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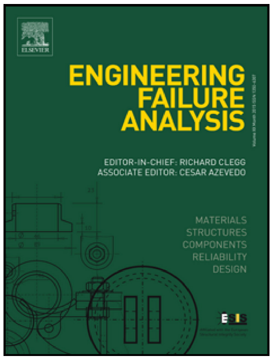

New simplified approach for obtaining a reliable plateau value in fatigue analysis of bituminous materials

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New simplified approach for obtaining a reliable plateau value in fatigue analysis of bituminous materials

Abstract:

The Plateau Value (PV) based on the Ratio of Dissipated Energy Change (RDEC) approach has been proven to provide a unique relationship with the fatigue life, N_f, independent of loading mode, temperature and frequency. In this paper, a new simplified approach is proposed to compute the unique energy parameter PV. The results of this study show that applying the proposed method allows a unique fatigue power law to be produced and eliminates the ambiguity and variability in calculating PV. However, the study also shows that the PV-N_f fatigue curves for bituminous materials are dependent on material type which is contradictory to other studies dealing with PV. The study also highlights the importance of appropriately identifying the fatigue failure point prior to commencing any fatigue analysis.

1. Introduction

Fatigue is a very complicated distress mode and no single asphalt mixture property has been found to reliably predict or control the fatigue of a flexible pavement [1]. However, the fatigue life of hot-mix asphalt (HMA) has been recognized to be highly sensitive to the properties of the binder and fatigue cracking normally initiates and propagates within the binder, binder-filler mastic or at the bitumen-aggregate interface. A large number of research groups have attempted to identify testing procedures and fundamental parameters that can accurately reflect the contribution of the binders' properties on the fatigue resistance of asphalt mixtures and subsequent pavement performance [2-11]. In this regard, time sweep repeated cyclic loading tests, adopted in this study, have been successfully used to evaluate the fatigue properties of binders [3, 5, 12]. This procedure simulates the fatigue phenomenon and directly monitors the damage behaviour of binders through the change in their viscoelastic properties, i.e. stiffness modulus and phase angle. Other studies have also shown that applying the dissipated energy approach for fatigue analysis can provide more fundamental material properties and an intrinsic fatigue law [13-16]. The Ratio of Dissipated Energy Change (RDEC) approach, from which the Plateau Value (PV) is derived, was first introduced by Ghuzlan and Carpenter [16]. The uniqueness associated with the RDEC approach compared to other energy approaches, such as the total accumulated dissipated energy, is its ability to minimise the effect of energies that are involved in nonlinearity, heating and thixotropy which may not be directly related to fatigue damage. It has been argued that these energies could lead to totally wrong analyses if there was not a clear and rational quantification for them [17].

Despite the fundamental uniqueness behind the RDEC approach and the PV parameter, there are still limited studies applying this approach. The difficulties and uncertainty associated with obtaining a valid and accurate PV could possibly be the main obstacle limiting the widespread use of this methodology. Therefore, a new and simplified approach is suggested in this study to determine a reliable PV. The new method was applied successfully on both neat and modified binders and could contribute suitably in characterising the fatigue behaviour of bituminous binders and integrating their behaviour in asphalt mixtures and pavement performance. This paper also seeks to provide a review and critical evaluation of different approaches used to define the fatigue failure in order to accurately assess the fatigue damage resistance.

2. Background and theory

2.1 Dissipated energy approach

Several research studies have supported the use of the dissipated energy approach for fatigue damage analysis. This approach enables an independent fatigue law to be derived regardless of loading mode, frequency, rest periods and temperature [13, 15, 16, 18]. When viscoelastic materials are subjected to cyclic loading, they generate different paths for the loading and unloading cycles leading to hysteresis loops. The dissipated energy per cycle is computed as the area within the hysteresis loop and calculated by the following equation:

$$w_i = \pi \sigma_i \varepsilon_i \sin \delta_i \qquad (1)$$

Where w_i is the dissipated energy at cycle i while σ_i, ε_i, δ_i are the stress amplitude, strain amplitude and phase angle at cycle i, respectively. It can be seen that this approach contains the main viscoelastic parameters (stress, strain and phase angle) and thus monitoring the variation in these parameters during the fatigue evolution allows an intrinsic fatigue law to be derived. The early studies of applying the dissipated energy approach to characterize fatigue cracking in asphalt mixtures were introduced by Van Dijk and his colleagues [15, 19, 20]. They showed that the relation between accumulated dissipated energy (W_{fat}) at failure and number of cycles N_f to failure depends solely on material properties and it is constant irrespective of the mode of loading, frequency and temperature. The accumulated dissipated energy after n cycles can be calculated as:

$$W_n = \sum_{i=0}^{n} w_i \qquad (2)$$

The relationship between cumulative dissipated energy to the number of load cycles to failure was found to be a power law relation as following:

$$W_{fat} = A.N_{fat}^{z} \qquad (3)$$

Where W_{fat} = total dissipated energy until failure due to fatigue cracking, N_{fat} = number of loading cycles to fatigue; and $A\ and\ z$ = material constants. The main concern with this approach is that the sum of dissipated energy computed using Eq.1 includes energies that are not responsible for fatigue damage such as recoverable viscoelastic energy and heat energy. Therefore, Ghuzlan and Carpenter [16] proposed the use of the Dissipated Energy Ratio (DER) to study the fatigue behaviour. The DER or the Ratio of Dissipated Energy Change (RDEC) approach was then developed by Carpenter and Shen [21] who emphasised the fact that damage will only be generated when there is a difference in dissipated energy between consecutive cycles. RDEC is expressed as:

$$For\ controlled\ stress\ mode: RDEC_i = \frac{(w_i - w_j)}{w_i.(i-j)} \qquad (4)$$

$$For\ controlled\ strain\ mode: RDEC_i = \frac{(w_j - w_i)}{w_i.(i-j)} \qquad (5)$$

Where $RDEC_i$ = ratio of dissipated energy change value at cycle i; $w_i\ and\ w_j$ =dissipated energies at cycles i and j; and i, j = loading cycle, $i > j$. The subtraction in the numerator of Eq.4 and Eq.5 between the consecutive cycles is believed to eliminate energies like viscoelastic damping, plastic deformation energy and thermal energies that are not causing damage while keeping the relative amount of incremental damage coming from each additional load cycle [13, 22, 23]. As previously depicted by Ghuzlan and Carpenter [16] and Shen, Chiu and Huang [23], three distinct phases can be identified when the RDEC is plotted versus the number of cycles as shown in Fig. 1. Phase I is defined by a rapid decrease of the RDEC. The decrease is considered to be not only caused by fatigue damage but includes molecular reorientation and other reversible phenomena such as thixotropy. Phase II reflects the internal damage characteristic of materials and is defined by a plateau of steady-state and micro-crack development. The change in the dissipated energy is almost constant with a relatively constant percentage of input energy being transformed into damage. Phase III is defined by a rapid increase in RDEC and thus indicates a sign of fatigue failure. Carpenter and Shen [21] proposed that the RDEC value at Phase II or the plateau value (PV) is insensitive to the mode of loading. Several studies have showed that PV can provide a unique relationship with the number of loading cycles to failure for different mixtures, loading modes and loading levels [13, 21, 23, 24].

