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ORIGINAL ARTICLE

Fatigue and healing performance assessment of asphalt binder from rheological and chemical characteristics

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Abstract The fatigue and healing performance of asphalt binder affect the durability of asphalt concrete and by extension, asphalt pavements. The objectives of this paper are to (1) estimate the fatigue and healing characteristics of asphalt binder by newly developed linear amplitude sweep (LAS) and LAS-based Healing (LASH) protocols, and (2) investigate the relationship between chemical composition of asphalt and engineering performance. Three neat asphalt binders (Pen-30, Pen-50 and Pen-70) and one SBS modified binder are selected for this study. Experimental results indicate that the SBS binder has advanced fatigue resistance among all tested binders and the softer neat binder with a higher penetration grade generally displays better fatigue performance. The fatigue failure occurrence is a significant threshold for healing potential comparison. The rate of healing (H^{R}) results suggest that the best healing potential is with Pen-70 binder in pre-failure conditions followed by the SBS binder, Pen-50 and Pen-30 binders. However, the SBS binder presents better healing performance than Pen-70 binder in post-failure condition. Further solvency fractionation, into saturates, aromatics, resins and asphaltenes, indicates that the asphaltene content is negatively proportional to the quantified binder fatigue life whereas the H^{R} index is found to be well correlated to the weight percents of saturates and ratio of saturates to aromatics (S/Ar). The combined use of LAS and LASH tests is recommended for effectively distinguishing and designing the fatigue-healing performance of neat and modified asphalt binders. Limiting the contents of asphaltenes would be of help to improve the binder fatigue resistance and either saturates percent or S/Ar parameter should be considered to assure the self-healing potential of asphalt binder.

Keywords Asphalt binder · Fatigue damage · Healing · Rheology · Chemical composition

1 Introduction

Fatigue cracking due to the repeated traffic loading is a main distress in asphalt pavements [1]. Though the mechanism of fatigue failure in pavements is complex, it is also widely accepted that the fatigue resistance of

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asphalt concrete significantly impacts the fatigue performance of asphalt pavements [2–5]. Actually, the fatigue cracks normally initiate and further propagate along the asphalt binder and mastic phases since they are the weakest parts within the asphalt concrete. Therefore, it is meaningful to quantify the asphalt binder fatigue characteristics to accurately predict the fatigue behaviour of asphalt concrete and pavements [6, 7].

The strategic highway research program (SHRP) introduced the dynamic shear rheometer (DSR) to assess the rheological properties of asphalt binder. An intermediate temperature parameter of $|G^*|\ x\ \sin\delta$, which is defined as the product of the dynamic shear modulus and the sine of the phase angle, was proposed to limit the amount of energy dissipation that would occur within an asphalt at temperatures where fatigue was likely to occur [8, 9]. It was later found that the binder $|G^*|\ x\ \sin\delta$ is not able to correlate to fatigue performance of asphalt concrete and pavements especially for modified binders [10]. This is probably caused due to a fact that the $|G^*|\ x\ \sin\delta$ is measured within the linear viscoelastic domain and thus, no damage effects can be quantified. The NCHRP 9-10 project proposed a new test, the time sweep (TS) for binder fatigue characterization, in which a repeated sinusoidal loading is applied on the binder sample at a fixed frequency, temperature and amplitude either in control stress or control strain modes [11, 12]. The TS procedure typically follows the common fatigue definition of material integrity deterioration under repeated cyclic loading and thus, the asphalt binder fatigue performance can be fully characterized [13–15]. However, the time duration for completing a single TS test is unknown and strongly dependent on the selected loading amplitude. In recent years, the *linear amplitude sweep* (*LAS*) (AASHTO TP101-14) test was developed as a specification procedure to estimate the fatigue resistance of asphalt binders [16]. Johnson et al. proposed the initial step-loading LAS procedure and Hintz et al. further simplified the loading procedure [17, 18]. Wang et al. [19, 20] proposed a new energy-based failure definition for LAS test and further developed the unified failure criterion for interpreting the LAS data under different loading rates to improve the accuracy of TS fatigue life prediction. The fatigue performance of both neat and highly modified asphalt binders can be effectively quantified through the LAS-based fatigue modeling approach [21–24]. Additionally, the binder fracture tests, which employ a monotonic loading in either shear or tension modes, also have shown potential in characterizing binder cracking performance at intermediate temperatures [25–28].

