

Article

Not peer-reviewed version

Proposal of a New Procedure for Assessing the Performance of the Self-Healing Polymer-Modified Asphalt Binders with an Integral Vision of the Damage Characteristic Curves

[Songtao Lv](#) , [Dongdong Ge](#) , Shihao Cao , Dingyuan Liu , Wenhui Zhang , [Cheng-Hui Li](#) , [Milkos Borges Cabrera](#) *

Posted Date: 26 June 2024

doi: 10.20944/preprints202406.1798.v1

Keywords: bitumen fatigue performance; failure definition; self-healing polymers; self-restoration performance; self-healing behaviour



Preprints.org is a free multidiscipline platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Article

Proposal of a New Procedure for Assessing the Performance of the Self-Healing Polymer-Modified Asphalt Binders with an Integral Vision of the Damage Characteristic Curves

Songtao Lv¹, Dongdong Ge¹, Shihao Cao¹, Dingyuan Liu¹, Wenhui Zhang¹, Cheng-Hui Li² and Milkos Borges Cabrera^{1,*}

¹ School of Traffic and Transportation Engineering, Changsha University of Science & Technology, Changsha, 410114, Hunan, PR China; lst@csust.edu.cn (S.L.); dge1@csust.edu.cn (D.G.); csh@stu.csust.edu.cn (S.C.); nf@stu.csust.edu.cn (D.L.); whzz@stu.csust.edu.cn (W.Z.)

² State Key Laboratory of Coordination Chemistry, School of Chemistry and Chemical Engineering, Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing 210093, P. R. China; chli@nju.edu.cn

* Correspondence: combigra2013@gmail.com

Abstract: Fatigue performance and self-repairing activity of asphalt binders are two properties that highly influence the fatigue cracking response of asphalt pavement. There are still numerous gaps of knowledge to fill linked with these two characteristics. For instance, current parameters fail to fully accommodate these two bitumen phenomena. This study aims to propose a new procedure to address this issue utilizing the linear amplitude sweep (LAS) test, LAS with rest period (RP) (LASH) test, and simplified viscoelastic continuum damage (S-VECD) model. This research work used four different types of asphalt binders: neat asphalt (NA), self-healing thermoplastic polyurethane (STPU)-modified bitumen (STPB), self-healing poly (dimethyl siloxane) crosslinked with urea bond (IPA1w)-modified bitumen (IPAB), and styrene-butadiene-styrene (SBS)-modified bitumen (SBSB). Before the testing process, all the materials were subjected to short-term and long-term aging. The new procedure showed a superior capacity to analyze and accommodate all bitumen fatigue performances and self-repairing activities compared to the current method. Another finding proved that asphalt binders with higher self-restoration behavior failed to show better fatigue performance. A breakthrough finding demonstrated that asphalt binder fatigue response augmented when the RP was applied at a higher damage intensity (S) value. STPBs and IPABs reached their highest increments of fatigue response, containing 1.0% of STPU and 0.5% of IPA1w, respectively. Those augmentations were 207.54% and 232.64%, respectively.

Keywords: bitumen fatigue performance; failure definition; self-healing polymers; self-restoration performance; self-healing behaviour

1. Introduction

Asphalt pavement distress and failures mainly originate from cracks, like fatigue cracks [1,2]. Fatigue cracks mainly occur and proliferate in asphalt mixtures through the asphalt binder phase, resulting from cyclic traffic loading and seasonal weather changes [3]. Hence, the bitumen fatigue cracking performance significantly affects the asphalt mixture and pavement fatigue cracking responses [4–6].

One way to mitigate cracking occurrence is to study, understand, and promote the self-healing properties of asphalt pavements throughout their bitumen. This topic is attracting more and more attention from scholars [7]. Linear amplitude sweep (LAS) test (AASHTO TP 101) and simplified

viscoelastic continuum damage (S-VECD) theory are effective and efficient tools to evaluate bitumen fatigue cracking and self-healing performances [8]. After conducting the LAS test and obtaining the corresponding results, the S-VECD method processes those data for evaluating and predicting the fatigue performance (including self-healing activity) of asphalt binder [9–11].

Subsequently, the material integrity (C) and S values can be determined. The former is also known as pseudo-stiffness and normalized dynamic shear modulus; the latter represents the material internal state variable resulting from applying the damage evolution of Schapery's work potential theory (see equation 1). Then, the damage characteristic curve (DCC) can be plotted in a C vs. S graph [12,13].

$$\frac{dS}{d\vartheta} = \left(\frac{\partial W^R}{\partial S} \right)^\alpha, \quad (1)$$

Where α , ϑ , and W^R are damage evolution rate, reduced time, and pseudo-strain energy, respectively.

Numerous studies have assessed the self-healing capacities of neat asphalt binders (NA) and polymer-modified bitumens (PMBs). Xie et al. [14] evaluated the self-healing capabilities of NA and SBSB by utilizing LAS, LASH, and S-VECD methods. This research team introduced the percent healing (%Hs) parameter and the rest-damage superposition principle to build the %Hs mastercurve. This study found a superior %Hs in NA than in SBSB. Wang et al. [15] appraised the NA and SBSB self-healing performances after short- and long-term aging processes by using LASH, VECD, and %Hs mastercurve. Besides, this research work correlated the bitumen composition with self-healing behavior. This study identified two factors that diminished bitumen self-healing activity: the aging process and SBS. However, light fractions, small molecules, and longer molecules augmented the bitumen's self-healing performance.

Wang et al. [8] assessed the self-healing activity of NA and SBSB by conducting LASH, VECD, and microstructures tests. Researchers found that a superior number of saturates/aromatic fractions and small molecules promoted the bitumen self-healing behaviour. SBSB and NA exhibited similar self-healing activity, which is not in line with the findings of Xie et al. [14] and Wang et al. [15]. Aurilio [16] and Aurilio and Baaj [17] analyzed the performances of self-healing polymer(SP)-modified bitumen (SPB) and SBSB by utilizing LASH, a simplified LASH (SLASH), and S-VECD methods. Researchers found that the elastomeric properties of bitumen improved by adding the SP, but this material could not promote the self-healing capability in the asphalt binder. Besides, SBS stimulated the crack healing activity in the bitumen, which is in the opposite direction of findings in Xie et al. [14] and Wang et al. [15].

Aurilio et al. [18] assessed the performances of chemical warm mix additive-modified bitumen (WMAB) and NA by utilizing SLASH and S-VECD methods. This study found that aged NA exhibited superior self-healing behavior than aged WMAB. Almutairi and Baaj [19] appraised the behavior of NA, SBSB, glass powder (GP)-modified bitumen (GPB), GP- and phase-change material(GPCM)-modified bitumen (GPCMB) by conducting LASH and S-VECD methods. This study found that GPCM maintained similar and improved self-healing capacity of base asphalt when 5 and 30 minutes of RP were applied, respectively. Besides, GP increased and reduced the self-healing performance of NA and SBSB, respectively.

Lv et al. [20] analyzed the self-healing performances of NA and STPB. This study utilized LASH and S-VECD in the testing process. Researchers found that STPU promoted the self-healing performance of base asphalt. Another finding was that the current framework could not fully accommodate the self-healing behavior of asphalt binders. As a result, a new procedure was proposed considering the area below the DCC.

All previous research works on bitumen self-healing analysis utilized the peak of stored pseudo-strain energy (PSE) to define the bitumen fatigue life (N_f). This concept identifies the needed number of loading cycles (N) to reach the bitumen failure point. However, Lv et al. [20] and Wang et al. [9] proved the existence of ranking inconsistency between bitumen fatigue life and DCC analysis in terms of asphalt binder fatigue performance. Hence, those studies reached conclusions based on a concept with inadequacy issues. As a result, Lv et al. [21] introduced a new framework based on S

instead of N to overcome the inconsistency mentioned above. Nonetheless, the effectiveness of this new framework in assessing the bitumen self-healing performance has yet to be verified.