The relationship between PV and the number of load cycles to failure was found to be a power law relation as follows [16]:

$$PV = C.N_{fat}^{d} \qquad (6)$$

Where c and d = regression constants; and N_{fat}= number of load cycles to failure.

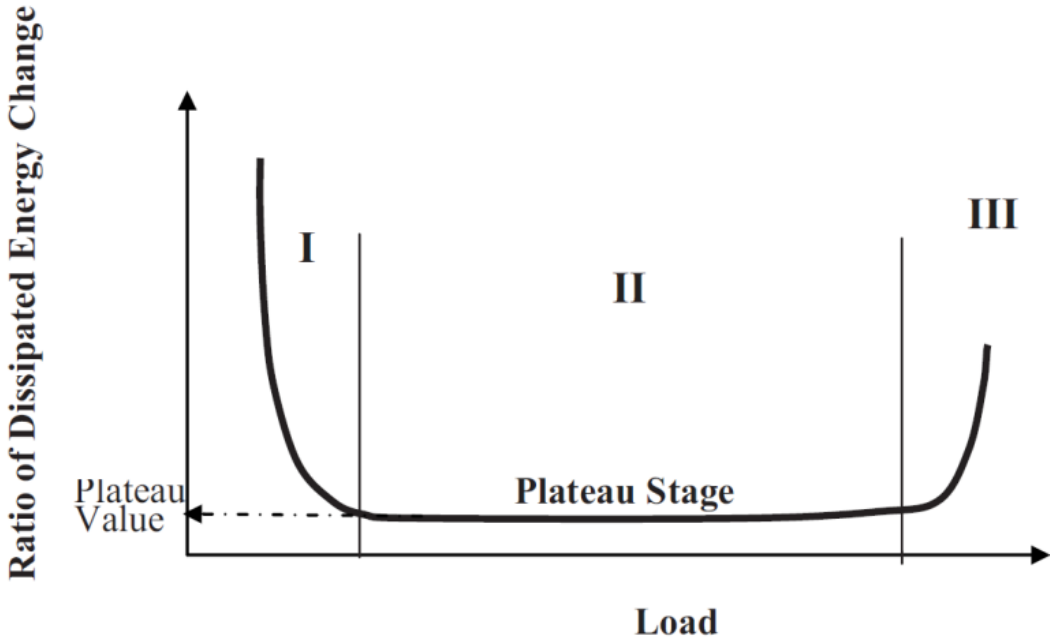

Fig. 1. Typical RDEC plot versus load cycles [23]

2.2 Definition of fatigue failure

Under repeated cyclic loading, the fatigue life should correspond to the transition point between crack initiation and crack propagation. Several approaches have been adopted to correctly identify the fatigue failure point [25-27]. The classical approach of a 50% decrease in the initial stiffness is the most commonly used approach to identify the fatigue failure in bituminous materials. However, many studies have shown that this criterion may not always be appropriate for analysing fatigue properties [3, 26, 27]. In addition, the different stress/strain loading modes do not always produce a unique intrinsic fatigue law if this arbitrary definition is applied. Therefore, it is important to find other approaches that are not arbitrary but can define the fatigue failure based on a more fundamental analysis. The Dissipated Energy Ratio (DER) concept shown below was proposed to provide a reasonable criterion for defining the fatigue failure of bituminous mixtures [14].

$$DER = \frac{\sum_{i=1}^{n} W_i}{W_n} \qquad (7)$$

Where, W_i= dissipated energy per cycle, W_n= dissipated energy at cycle n. The plotting of the relationship between DER and number of cycles in the stress-controlled mode provides a distinctive way to evaluate the stage of fatigue damage at which the material undergoes a transition from crack initiation to crack propagation. Fig. 2 shows the evolution between DER and loading cycles, where during the first portion there is negligible damage of the materials and DER = n, i.e. the dissipated energy is almost equal for consecutive cycles. As the relative difference in dissipated energy between consecutive cycles becomes significant, DER starts deviating from the equality line which is interpreted as crack initiation. The fatigue failure N_f point in Fig. 2a is defined by the sudden change in DER which can be related to the point of transition from crack initiation to crack propagation. This change is considered to be highly material specific and independent of the mode of loading [3, 25]. Under strain controlled testing the N_f is defined by the intersection of two tangents as shown in Fig. 2b.

Another fatigue failure criterion was evaluated from the evolution of phase angle versus complex modulus (Black diagram), see Fig. 2c. Di Benedetto et al. [28] demonstrated that using the Black diagram during fatigue evolution is a promising approach to define the stages of fatigue development. The change in the process evolution of the Black diagram in Fig. 2 gives a definitive limit between crack initiation and crack propagation. The N_f value can be defined from the value of the phase angle at the intersection of two straight lines. These lines are used to linearize the evolution of phase angles for each period; N_f corresponding to the defined phase angle is then determined.

In terms of continuum damage mechanics, fatigue damage commences with a homogeneous global damage which is distributed in the bulk body of material. The microstructural state of material during this stage is reflected by a steady change in the stress-strain relationships (stiffness modulus, phase angle, dissipated energy…etc.). On the other hand, a rapid change in the mechanical properties of the material happens corresponding to the occurrence of coalescence and unstable propagation of cracking by the means of molecular rupture and molecular scission leading to the structural failure. Thus, unlike the phenomenological approach of 50% decrease in the initial stiffness, the DER and the Black diagram can be considered a mechanistic based approach as they account for the evolution of damage mechanics based on the evolution of G* and phase angle throughout the fatigue process.

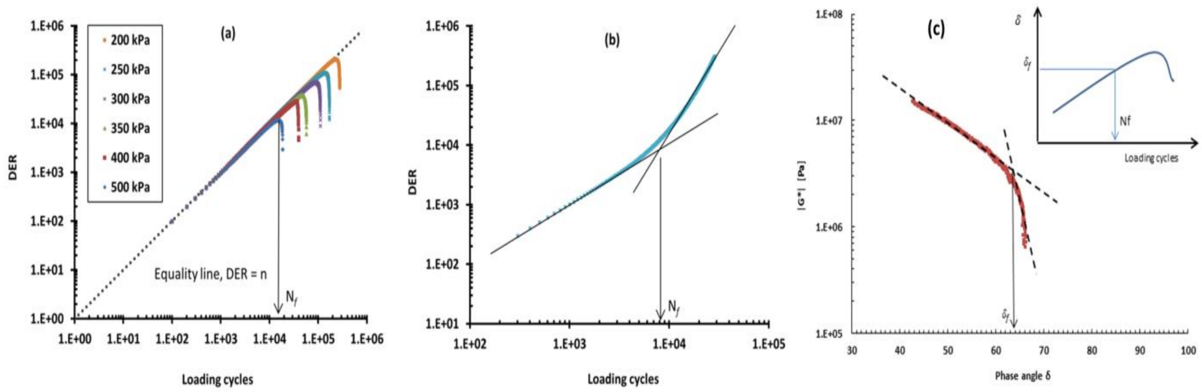

Fig. 2. Identifying N_f (a) from the DER vs. number of load cycles under controlled stress loading conditions, (b) from the DER vs. number of load cycles under controlled strain loading conditions and (c) from the evolution of phase angle versus complex modulus (Black diagram)