One drawback to the TS and LAS experiments is that they focus exclusive on the damage behavior under continuous loading. However, noteworthy discrepancies between fatigue performance observed under continuous loading and field fatigue performance are well documented [29, 30]. The self-healing potential of asphalt materials is known as a key contributor to these discrepancies [31–33]. As previous described, continuously repeated loading is utilized by most laboratory fatigue testing procedure to quantify the fatigue life (number of cycles to failure) of asphalt materials. The field pavement, however, is actually subjected to a combination of both the load pulses and the rest periods. During these rest periods, it is well documented that asphalt materials are able to heal and recover their mechanical properties (stiffness or strength). In 1967, Bazin et al. [34] firstly observed that the tension strength of damaged asphalt concrete could be recovered to 90% of its initial level after 3 days of rest. Since this initial study, many others have demonstrated the healing occurrence both in laboratory testing and field asphalt concrete layers [35–38]. The healing mechanism of asphalt material has been studied by several researchers, primarily using techniques that emerged from studies on polymeric materials [39–42]. A significant amount of research has also been conducted to develop a laboratory test procedure to quantify the self-healing behaviour of asphalt materials, which covered both multiple-scale material phases from asphalt binder to asphalt concrete and multiple-loading modes (indirect tension, bending, direct tension, shear loading) [43–52]. The recovery ratio of dynamic/resilient modulus is the most common mean to represent the healing performance, however, it is also acknowledged that two materials behaviour of *viscoelastic recovery (relaxation)* and *damage-healing recovery* simultaneously contribute to the recovery of material modulus during the rest periods [45, 46, 53]. In 1980s, Schapery proposed the elastic–viscoelastic correspondence principle that effectively convert the viscoelastic constitutive equations to an elastic solution [54]. Several studies by Lee et al., Daniel et al., Si et al., Palvadi et al. and Karki et al. successfully separated time-dependent relaxation of asphalt materials through this correspondence principle and further characterize the fatigue damage and healing effects using continuum damage approach, which is also known as the viscoelastic continuum damage (VECD) model with healing [55–60]. Recently, a *LAS-based healing (LASH)* test was proposed to quantify the healing characteristics of asphalt binder, followed by establishment of the unified healing mastercurve to access the asphalt binder healing performance [61].

In addition to the rheological modeling for asphalt binder fatigue and healing behaviour, micro-chemical characteristics of asphalt binder and its relationship to macro-engineering properties is also a promising approach. Asphalt binder is typically separated into four solvency based chemical fractions, Saturates, Aromatics, Resins, and Asphaltenes, which are often referred to simply by their acronym SARA. The crude source, refining process and aging normally impact the SARA fractions. Mangiafico et al. [62] found that the asphaltenes content and colloidal structure of asphalt binder correlated well to some physical properties. Many other researchers demonstrated the relationship between chemical composition and rheological properties of asphalt binder [63–66]. Kim et al. [67] investigated the chemical function groups of asphalt binder and found that a higher CH_2/CH_3 value, which represents a lower branched-chain and longer and thinner molecule content, could promote the self-healing of asphalt concrete under a constant strain-rate fracture test with rest period. Santagata et al. [68] reported that binder fatigue performance is directly linked to the colloidal structure while the binder healing index can be expressed as a function of the ratio between saturates and aromatics. Sun et al. [69] verified that asphalt binder with a higher ratio of small molecule content/large molecular content combined with higher aromatics content has a greater self-healing ability.

The objectives of this study are to:

1. Estimate the fatigue and healing performance of neat and modified asphalt binders by newly developed LAS and LSAH testing protocols and data interpretation.
2. Identify the chemical composition property of asphalt binder and further investigate its relationship to the measured engineering performance.

2 Materials and testing

2.1 Materials

Three neat asphalt binders with penetration grades of 30, 50 and 70 and one SBS modified binder were selected for this study. All four binders that briefly labeled as Pen-30, Pen-50, Pen-70 and SBS, were firstly subjected to the rolling thin film oven (RTFO) test to simulate the short-term aging process during the pavement construction [70]. Then the RTFO-aged binder samples were further tested for rheological and chemical characterization.

2.2 Frequency sweep test

The undamaged linear viscoelastic behaviour of asphalt binder, which can be measured from frequency sweep test, is a fundamental material property for fatigue and healing constitutive model. In this study, the frequency sweep tests were conducted from 0.1 to 100 rad/s respectively at the intermediate temperature of 5 °C, 20 °C, and 35 °C. Based on time–temperature superposition principle, the dynamic shear modulus ($|G^*|$) mastercurves were constructed based on Christenson–Anderson–Marasteanu (CAM) model [71] and temperature shift factors were fitted with Williams–Landel–Ferry (WLF) nonlinear model [72].