Hence, this study combines the new procedures from Lv et al. [20] and Lv et al. [21] to propose a composite process to comprehensively analyze the self-healing performance of NA, SPBs, and SBSB. Besides, the efficiency of the new method will be verified. This research work will introduce new parameters to assess and analyze the self-healing behavior of NA, SPBs, and SBSB. The new composite process will also verify the STPU and IPA1w capacities to promote the self-healing activity in the base asphalt.

2. Materials and Methods

2.1. NA

This study bought and utilized 70# NA from SINOPEC (China Petroleum & Chemical Corporation) Jinling Branch in Nanjing City (Jiangsu Province, China). This type of NA is popular in China and it has prominently exhibited excellent capacity in withstanding the traffic loading cycle [22]. NA’s physical properties (see Table 1) observe the standard required values in Chinese specifications. These documents are based on AASHTO and ASTM standard specifications.

Table 1. Physical properties of NA.

Tests	Standard value	Measured value	Standard test
Penetration (25°C, 5s, 100g) (0.1mm)	60 ~ 80	60.1	T0604
Penetration index (PI)	-1.5 ~ 1.0	-0.4	T0604
Softening point (°C)	≥ 46	51.1	T0606
Viscosity (60°C) (Pa*s)	≥ 180	219	T0620
Ductility (10°C)	≥ 45	62	T0605
Wax content (%)	≤ 2.2	1.8	T0615
Flash point (°C)	≥ 260	300	T0611
Density (15°C) (g/cm³)	-	1.033	T0603
Solubility (%)	≥ 99.5	99.91	T0607
After RTFO ¹ :			
Mass change (%)	≤ ± 0.8	0.021	T0609
Residual penetration ratio (%)	≥ 61	67	T0604
Residual ductility (10°C)	≥ 0.6	8	T0605

¹ Rolling thin film oven (RTFO) test.

2.2. SBSB

SBS is an asphalt binder modifier that increases NA’s rutting resistance, cohesion, adhesion, and elasticity properties [23]. Accordingly, SBS has become a popular bitumen modifier to produce SBSB, which is globally used for road construction [24]. Hence, this study included SBSB as bitumen to test, and Table 2 illustrates its physical properties.

Table 2. Physical properties of SBSB.

Tests	Standard value	Measured value	Standard test
Penetration (25°C, 5s, 100g) (0.1mm)	30 ~ 60	52.0	T0604
Penetration index (PI)	≥ 0	0.15	T0604
Softening point (°C)	≥ 76	83.2	T0606
Viscosity (135°C) (Pa*s)	≤ 3	2.45	T0625
Ductility (5°C)(cm)	≥ 25	35	T0605
Flash point (°C)	≥ 230	310	T0611
Solubility (%)	≥ 99.0	99.78	T0607
SBS block ratio (B/S)	-	70/30	-

SBS molecular weight (g/mol)	-	120000	-
SBS content (%)	-	5	-
After RTFO ¹ :			
Mass change (%)	≤ ± 1.0	-0.04	T0610
Residual penetration ratio (%)	≥ 65	78	T0604
Residual ductility (10°C)(cm)	≥ 20	22	T0605

2.3. STPU

This research work continues two studies mentioned above: Lv et al. [20] and Lv et al. [21]. Both studies utilized STPU. Hence, this research team decided to include STPU in this new round of experiments, which Nanjing University elaborated.

The material components utilized in the synthesis of the STPU are as follows: polytetramethylene ether glycol (PTMEG, Mn = 1000 g/mol, f = 2), the catalyst dibutyltin dilaurate (DBTDL), and chain extender 3-Dimethylaminopropylamine (DMAPA), all of them were bought from Aladdin. Adams Enterprise sent us the isophorone di-isocyanate (IPDI). All these substances were used without further purification process. Tetrahydrofuran (THF, Sigma-Aldrich, St. Louis, MO, USA) and chloroform (CHCl3, Sigma-Aldrich) were used after CaH2 redistillation.

A crystallizable soft segment (PTMEG) is one of the main components of STPU, and its meticulously selected length ensures a lower crystallization energy threshold when subjecting the STPU to the stretching process in the elongation test. Stratified H-bonding interactions are named bonds with sacrificial and active properties, guaranteeing hard domains with as low as possible binding energy characteristics. This fact raises the probability that hard domain segments connect with small-sized hard domains via H-bonding. As a result, the self-healing activity is promoted without extra stimulus (microwave and heat). This phenomenon is appropriate for mitigating crack occurrence on road surfaces. Furthermore, a strain-induced crystallization property of STPU ensures a retarded but reversible self-reinforcing effect [25]

Table 3 illustrates the physical properties of STPU. For more details on this novel polymer, readers can see Li et al. [25], Lv et al. [20], and Lv et al. [21].

Table 3. Physical properties of STPU.

Parameters	STPU values
Tensile strength (MPa)	13.5 ± 2.2
Elongation (dried state, %)	1460 ± 87
Density (g/cm ³)	1.07
Melting point (°C)	120 ^a
Molecular weight (g/mol)	72700

^a = obtained from the temperature sweeping of the rheological test.

2.4. IPA1w

As mentioned before, this research work is a continuation of previous studies by Lv et al. [20] and Lv et al. [21]. This latter study introduced IPA1w because it exhibited suitable properties for road construction. As a result, this research team included the IPA1w in this new group of tests, and Nanjing University produced it. In addition, IPA1w is a room temperature (25 °C) self-healing polymer that promotes self-healing behavior without extra stimuli (microwave and heat). This property could be proper for road surfaces.

The substance components utilized in synthesizing IPA1w are Bis(3-aminopropyl)-terminated PDMS (Mn = 10,000 g mol⁻¹, noted as A1w) received from Gelest. This study bought isophorone diisocyanate (IPDI) from Sigma-Aldrich and further distilled Tetrahydrofuran (THF) for use later.

The synthesis of IPA1w was as follows: The redistilled THF (100 mL) and the A1w (4.00 g, 0.4 mmol) were mixed and continuously stirred in an ice bath for 30 minutes. Then, 30 mL of THF was slowly mixed with the solution of IPDI (91.13 mg, 0.41 mmol) using a constant pressure funnel. These

substances reacted, and the mixture was stirred for 24 hours under an N₂ atmosphere at room temperature until a concentrated sticky mucus was obtained. The resultant product was purified by utilizing cycles of the dissolution-precipitation-decantation process. The collected solution was then decanted into the customized polytetrafluoroethylene molds and subjected to a drying process at 85 °C for 24 hours. The obtained IPA1w polymer film was then peeled off for further testing.

The self-healing activity in IPA1w can be stimulated by breaking and relinking the hydrogen bonds and taking down and rebuilding the polymer chains at room temperature. The polymer units containing hydrogen bonds are more likely to join their chains and ensure entanglements [26]. Table 4 displays the physical properties of IPA1w. For more details associated with IPA1w, see Wang et al. [26] and Lv et al. [21].

Table 4. Physical properties of IPA1w.