3. Materials and testing programme

3.1 Materials

Two neat bituminous binders were selected with large differences in their physical and rheological properties and labelled as ‘H’ and ‘S’. The addition of crumb rubber can considerably alter the mechanical properties of bitumens by acting both as an inert filler and as a dissolved polymer modifier [29, 30]. Therefore, the two neat bitumens were modified by adding recycled tyre rubber in order to validate the proposed method on modified bitumens. This has done by blending the base bitumens with a standard recycled tyre rubber labelled

'TRN' using the wet process. TRN is a recycled rubber, derived from discarded truck and passenger car tyres and produced by ambient grinding. The rubberised bitumens were produced by pre-heating the neat bitumen at 180^{o}C and then 15.25% of rubber by mass were added gradually to the binder. The blending continued at 180^{o}C for 100 minutes using a Silverson L4RT high shear laboratory mixer. The produced rubberised bitumens were labelled as 'HTRN' and 'STRN'. The HTRN binder refers to the neat bitumen H blended with TRN while the STRN binder refers to the neat bitumen S blended with TRN. Physical and rheological properties of the neat binders and modified binders are presented in Table 1. The effect of ageing was not considered in this study and all fatigue tests was carried out on unaged binders.

Table 1 Properties of base binder and RTR-MBs used in this study

Index	*H*	*HTRN*	*S*	*STRN*
Penetration @25 ^{o}C, 0.1mm	40	----	200	-----
Softening point ^{o}C	51.4	70.3	37.0	62.0
Rotational viscosity, mPa.s @135 ^{o}C	474	10829	192	5654
Asphaltenes content	15.2%	----	4.2%	----
$\|G^*\|.\sin\delta$ @ 0 ^{o}C & 10Hz, kPa	----	----	32020	15340
$\|G^*\|.\sin\delta$ @ 10 ^{o}C & 10Hz, kPa	35312	16360	9378	4289
$\|G^*\|.\sin\delta$ @ 20 ^{o}C & 10Hz, kPa	12607	7318	1635	1239

3.2 Testing programme

The time sweep binder fatigue test was performed using a Kinexus Model Dynamic Shear Rheometer (DSR) supplied by Malvern Instruments Ltd. This DSR model uses a Peltier system to control the testing temperature. Most of the fatigue tests were carried out under controlled stress conditions with one set of data being produced under controlled strain conditions in order to examine the effect of loading mode. All tests were conducted at a single frequency of 10Hz using a 2mm gap with the 8 mm plate-plate testing geometry. The effect of gap size on the rheological measurements was investigated due to the presence of rubber particles, and a 2mm gap size has been shown to provide reliable and repeatable measurements [29]. Different testing temperatures were selected for bitumen H and its rubberised bitumen and for bitumen S and its rubberised bitumen to ensure high initial complex modules |G*| (higher than 15 MPa) so that edge effects or plastic flow can be eliminated and the binders fail due to "true" fatigue damage rather than "instability flow" [12]. Various stress levels were applied on the different binders to induce different initial strains. Table 2 shows test conditions and parameters applied in this study. To investigate the impact of rest period duration on bitumen fatigue, an intermittent loading sequence was used by introducing different short rest times (10 and 20 seconds) after every 500 load pulses. The intermittent loading sequence is believed to provide better simulation of field loading conditions compared with other loading sequences in which a single long stop period is used [23].

Table 2 Tests conditions and parameters

Material	Temperature (°C)	Stress-control (kPa)	Strain-control (%)	Rest period RP (s)	Initial stiffness (MPa)
H	10	900, 1000, 1100, 1200, 1300, 1400, 1500	n/a	0	82
	10	900, 1000, 1100, 1200, 1300, 1400, 1500	n/a	10	82
	10	900, 1000, 1100, 1200, 1300, 1400, 1500	n/a	20	82
	10	n/a	1.25, 1.5, 1.75, 2	0	82
	20	200, 250, 300, 350, 400, 500	n/a	0	21
	20	200, 250, 300, 350, 400, 500	n/a	20	21
HTRN	10	400, 450, 500, 550, 600, 650, 700, 800	n/a	0	33
	10	400, 450, 500, 550, 600, 650, 700, 800	n/a	20	33
	20	125, 150, 200, 250, 300	n/a	0	11
S	0	250, 300, 350, 400, 450	n/a	0	40
	0	250, 300, 350, 400, 450	n/a	20	40
STRN	0	250, 300, 350, 400, 450	n/a	0	28
	0	250, 300, 350, 400, 450	n/a	20	28

4. Results and fatigue analysis

4.1 Definition of fatigue failure

The different failure criteria: 50% decrease in the initial stiffness, DER and the Black diagram approaches were compared to see if there is a significant difference between them that could affect the fatigue analysis. Fig. 3 shows the evolution of the complex modulus |G*| as a function of load cycles for all the binders during a fatigue test with no rest periods. The 50% reduction in stiffness was applied on the initial stiffness as taken from:

1. The raw data without manipulation, $|G_o^*|$
2. Extrapolation process by fitting the raw data using a third order polynomial relationship, $|G_{oi}^*|$ as shown in Fig. 3.

The extrapolated initial stiffness, $|G_{oi}^*|$, is often considered in fatigue analysis instead of the initial complex modulus, $|G_o^*|$. The rapid decrease at the beginning of fatigue test is thought to be due to other artefact effects such as heating and thixotropy and not only by fatigue [17, 28].

Previous studies have shown that the distinction between crack initiation and crack propagation could be defined by focusing on the rate of change in the material's response with load applications, dG*/dN [31, 32]. When the rate of change of dG*/dN is constant (linear), the materials can be considered to be undergoing crack initiation and stable crack propagation. When the rate of change of dG*/dN is no longer linear, then the material can be considered to be experiencing unstable crack propagation. Therefore, the transition zone between crack initiation and unstable crack propagation can be considered to lie between the two dashed lines shown in Fig. 3. It can be seen that the failure points based on the 50% classical approach for the modified binders were not totally in agreement with the estimated transition zone or with the other failure criteria. The relative difference between the different failure points to the transition zone for each binder is also significant. For example, if a fatigue comparison was made based on the classical failure criterion between the rubberised bitumens and neat bitumens, the fatigue analysis would be biased and misleading as the difference in their viscoelastic properties and deterioration path would not have been considered. The viscoelastic properties of rubberised bitumens allow larger strains to be sustained before the material is fractured and thus larger continuous decreases in stiffness (more than 50%) would still be within the fatigue life-span. Conversely, the neat bitumens and especially the hard bitumen H were less strain tolerant and hence do not allow larger continuous decreases in stiffness. Other failure criteria, i.e. DER and the Black diagram, cannot be taken as arbitrary and indeed they have been shown to correspond to a particular stage of fatigue damage. As the results show that the fatigue failure point based on the Black diagram is the closest to the transition zone, it has been taken as the failure criterion for fatigue analysis in the next sections.