2.3 LAS test

The standard LAS procedure (AASHTO TP101-14) utilized an oscillatory sweep with the loading amplitudes linearly ranging from 0.1 to 30% within 5 min [16]. An newly integrated LAS-based fatigue modeling for fatigue life simulation was employed in this study, which composes of three material-dependent characteristics, in terms of dynamic shear modulus mastercurve, damage characteristic curve (DCC), and failure criterion [19, 20]. The fatigue failure criterion, which reveals the characteristic relationship between the releasing rate of pseudo strain energy and the measured binder fatigue life, unifies the fatigue failure behaviors of asphalt binder under various loading modes and loading amplitudes. To develop the fatigue failure criterion of asphalt binder, it is required to respectively extend the strain sweep time to 10 min and 15 min. An excel-based software namely the AsphaFAT 1.0 was recently developed to provide a quick and efficient analysis tool for LAS test data interpretation.

2.4 LASH test

The LASH test was developed based on the standard LAS procedure for a rapid and effective measurement of healing potential of asphalt binders [61]. The key concept of the LASH procedure is to first define a critical damage parameter, S_f, which represents the value of damage intensity (S) at fatigue failure. Then analysis damage states are defined at 25%S_f, 50% S_f, 75%S_f, and 125%S_f at which rest periods can be applied during the experiment. Note that the analysis states include values above and below the critical damage parameter so that both the *pre-failure* and *post-failure* healing properties can be quantified. For each S_f-based damage level, multiple rest periods of 60 s, 300 s, 900 s, and 1800 s are introduced to characterize the healing behaviour.

The typical DCC results from LAS test and LASH test are compared in Fig. 1, where the C and S respectively represent the pseudo stiffness and damage intensity. A percent healing (%H_S) parameter was proposed based on the damage recovery as expressed in Eq. (1), in which the S_1 and S_2 respectively represent the measured S values immediately preceding and after the rest period. The %H_S index is utilized to access the healing performance of asphalt binders under various damage levels and rest period durations.

$$\%\ H_S = \frac{S_1 - S_2}{S_1} \tag{1}$$

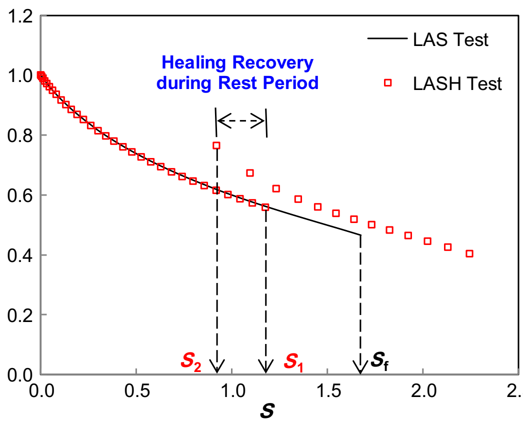


Fig. 1 Schematic illustration for %H_S calculation from the LASH test

To remove the effects of damage levels and rest periods, the %H_S results from three pre-failure cases can be horizontally shifted to develop the *healing mastercurve* based on "rest-damage superposition principle". Details of the healing mastercurve construction are provided elsewhere [61]. Additionally, four candidate healing indices were proposed based on the healing mastercurve, namely the instantaneous %H_S (%H_{S0}), minimum rest period (RP_{min}), rate of healing (H^R), and maximum rest period (RP_{max}) [61]. Among these healing indices, H^R should be the most critical healing index since it is fitted from the truly measured data whereas other three indices are obtained from the extrapolation of healing mastercurves in some degrees.

The rheological LAS and LASH tests under various damage conditions are conducted at a single temperature of 20 °C. At least two replicates were run for each binder to limit the test variability within 10%.

2.5 SARA fractionation test

The asphalt binder is a produced from vacuum distillation of crude oil and consists of many kinds of chemicals. In this study, each RTFO-aged asphalt binder was tested by using the thin-layer chromatography according to ASTM D4124 [73]. The relative fractions of *saturates, aromatics, resins and asphaltenes* (*SARA*) can be identified based on their differences in solubility in organic solvents. Such a procedure has been widely used for the chemical composition characterization of asphalt binder [62–66, 68, 69].