Parameters	STPU values
Tensile strength (MPa)	1.61 ± 0.15
Elongation (dried state, %)	1700
Young’s modulus (MPa)	0.59 ± 0.02
Toughness (MJ m ⁻³)	17.89 ± 0.18
Molecular weight (g/mol)	82000

2.5. Preparation Method of STPBs

The preparation method to elaborate STPBs explained in Lv et al. [20], and Lv et al. [21] was followed to produce this type of PMB in this study. Besides, the 0.5, 1.0, and 1.5 wt% of STPU were the amounts of polymer mixed with NA to produce STPB0.5, STPB1.0, and STPB1.5, respectively. Those percentages of polymer were decided according to previous experience [20,21] because these STPBs showed superior fatigue performances in terms of DCC assessment, self-healing capacities, and fatigue failure points regardless of the test conditions.

2.6. Preparation Method of IPAB

The preparation method to produce IPAB, explained by Lv et al. [21], was followed to obtain this type of PMB in this study. Furthermore, the 0.5, 1.0, and 1.5 wt% of IPA1w were the percentages of polymer mixed with NA to elaborate IPAB0.5, IPAB1.0, and IPAB1.5, respectively. Those amounts of polymers were decided considering the previous experience from Lv et al. [21] and Yang et al. [27] because these IPABs exhibited higher self-restoration capacity, rutting resistance, and viscoelasticity.

2.7. Aging Procedure

This study used short-term and long-term aging procedures to cause the aging effect on NA, SBSB, STPB0.5, STPB1.0, STPB1.5, IPAB0.5, IPAB1.0, and IPAB1.5. All bitumens were subjected to both tests. The former process is described in the AASHTO T240 [28], and it is known as the rolling thin film oven (RTFO) test. The latter one is explained in the AASHTO R28-12 [29] and is known as the pressurized aging vessel (PAV) test.

2.8. Performance Grade (PG) Characterization Method

This research work conducted a group of tests to determine the PG of each bitumen. The unaged bitumens were subjected to a flash point temperature test (FPT) (AASHTO T48-06) [30] and a rotational viscosity test (RV) (AASHTO T316) [31]. The RTFO-aged and unaged asphalt binders were tested to calculate the rutting index (RI) (AASHTO T315-20) [32]. The RTFO+PAV-aged bitumens were subjected to fatigue cracking index (FCI) (AASHTO T315-20) [32] and bending beam rheometer test (BBR) (AASHTO T313-12) [33]. The PG of each bitumen was identified by utilizing AASHTO M320-10 [34]. The determined PGs are as follows: NA (PG 64-16), SBSB (PG 76-22), STPB0.5 (PG 64-22), STPB1.0 (PG 64-22), STPB1.5 (PG 64-16), IPAB0.5 (PG 64-22), IPAB1.0 (PG 64-16), and IPAB1.5 (PG 64-10).

2.9. LAS Test

In this study, the mastercurve and damage evolution rate “ α ” were determined by conducting the frequency sweep tests (FS) from 0.1 rad/s to 100 rad/s at different temperatures (20 °C, 25 °C, 30 °C, 35 °C, and 40 °C) with strain level equal to 0.1 %. The α value was determined as follows: $\alpha = 1/m + 1$, where “ m ” is the mastercurve higher slope (absolute value) in a log-log graph [35]. Afterward, the effective procedure LAS test (AASHTO TP101) was carried out to analyze the intermedia temperature fatigue performance of RTFO + PAV aged bitumens. This test was carried out at 10 Hz, with the strain amplitude linearly going up from 0.1% to 30% for 3100 cycles (standard value), and it is called the continuous LAS test (cLAS) [14]. The parallel plate geometry and its gap were set in the DSR at 8 mm and 2 mm, respectively, to appraise the asphalt binder performance of RTFO + PAV-aged bitumens. The temperature was set at 28 °C because, in a previous study (Lv et al. [21]), most of the time, all asphalt binders exhibited superior fatigue performances at this temperature.

2.10. S-VECD Model

The S-VECD model was utilized to analyze and process the LAS experimental data. This procedure determines C and S values, and its correlation is independent of loading history, regardless of bitumens. As a result, different asphalt binder fatigue responses under any selected conditions with few experimental data can be determined [14,36,37]. After obtaining the C-S correlation (see Equation 2), the DCC can be plotted in a C vs. S graph [20]. The C and ΔS (damage increment) values were calculated by utilizing Equation (3) and (4), respectively [35].

$$C = 1 - C_1 * (S^{C_2} + C_3) \text{ with } S = \sum_{i=1}^{S_f} \Delta S_i, \quad (2)$$

$$C = \frac{|G^*|}{|G^*|_{LVE} \cdot DMR} \text{ with } DMR = \frac{|G^*|_{fingerprint}}{|G^*|_{LVE}}, \quad (3)$$

$$\Delta S_i = \left(\frac{1}{2} DMR \cdot (\gamma_i^R)^2 \cdot (C_{i-1} - C_i) \right)^{\frac{\alpha}{1+\alpha}} \cdot Q \text{ with } Q \equiv \left[\int (\sin(w_r \vartheta))^{2\alpha} d\vartheta \right]^{\frac{1}{1+\alpha}}, \quad (4)$$

In Equation (2), C_1 , C_2 , and C_3 are regression constants, and S_f represents the S value at the failure point. For Equation (3), the parameters G^* , $|G^*|_{LVE}$, DMR , and $|G^*|_{fingerprint}$ signify dynamic shear modulus (damaged), undamaged dynamic shear modulus (linear viscoelastic range (LVE)), dynamic modulus ratio, and the initial dynamic shear modulus when conducting cLAS, respectively. Besides, the parameters γ_i^R , w_r , ϑ , and i -th in Equation (4) denote pseudo-strain amplitude, reduced angular frequency, reduced time, and the cycle of interest, respectively. The terms W^R (stored PSE) and γ_i^R are calculated by using Equation (5) and (6), respectively [35].

$$W^R = \frac{1}{2} DMR \cdot C(S) \cdot (\gamma^R)^2, \quad (5)$$

$$\gamma_i^R(\vartheta) = \gamma_i \cdot |G^*|_{LVE} \cdot \sin(\omega_r \vartheta), \quad (6)$$

Where γ_i illustrates the shear strain amplitude in Equation (6). Lv et al. [21] introduced a new framework with a new concept of failure definition (which is the parameter that defines the fatigue life) that solved the ranking inconsistency issue between the traditional failure definition (stored PSE peak) and DCC analysis in terms of bitumen fatigue performance. Accordingly, this research team utilized that new framework and new failure definition in this study.

Then new framework mentioned above defined numerous new parameters, but there are three essential definitions: total potential cohesion (TPC), stored potential cohesion (SPC), and released potential cohesion (RPC). TPC determines the imaginary bitumen strength capacity at each loading cycle to keep its C values equal to 1 while carrying out the cLAS procedure, although the damage has occurred. TPC is represented by the imaginary rectangular area (A, B, F, and E) in Figure 1, and its formula is Equation 7. SPC identifies the bitumen strength capacity at each loading cycle to maintain the C values as high as possible when conducting the cLAS test, even if damage has occurred. The rectangular area C, D, F, and E in Figure 1 depicts SPC; its formulation is Equation 8. RPC reveals the

dissipated bitumen strength capacity at each loading cycle to uphold C values as high as possible while undertaking the cLAS test. RPC is defined by the rectangular area (A, B, D, and C) in Figure 1, and its expression is Equation 9 [21].

$$TPC_i = S_i \cdot C_0 \text{ (where } C_0 = 1), \quad (7)$$

$$SPC_i = S_i \cdot C_i, \quad (8)$$

$$RPC_i = TPC_i - SPC_i, \quad (9)$$

In Equation 7, TPC_i , S_i , and C_0 represent the total potential cohesion at the i -th cycle, the S value at the i -th cycle, and the constant material integrity equal to 1, respectively. In Equation 8, SPC_i and C_i are the stored potential cohesion and the C value at the i -th cycle, respectively. In the case of Equation 9, RPC_i is the released potential cohesion at the i -th cycle [21].

