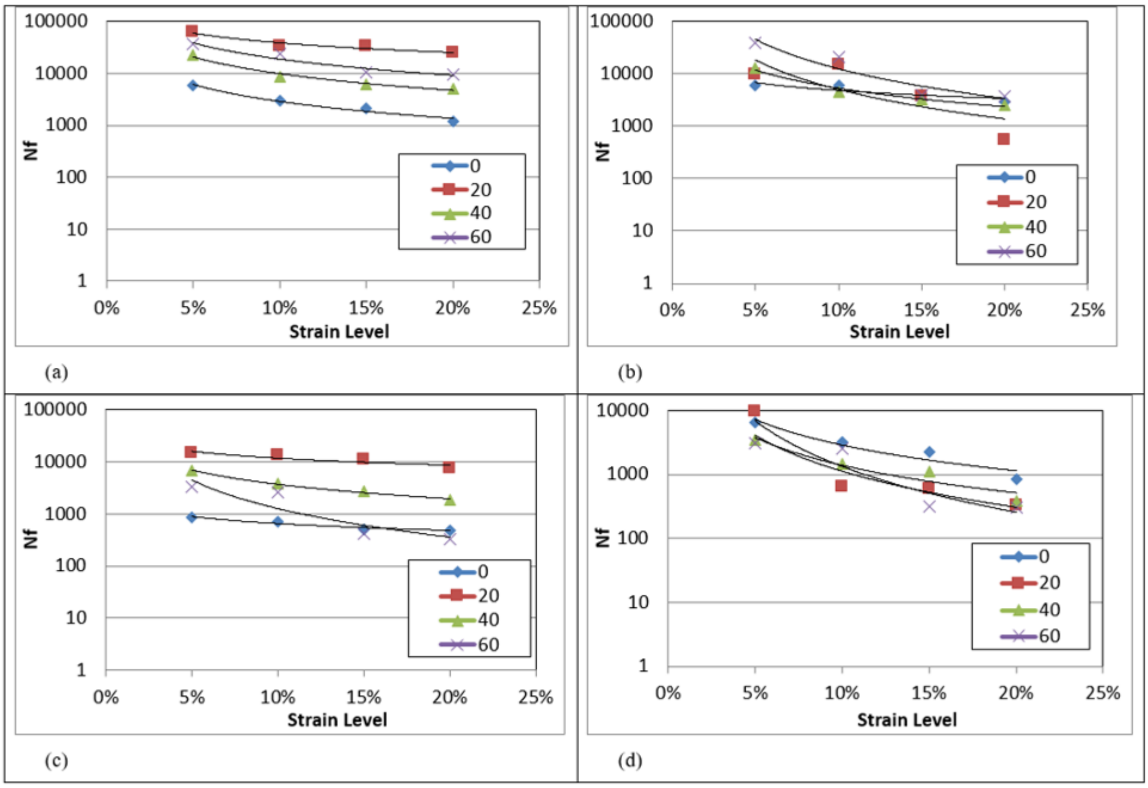

Figure (7): Effect of strain level on fatigue failure for aged SBS-modified asphalt binder at a) 22°C, b) 25°C, c) 28°C and d) 31°C

In a similar manner, the increase in the strain level resulted in a reduction in fatigue life. As shown in Table 5, the reduction in fatigue life for the SBS-modified asphalt binder at 20-hr aging and 31°C was about 81 percent when the strain level increased from 5 to 10%. However, it was smaller (about 50 percent) when the strain level increased from 15 to 20% for the same asphalt binder at the same conditions. The reduction values in fatigue life for the SBS-modified asphalt binders as the strain value increased from one level to another level decreased constantly with the increase in the strain level; i.e., at higher strain levels, the fatigue life reduction values are smaller and this is true for all aging periods and temperatures. There is no explainable trend for the fatigue life reduction values from temperature to another temperature or from aging period to another aging period for all strain levels for the SBS-modified asphalt binders as well.