3 Fatigue and healing performance assessment

3.1 LAS-based fatigue resistance

The constructed dynamic modulus mastercurves of four tested binders are given in Fig. 2a. It can be observed that the Pen-30 binder displays highest stiffness level followed by Pen-50, Pen-70 and SBS binder. The stress–strain curves up to failure from the LAS test of 5 min are compared in Fig. 2b. The Pen-30 binder shows the highest peak stress and the lowest failure strain whereas the Pen-50 and Pen-70 binders display similar stress–strain curves and slightly higher failure strain than Pen-30 binder. The SBS binder

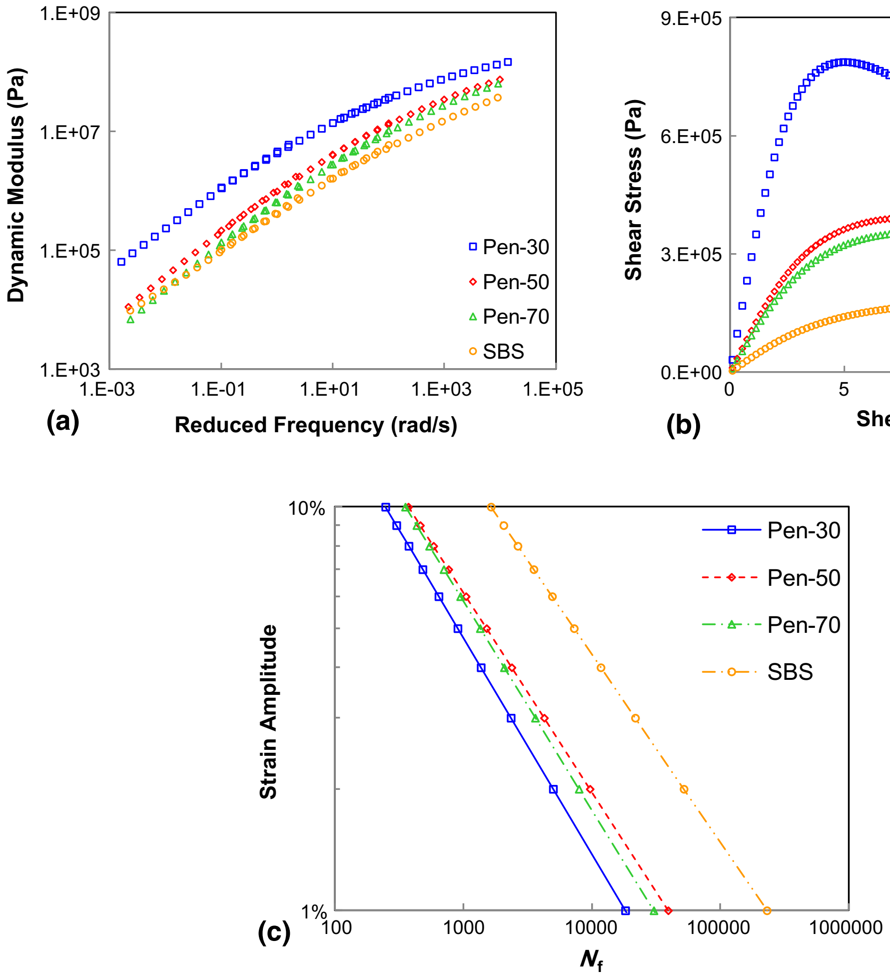


Fig. 2 LAS-based fatigue characterization of asphalt binders **a** dynamic modulus mastercurves **b** stress–strain response in LAS test **c** fatigue life simulation results

exhibits an obvious ductile failure mode and the largest failure strain among all binders. However, the failure strain is just one parameter for estimating the strain tolerance of asphalt binder under cyclic loading, and only partly indicate the fatigue performance. More accurate fatigue assessments needs further analysis on binder fatigue damage and failure characteristics.

The LAS-based fatigue modeling approach composed of three material-dependent properties: linear viscoelasticity in non-damaged domain, damage property, and failure criterion. These fundamental material characteristics were analyzed with AsphaFAT 1.0 software for each binder and the simulated fatigue lives under constant strain amplitude are compared in Fig. 2c. It can be observed that the SBS modified binder shows the best fatigue performance followed by Pen-50, Pen-70 and Pen-30. It is generally not surprising that SBS binder is identified as the most fatigue resistant material since the polymer addition and modification within the binder structure. However, Pen-70 is actually a softer binder than Pen-50 binder but interestingly presents a slightly worse fatigue resistance especially at smaller strain amplitudes. This may be resulted from the RTFO aging effects on the binder chemical composition properties which will be also addressed in next section. Besides, the Pen-30 binder is demonstrated for the worst fatigue performance due to it having the highest modulus and hardness.