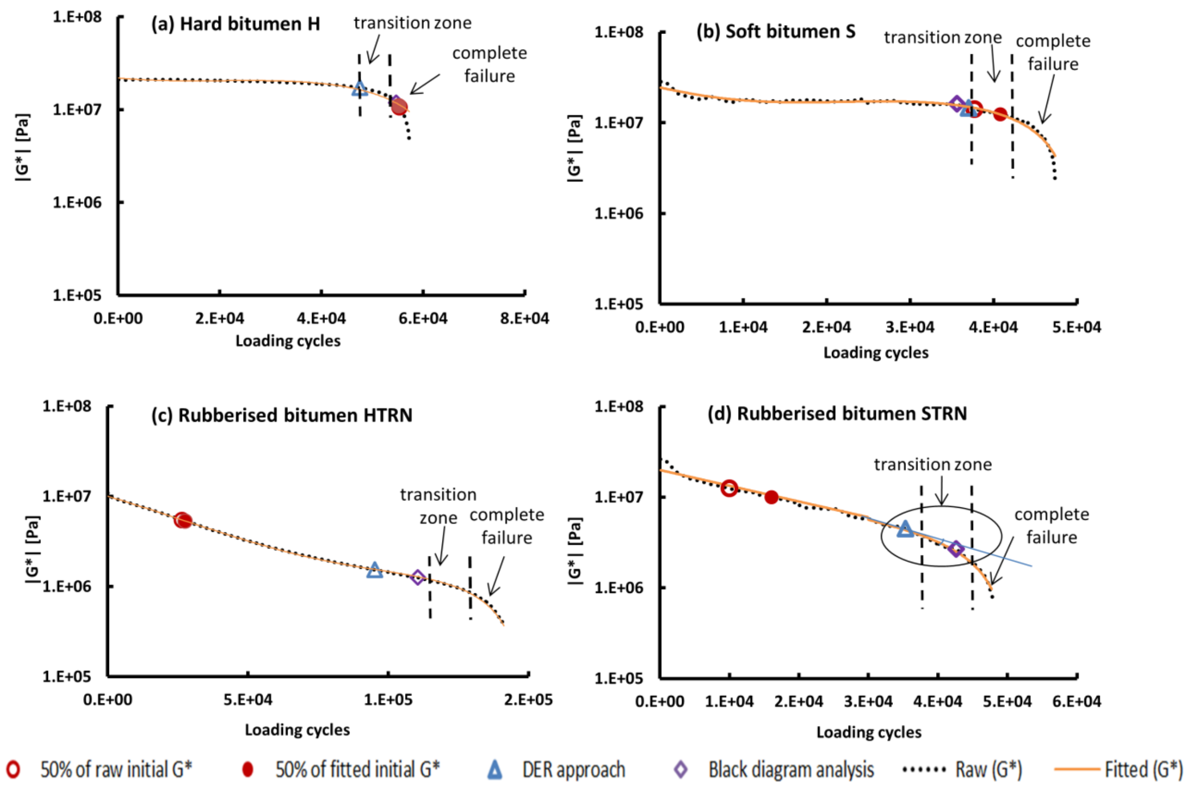

Fig. 3. The failure points identified by different methods located at the evolution of |G| vs. load cycles during fatigue tests for all binders*

4.2 Ratio of dissipated energy change

Although the RDEC and PV concept is fundamental and has a direct relation to damage accumulation, the determination of a consistent PV is not a straightforward exercise and needs special calculations. Fig. 4 shows an example of the RDEC evolution calculated directly from the raw data based on Eq.4 versus the number of load cycles. It can be seen that obtaining a direct representative PV is not possible due to the amount of scatter in the measured data. Shen and Carpenter [33] proposed a simplified approach to calculate the PV. The approach is based on obtaining the best fit regression equation for dissipated energy, w_i , versus the number of load cycles which generally follows a power law relationship ($A.x^k$). The exponential slope of the curve, k, is then used with the defined failure point, N_f, to calculate the PV using the following equation:

$$PV = \frac{1 - (1 + \frac{100}{N_f})^k}{100} \qquad (8)$$

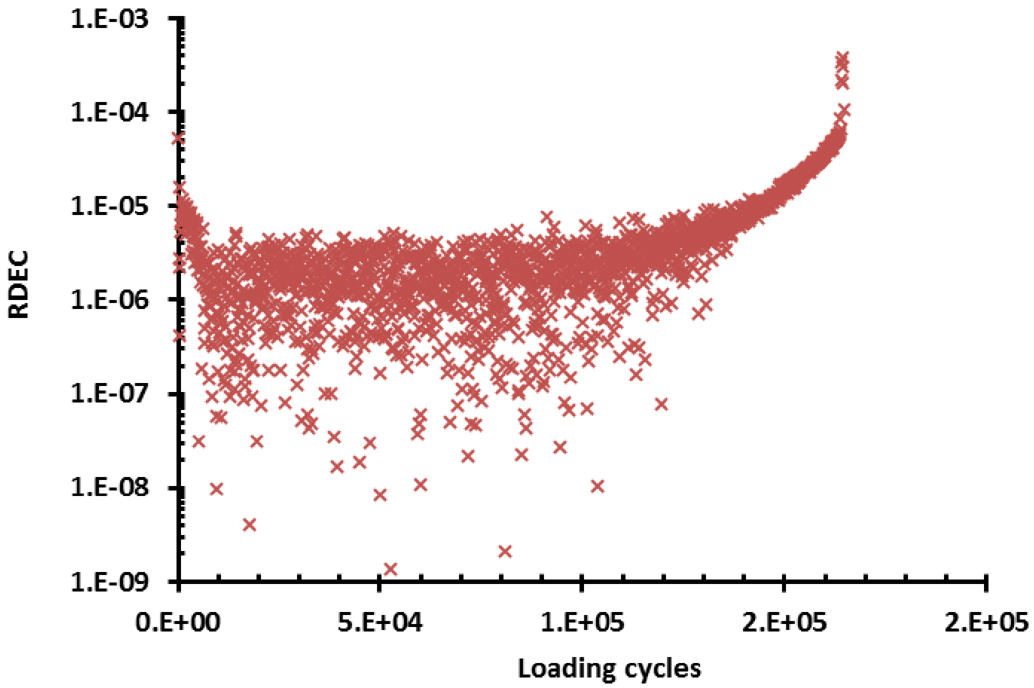

Fig. 4. RDEC evolution vs. the number of load cycles for H binder tested under stress control mode, 20 ˚C and no RP

In this study, obtaining a consistent power law model was not possible due to the complicated shape of the dissipated energy vs. the number of load cycles plot, as shown in Fig. 5. In addition, when skipping the data in Phase I and Phase III and keeping only the data in Phase II (the steady-state damage development phase) to make the curve shape simpler, the best fit is still poor. Table 3 shows R^2 and k values obtained when considering either the entire data or data within Phase II. It can be seen that the best fit regression gives significantly different exponential slopes, k, for the complete w_i vs load cycles curve versus the values obtained when only considering Phase II. This results in differences in the intrinsic PV fatigue law once calculated as shown in Fig. 6. It should be mentioned that high variability and difficulties in obtaining a "correct" PV were also reported in other studies [22, 34-36].

