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Comparative analysis of time sweep testing evaluation methods for the fatigue characterisation of aged bitumen

Yongping Hu [a], Anand Sreeram [a,*], Gordon D. Airey [a], Bo Li [a,b], Wei Si [c], Haopeng Wang [d]

[a] Nottingham Transportation Engineering Centre (NTEC), Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD, United Kingdom
[b] National and Provincial Joint Engineering Laboratory of Road & Bridge Disaster Prevention and Control, Lanzhou Jiaotong University, Lanzhou 730070, China
[c] Key Laboratory for Special Area Highway Engineering of Ministry of Education, Chang'an University, Xi'an, Shaanxi 710064, China
[d] Department of Civil and Environmental Engineering, University of Liverpool, Liverpool L69 3BX, United Kingdom

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ABSTRACT

Ageing of bitumen changes its stiffness related properties and is thought to have a considerable impact on its fatigue performance. Time sweep tests are a commonly used methodology to evaluate the fatigue performance of bitumen over the course of its lifetime. This study comparatively evaluated the fatigue performance of six aged bitumen samples using various commonly employed time sweep testing-based approaches, including conventional methods (50% reduction in complex modulus and peak in phase angle) and newer methods (peak in $S \times N$ and two dissipated-energy-based approaches). The statistical analysis of the results illustrated that although the trends of fatigue life versus ageing levels were similar, different methods had significantly varying results. It was generally seen that ageing increased stiffness and the calculated fatigue life of bituminous binders improved when commonly applied strain levels of 5% and 7.5% were used. This result demonstrates the need to develop more robust methods to fully capture the true fatigue related deterioration of aged binders in the future. Among all the methods, the peak in $S \times N$ approach was found to be the most efficient based on the criteria used in the study and was the recommended approach considering current limitations. It showed no apparent defects and had the best correlations with other methods when the applied strains were 5% and 7.5%.

1. Introduction

Due to the combined effects of temperature, ultraviolet (UV) and visible radiation etc., bitumen within asphalt mixtures gets oxidated and aged over time. This inevitably leads to significant deterioration of its performance and serviceability [1–3]. Among the ageing-induced pavement distress, cracking such as thermal and fatigue cracking is one of the most significant forms of distress, seriously impacting the usability of pavements [4–6]. Bitumen ageing primarily occurs through two processes: 1) mixing, transport, and paving activities, referred to as short-term ageing, which can be simulated in laboratory settings using the rolling thin film oven test (RTFOT), and 2) the entire service life, referred to as long-term ageing and can be simulated by the pressure ageing vessel (PAV) test [7].

Fatigue cracking is understood to occur during the long-term lifespan of asphalt pavements due to repetitive loading. The physical and mechanical properties of bitumen deteriorate under the repetitive loading and when the loading accumulates up to a certain extent, bitumen is damaged and fatigue cracking appears [8]. The fatigue tolerance of bituminous materials is their ability to resist this repetitive loading during its long-term service life. In field conditions, the loading is applied through the movement of vehicles. Heavy vehicles apply larger loading to pavements, resulting in large stresses, and when pavement thickness is less, a large strain can be induced [9]. Characterising the fatigue performance of bitumen has been a focus of researchers to design asphalt mixtures and ensure the longevity of pavements [10]. Traditionally, the Strategic Highway Research Program (SHRP) suggested using the fatigue parameter ($G^* \cdot \sin \delta$) to characterise the fatigue resistance of bituminous materials [11]. However, this parameter is considered inadequate to evaluate the actual fatigue performance of some binders, especially for modified binders [12,13]. Similarly, G-R parameter can also be used to illustrate the fatigue performance of binders and has been shown to have a reasonable correlation with the fatigue performance of asphalt mixtures [14]. The G-R parameter ($G^* \cdot \cos^2\delta / \sin\delta$) is a mathematical expression that represents the cracking resistance of bituminous binders. However, G-R fatigue

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* Corresponding author.
E-mail address: anand.sreeram@nottingham.ac.uk (A. Sreeram).

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parameters has the same deficiencies to the G*sin δ parameter: Firstly, both these parameters are calculated using a single temperature and frequency, which does not adequately address the entire range of temperatures and loads. Secondly, both parameters are based on linear viscoelastic (LVE) theory, where binders are subjected to small strains. However, in actual situations, the strain levels normally are higher than that in the LVE range. Lastly, both parameters are not measured through repeated loading, which may lead to inaccurate representation of the binders realistic fatigue resistance [15].

Alternatively, there are more sophisticated approaches for characterising the fatigue performance of bitumen, such as time sweep (TS) tests proposed in the National Cooperative Highway Research Program (NCHRP) project 9–10 [10] and linear amplitude sweep (LAS) based on viscoelastic continuum damage (VECD) theory [16]. The main difference between time sweep and LAS is the loading scheme. Time sweep is a factual fatigue test which applies thousands of repetitive loading to the specimen while LAS is an accelerated testing protocol which uses a large range of strain amplitude to simulate fatigue during a short loading period [17]. Though time sweep is time-consuming, it is considered as the superlative approach to measure the fatigue properties of bitumen since it is the only method which applies continuous repetitive loading to specimens until damage occurs. Therefore, time sweep is an integral testing methodology used by asphalt researchers to characterise the fatigue resistance of binders [18,19].

Many parameters have been proposed to define the fatigue related “failure” of binders during time sweep testing to compare the fatigue performance after modification, ageing, rejuvenation etc., as well as to design mixes [20,21]. The most commonly utilised failure criterion is related to the 50% reduction in the stiffness [22,23]. However, using stiffness reduction approach to define fatigue failure has been challenged because it is arbitrary, without any theoretical justification. It is acknowledged that this method might not be suitable as some studies have found it to be poorly correlated with the actual fatigue performance of pavements in field [24]. The method based on the peak of phase angle faces similar challenges and some research efforts have pointed out that the fatigue damage occurs after the peak rather at the peak [25,26]. Alternatively, the concepts of dissipated energy were introduced such as the dissipated energy ratio (*DER*) and the ratio of dissipated energy change (*RDEC*), these indices are more sophisticated as they have theoretical basis rather than simple observations [27,28]. Moreover, another indicator, the $S \times N$ was also utilised as the failure criterion to evaluate the fatigue performance of bituminous materials, where S represents the stiffness ratio and N represents the loading cycles [29–31]. The index of $S \times N$ have been implemented successfully in characterising the fatigue performance of asphalt mixtures and is potentially promising for characterising the fatigue related failure of binders [32,33].

Though several metrics have been employed to calculate the fatigue life and accurately identify the fatigue performance of aged bitumen based on time sweep, no research efforts have compared these metrics with each other. The fatigue performance evaluation of aged bitumen is critical as incorrect utilisation might lead to misinterpretation of the fatigue performance, leading to mismatch of the fatigue characterisation between bituminous binders and asphalt mixtures. Increased use of Reclaimed Asphalt Pavement (RAP) materials also makes it even more important to use correct metrics for fatigue performance evaluation since RAP materials contain aged and stiffer binders that are likely more susceptible to fatigue cracking [34,35].

This study will comprehensively evaluate the fatigue performance of laboratory aged bitumen using time sweep tests, based on various promising approaches. The conclusions drawn from this study are anticipated to shed insights into the fatigue properties of aged bitumen and recommend appropriate approaches for the accurate characterisation of its fatigue performance.