Table 5. Fatigue life reduction with strain level for SBS-modified asphalt binders

Aging Period (hr)	0				20				40				60			
	T = 22C															
Strain Level	k_1	k_2	N_f	Reduction (%)	k_1	k_2	N_f	Reduction (%)	k_1	k_2	N_f	Reduction (%)	k_1	k_2	N_f	Reduction (%)
0.05	237.38	-1.087	6161		9296.7	-0.622	59920		846.88	-1.069	20827		1742.4	-1.037	38933	
0.10			2900	52.9			38934	35.0			9927	52.3			18974	51.3
0.15			1867	35.6			30255	22.3			6436	35.2			12461	34.3
0.20			1365	26.9			25298	16.4			4732	26.5			9247	25.8
	T = 25C															
0.05	1493.7	-0.503	6740		67.57	-1.868	18201		359.76	-1.163	11725		165.36	-1.871	44943	
0.10			4756	29.4			4986	72.6			5236	55.3			12287	72.7
0.15			3879	18.4			2338	53.1			3268	37.6			5754	53.2
0.20			3356	13.5			1366	41.6			2338	28.4			3359	41.6
	T = 28C															
0.05	234.55	-0.444	887		4246.4	-0.442	15962		449.63	-0.915	6971		19.14	-1.819	4451	
0.10			652	26.5			11750	26.4			3697	47.0			1262	71.7
0.15			545	16.5			9822	16.4			2551	31.0			603	52.2
0.20			479	12.0			8649	11.9			1961	23.1			358	40.7
	T = 31C															
0.05	133.33	-1.336	7296		5.63	-2.376	6948		51.39	-1.435	3783		15.12	-1.873	4134	
0.10			2890	60.4			1338	80.7			1399	63.0			1129	72.7
0.15			1681	41.8			511	61.8			782	44.1			528	53.2
0.20			1145	31.9			258	49.5			518	33.8			308	41.7

Temperature Effects on Fatigue Failure

Temperature variation affects the stiffness of asphalt binder; lower temperatures result in higher stiffness. According to the results of this study, higher stiffness at the intermediate temperature range for fatigue cracking considered in this study (22 to 31°C) provided higher fatigue resistance. This is valid for all strain levels (5, 10, 15 and 20%) and also for all aging periods (0, 20, 40 and 60 hrs). An example of this behavior is shown in Figure 8 for PAV20 unmodified asphalt binder and another example is illustrated in Figure 9 for PAV40 SBS-modified asphalt binder.

The results showed a power relationship between the temperature and the number of cycles to fatigue failure for all aging periods and strain levels. As the temperature increases, a lower stiffness (complex modulus value) is obtained for the asphalt binder; hence, a lower number of cycles to fatigue failure is also obtained.