DCC (Imaginary and Real)

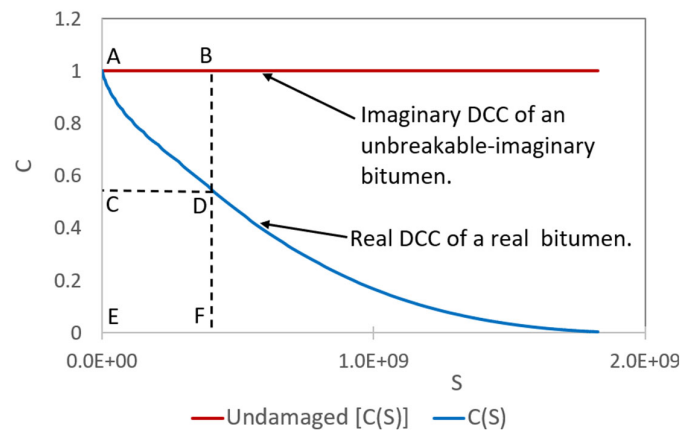


Figure 1. Representation of imaginary and real DCC to define TPC, SPC, and RPC.

Figure 2 illustrates the SPC and RPC curves. While the SPC curve increases, the asphalt binder maintains the strength capacity to store additional damage intensity when conducting the cLAS procedure. Nevertheless, when the SPC curve decreases, the bitumen fails to uphold the strength capacity to store additional damage intensity, and as a result, asphalt binder failure occurs. Hence, the peak of the SPC curve is considered the failure definition, and this new concept has the novelty that it is mainly based on S instead of N . Moreover, a higher SPC value means superior fatigue response at the chosen loading cycle. The RPC curve grows from the starting point of the test (i.e., the asphalt binder loses strength capacity from the beginning) [21]. For more details about the new failure definition concept, see Lv et al. [21].

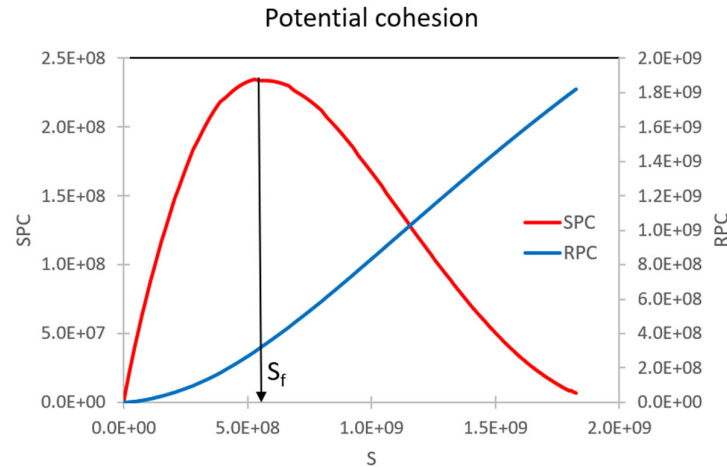


Figure 2. SPC and RPC curves.

2.11. LASH Test (Traditional)

In this research work, the traditional LASH test considered as failure definition the peak of the SPC, instead of the peak of the stored PSE (the previous traditional failure definition). Lv et al. [21] proved that the locations of the SPC and stored PSE peaks on the stored PSE curve were similar, regardless of the asphalt binder, temperature, and aging conditions. This fact demonstrated that both definitions were compatible in identifying the failure point, even though their basements differed. This research team utilized the SPC peak as the failure definition because it eliminated the ranking inconsistency between the fatigue life (the traditional failure definition) and DCC analysis regarding bitumen fatigue performance.

The LASH procedure was conducted with different rest periods RPs and s (DLs). The former parameter was set at 1, 5, 15, and 30 minutes. The latter was set to be 25%, 50%, 75%, and 125% of S_f (to test the bitumen before and after the failure point). These testing conditions were selected according to previous experience [14,18,20]. The conditions for the DSR to carry out the LASH were the same as those for the LAS test, and the temperature was set at 28 °C.

Thixotropy is an important bitumen property for assessing its self-healing performance [38]. Currently, the LASH procedure determines restoration, as this concept was defined by Leegwater et al. [39]. The restoration includes “real” self-healing activity as a reversible phenomenon and thixotropy. As a result, this study utilized the term “percent restoration” (% R_s) instead of percent healing, as introduced by Aurilio et al. [18]. % R_s was determined as follows:

$$\%R_s = \frac{(S_1 - S_2)}{S_1} \cdot 100, \quad (10)$$

Where S_1 and S_2 are S values at the end of the first loading phase and at the starting point of the second loading phase, respectively (see Figure 3).

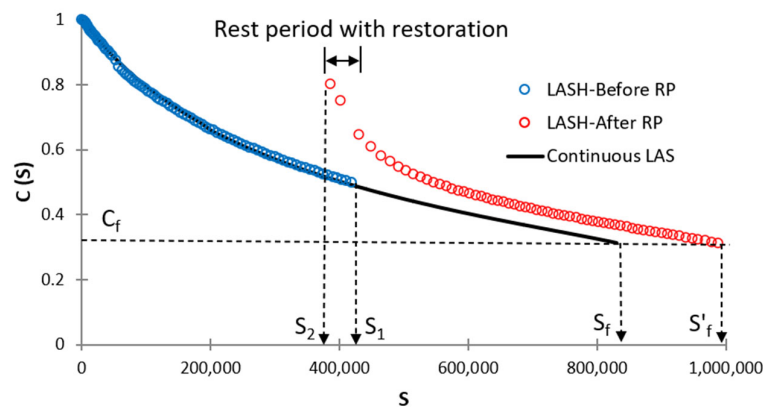


Figure 3. Graph to identify S_f and S'_f when conducting LASH (RP before S_f).

2.12. LASH Test (Updated)

The updated LASH test in this research work also considered the peak of the SPC curve, instead of the peak of the stored PSE curve (the previous traditional failure definition), as the failure definition.

The updated LASH procedure was conducted with the same RPs, DLs, and temperature utilized in the section “2.11 LASH test (traditional)”. This research work utilized the “percent restoration efficiency” (% ξ) concept, introduced by Lv et al. [20], to evaluate the self-restoration capacity and fatigue performance of bitumens at the same time. This concept was proposed by Lv et al. [20] because this research team identified that higher self-restoration capacity did not always ensure superior fatigue performance for asphalt binders in terms of DCC analysis.