2. Scope

This study investigates the fatigue performance of aged bitumen using time sweep testing and comparatively analyses various evaluation methods for its fatigue characterisation. Six different bitumen were aged using rolling thin film oven (RTFO) and pressure ageing vessel (PAV) at different duration periods. Each binder with varying ageing levels were subjected to time sweep testing with a strain-controlled mode under two strain levels, 5% and 7.5% respectively. The criteria for defining the fatigue life of bitumen were comprehensively evaluated and compared based on established methods such as 50% reduction in complex modulus, peak in phase angle, dissipated energy ratio (*DER*), ratio of dissipated energy change (*RDEC*) and normalised modulus times loading cycles. Overall, this study presents comprehensive comparison of different methods to evaluate the fatigue performance of aged bitumen based on time sweep testing. The results are anticipated to be beneficial to judge the appropriateness of existing methods to accurately characterise the fatigue resistance of aged bitumen and aid future specifications.

3. Materials and methods

3.1. Materials

In this study, six bitumen with different physical properties were used to evaluate the changes in fatigue performance of bitumen with different ageing levels, as shown in Table 1.

3.2. Testing methods

The bitumen was first aged using the standard RTFOT test at 163°C for 85 minutes, as per BS EN 12607–1. The residue was then subjected to the PAV as per BS EN 14769. In addition to the standard PAV procedure for 20 hours at 2.1 MPa and 100°C, this study also employed extra ageing periods of 15, 30, and 40 hours. The fatigue lives of binders were determined using time sweep, which was carried out at 25°C and 10 Hz in a strain-control mode using a DSR (Kinexus Pro, Netzsch) with an 8-mm parallel plate configuration with a 2-mm gap. The strain levels employed in this study were 5% and 7.5% as a smaller strain would result in long testing times while too large strain results in damage to the samples, leading to the failure of samples being fractured rather than fatigued [36]. Therefore, this study employed moderate strains as reported in literatures [37–39].

3.3. Data interpretation based on dissipated energy methods

The dissipated energy ratio (*DER*) can be calculated using Eq. (1).

Table 1
Fundamental information of the materials.

Binders	Penetration (0.1 mm)	Softening point (°C)	PG grades	Continuous PG grades
Neat 35/50 A	37	52.7	PG 70–16	PG 75.6–21.1
Neat 40/60B	45	51.5	PG 70–16	PG 71.5–21.3
Neat 40/60 C	57	50.0	PG-70–22	PG 73.3–22.2
Neat 70/100D	81	45.4	PG 64–22	PG 67.8–27.4
Neat 70/100E	83	46.0	PG 70–22	PG 71.8–25.2
Neat 70/100 F	86	44.4	PG 64–22	PG 64.0–25.8

$$DER_n = \frac{\sum_{i=1}^{n} W_i}{W_n} \tag{1}$$

Where, W_i is the dissipated energy for a given cycle, which is a function of strain, complex modulus, and phase angle; W_n is the dissipated energy at the nth cycle. For a strain-controlled time sweep, the dissipated energy of bitumen at a given cycle can be calculated by Eq. (2) [40].

$$W_i = \pi \gamma_i^2 G_i^* \sin \delta_i \tag{2}$$

Where, γ is the strain, G^* is the complex modulus and δ is the phase angle.

In addition to the *DER* against loading cycle curves, other parameters, named N_p and N_{p20} were also proposed to predict the fatigue lives of bituminous binders based on the concept of dissipated energy ratio. The definition of N_p is the number of cycles to cracking propagation and the definition of N_{p20} is the number of cycles at which the *DER* deviates from the equality line (*DER* equals to the number of loading cycles) by 20%. The N_{p20} can be calculated by Eq. (3) [9].

$$N_{p20} = K_2 \left(\frac{1}{W_i} \right)^{k_1} \tag{3}$$

Where, K_1 and K_2 are the fitting parameters related to the energy input of binders and testing temperatures [41]. To determine the N_{p20} of bituminous binders, the fitting model based on the strain-controlled time sweep was developed, as shown in Eq. (4) [9].

$$N = N_c + b_1(R - R_c) + T(b_2 - b_1)\ln\{1 + \exp[(R - R_c)/T]\} \tag{4}$$

Where, N is the fitted number of loading cycles, N_c and R_c are the fitting parameters, respectively, representing the numbers of loading cycles and *DER* respectively, b_1 and b_2 are the fitting parameters of the slopes of the lower and upper asymptotes of the fitting curves of N (loading cycle) against R (dissipated energy ratio), respectively, R is the dissipated energy ratio, and T is the fitting shape parameter. To solve this equation, a built-in function of Microsoft Excel named Solver was adopted in this study by the means of least-square method.

Based on dissipated energy concepts, an approach named ratio of dissipated energy change (*RDEC*) was proposed to identify the fatigue performance of bituminous materials [21,42]. The definition of *RDEC* is the ratio of dissipated energy (*DE*) change between two loading cycles divided by the differences of loading cycles is shown in Eq. (5).

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

Where, $RDEC_a$ is the average ratio of *DEC* at cycle a, a and b are cycle numbers, in this study, a 20-cycle interval was adopted.

4. Results and discussions

4.1. *Conventional fatigue life calculation approaches*

Conventional definitions of fatigue life for bitumen mainly include the cycle number at the 50% reduction in modulus and at peak of phase angle [10]. In the conducted time sweep testing, two strain levels of 5% and 7.5% were applied and the representative results are presented in Fig. 1.

The "solid lines" in Fig. 1 illustrates the complex modulus, while the "double lines" show the phase angle. It was observed that the complex moduli exhibited a sharp decrease at the beginning, followed by a relatively stable phase, then another sharp decrease, and finally, a gradual decrease, which is consistent with previous studies [10,24,43]. The rate of decrease for binders at 7.5% strain level was higher than that at 5%, indicating that higher strain levels resulted in greater damage [36]. According to the conventional definition of fatigue damage, the damage occurs after the intermediate stable phase for both strain levels, with the damage occurring at a lower cycle number for the 7.5% strain level compared to the 5% strain level.

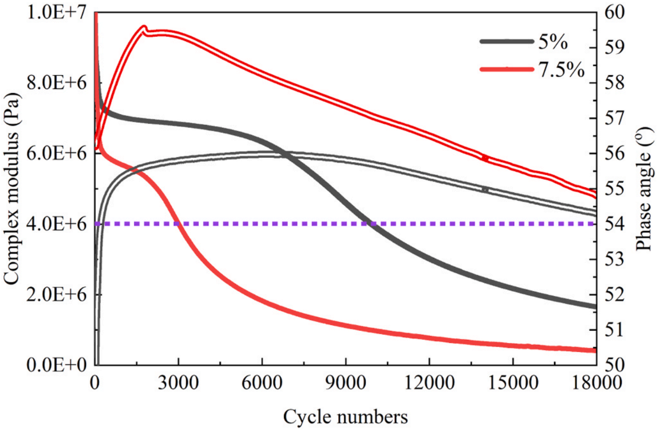


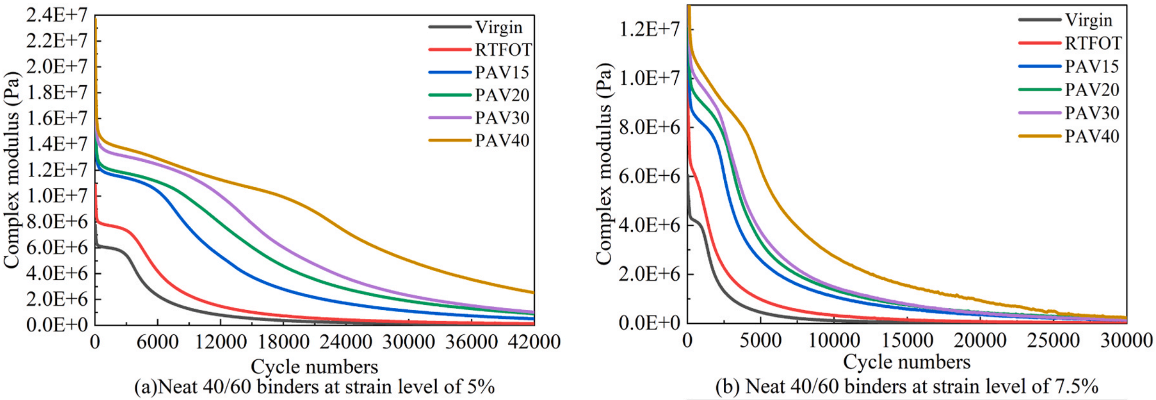
Fig. 1. Complex modulus & phase angle versus loading cycle.