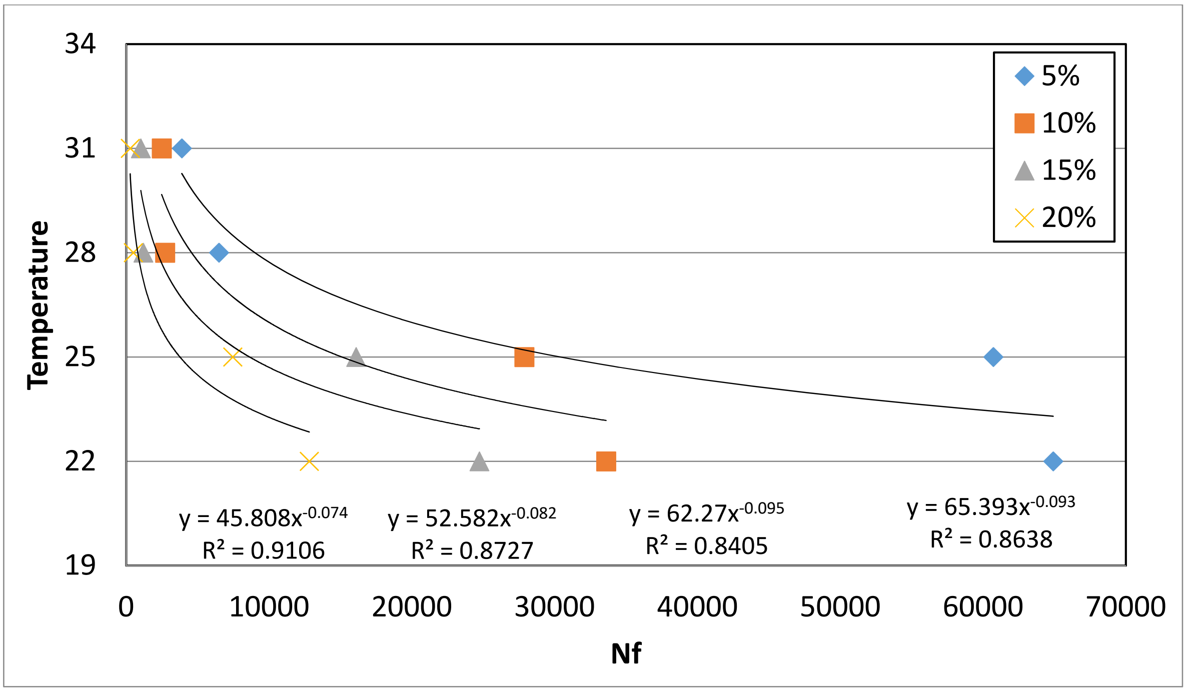

Figure (8): Effect of temperature on fatigue failure for PAV20-aged unmodified asphalt

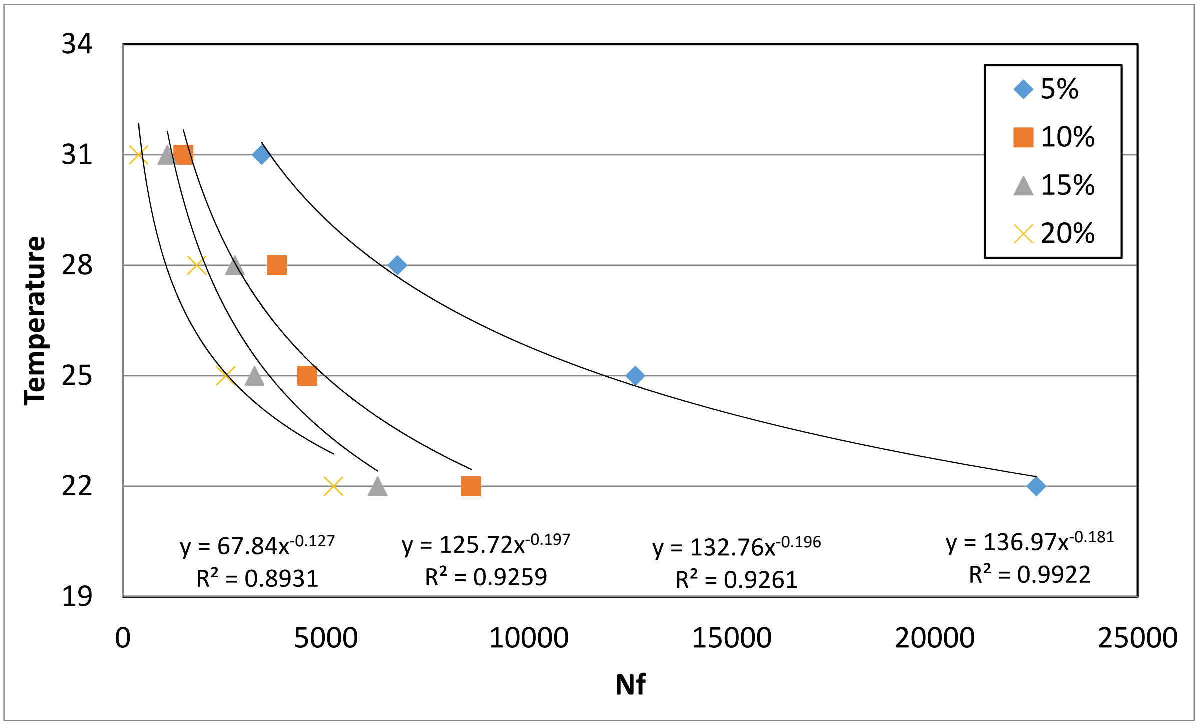

Figure (9): Effect of temperature on fatigue failure for PAV40-aged SBS-modified asphalt