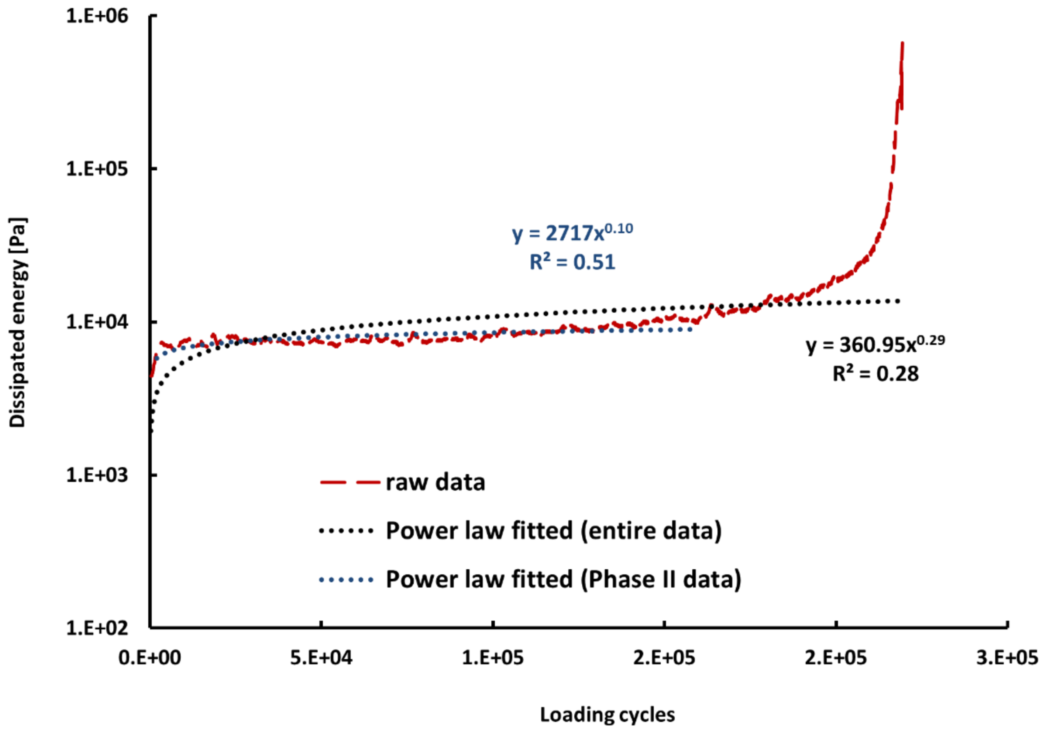

Fig. 5: Shape of dissipated energy vs. number of load cycles and the best fit regression of different segments

Table 3 Calculated PV based on Eq. 8 for H binder tested under stress control mode, 20 °C and no RP

Stress level	Nf	Entire data fitting			Phase II fitting		
		k	R^2	PV	k	R^2	PV
200	221300	0.08	0.16	3.61E-07	0.02	0.31	9.04E-08
250	137300	0.14	0.24	1.02E-06	0.06	0.71	4.37E-07
300	90700	0.14	0.25	1.54E-06	0.073	0.71	8.04E-07
350	47500	0.12	0.2	2.52E-06	0.07	0.6	1.47E-06
400	36600	0.09	0.14	2.46E-06	0.06	0.67	1.64E-06
500	15600	0.12	0.2	7.66E-06	0.075	0.65	4.79E-06

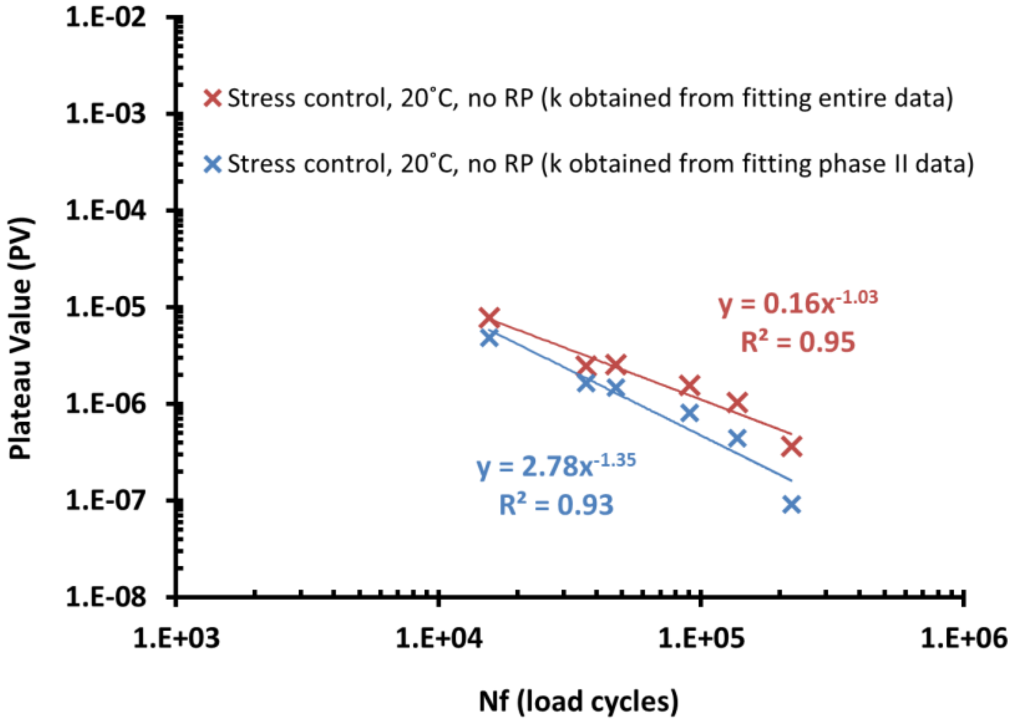

Fig. 6. PV fatigue curves based on Eq. 8 for H binder tested under stress control mode, 20 ˚C and no RP