The phase angle increased then decreased, showing a single peak trend. This is observed as the materials accumulate distress in the form of microcracks, leading to loss of elasticity (numerically increasing phase angle). When the samples stop accumulating distresses, i.e., when the phase angle versus time reverses direction, this is the "failure" point. The cycle number corresponding to the peak in phase angle was defined as the fatigue life of bitumen [44]. It was also observed that the peak appeared earlier at the 7.5% strain level compared to the 5% strain level, and this pattern was consistent for all binders. To investigate the effect of ageing on the fatigue life, two binders with different ageing levels were selected to illustrate the results, as shown in Fig. 2.

From Fig. 2, it can be observed that the fatigue life of binders increased with ageing levels under different strain levels. The deterioration of material integrity followed a consistent pattern: initially, the complex moduli of all binders dropped dramatically, followed by a slight plateau, especially for the virgin and short-term aged binders. Then, the decrease of the complex moduli accelerated, and another sharp decrease was observed. Finally, the materials were completely damaged and the decrease rate of the complex moduli of all binders reached a relatively stable stage, which is consistent with previous studies [15]. The evolution of the complex modulus of binders can be summarised as shown in Fig. 3.

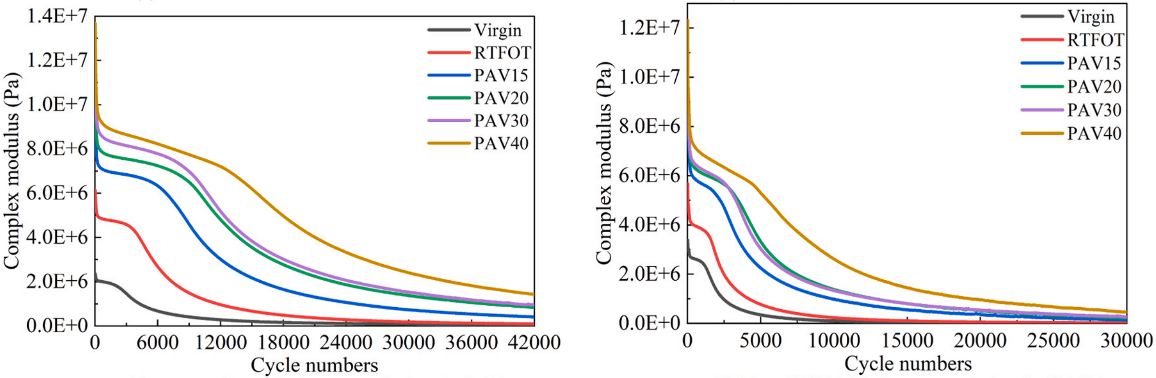
The fatigue lives of all tested binders calculated by both 50% reduction in complex modulus and peak of phase angle are summarised in Table 2.

It can be seen from Table 2 that all fatigue lives of bitumen based on the 50% reduction in complex modulus showed a consistent trend i.e. the fatigue lives of binders increased with ageing levels at both strain levels of 5% and 7.5%. The conclusion based on peak phase angles of bitumen agreed with the conclusion based on 50% reduction in complex modulus, although some fluctuations in the fatigue lives of long-term aged binders were observed. Contrary to the prevalent notion that ageing lowers the fatigue performance of binders as widely assumed [45], the data indicates that ageing related stiffness increment could increase the fatigue resistance of bitumen when the strain levels used are 5% and 7.5%. While the exact reasons for this remain a topic of debate [8], ongoing investigations have demonstrated that the fatigue life of bitumen is contingent upon strain levels. Specifically, at lower strains, stiffer binder could have a longer fatigue life, whereas at higher strains, their fatigue life tends to diminish [46]. This relationship between strain level and the ageing process, especially noted at 5% and 7.5% strains, offers a plausible explanation for the observed improvement in fatigue life with ageing. This observation is not fortuitous as various studies reported similar results, suggesting that it is factual that at lower strain levels, fatigue performance of bitumen might improve with ageing while



(a)Neat 40/60 binders at strain level of 5%

(b) Neat 40/60 binders at strain level of 7.5%



(c) Neat 70/100 binders at strain level of 5%

(d) Neat 70/100 binders at strain level of 7.5%

Fig. 2. Fatigue lives of binders calculated by the 50% reduction in complex moduli.

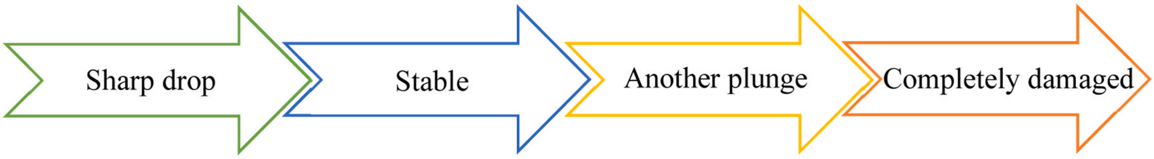


Fig. 3. Evolution of complex modulus.

it is opposite when the strain levels are relatively high [47]. In that sense, the critical strain is strongly material-dependent but normally this strain ranges between 10% and 15% [46,47].

It should be mentioned that the existing fatigue performance evaluation methods essentially use fatigue life as the indicator to represent the fatigue performance of bitumen [48,49]. It is suggested that other metrics for fatigue performance evaluation should also be considered to have a more comprehensive understanding of the change of fatigue performance of bitumen during ageing.

4.2. Peak in $S \times N$

There have been suggestions to consider new criteria to determine the fatigue life of bitumen as surrogates of the 50% reduction in complex modulus. One such criterion is based on the “peak in normalised modulus ratio” times “loading cycle”($S \times N$) [32], as illustrated in Fig. 4.

This method has been adopted in ASTM D7460 for evaluating the fatigue life of asphalt mixtures while it has yet to be standardised for binders [50]. According to this criterion, the cycle number at which the $S \times N$ reaches its peak value is considered to be the fatigue life of the sample. The results of the fatigue life calculated by this method are summarised in Table 3.

Table 3 shows the results of the fatigue lives of the binders at both strain levels of 5% and 7.5%. The results indicated that the fatigue lives of the binders increased with the ageing levels, meaning that more higher levels of ageing leads to higher fatigue life of the binders. This conclusion is in line with those obtained from the peak phase angle and the 50% reduction in modulus criteria, and is observed at both strain levels. As compared to the previous method, the method of peak in $S \times N$ is easier to calculate and well-defined compared to the other two methods. It also eliminates the difficulties in defining the initial value of complex modulus as observed in the 50% reduction in complex modulus method. Lastly, issues such as the vibrations observed in the data of the peak phase angle method were not observed, especially for stiffer binders after ageing.