3.2 LASH-based healing performance

The measured $\%H_S$ results under different damage levels and rest periods of all binders are summarized in Fig. 3. For pre-failure conditions in Fig. 3a–c, the Pen-70 neat binder displays higher $\%H_S$ levels than other three binders. However, the $\%H_S$ difference between Pen-70 binder and SBS binder is found to be gradually narrowed when increasing the damage levels. Finally, in the post-failure case of $125\%S_f$ damage level, the $\%H_S$ of SBS binder exceeds that of the Pen-70 binder. This implies that the fatigue failure occurrence represents a significant threshold when quantifying the healing characteristics especially for the modified asphalt binders. In other words, the soft neat asphalt like Pen-70 binder may show better damage-healing ability than modified binder in the slight damage conditions; however, when approaching the fatigue failure occurrence, the modified binders tend to show better healing potential. For the three neat binders tested in this study, the healing performance is well correlated to their penetration grades indicating softer binder would provide better self-healing behaviour. The Pen-30 binder is demonstrated as the worst healing potential for all damage levels especially in post-failure condition as shown in Fig. 3d, in which none damage healing recovery can be observed.

Based on the measured $\%H_S$ data in pre-failure conditions under various damage levels and rest period durations, the constructed healing mastercurves of all tested binders are compared in Fig. 4. It can be observed that the Pen-70 binder displays better healing performance than other three binders, which is independent on the damage levels and rest period durations. The H^R of four tested binders (Pen-30, Pen-50, Pen-70 and SBS) are respectively determined

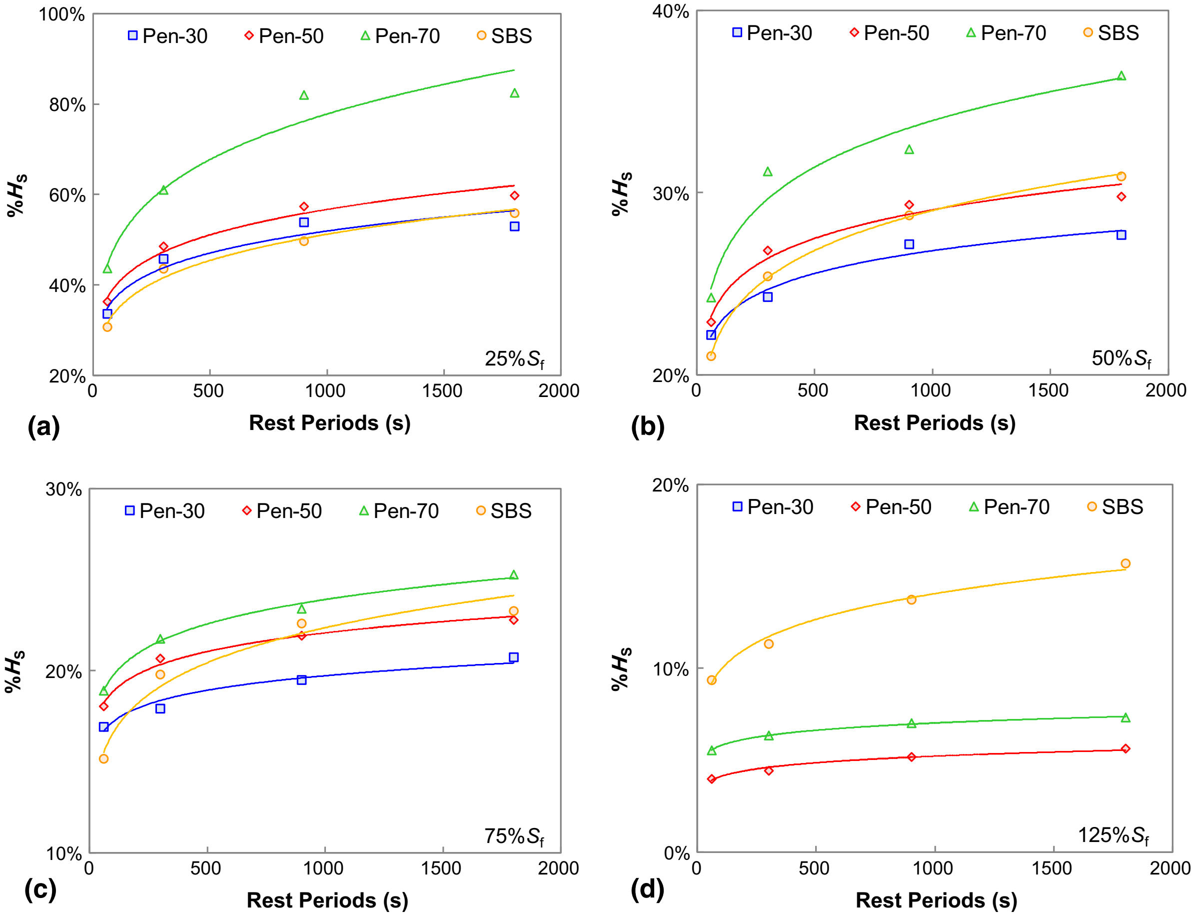
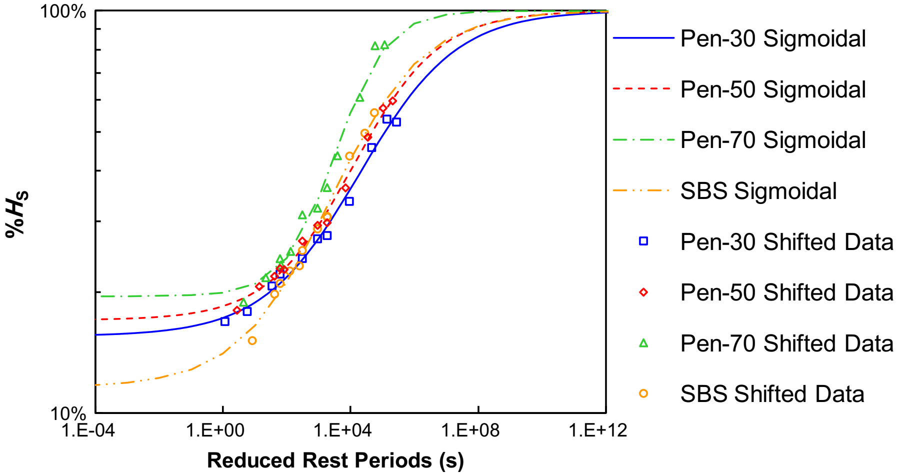