The φ^p , φ^{ph} , $\varphi^{p'}$, and $\varphi^{ph'}$ parameters are named bitumen fatigue-potential performances up to S_f (see Figure 3), S'_f (see Figure 3), S_1 (see Figure 4), and S'_1 (see Figure 4), respectively. These parameters can be determined by obtaining the area under the DCC in each specific case of Figure 3 or 4. Equations 11, 12, 13, 14, and 15 show how to calculate φ^p , φ^{ph} , $\varphi^{p'}$, $\varphi^{ph'}$, and % ξ , respectively.

$$\varphi^p = \int_0^{S_f} 1 - C_1 \cdot (S^{C_2} + C_3), \quad (11)$$

$$\varphi^{ph} = \int_0^{S_1} 1 - C_4 \cdot (S^{C_5} + C_6) + \int_{S_2}^{S'_f} -\log_{C_7} (S + C_8) + C_9, \quad (12)$$

$$\varphi^{p'} = \int_0^{S_1} 1 - C_{10} \cdot (S^{C_{11}} + C_{12}), \quad (13)$$

$$\varphi^{ph'} = \int_0^{S_1} 1 - C_{13} \cdot (S^{C_{14}} + C_{15}) + \int_{S_2}^{S'_1} -\log_{C_{16}} (S + C_{17}) + C_{18}, \quad (14)$$

$$\% \xi = ((\varphi^{ph} - \varphi^p) / \varphi^p) \cdot 100 \text{ or } \% \xi = ((\varphi^{ph'} - \varphi^{p'}) / \varphi^{p'}) \cdot 100, \quad (15)$$

Where C_4 , C_5 , C_6 , C_7 , C_8 , C_9 , C_{10} , C_{11} , C_{12} , C_{13} , C_{14} , C_{15} , C_{16} , C_{17} , and C_{18} are regression constants; and S_2 represents the S value after the RP in both Figures 3 and 4. A higher % ξ value means that the testing asphalt binder has superior fatigue performance concerning the fatigue-potential performance of the selected control bitumen. Accordingly, researchers can evaluate the asphalt binder fatigue performance by referencing any decided bitumen. The % ξ evaluates the bitumen fatigue behaviour considering the effect of adding polymer into NA, RP, and DL simultaneously. Readers can see Lv et al. [20] for more details about this procedure.

Moreover, this study introduces a new concept to compare the cLAS test results of two bitumens of interest. The new parameter is named “fatigue-potential performance increment (% β)” (see Equation 16), and it is defined as the percent increment of φ^p or $\varphi^{p'}$ related to one asphalt binder of interest concerning φ^p or $\varphi^{p'}$ linked with a defined control bitumen. This parameter assesses the fatigue performance of a specific bitumen of interest concerning a decided control asphalt binder when subjected to the cLAS test. The % β parameter appraises the fatigue behaviour of the bituminous materials only considering the effect of adding polymer into NA (without considering RP and DL).

$$\% \beta = ((\varphi^{p_1} - \varphi^p) / \varphi^p) \cdot 100 \text{ or } \% \beta = ((\varphi^{p'_1} - \varphi^{p'}) / \varphi^{p'}) \cdot 100, \quad (16)$$

Where φ^{p_1} and $\varphi^{p'_1}$ are φ^p values of the asphalt binders of interest when assessing the fatigue performance up to S_f and after S_f , respectively. Hence, obtaining the difference between the corresponding % ξ and % β makes it possible to determine the fatigue performance of the bitumen of interest concerning a decided control asphalt binder only considering the effect of RP and DL. This parameter is defined as “fatigue-potential performance difference” (% δ) (see Equation 17). Figure 5 illustrates the general flowchart of all procedures carried out in this study.

$$\% \delta = \left[\left(\frac{\varphi^{ph} - \varphi^p}{\varphi^p} \right) \cdot 100 \right] - \left[\left(\frac{\varphi^{p_1} - \varphi^p}{\varphi^p} \right) \cdot 100 \right] \text{ or } \% \delta = \left[\left(\frac{\varphi^{ph'} - \varphi^{p'}}{\varphi^{p'}} \right) \cdot 100 \right] - \left[\left(\frac{\varphi^{p'_1} - \varphi^{p'}}{\varphi^{p'}} \right) \cdot 100 \right] \quad (17)$$

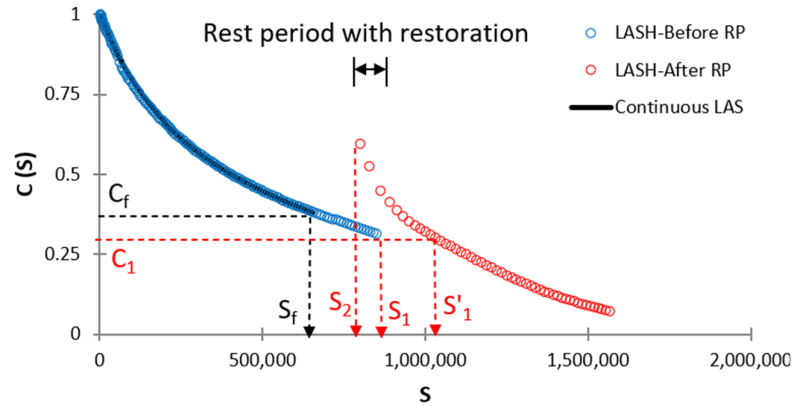


Figure 4. Graph to identify S_1 and S'_1 when conducting LASH (RP after S_f).

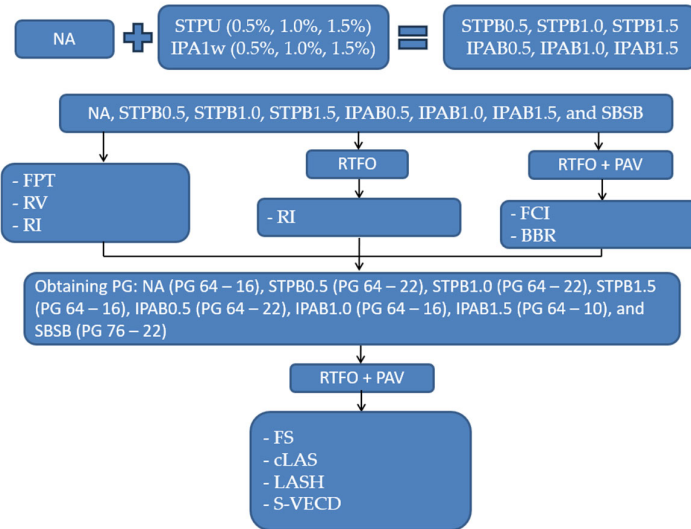


Figure 5. General flowchart of all procedures conducted in this research work.

3. Results

3.1. Analysis of $\%R_s$ and $\%\xi$ (Respect to cLAS of PAV.SBSB) Values

3.1.1. Subsubsection

Figures 6 and 7 exhibit the $\%R_s$ and $\%\xi$ values associated with each asphalt binder in this study, respectively. The $\%\xi$ values were calculated regarding the cLAS test value linked with PAV. SBSB because this bitumen exhibited the lower φ^p among the studied bituminous materials. Hence, all $\%\xi$ values in Figure 7 are positive. “Supplementary materials” include Figures S1–4, which exhibit DCCs of all bitumens associated with LASH test results of 25%, 50%, 75%, and 125% of S_f , respectively. Besides, each figure contains the DCCs related to 1, 5, 15, and 30 minutes of RPs, and these periods are named RP1, RP5, RP15, and RP30, respectively. Figures S1–4 depict DCCs up to the failure point defined by the SPC peak.

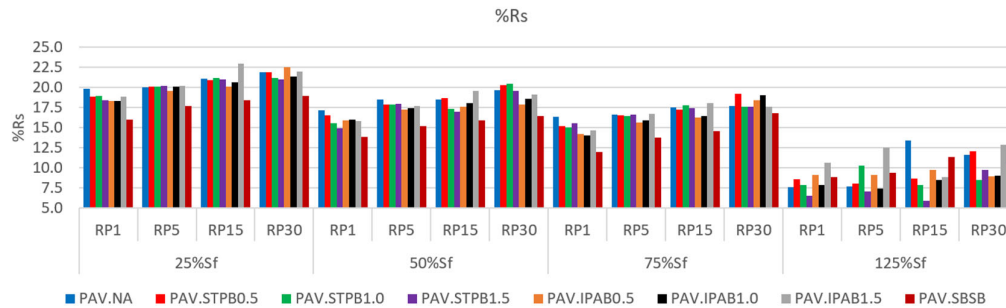


Figure 6. % R_s values linked with each bitumen at different DLs and RPs.