4.3. Dissipated energy ratio analysis

Typically, when a load is applied to an elastic material, energy is stored and then recovered when the load is removed. However, bitumen is a viscoelastic material rather than a purely elastic material, so energy is dissipated in the form of mechanical work, heat, or damage during the loading and unloading process [51]. Dissipated energy is the energy put into the material from external work due to loading, and is defined as the area under the stress-strain curve [52]. Fatigue failure of bitumen can be defined by three main damage evolution stages bracketed by two specific points that occur as a result of damage accumulation [9]. The first stage is known as the “no-damage stage”, where all energy is dissipated as viscoelastic damping and there is no damage to the bitumen. The second stage is called the “crack initiation stage”, where cracks begin to

Table 2
Fatigue lives of different binders with different ageing levels obtained from time sweep.

Bitumen types	Polarity	N_f based on 50% complex modulus		N_f based on peak phase angle	
		5%	7.5%	5%	7.5%
Neat 35/50 A	Virgin	4740	2360	4200	2020
	RTFOT	6160	3940	9000	3460
	PAV15	6480	3960	39960	15640
	PAV20	9680	4140	47740	18550
	PAV30	10560	4300	51960	24640
	PAV40	11240	4720	54120	25700
Neat 40/60B	Virgin	6560	2260	1920	1340
	RTFOT	8260	2940	6120	1900
	PAV15	17240	5640	13980	23420
	PAV20	21180	6720	17700	22120
	PAV30	22340	6940	22720	22700
	PAV40	20160	7180	19420	21360
Neat 40/60 C	Virgin	4740	1660	3080	980
	RTFOT	5960	1700	3420	1000
	PAV15	10060	3020	6440	2280
	PAV20	13760	3580	10480	2840
	PAV30	15300	3780	12920	3060
	PAV40	22320	5620	20220	4600
Neat 70/100D	Virgin	8700	2720	5860	1520
	RTFOT	10200	4660	6440	2320
	PAV15	15620	5660	13200	3380
	PAV20	16680	8620	14460	6900
	PAV30	18720	9420	15680	5940
	PAV40	20020	10480	16840	7380
Neat 70/100E	Virgin	4040	1900	1160	1240
	RTFOT	6060	2300	4160	1560
	PAV15	9880	3400	5860	2300
	PAV20	12080	4280	9520	3360
	PAV30	12640	4340	10680	3220
	PAV40	17100	6600	14700	5740
Neat 70/100 F	Virgin	5320	2000	4400	1460
	RTFOT	7440	2460	4520	1480
	PAV15	8940	3580	8740	2640
	PAV20	10960	3880	8600	2700
	PAV30	15000	4340	11640	3440
	PAV40	18080	6180	14860	5380

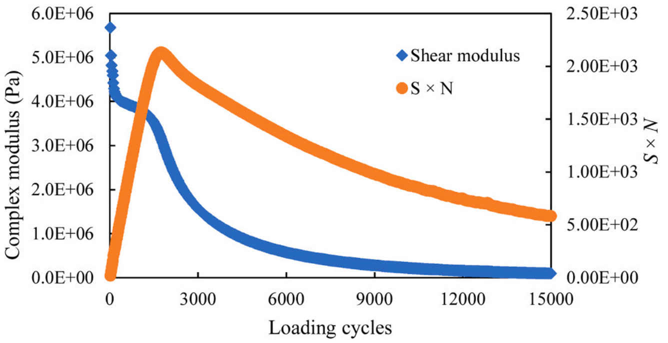


Fig. 4. Definition of the damage criterion of peak in S × N.

form and the material's integrity starts to deteriorate, resulting in an increase in damage with each cycle. The final stage, known as the "crack propagation stage", is characterised by a rapid change in response, leading to severe damage and eventual failure [53]. The dissipated energy ratio (*DER*) was introduced to symbolise the transition from the stage with no damage to the crack initiation stage, and ultimately to the crack propagation stage [54]. These two inflection points are notable and clearly indicate a significant change in the damage behaviour of samples. The second inflection point is considered a reliable definition of fatigue failure as it has been found to have a strong correlation with the peak values of phase angles [26].

Based on the equations, the *DER* of different binders with different ageing levels against loading cycles are plotted in Fig. 5.

The *DER* versus loading cycle curves for all binders at 5% and 7.5% strain levels exhibit similar trends. As shown in Fig. 5, in the initial stage, the *DERs* for all binders increase linearly with the number of loading cycles since no damage has been induced at this stage and the dissipated energy only contributes to viscoelastic damping. However, as damage accumulates, the trend line of *DERs* deviates from a linear slope and the deviation point is considered the damage initiation point. Afterwards, the *DERs* increase more rapidly until reaching the cracking propagation point [15]. The graphs indicate that ageing related stiffness increase delays both the crack initiation and propagation points, resulting in a significant improvement in the fatigue resistance of binders. This improvement is more significant after long-term ageing compared to short-term ageing, which is consistent with the previously mentioned findings on fatigue life, confirming that ageing enhances the fatigue performance of bituminous binders at the strain levels applied in this study [55].The definition of N_p can be expressed as the number of loading cycles at which the intersection of two asymptotes [9], as shown in Fig. 6.

The predicted fatigue lives for all tested binders at both strain levels were summarised in Table 4.

The results indicated that ageing has a positive effect on the fatigue life of bitumen. The findings are consistent with the results obtained from the conventional 50% reduction in complex modulus scenario and the peak in phase angle scenario. Ageing has a hardening effect on the binders, which delays the initial cracking point and the cracking propagation point, resulting in improved resistance to fatigue damage and a higher value of fatigue life N_{p20} [56].

4.4. *Ratio of dissipated energy change (RDEC) analysis*

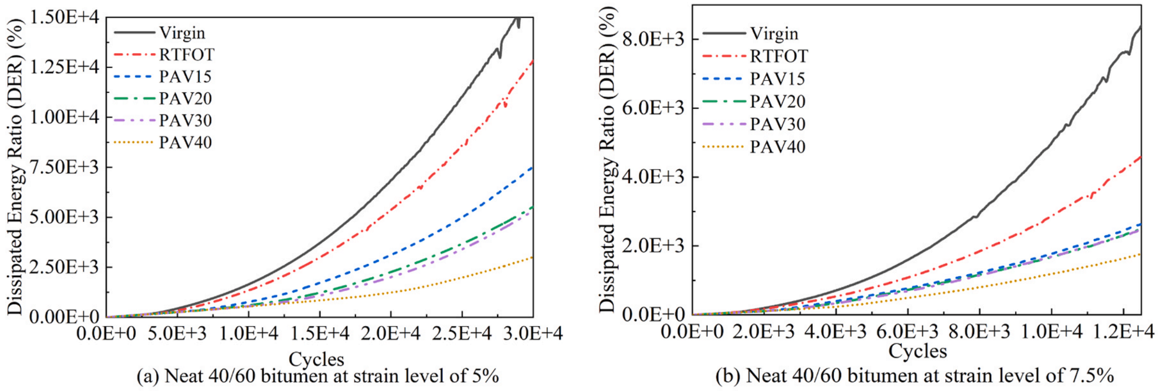
The dissipated energy change provides a true indication of the damage from one cycle to another by comparing the previous cycle's energy level and determining how much of it contributed to damage [57]. The main advantage of this approach is that it is not dependent on the material or loading mode being used and provides an indication of the damage accumulation from one cycle to another. The approach of *RDEC* has been widely adopted for the evaluation of fatigue performance of bituminous materials [24,58]. A lower amount of energy dissipation indicates better fatigue resistance because cracking will only grow when there are differences in energy dissipation from cycle to cycle, which can be considered as the amount of damage done to specimens [59]. Fig. 7 shows a typical *RDEC* curve plotted against the number of loading cycles.