The same phenomenon is noticed when the aging period is plotted with the number of cycles to fatigue failure at different temperatures. At lower temperatures, the fatigue life is longer and *vice versa*. That is valid for the unmodified asphalt binders as well as the SBS-modified asphalt binders at all strain levels (5, 10, 15 and 20%). An example per each type of asphalt binder is shown in Figures 10 and 11. The results for the SBS-modified asphalt binders showed a similar behavior to that of the unmodified asphalt binders although the R^2 value for the power relationships of the modified asphalt binders was smaller.

The complex modulus results also showed a power relationship between the complex modulus value and the strain level at different temperatures. An example for this behavior is shown in Figure 12 for PAV60 unmodified asphalt binder. Increasing the strain level resulted in a decrease in the complex modulus value.

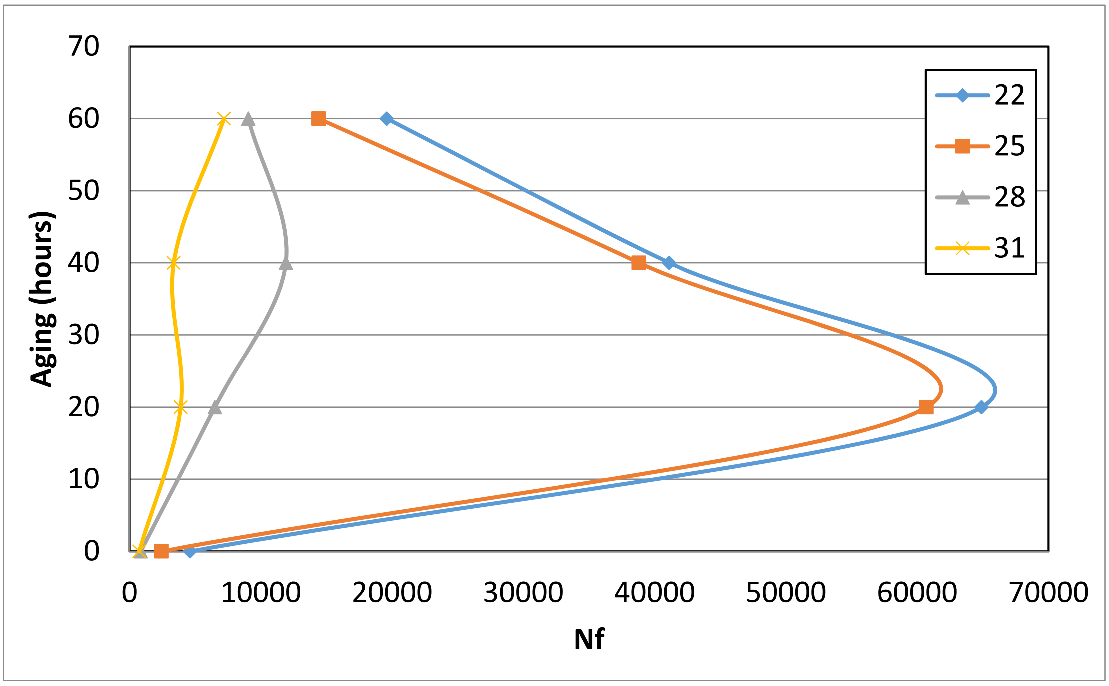

Figure (10): Effect of aging on fatigue failure for unmodified asphalt at 5%

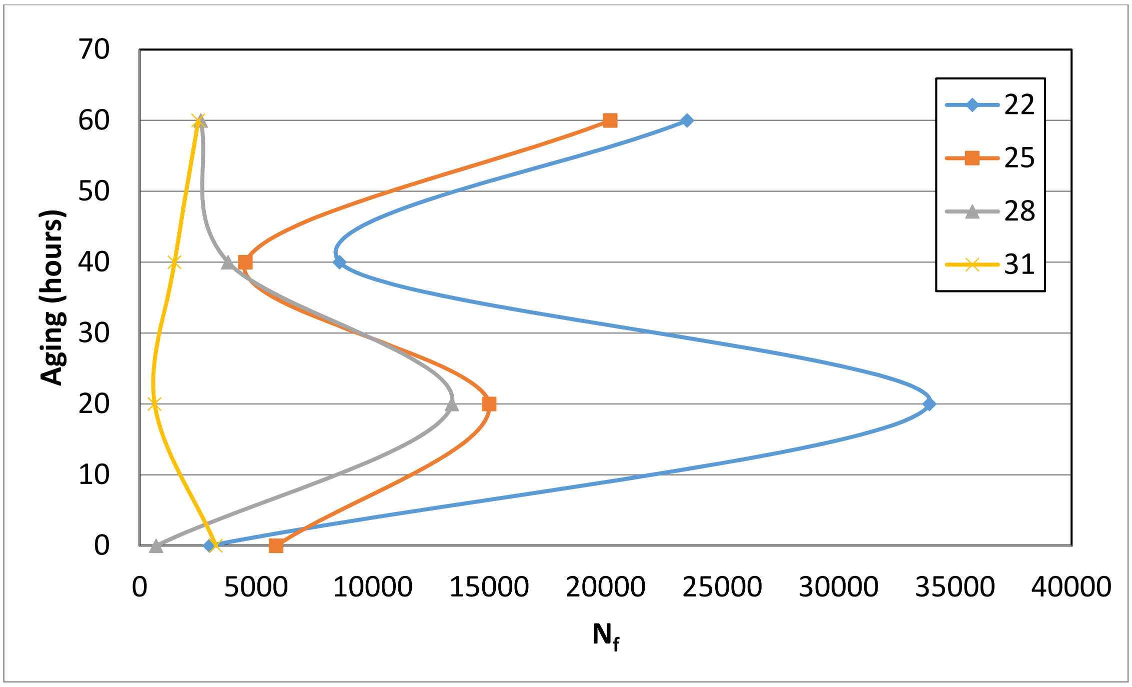

Figure (11): Effect of aging on fatigue failure for SBS-modified asphalt at 10%

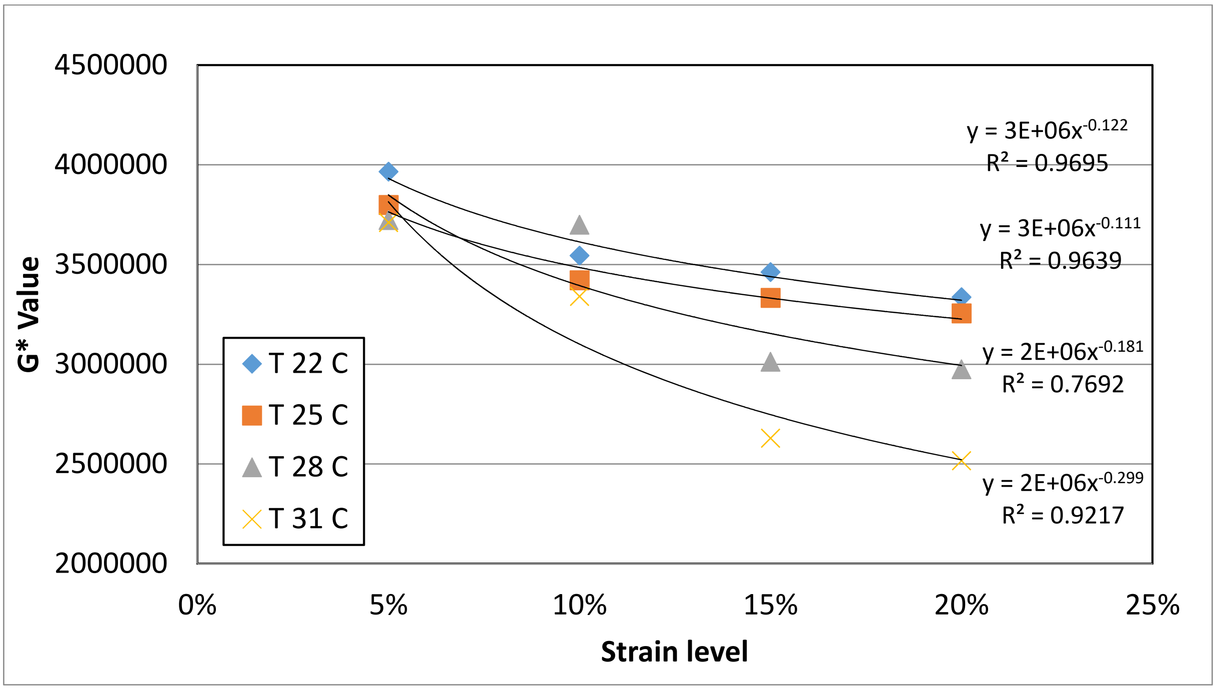

Figure (12): Effect of temperature on complex modulus for PAV60-aged unmodified asphalt