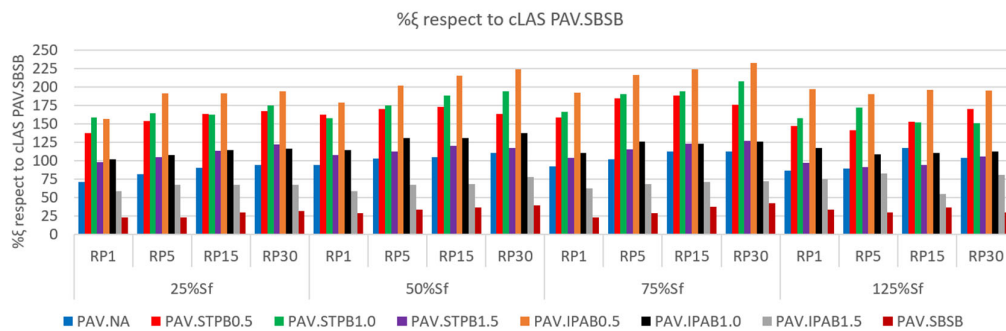


Figure 7. % ξ values related to each asphalt binder at different DLs and RPs.

Figure 6 shows that % R_s generally increases and decreases while the RP and the DL rise, respectively, regardless of the asphalt binder (in the pre-failure stage: 25%, 50%, and 75% of S_f). At the post-failure stage (125% of S_f), the % R_s values suddenly decline, and the propensity mentioned above related to RP is not evident as proof that all bitumen responses fail to follow a tendency. The possible explanation for this phenomenon is that all bitumens should have surpassed the failure point. These findings agree with previous research works [15,16]. This fact demonstrates that the failure definition (S_f) based on the SPC peak (instead of the PSE peak) is a convenient concept for differentiating pre- and post-failure stages in asphalt binders.

After analyzing data linked with Figure 6, it is possible to confirm that IPAB1.5 and NA exhibit eight and five times higher % R_s than the other bitumens, respectively. Accordingly, these two bituminous materials generally show superior self-restoration activity after the RP. However, after evaluating the bitumen performance in Figures S1–4, this research team realizes that IPAB0.5, STPB1.0, and STPB0.5 commonly exhibit higher fatigue performance than the other asphalt binders, in terms of DCC analysis. As a result, bitumens with larger % R_s fail to show superior fatigue performance in terms of DCC assessment. This finding agrees with the previous study by Lv et al. [20]. This phenomenon justifies the proposal of % ξ .

Figure 7 illustrates the % ξ values associated with all bitumens (in this study). This figure proves that % ξ generally increases when the RP and DL increase, regardless of the bitumen (in the pre-failure stage: 25%, 50%, and 75% of S_f). The finding related to RP agrees with previous studies, for instance, Almutairi and Baaj [19]. Nevertheless, in the case of the finding linked with DL is in the opposite direction of previous research works, for example, Xie et al. [14] and Wang et al. [8], because these research teams reported lower performance while increasing DL. The finding from Figure 7 proves that the combination effect of RPs, DLs, and adding polymer into NA can promote or diminish the fatigue performance of modified bitumens, depending on the specific case. Besides, PAV.IPAB0.5 generally exhibits superior % ξ values than the other bitumens, regardless of the RP and DL. After analyzing all data linked with Figure 7, this research team concludes that STPU and IPA1w cause their highest values of % ξ at 1.0% (% ξ = 207.54) and 0.5% (% ξ = 232.64) contents concerning NA, respectively. Both results are obtained at DL = 75% and RP = 30 minutes.

The possible explanation for the finding related to DL might be because the procedure foundations for calculating %R_s and %ξ are different. %R_s reflects the material response (self-restoration) at one specific point on the DCC. In contrast, %ξ represents the bitumen behaviour (self-restoration and fatigue performance) considering the whole extension of the DCC up to the point of interest. Moreover, %ξ includes the influence of self-restoration activity on the asphalt binder fatigue response. The finding from %ξ values and Figure 7 could define a turning point and create a new foundation for studying bitumen fatigue performance. To date, researchers have believed that higher DL (up to the failure point) reduces the bituminous material fatigue behaviour, and the possible explanation could be linked with the thixotropy phenomenon (see deeper explanation in the section “Discussion”). The finding mentioned above, linked with DL, agrees with Lv et al. ‘s study [20].

Table 5 shows the fatigue performance rankings of all asphalt binders in all test conditions, linked with %ξ values. PAV.IPAB0.5, PAV.STPB1.0, and PAV.STPB0.5 exhibit the ranking numbers 1, 2, and 3, respectively, which means that considering the effect of polymers, RPs, and DLs, these asphalt binders show the three best fatigue performances in terms of %ξ. Even though PAV.IPAB0.5 shows ranking number 1 in the final ranking; in the case of DL (25%*S_f*) and RP1, this bitumen reaches ranking number 2. The same phenomenon occurs with PAV.STPB1.0 and PAV.STPB0.5, because these asphalt binders do not always exhibit the ranking numbers 2 and 3, respectively, in Table 5, while changing DLs and RPs. This fact demonstrates the influence of these parameters on the bitumen fatigue response. Even though IPA1w promotes the highest %ξ value in NA, the STPU shows more stability to improve the NA fatigue response because the sum of rankings (44 + 35 + 79 = 158) of the latter polymer is lower than that (17 + 67 + 112 = 196) of the former one.

Table 5. Bitumen fatigue performance rankings related to %ξ.

Bitumen (agedPAV)	Materials ranking																Sum of rankings	Final rankings
	25%Sf				50%Sf				75%Sf				125%Sf					
	RP1	RP5	RP15	RP30	RP1	RP5	RP15	RP30	RP1	RP5	RP15	RP30	RP1	RP5	RP15	RP30		
NA	6	6	6	6	6	6	6	6	6	6	6	6	6	6	4	6	94	6
STPB0.5	3	3	2	3	2	3	3	3	3	3	3	3	3	3	2	2	44	3
STPB1.0	1	2	3	2	3	2	2	2	2	2	2	2	2	2	3	3	35	2
STPB1.5	5	5	5	4	5	5	5	5	5	5	5	4	5	5	6	5	79	5
IPAB0.5	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	17	1
IPAB1.0	4	4	4	5	4	4	4	4	4	4	4	5	4	4	5	4	67	4
IPAB1.5	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	112	7
SBSB	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	128	8

3.2. Analysis of %β (Respect to cLAS of PAV.SBSB) Values

Figure 8 depicts %β values related to PAV.NA, PAV.STPB0.5, PAV.STPB1.0, PAV.STPB1.5, PAV.IPAB0.5, PAV.IPAB1.0, PAV.IPAB1.5 regarding PAV.SBSB. The horizontal axis that intercepts the vertical axis at %β equal to 0 represents the %β value associated with PAV.SBSB. Figure S5 (Supplementary materials) shows the DCCs associated with all asphalt binders obtained from the cLAS test results. These DCCs are plotted up to the *S_f* related to each asphalt binder. Table 6 displays the fatigue behaviour ranking of bitumens related to the %β parameter.

Figure 8 shows that when the STPU content in NA increases, the fatigue performance (%β value) of STPBs first increases and then decreases. However, while increasing the IPA1w content in NA, the fatigue behaviour (%β value) of IPABs always decreases. PAV.STPB1.0 exhibits a higher %β value than the other two STPBs and PAV.IPAB0.5 shows a superior %β value than those linked with PAV.IPAB1.0 and PAV.IPAB1.5. Hence, 1.0% of STPU and 0.5% of IPA1w contents are the most convenient amount of these SPs to mix with NA. Nevertheless, the fatigue performance (%β value) of IPABs always decreases while increasing the IPA1w content in NA; PAV.IPAB0.5 displays the highest %β value among the tested bitumens in this study. Besides, PAV.IPAB1.5 shows the lowest %β value among the SPBs in this research work and is even lower than that linked with PAV.NA.