Fig. 3 $\%H_S$ Comparison of tested binders under different damage levels **a** $25\%S_f$ **b** $50\%S_f$ **c** $75\%S_f$ **d** $125\%S_f$

Fig. 4 Comparison of healing mastercurves of tested binders



as 0.105, 0.127, 0.176 and 0.141, which are identified as the slope of the linear part of the healing mastercurve in log–log scale and further utilized as the critical healing index of asphalt binder.

4 Chemical composition and its relationship to performance

4.1 SARA versus LAS

The SARA based chemical composition analysis are completed for all binders to further investigate possible relationship from micro-chemical properties to macro-engineering performance. The simulated binder fatigue life under stain amplitude of 3% (N_f@3%) from Fig. 2c is utilized here as the fatigue performance index. The weight percentage of each SARA component are firstly compared to corresponding fatigue resistance in Fig. 5. It can be observed that for the three neat binders, the N_f@3% is positively proportional to the oil composition weights (saturates and aromatics) and decrease with increasing the weight percents of resins and asphaltenes. The percentages of saturates and aromatics represent the content of small molecules within the asphalt binder. With more small molecules, the averaged molecular weight is smaller. Consequently, it is believed that the molecular motion will be fast and the asphalt binder is more flexible to resist the fatigue loading. The opposite effects on N_f@3% can be explained for relatively large molecules of resins and asphaltenes. Especially the Pen-50 binder previously displayed better fatigue resistance than Pen-70 binder, which can be verified here for its lower asphaltenes percents results in Fig. 5d. However, the SBS binder is the outlier for this SARA versus LAS comparison in Fig. 5. This is due to the fact that the excellent fatigue performance of SBS binder mainly comes from the polymer modification that significantly enhanced the binder molecular structure.

4.2 SARA versus LASH

Similar comparisons are also made between the SARA composition weights and critical healing index of H^R. As shown in Fig. 6a, it is interestingly found that the rate of healing (H^R) behaves as an increasing function of the saturates percentage for all tested neat and modified binders. This correlation can be explained by a fact that the healing process across the micro-cracks mainly happens as the molecular bonding in the oil phase of the binder. Other researchers utilized the parameter of S/Ar, which is defined as the ratio between saturates and aromatics, to represents the distinguished binder healing performance [68, 69]. It is further observed in Fig. 6b that the H^R in this study is also well correlated to the S/Ar parameter. A higher S/Ar value indicates that the molecule structure of asphalt binder tends to be longer and thinner, which makes the molecular diffusion more active and effective across the micro-crack interface and results a greater healing potential of asphalt binder [40].