Fig. 7 showed three stages, with the second stage being a plateau representing the damage initiation stage. The value of the *RDEC* at this stage, known as *PV*, is closely related to the fatigue life of the binders [60,61]. The fatigue life is defined as the point at which there is a 20% deviation of the *RDEC* from the plateau trend line. The results of the *PV* and fatigue life for each binder at different ageing levels and strain levels are summarised in Table 5.

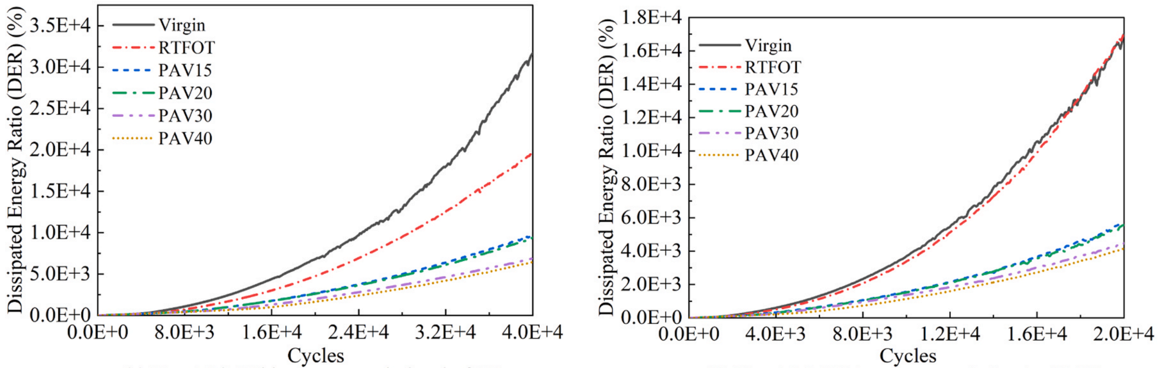
When materials are subjected to external work, they must maintain energy balance through dissipation. The *PV* is a key parameter in evaluating damage and fatigue failure in materials. A lower *PV* is preferable, as it indicates a gentle change in the dissipated energy of the binders, allowing for better preservation of the material's integrity under repeated loading. Studies have consistently shown that a lower *PV* is associated with a higher fatigue life, as documented by several researchers [56,62]. The results of the present study supported this relationship, as the *PV* of the binders decreased as ageing continues, while the fatigue life increased. This observation was seen across all types of binders, with binders tested at higher strain levels exhibiting higher *PV* values. The higher strain levels weakened the binders capacity to resist energy dissipation, leading to a reduction in their fatigue life. The *RDEC* approach provides a theoretical method for evaluating the change in dissipated energy of bitumen and sheds light on the mechanisms of

Table 3
Fatigue lives of binders based on S × N damage criterion.

Bitumen types	Polarity	Fatigue life		Bitumen types	Polarity	Fatigue life	
		5%	7.5%			5%	7.5%
Neat 35/50 A	Virgin	6460	1980	Neat 70/100D	Virgin	6580	2000
	RTFOT	9580	3460		RTFOT	8560	3580
	PAV15	37954	19680		PAV15	11960	4320
	PAV20	41980	22630		PAV20	13140	7280
	PAV30	48000	28820		PAV30	14660	8460
	PAV40	51840	35860		PAV40	16860	9460
Neat 40/60B	Virgin	4860	1720	Neat 70/100E	Virgin	3200	1460
	RTFOT	6260	2160		RTFOT	4620	1740
	PAV15	14560	4780		PAV15	7960	2940
	PAV20	19320	5840		PAV20	10000	3880
	PAV30	24560	8260		PAV30	10120	5520
	PAV40	26920	9660		PAV40	15060	7220
Neat 40/60 C	Virgin	3480	1260	Neat 70/100 F	Virgin	4040	1480
	RTFOT	4580	1620		RTFOT	5560	1920
	PAV15	7940	2340		PAV15	8560	2800
	PAV20	12120	2820		PAV20	8840	3000
	PAV30	13240	3200		PAV30	11800	3540
	PAV40	20520	4580		PAV40	15220	5440



(a) Neat 40/60 bitumen at strain level of 5%
(b) Neat 40/60 bitumen at strain level of 7.5%



(c) Neat 70/100 bitumen at strain level of 5%
(d) Neat 70/100 bitumen at strain level of 7.5%

Fig. 5. Representatives of *DER* against loading cycles curves for binders.

fatigue damage.

4.5. Comparation between different fatigue life prediction methods

The comparison between different approaches was performed to determine which methods were the most efficient and reliable to predict the fatigue life of binders with varying ageing levels. This study employed two strain levels, for simplicity, only the fatigue lives calculated at a strain level of 7.5% were compared as at higher strain levels, the fatigue performance of binders has a stronger correlation with the fatigue performance of asphalt mixtures [45]. Firstly, the Analysis of Variance (ANOVA) was carried out to illustrate whether the fatigue life of bitumen calculated using different methods were significantly different, the ANOVA results are shown in Table 6.

As shown in Table 6, at the significance level of 0.05, the population means were significant different, which suggests that using different methods to calculate the fatigue life of binders can results in significantly different results. These results suggested that though all results were calculated based on time sweep tests, significant differences/variances were found. Therefore, identifying an effective and universally reliable method is necessary. To identify the extent of differences, the boxplots for the fatigue life of each binder is shown in Fig. 8. In a boxplot, the lower whisker represents the minimum value, the lower quartile (Q1) marks the 25th percentile, the median indicates the

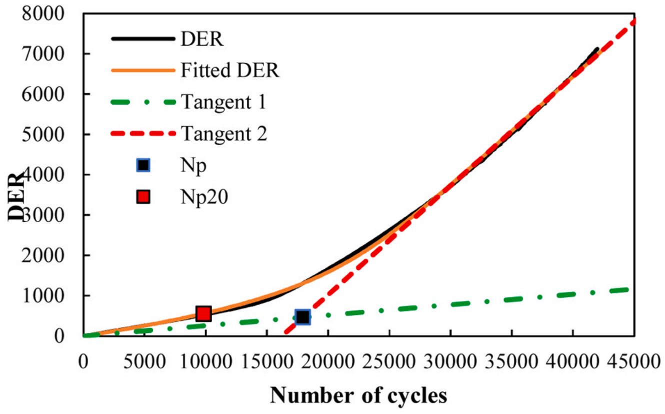


Fig. 6. Definition of the parameters of N_{p20} and N_p [53].

Table 4
Fatigue life of bitumen based on DER.