To minimize the ambiguity in calculating the plateau value, an alternative approach has been proposed to compute the PV based on the direct linear slope of the steady-state phase and also based on the fundamental definition of RDEC. In Eq.4 the term $\frac{(w_i - w_j)}{(i-j)}$ represents the linear slope of a small segment in Phase II of the dissipated energy w_i vs. load cycles curve. To overcome experimental data noise and optimise the best fit regression process, the linear slope of Phase II was defined from the raw data of dissipated energy as following:

$$\mu = \frac{(w_f - w_a)}{(N_f - a)} \qquad (9)$$

Where μ = the linear slope of Phase II; $\dot{w}_f$ = the dissipated energy at the defined failure point; $\dot{w}_a$ = the dissipated energy at the end of Phase I; N_f = the number of load cycles to the defined failure and a = the number of cycles at the end of Phase I. The PV is then calculated by dividing μ by the initial value of dissipated energy, w_o, to resemble the original equation of PV, Eq.4.

$$PV = \frac{\mu}{w_o} \qquad (10)$$

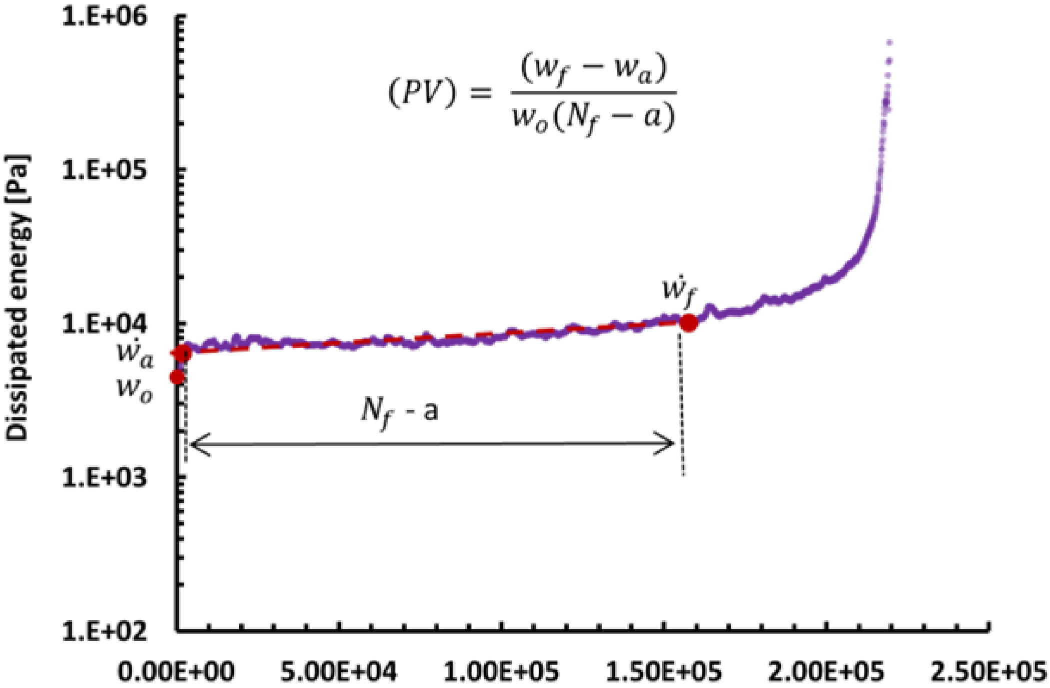

Fig. 7. Graphical illustration of determining PV according to the proposed approach

Fig. 7 illustrates graphically the procedure of calculating PV. An assessment was carried out to investigate the sensitivity of selecting $\dot{w}_a$ on PV vs N_f curves. The percent of difference between the consecutive dissipated energies are calculated as follows:

$$\Delta w_i = \frac{ABS(w_{i+1} - w_i)}{w_i} \, x \, 100 \, \% \quad (11)$$

Where Δw_i= the percent of difference; w_i = the dissipated energy at cycle i; w_{i+1}= the dissipated energy at the following cycle. Fig. 8 shows the results of Δw vs the number of load cycles. It can be seen that after the first 500 cycles the differences between the consecutive cycles becomes very small indicating the end of Phase I. However, three $\dot{w}_a$ values were chosen, at 500 cycles, 1000 cycles and 1500 cycles for PV calculation in order to evaluate how PV vs N_f can change with defining $\dot{w}_a$. Fig. 9 presents the results of PV calculated based on the proposed approach for different $\dot{w}_a$ values versus the N_f. The PV fatigue curves shown in Fig. 8 suggest that there is not a significant variation between the curves computed by the different $\dot{w}_a$values. Thus, the end of phase I for fatigue results in this study can be defined appropriately after 500 load cycles.

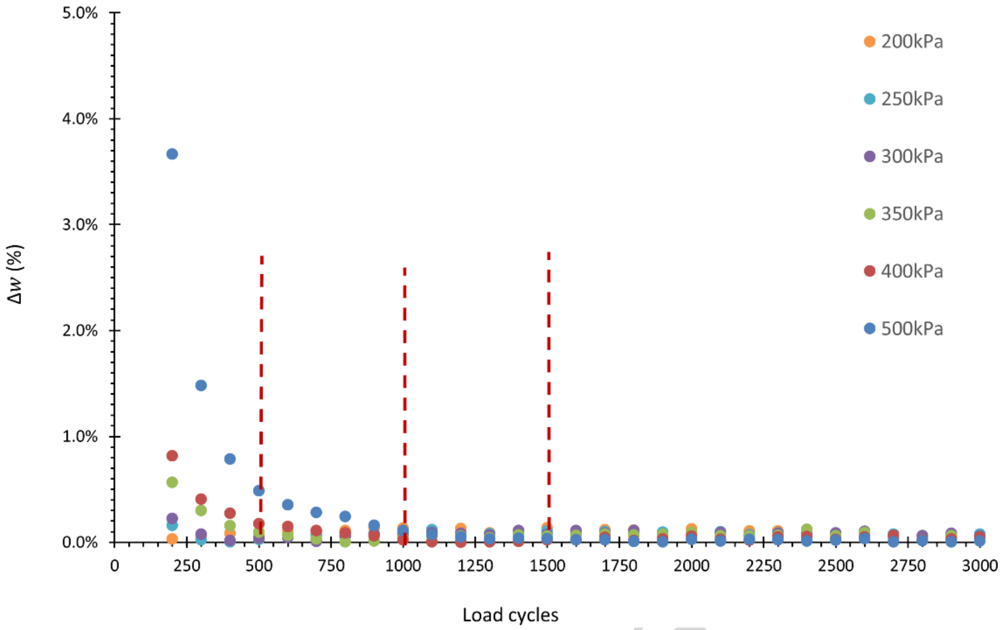

Fig. 8. Identifying the end of Phase I, for H binder tested under stress control mode, 20 °C and no RP