One very interesting observation from this figure is that the healing behaviors for the SBS binder aligns with the other asphalts in terms of both saturates

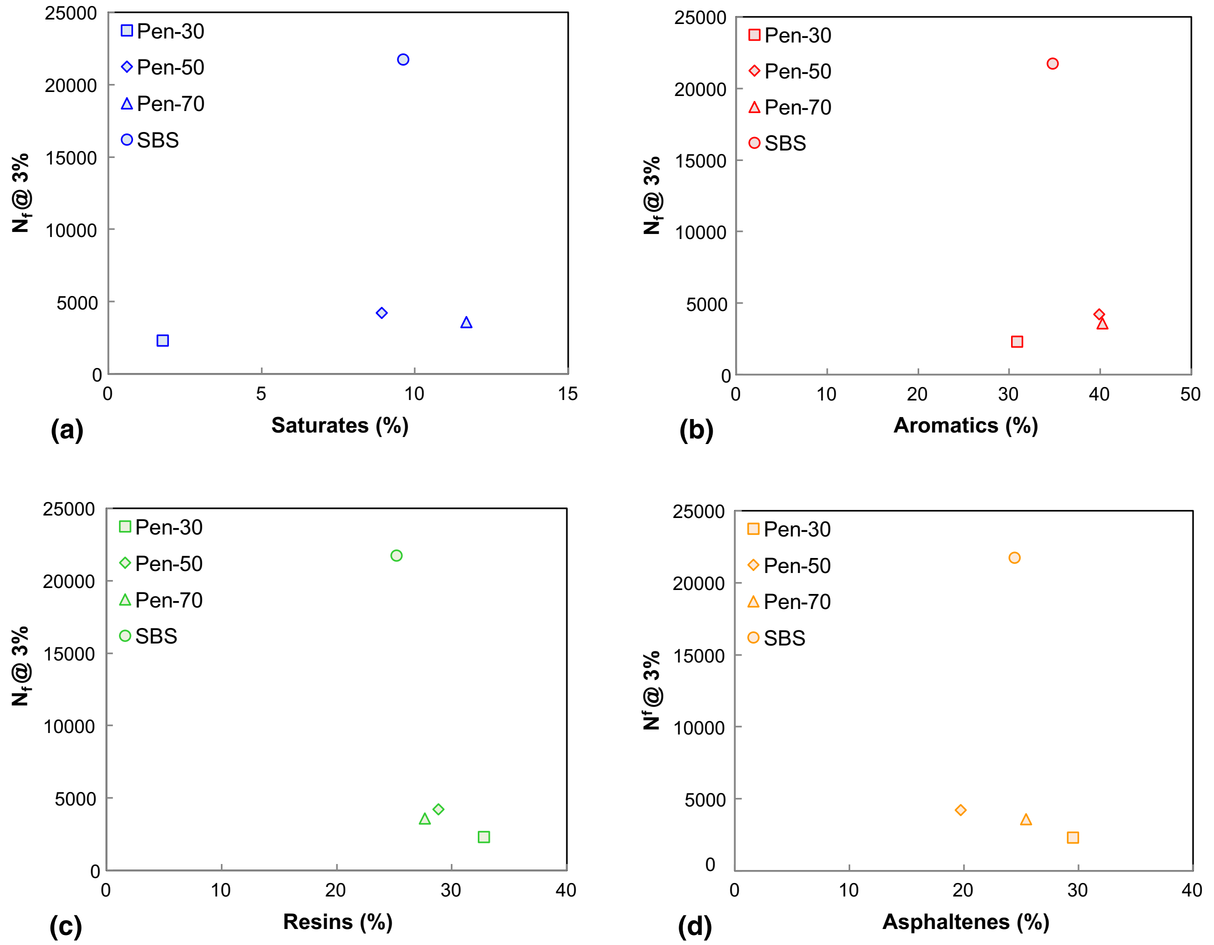


Fig. 5 Comparison between fatigue life under 3% strain and SARA composition weight percents **a** saturates **b** aromatics **c** resins **d** asphaltenes