Bitumen types	Polarity	N_p		N_{p20}	
		5%	7.5%	5%	7.5%
Neat 35/50 A	Virgin	10341	8102	5606	3599
	RTFOT	12440	8657	8737	4556
	PAV15	12245	13553	6815	11718
	PAV20	20520	14969	18390	12236
	PAV30	29116	18162	23082	15982
	PAV40	31556	18005	31037	15793
Neat 40/60B	Virgin	10549	5293	5361	2693
	RTFOT	10954	5691	5726	2949
	PAV15	18715	7068	9924	3731
	PAV20	26706	9133	13354	4746
	PAV30	27658	9284	14499	4927
	PAV40	24964	10783	20918	5497
Neat 40/60 C	Virgin	10013	3659	5070	1867
	RTFOT	10589	3636	5392	1947
	PAV15	14275	4113	7361	2236
	PAV20	16667	4687	8709	2536
	PAV30	20435	4566	10472	2678
	PAV40	21463	5906	11703	3296
Neat 70/100D	Virgin	9183	5938	4814	3063
	RTFOT	10049	7920	6023	4037
	PAV15	11965	7689	8881	4136
	PAV20	12110	9240	10069	4937
	PAV30	13369	10974	12666	5851
	PAV40	15557	13459	14224	6983
Neat 70/100E	Virgin	9284	5588	4960	2839
	RTFOT	10394	7583	5315	3824
	PAV15	11858	8079	6264	3426
	PAV20	12788	7531	7032	4002
	PAV30	13834	6312	7571	4272
	PAV40	16705	9173	15226	4938
Neat 70/100 F	Virgin	9506	5675	4795	2882
	RTFOT	10420	7085	5329	3548
	PAV15	12034	7290	6475	3848
	PAV20	12078	7347	6529	3873
	PAV30	14005	7803	7776	4414
	PAV40	17933	8521	9820	4532

midpoint, the upper quartile (Q3) denotes the 75th percentile, the upper whisker represents the maximum value. For every sample, the fatigue life was calculated using five methods, therefore, there were five data points for every box in the boxplot. Ranking the fatigue life of every single sample from the lowest to the highest, the five lines (two whiskers, two borders of the box and the median line) represented the values of fatigue life calculated by five methods and the square within the box was the average of these values.

As illustrated in Fig. 8, the boxplots of Neat 35/50 A and Neat 40/60B binders showed poor data consistency when the binders were long-term aged while the boxplots for other binders showed relatively better

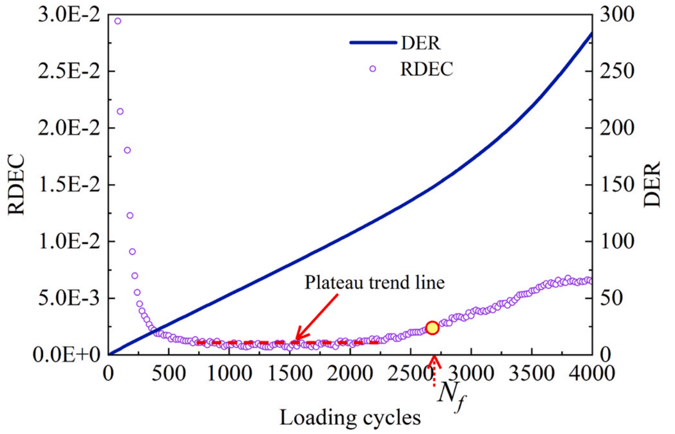


Fig. 7. Schematic of *DER & RDEC* versus loading cycles curve.

Table 5
Summary of Plateau Value (PV) and fatigue life.

Bitumen types	Polarity	*Strain level of 5%*		*Strain level of 7.5%*	
		PV	N_f	PV	N_f
Neat 35/50 A	Virgin	7.41E-4	2940	2.06E-3	1240
	RTFOT	3.73E-4	3480	2.05E-3	3060
	PAV15	1.61E-4	41680	3.47E-4	17680
	PAV20	1.52E-4	44560	3.11E-4	21550
	PAV30	1.21E-4	49680	2.68E-4	27980
	PAV40	1.04E-4	61640	2.24E-4	30420
Neat 40/60B	Virgin	3.28E-4	2720	1.41E-3	825
	RTFOT	2.95E-4	4740	1.23E-3	1422
	PAV15	2.28E-4	9980	9.98E-4	4040
	PAV20	2.27E-4	16900	9.45E-4	5180
	PAV30	2.26E-4	18360	9.17E-4	5460
	PAV40	2.21E-4	20020	7.69E-4	5720
Neat 40/60 C	Virgin	4.66E-4	2360	4.30E-3	540
	RTFOT	4.24E-4	3260	1.59E-3	680
	PAV15	4.03E-4	6500	1.34E-3	1840
	PAV20	4.01E-4	8760	1.24E-3	2020
	PAV30	3.87E-4	10660	1.22E-3	2320
	PAV40	2.55E-4	17360	1.09E-3	4100
Neat 70/100D	Virgin	7.89E-4	880	9.35E-4	780
	RTFOT	3.12E-4	2820	5.16E-4	2020
	PAV15	2.38E-4	6140	4.03E-4	2760
	PAV20	1.78E-4	8940	3.65E-4	4740
	PAV30	1.55E-4	9340	3.32E-4	5280
	PAV40	1.19E-4	10180	2.89E-4	6960
Neat 70/100E	Virgin	7.89E-4	960	1.57E-3	680
	RTFOT	4.64E-4	2560	1.35E-3	1028
	PAV15	2.17E-4	4760	1.02E-3	1560
	PAV20	2.09E-4	7460	9.28E-4	2120
	PAV30	2.06E-4	8380	8.68E-4	2240
	PAV40	2.00E-4	11060	8.26E-4	3980
Neat 70/100 F	Virgin	4.54E-4	1920	1.41E-2	780
	RTFOT	3.24E-4	2280	1.40E-2	1000
	PAV15	2.45E-4	4740	1.15E-2	1610
	PAV20	1.86E-4	5980	1.03E-2	1680
	PAV30	1.52E-4	7140	1.00E-2	2160
	PAV40	1.25E-4	11080	9.67E-3	3520

Table 6
ANOVA results of the mean values of fatigue life.

	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	35	4.75E9	1.36E8	8.01	< 0.0001
Error	144	2.44E9	1.69E7		
Total	179	7.19E9			