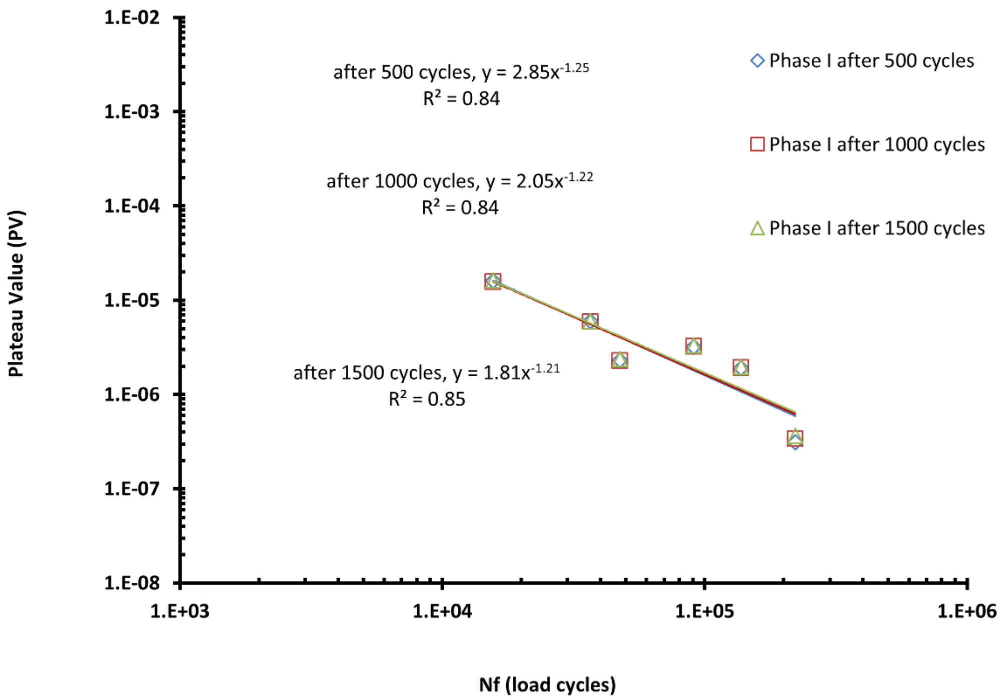

Fig. 9. PV vs N_f calculated at different $\dot{w}_a$ for H binder tested under stress control mode, 20 °C and no RP

This approach provides a consistent method to obtain a reliable PV and produces an intrinsic fatigue law. The main advantage of the current method is that the PV calculation is not considerably influenced by the data noise and fitting process throughout the fatigue development but rather it is computed based on defining two important dissipated energies in phase II, w_a, and,w_f. Those dissipated energies correspond to the main microstructural changes during the fatigue evolution.

Applying the proposed approach, the plateau value was computed for all the binders in the study under different testing conditions (stress levels, temperature and rest periods).

The PVs are then plotted against the defined failure point N_f, as shown in Fig. 10. The results show that there is a unique power-law relationship between PV and N_f with acceptable $R^2 \approx 0.95$ regardless of loading mode, temperature or rest periods, but the power law relationship was strongly dependent on material type. These PV-N_f curves are contradictory to the other fatigue findings presented by Shen and her co-workers [13, 23, 24, 33]. They showed that this relationship is unique regardless of mixture type. However, considering the results in this study, as well as other studies [34-39], the PV-N_f relationship cannot always be considered to be independent of material type.

The fatigue resistance of different asphalt mixtures or binders can, therefore, be evaluated on the basis of the PV-N_f curve. In that sense, the material with desirable fatigue properties is the material that has the higher number of fatigue cycles at a certain amount of relative dissipative energy, PV. Thus, the PV-Nf curves in Fig. 11 verify that the addition of rubber resulted in better fatigue performance. The fatigue resistance of bituminous binders is strongly dependent upon the physical and mechanical properties and these properties are largely governed by the chemical composition and the modification type. An appropriate binder selection and modification process can, therefore, be defined based on the PV-N_f curves.

Figure 12 shows comparison of different PV-Nf curves (asphalt mixtures and binders) adopted from other studies [13, 23, 34-37] in addition to the PV-Nf curve of HTRN binder taken from the current study. The results in Figure 12 clearly show that the PV-Nf relationship is dependent on material type. It can be seen that there is a considerable difference between mixtures and binders with binders generally have superior fatigue resistance than mixtures. This is logical since the air voids and discontinuity within the binder matrix due to the interaction between the binder and the aggregate reduce the mixture's ability to sustain higher damage input during the fatigue evolution