Figure 8 demonstrates that SPs can promote the fatigue response of SPBs, mixing the convenient proportion of this type of polymer and NA.

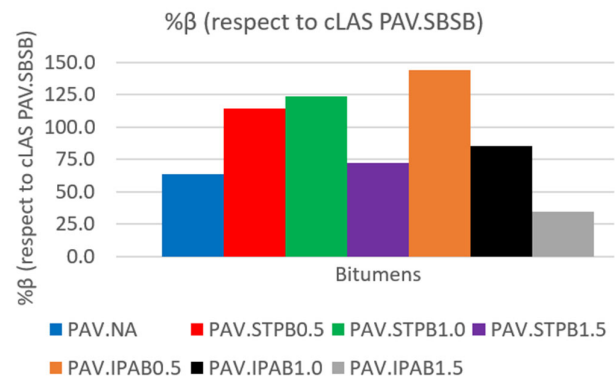


Figure 8. %β values of asphalt binders with respect to cLAS of PAV.SBSB.

In Figure S5, the DCCs linked with PAV.IPAB0.5, PAV.STPB1.0, and PAV.STPB0.5 exhibit superior fatigue performance than the other bitumens in this research work. The DCCs of these bituminous materials almost overlap in the C vs S graph, which means that the C-S relationships linked with PAV.IPAB0.5, PAV.STPB1.0, and PAV.STPB0.5 are almost the same. However, these asphalt binders reach the failure points at different positions in the graph mentioned above, where the PAV.IPAB0.5 even reaches the S_f at lower C value than those linked with PAV.STPB1.0 and PAV.STPB0.5, exhibits superior fatigue performance than these two materials because it reaches the failure point at higher S value. This conclusion agrees with Figure 8. This fact demonstrates the importance of C-S relationships and the area below the DCC to assess the bitumen fatigue performance. These two parameters are included when calculating %β values, and Table 6 displays their ranking. This table agrees with Figure 8 regarding fatigue response. It demonstrates that although IPA1w promotes the highest %β in this study, STPU shows more stability to promote NA fatigue performance (without considering RP and DL). Because the sum of rankings (equal to 10) linked with STPBs is lower than that associated with IPABs (sum equal to 12).

Table 6. Bitumen fatigue performance rankings related to %β.

Bitumen (aged-PAV)	Rankings
NA	6
STPB0.5	3
STPB1.0	2
STPB1.5	5
IPAB0.5	1
IPAB1.0	4
IPAB1.5	7
SBSB	8

3.3. Analysis of %δ (Respect to cLAS of PAV.SBSB) Values

Figure 9 depicts %δ values of all bitumens at different DLs and RPs concerning cLAS related to PAV.SBSB. Table 7 displays the fatigue performance rankings of all asphalt binders at different test conditions associated with %δ values.

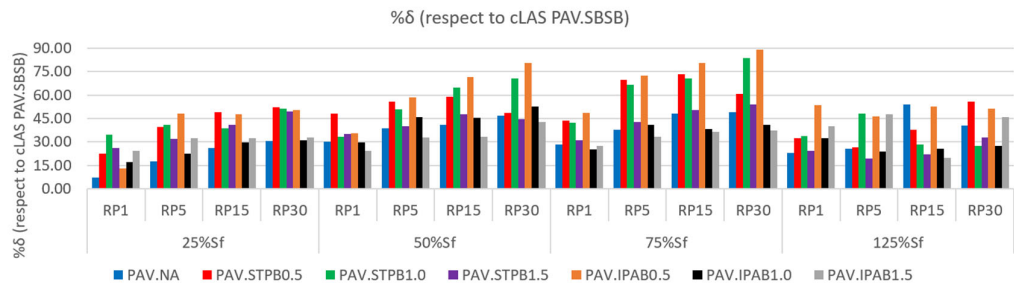


Figure 9. %δ values of asphalt binders with respect to cLAS of PAV.SBSB.

Figure 9 shows that %δ values commonly grow when RP and DL increase at the pre-failure stage (DL = 25%, 50%, or 75% of S_f), regardless of the asphalt binder. The finding associated with the RP agrees with previous research works, like Almutairi and Baaj [19], as mentioned before. Nevertheless, in the case of the finding related to DL fails to support the conclusions from previous studies, for instance, Xie et al. [14] and Wang et al. [8], because these research works found lower fatigue response when increasing the DL. The findings from Figures 7 and 9 agree, which confirms the consistency of the conclusion. At the post-failure stage (DL = 125% of S_f), %δ values commonly decrease concerning those values related to 75% of S_f , regardless of the bitumen. This fact confirms the failure occurrence and demonstrates the efficacy of SPC peak as a failure definition. Besides, the SPBs generally display higher % δ values than those linked with NA, evidencing the efficacy of the SPs in promoting self-restoration activity in NA. This SP property might be convenient for road surfaces.

The finding from Figure 9 demonstrates that the combination of RP and DL effects promotes the self-restoration of asphalt binders, regardless of the material. This finding represents a turning point because, until now, research works have found that applying RP at higher DL diminishes the bitumen fatigue response, as mentioned before. Self-restoration mainly includes self-healing and thixotropy, as commented before. The former represents the reduction of fracture cracks and expanding the effective area, which is the area without cracks [39]. The latter signifies a diminished dynamic shear modulus at the loading cycle stage due to the breakdown of the microstructure and restoration of dynamic shear modulus when removing the loading cycle due to the building-up of the microstructure [39]. Hence, this research team believes that the combination of both phenomena produces an internal process in the asphalt binders that allows them to promote self-restoration activity. This internal process is explained in detail in the section “Discussion”.

In Table 7, PAV.IPAB0.5, PAV.STPB0.5, and PAV.STPB1.0 exhibit the ranking numbers 1, 2, and 3 (see “Final ranking”), respectively, in terms of %δ value analysis. This fact means that these three bitumens show the three higher self-restoration rates when the combination effect of RP and DL is simultaneously considered. Although PAV.IPAB0.5 does not always show the ranking (number 1) mentioned above, when changing the DL (from 25% to 125% of S_f) at different RPs, and this phenomenon also occurs with PAV.STPB0.5, and PAV.STPB1.0. This fact means that the RP and DL influence bitumen self-restoration activity. Moreover, STPU exhibits more stability in promoting the self-restoration phenomenon in NA than IPA1w because the sum of rankings linked with STPBs (sum = 9) is lower than that value corresponding to IPABs (sum = 12).

Table 7. Bitumen fatigue performance rankings related to %δ.