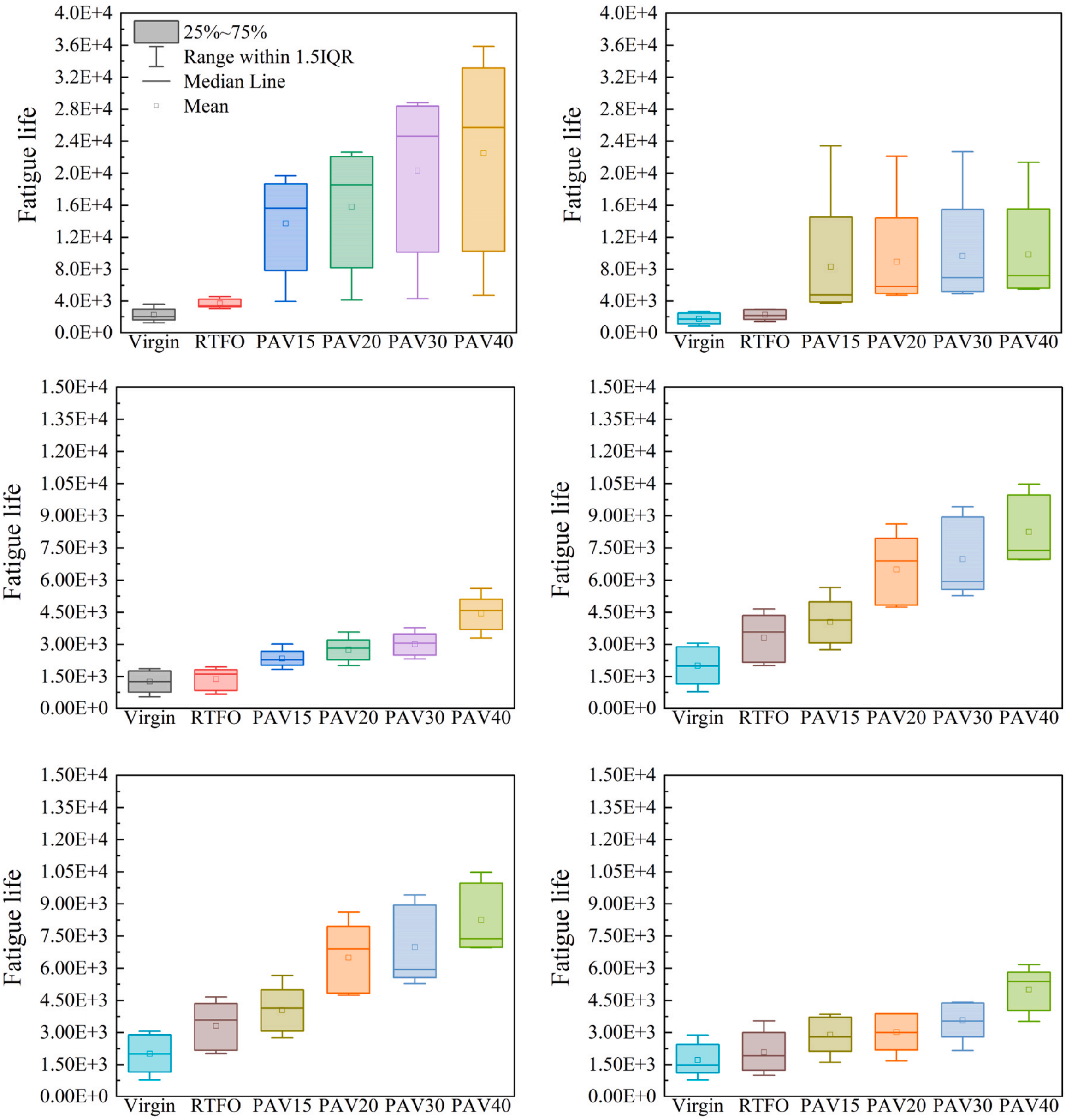


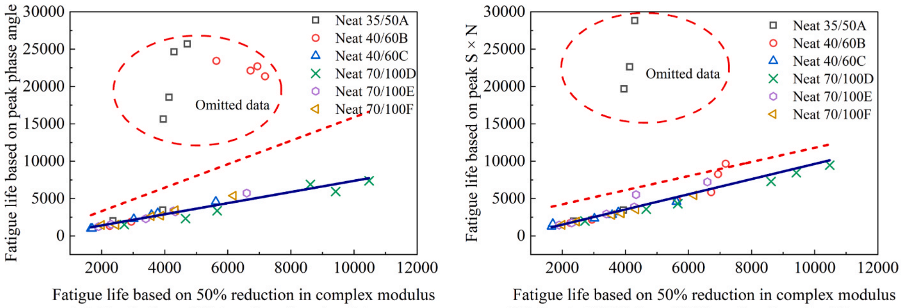
Fig. 8. Boxplots of the fatigue life of binders (from left top to right bottom, the boxplots are for binders A, B, C, D, E, F respectively).

consistency regardless of ageing conditions. It should be mentioned that for the binders at unaged conditions, the stiffness of binders increases from Neat 35/50 A to Neat 70/100 F. Therefore, binder 35/50 A was the stiffest binder while the binder 40/60B was the second stiffest binder. After long-term ageing, the aged Neat 35/50 A binders were the stiffest one among all aged binders. Similarly, the aged Neat 40/60B binders were slightly softer than those of aged Neat 35/50 A binders while stiffer than other aged binders. To identify which methods might not be fully capable to measure the fatigue life of binders at certain circumstances, the correlations between the fatigue life calculated by different methods were compared, as displayed in Fig. 9. The dashed red lines are the fitting line with all data points while the solid lines are the fitting lines ignoring the abnormal data points.

The correlation between the fatigue lives predicted by different models was analysed using Pearson correlation coefficient (PCC). The PCC is a measure of the linear correlation between two variables and its value ranges from −1–1. A value of +1 or −1 indicates a perfect linear relationship between the two variables, while a value of 0 suggests no linear correlation exists. Table 7 summarises the PCC values.

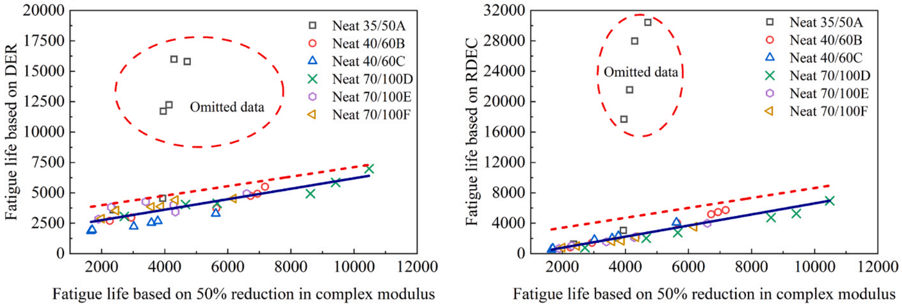
The results showed that the different models have different levels of correlation with each other, implying that some models may be more efficient and reliable in predicting the fatigue lives of binders than others. The PCC value in bold fonts were calculated using the data ignoring the abnormal data points while the bracketed values were calculated using all data points. It was found that the peak in $S \times N$ approach and the two dissipated-energy-based approaches correlated well in capturing the change in fatigue life of binders after long-term ageing compared to the conventional 50% reduction in complex modulus and peak in phase angle methods, as the peak in $S \times N$ approach and the two dissipated-energy-based approaches showed higher correlation coefficients while the conventional 50% reduction in complex modulus and peak in phase angle methods showed fairly poor correlation coefficients. This was concluded from the observation that the conventional methods were unable to capture the dramatic increase in fatigue life of the stiffest binders, as shown in Fig. 9, while the dissipated-energy-based approaches were capable of doing so.

The red dashed lines in Fig. 9 represents the linear correlation between each set of fatigue lives of binders determined by different