The above temperature results agree with Martono and Bahia (2003) findings and those of Al-Khateeb et al. (2008) for similar temperatures. For higher temperatures, the fatigue failure occurs faster than that for lower temperatures. These results, however, do not agree with the superpave criteria for fatigue failure. It can be concluded from field analysis that samples supposed not to fail during the life of the pavement according to the superpave criteria suffer from severe fatigue cracks before the end of the design life of this pavement.

CONCLUSIONS

Based on the analysis of the data and the results obtained in this study, the following conclusions are drawn:

(1) For the unmodified asphalt binders at lower temperatures (22 and 25°C), the fatigue life decreases as the aging period increases, because the asphalt binders become too stiff to resist fatigue cracking.

(2) For the unmodified asphalt binders at higher temperatures (28 and 31°C), the number of cycles to failure for PAV60 is higher than that for PAV40, because the higher stiffness attained due to extended aging times is beneficial at higher temperatures.

(3) Conversely, for the SBS-modified asphalt binders at lower temperatures (22 and 25°C), the fatigue life for the 60-hr-aged binder is higher than that for the 40-hr-aged binder. This is due to the improvement in the low PG grade that enhanced the fatigue resistance at longer aging times.

(4) For SBS-modified asphalt binders at higher temperatures (28 and 31°C), lower fatigue life with increasing aging period can be obtained. This can be only explained by the interaction between the temperature, modification and extended aging effects.

(5) For both the unmodified and SBS-modified asphalt binders and at all aging periods and temperatures, the increase in the strain level resulted in a decrease in the fatigue life following a power trend.

(6) For the unmodified asphalt binders as well as the SBS-modified asphalt binders at all strain levels (5, 10, 15 and 20%), the increase in temperature resulted in a lower fatigue life due to the reduction in stiffness (complex modulus value).

(7) Increasing the strain level resulted in a decrease in the complex modulus value for both the unmodified and SBS-modified asphalt binders.

Practical Applications

Achieving the objectives of this study will help in improving the asphalt mix design, increasing the effective service life of asphalt pavement before maintenance, predicting the time and type (load-related or asphalt-related) of any fatigue failure in flexible pavements and reducing the cost of pavement construction.

The results of this study are expected to improve the understanding of the effect of aging on asphalt pavements and help engineers design asphalt mixes that ultimately will produce more economic and durable roads. Understanding the effect of aging on the fatigue of asphalt binders can be helpful in predicting when the pavement starts to have fatigue cracking.

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