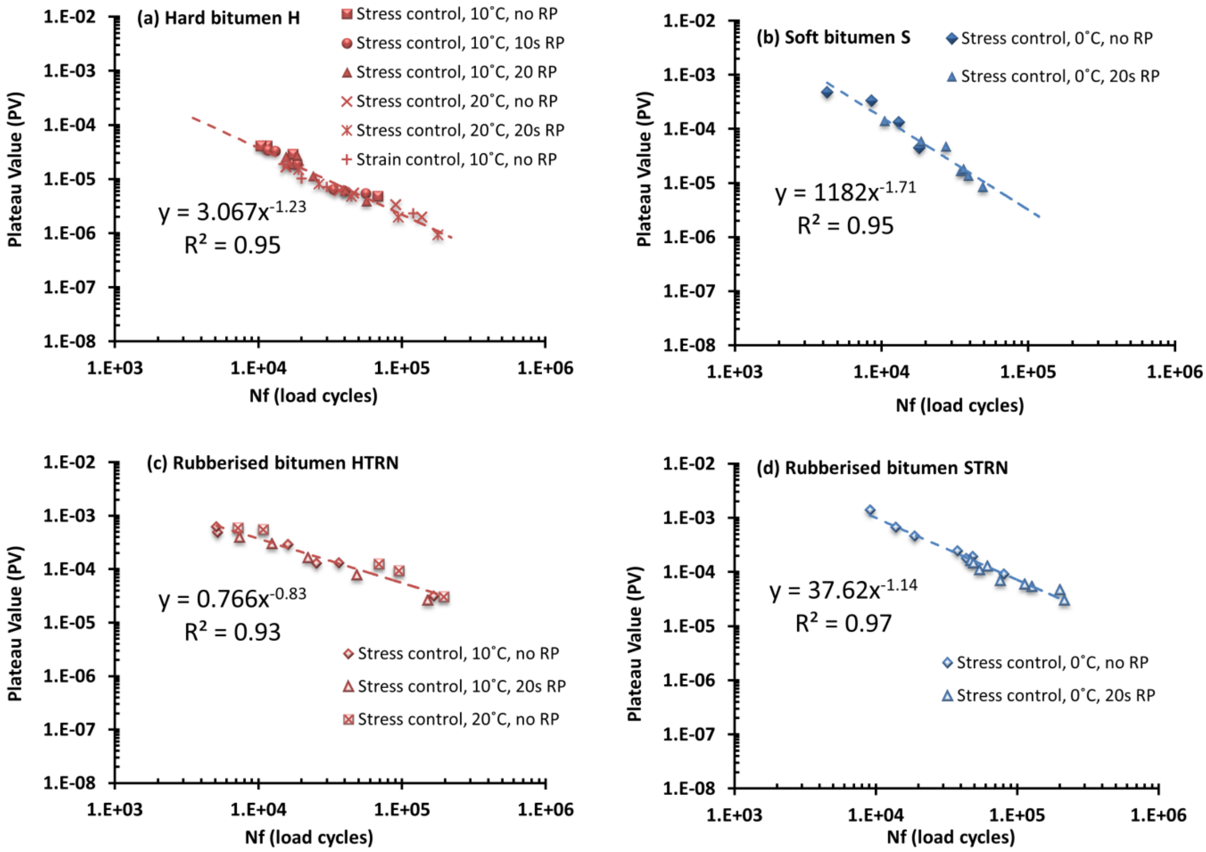

Fig. 10. PV vs. N_f computed by the proposed approach

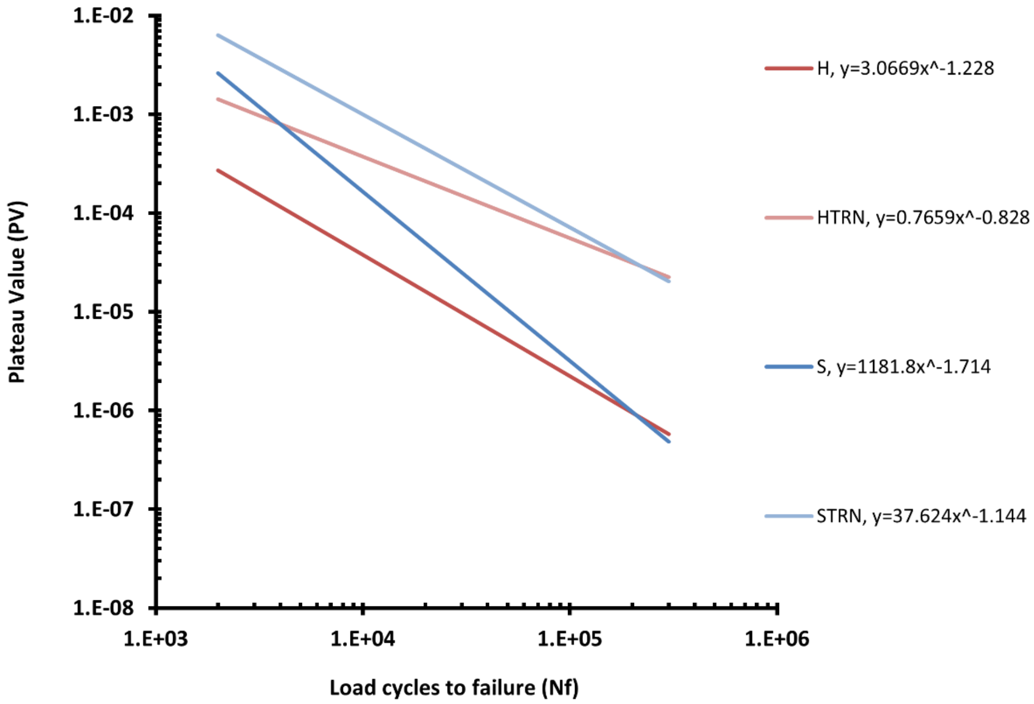

Fig. 11. Comparison of different PV-Nf curves

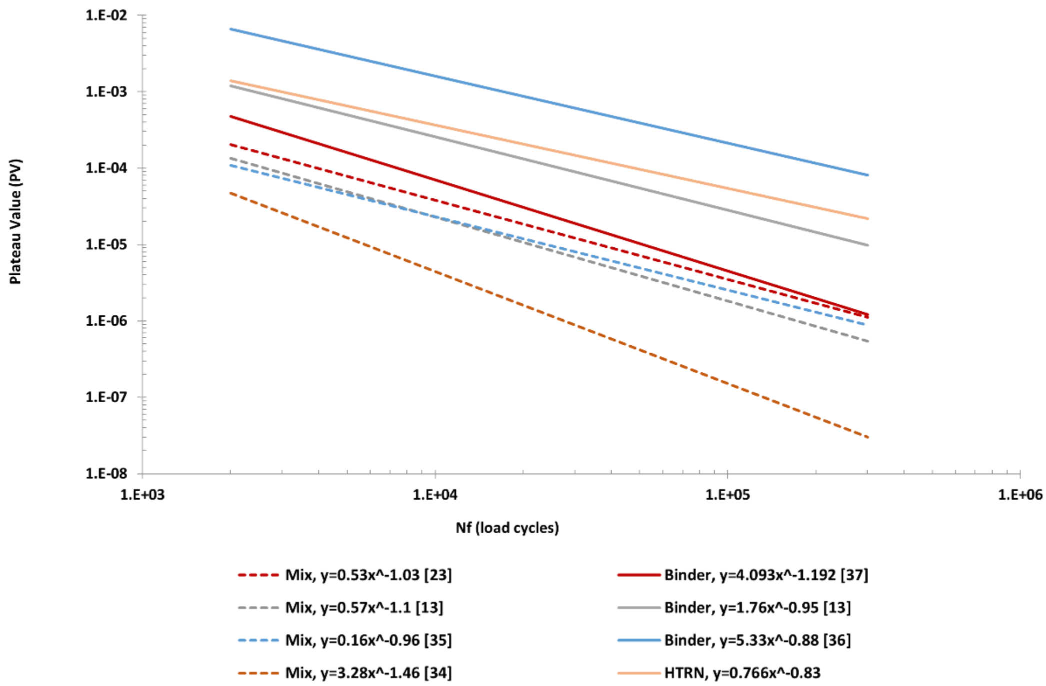

Figure 12. Comparison of different PV-Nf curves (asphalt mixtures and binders) adopted from literatures as well as the PV-Nf curve of HTRN of this study

5. Conclusions

In this study, the fatigue properties of neat and modified bitumens were studied by time sweep repeated cyclic loading tests under different test conditions using an oscillatory DSR. The Ratio of Dissipated Energy Change (RDEC) approach was employed for fatigue analysis. The study proposed a promising methodology for determining a consistent and reliable PV which was able to generate a unique fatigue law. Based on the discussion and analysis described in this paper, the following conclusions and findings can be drawn:

1. The PV obtained by the proposed method was material dependant. It was able to distinguish between the fatigue resistance of different materials, and thus it can be used as a reliable fatigue parameter.
2. The results of this study show that the PV-N_f is a material dependant relationship.
3. It is crucial to evaluate and then appropriately identify the fatigue failure point before commencing the fatigue analysis. The classical approach of 50% decrease in the initial stiffness is an arbitrary definition and can lead to incorrect analyses. Therefore more fundamental approaches should be considered to provide a more reliable definition of fatigue failure.
4. It is recommended that the PV calculation method proposed in this study be further evaluated on asphalt mastics or asphalt mixtures.

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Highlights

- A new and simplified approach was successfully applied and a unique power-law relationship between PV and N_f has been obtained.
- The proposed method can eliminate the ambiguity and subjectivity that associated with PV calculations.
- The PV obtained by the proposed method was material dependant.