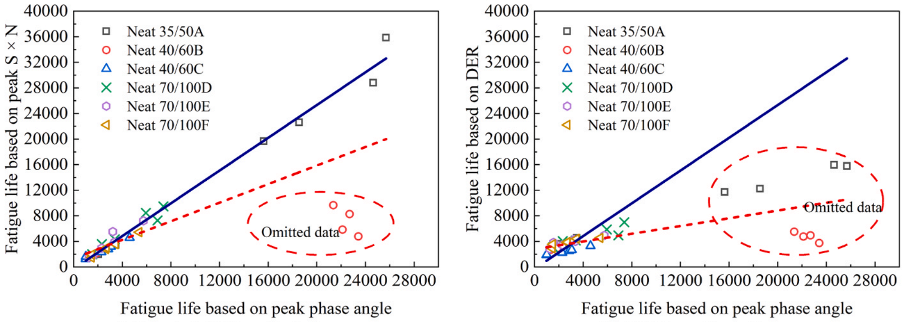
(a) Peak δ vs 50% reduction in G*

(b) Peak S X N vs 50% reduction in G*



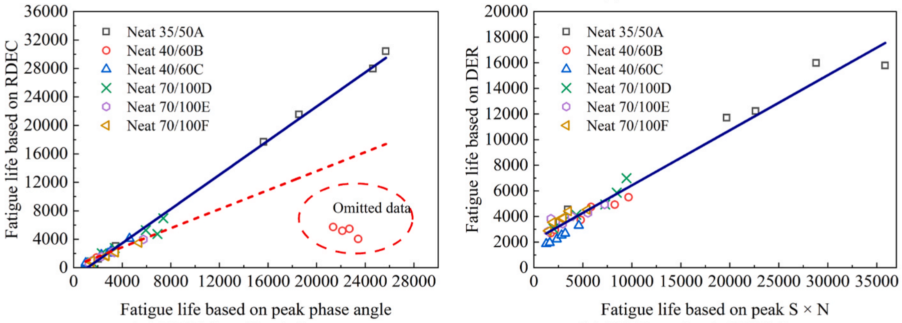
(c) DER vs 50% reduction in G*

(d) RDEC vs 50% reduction in G*



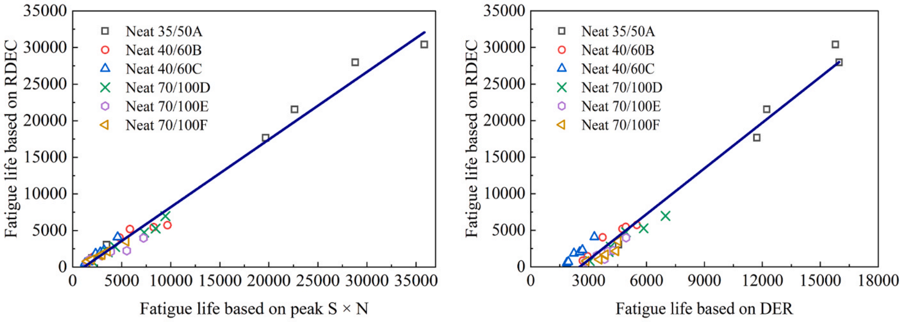
(e) Peak S X N vs Peak δ

(f) DER vs Peak δ



(g) RDEC vs Peak δ

(h) DER vs Peak S X N



(i) RDEC vs Peak S X N

(j) RDEC vs DER

Fig. 9. Comparation between the fatigue life of binders calculated by different methods.

Table 7
PCCs of the fatigue life calculated by different methods.

	50% |G*|	**Max δ**	**Max $S \times N$**	**N_{p20}**	**$N_{f\text{-}PV}$**
50% |G*|	1	**0.963** (0.419)	**0.947** (0.261)	**0.864** (0.246)	**0.953** (0.194)
Max δ	**0.963** (0.419)	1	**0.993** (0.753)	**0.827** (0.715)	**0.996** (0.743)
Max $S \times N$	**0.947** (0.261)	**0.993** (0.753)	1	0.980	0.991
N_{p20}	**0.864** (0.246)	**0.827** (0.715)	**0.980**	1	0.963
$N_{f\text{-}PV}$	**0.953** (0.194)	**0.996** (0.743)	**0.991**	0.963	1
Average	**0.945 (0.424)**	**0.956 (0.726)**	**0.982 (0.797)**	**0.927 (0.781)**	**0.981 (0.778)**

methods. It was seen that the lines were separated from the data points, indicating that the conventional methods were not fully effective in capturing the fatigue life of binders, especially when they were very stiff. However, when excluding the abnormal values of fatigue lives, the linear correlations between each set of data and the Pearson correlation coefficients were reasonable. This indicated that different methods for evaluating the fatigue life of binders gave consistent rankings and trends in terms of ageing. The Max in $S \times N$ approach was found to have the best consistency with other methods. To compare the effectiveness of different methods, their properties were summarised and shown in Table 8.

Comparing the different methods of evaluating the fatigue life of binders, some limitations were found. The 50% reduction in complex modulus method had difficulties in identifying the initial values of the complex moduli, as they decrease rapidly at the beginning of the test. The peak in phase angle method had unstable results at the later stage of testing, leading to errors. The *DSE* based N_{p20} method was complex because it uses many parameters which needs to be fitted using software and its value is dependent on the initial values of these parameters, which might lead to errors and inconsistency. The *RDEC* based N_f-PV method had difficulty in identifying the 20% deviation, as the *PVs* were vibratory. The peak in $S \times N$ method was recommended for use in the fatigue life prediction of aged bitumen for routine testing, as it had the best correlation with other methods and had no significant limitations, moreover, it's easy to calculate and there is no need for manual judgement.

Overall, the two dissipated-energy-based approaches are reliable to evaluate the fatigue life of aged binders, but their calculation process is complex. The peak in $S \times N$ method is recommended as it does not have obvious limitations and is easy to use or calculate and has strong correlation with other methods. The conventional methods such as 50% reduction in complex modulus and peak in phase angle are not recommended.

5. Findings and conclusions

This paper aims to evaluate the fatigue performance of aged bitumen using time sweep testing. Different approaches including the conventional 50% reduction in complex modulus and peak in phase angle methods, as well as the peak in $S \times N$ approach and the two dissipated-energy-based approaches were employed. The following findings and conclusions can be drawn from the results:

- With more severe levels of ageing, the fatigue life of bituminous binders improved when the loading strains were 5% and 7.5%, as evidenced by all damage criteria. This indicates that ageing related stiffness increases does not negatively impact the fatigue resistance of binders at such strain levels. This result also illustrates the need to develop more robust methods to fully capture the fatigue performance of aged binders in the future.
- The statistical analysis suggests that different time sweep based methods have significant differences in determining the fatigue life of aged binders, the most significant differences exists in the stiffer binders.
- The peak in $S \times N$ approach and the two dissipated-energy-based approaches (*DSE* based Np_{20} and *RDEC* based N_f-PV) were most efficient and reliable in capturing the fatigue life of bituminous binders as compared to the conventional 50% reduction in complex modulus and peak in phase angle methods.
- The peak in $S \times N$ method is the recommended approach for evaluating the fatigue life of aged binders based on time sweep tests as it has no apparent defects and has the best correlations with other methods.

Though this study performed a comparative analysis of time sweep testing methods for the fatigue characterisation of aged bitumen, some limitations still need further exploration. For example, fatigue life of bitumen is strain-dependent, and it is suggested to test the samples at a broader strain range, e.g. from 1% to 15% to have a comprehensive understanding of the strain dependence of fatigue life. Moreover, all binders used in this study were unmodified binders, it is suggested to use polymer modified bitumen for further investigations. Lastly, considering that time sweep is time-consuming, it is recommended to compare these testing results with accelerated tests such as LAS. This will help validate the feasibility and facilitate the application of more time-efficient surrogate tests.

CRediT authorship contribution statement

Wei Si: Investigation, Supervision, Writing – review & editing. **Gordon Dan Airey:** Writing – review & editing, Supervision, Conceptualization. **Bo Li:** Writing – review & editing, Supervision. **Haopeng Wang:** Writing – review & editing, Supervision, Methodology. **Anand Sreeram:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization. **Yongping Hu:** Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

Table 8
Comparison of different methods for evaluating the fatigue life of aged bitumen.

Method	Consistency	Calculation	Manual judgment	Recommendation
50% reduction in G*	Poor	Straightforward	Needed	Not recommended
Peak in phase angle	Poor	Straightforward	No	Not recommended
$S \times N$	Good	Straightforward	No	Recommended
DER	Good	Complex	Needed	Acceptable
RDEC	Good	Complex	Needed	Acceptable

the work reported in this paper.

Data availability

Data will be made available on request.

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