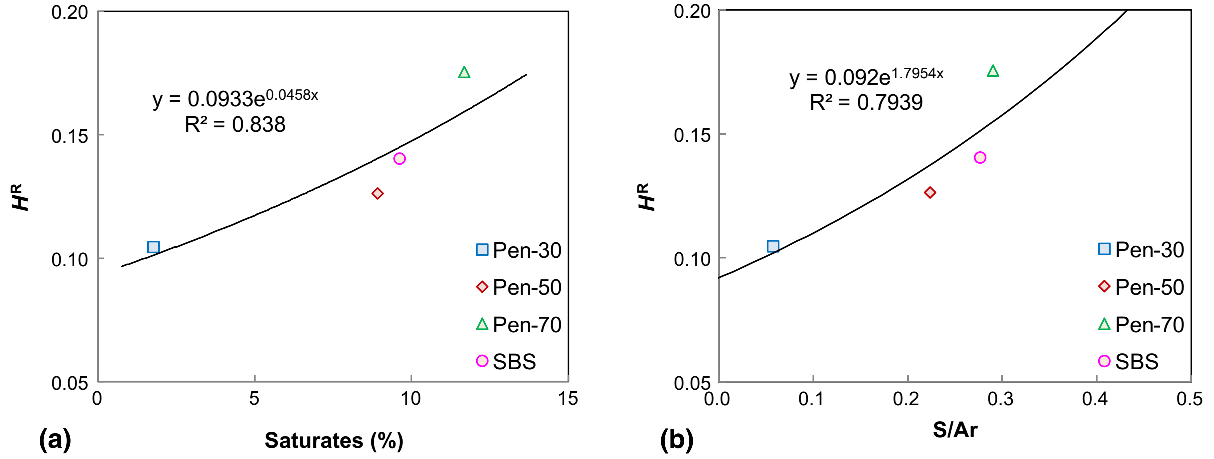


Fig. 6 Comparison between H^R and SARA composition parameters **a** saturates **b** S/Ar

content and S/Ar parameter. This alignment is between rheological behaviors and chemical composition is different from what was observed with respect to the fatigue life under continuous loading. A detailed study of the specific mechanisms is beyond the scope of this paper. However, it should be recognized that SARA fractions of the polymer modified asphalt reflects the molecular composition of the base asphalt. It is hypothesized that the disagreement of SBS in the correlation between fatigue life and SARA composition and agreement of SBS in the correlation between healing rate and SARA composition suggests that the two mechanisms (damage and healing) occur disproportionately in the polymer and base binder phases of the SBS modified asphalt. This may possibly suggest that while the rate of damage growth can be mitigated greatly by the inclusion of SBS (either because the SBS phase itself damages at a much slower rate or the SBS phase interacts with the base binder to mitigate damage growth in that base binder phase) the SBS does not aid (or hinder) self-healing (possibly because the SBS phase does not self-heal or heals at a substantially slower rate than the base asphalt). This effect, if proven to be true, has substantial practical implications as it suggests that the ultimate fatigue performance of an asphalt binder, which manifests because of the combined damage and healing behaviors of the binder, will need to explicitly consider the composition and behaviors of both the modified asphalt and the unmodified base binder.

5 Conclusions

This paper presents a laboratory study of fatigue and healing performance of neat and modified asphalt binders using both rheological and chemical approaches. The specific findings of this study are summarized as follows:

1. From LAS based binder fatigue modeling approach, the SBS binder showed advanced fatigue resistance than three neat binders either from failure strain or simulated fatigue life results. Though the Pen-50 binder displayed slightly higher fatigue life than Pen-70 binder, the softer neat binder with a higher penetration grade was generally demonstrated for a relatively better fatigue performance.
2. The LASH based binder healing characterization indicated that fatigue failure occurrence is a significant threshold for healing potential comparison. The Pen-70 binder showed better healing performance than other three binders in pre-failure conditions whereas the $\%H_S$ difference between Pen-70 binder and SBS binder was gradually narrowed with higher damage levels and finally, the $\%H_S$ of SBS binder exceeded that of the Pen-70 binder in post-failure condition. The rate of healing (H^R) results from constructed healing mastercurve demonstrated the best healing potential of Pen-70 binder in pre-failure conditions followed by the SBS, Pen-50 and Pen-30 binders.
3. The weight percentage of SARA components were generally found to be related to fatigue resistance of three neat binders, especially, the contents of asphaltenes was negatively proportional to the quantified binder fatigue life. Regarding to the binder healing behaviour, the critical healing index of H^R was well correlated to the saturates weights and S/Ar values, suggesting that the binder healing process across the cracking interface is mainly dominated by the oil phase (saturates and aromatics) components within the asphalt binder.

Generally, it is recommended that the combined use of LAS and LASH tests are able to effectively distinguish and design the fatigue and healing performance of neat and modified asphalt binders. Special cautions should be further taken for limiting the contents of asphaltenes components for designing a more fatigue resistant binder. Similarly, either saturates percent or S/Ar parameter should be considered to assure the damage healing potential of asphalt binder. Additionally, future work should also be conducted on other various modified binders, as well as the fatigue and healing performance of asphalt mixture scale to further verify the proposed findings in this study.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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