Bitumen (agedPAV)	Materials ranking																Sum of rankings	Final rankings
	25%Sf				50%Sf				75%Sf				125%Sf					
	RP1	RP5	RP15	RP30	RP1	RP5	RP15	RP30	RP1	RP5	RP15	RP30	RP1	RP5	RP15	RP30		
NA	7	7	7	7	5	6	6	5	5	6	5	5	7	5	1	4	88	7
STPB0.5	4	3	1	1	1	2	3	4	2	2	2	3	4	4	3	1	40	2
STPB1.0	1	2	4	2	4	3	2	2	3	3	3	2	3	1	4	7	46	3
STPB1.5	2	5	3	4	3	5	4	6	4	4	4	4	6	7	6	5	72	4
IPAB0.5	6	1	2	3	2	1	1	1	1	1	1	1	1	3	2	2	29	1

IPAB1.0	5	6	6	6	6	4	5	3	7	5	6	6	5	6	5	6	87	6
IPAB1.5	3	4	5	5	7	7	7	7	6	7	7	7	2	2	7	3	86	5
SBSB																		

Table 8 shows the final rankings associated with % ξ , % β , and % δ . After comparing the final rankings related to % ξ (considering the effect of adding polymer, RP, and DL) and % β (only considering the effect of adding polymer), it is possible to conclude that RP and DL have not a critical influence in the results, because when removing these parameters, the final rankings are the same. However, the corresponding results change while comparing final rankings related to % ξ and % δ (considering the effect of RP and DL). Hence, SPs significantly influence bitumen fatigue response because the results change when its effect is removed. This fact confirms that mixing the convenient polymer with NA (with the proper content) makes it possible to promote the self-restoration activity in the asphalt binder to increase its fatigue performance.

Table 8. Final rankings related to % ξ , % β , and % δ .

Bitumen (aged-PAV)	Final rankings (TableFinal rankings (TableFinal rankings (Table		
	5 [% ξ]	6 [% β]	7 [% δ]
NA	6	6	7
STPB0.5	3	3	2
STPB1.0	2	2	3
STPB1.5	5	5	4
IPAB0.5	1	1	1
IPAB1.0	4	4	6
IPAB1.5	7	7	5
SBSB	8	8	-

4. Discussion

This research team considers that the % R_s proposed by Aurilio et al. [18] has a limited view on asphalt binder fatigue performance because it only evaluates the bitumen behaviour at one specific point of DCC (during RP). As a result, this parameter cannot assess the performance of the bituminous materials before and after the RP. However, these two phases of the LASH test have a decisive influence on the bitumen’s final response. For instance, Xie et al. [14] reported that in some cases, the DCCs linked with the LASH test, after the RP, collapsed with respect to the corresponding DCC related to the cLAS test. This fact means that the quality of the restoration process needed to be higher to ensure a superior fatigue performance of the asphalt binder after the RP and the % R_s parameter fails to assess the occurrence of this phenomenon.

“Supplementary materials” include Figures S6, S7, S8, S9, S10, S11, S12, and S13. These figures represent the DCCs of LASH at different RPs and DLs linked with PAV.NA, PAV.STPB0.5, PAV.STPB1.0, PAV.STPB1.5, PAV.IPAB0.5, PAV.IPAB1.0, PAV.IPAB1.5, and PAV.SBSB, respectively. These figures comprise the DCC associated with the cLAS test as a reference curve. This study also reports in the “Supplementary materials” some DCCs (linked with the LASH test) that slightly collapse concerning the corresponding DCC (associated with cLAS). The cases are as follows: Figure S6 (a) PAV.NA (RP1 and 25%Sf), PAV.NA (RP1 and 125%Sf), (b) PAV.NA (RP5 and 25%Sf), PAV.NA (RP5 and 125%Sf); Figure S7 (b) PAV.STPB0.5 (RP5 and 125%Sf), (c) PAV.STPB0.5 (RP15 and 125%Sf); Figure S8 (a) PAV.STPB1.0 (RP1 and 25%Sf), PAV.STPB1.0 (RP1 and 125%Sf), (b) PAV.STPB1.0 (RP5 and 125%Sf), (c) PAV.STPB1.0 (RP15 and 125%Sf), (d) PAV.STPB1.0 (RP15 and 125%Sf); Figure S9 (a) PAV.STPB1.5 (RP1 and 125%Sf), (b) PAV.STPB1.5 (RP5 and 125%Sf), (c) PAV.STPB1.5 (RP15 and 125%Sf); Figure S10 (a) PAV.IPAB0.5 (RP1 and 25%Sf) and PAV.IPAB0.5 (RP1 and 50%Sf); Figure S11 (a) PAV.IPAB1.0 (RP1 and 25%Sf), (b) PAV.IPAB1.0 (RP5 and 25%Sf) and PAV.IPAB1.0 (RP5 and 125%Sf), (d) PAV.IPAB1.0 (RP30 and 75%Sf); Figure S12 (c) PAV.IPAB1.5 (RP15 and 125%Sf)

Hence, when conducting the LASH test at different RPs and DLs, the tendency of %R_s values fails to reflect the actual fatigue behaviour of asphalt binders during this test. This fact explains why bitumens with higher %R_s in Figure 6 differ from asphalt binders with superior fatigue performance in Figures S1, S2, S3, and S4. As a result, the %R_s parameter is no longer convenient to evaluate the bitumen performance. In contrast, the % ξ can evaluate the bituminous material response before, during, and after the RP when carrying out the LASH test at diverse RPs and DLs because this parameter evaluates the area below the DCC up to the point of interest. As % ξ assesses the influence of adding polymer into NA, RPs, and DLs on bitumen fatigue response, at the same time, this research work introduced % β and % δ . The former parameter only evaluates the effect of mixing polymer and NA on the fatigue performance of the base asphalt binder. The latter appraises the influence of DLs and RPs on bitumen fatigue response, as explained before. This research team wants to clarify that % ξ , % β , and % δ parameters represent an integral view of the DCC that shows the total (from the starting point of the LASH test to the point of interest) and actual fatigue performance of the testing asphalt binders. Depending on which factors (adding polymer into NA, RPs, and DLs) the researchers want to evaluate.

In the section “3.1. Analysis of %R_s and % ξ (respect to cLAS of PAV.SBSB) values”, Figure 7 shows that % ξ generally increases when RP and DL increase. This fact means bituminous materials in this study commonly improve their fatigue performance, considering all factors (addition of polymer into NA, RP, DL), while reaching closer to the failure point. This phenomenon represents a breakthrough finding because, until now, research works have found that applying the RP at higher DL (before the failure point) reduces bitumen fatigue response. For instance, Wang et al. [40] and Wang et al. [41]. Studying and fully understanding the self-restoration phenomenon in bituminous materials is crucial to fully understanding and modeling the fatigue response of asphalt pavement materials [40]. As a result, the explanation of the possible reason for the phenomenon found in Figure 7 is as follows:

The dissipative viscoelastic activity of bitumen can cause a temperature increment of this material while being subjected to loading cycles (cLAS or LASH test). This process causes the internal temperature in asphalt binder specimens to rise over the actual existing ambient temperature. Then, the asphalt binder cools back to its original temperature when the load is removed [42]. The temperature change causes the variation of dynamic shear modulus [43]. This phenomenon is named “self-cooling” [44]. Thixotropy is an asphalt binder intrinsic property that diminishes its dynamic shear modulus during the loading phase because of microstructure breakdown and recovers its dynamic shear modulus when eliminating the load because of the building-up of microstructure [43]. The evolution of asphalt material thixotropy highly depends on temperature augmentation. As a result, bitumen viscosity also influences on this phenomenon [45]. Moreover, the temperature increment promotes the healing activity [46], and this phenomenon represents the fracture crack reduction and effective area growth (which is an uncracked area) [43].

As a result, this research team believes that by applying the RP at a higher DL (before the failure point), the asphalt binder will reach a higher internal temperature because of the phenomena mentioned above when applying loading cycles. If the asphalt binder reaches a superior internal temperature, its dynamic shear modulus and viscosity decrease. According to the explanation, this scenario creates the condition to promote thixotropy and self-healing processes during the RP. Hence, the material will have a superior opportunity to recover its original stage, dynamic shear modulus, and strength capacity, even though the bituminous material has a higher DL. This research team believes the asphalt binder follows the process described above while applying the RP before the failure point. Because the S values are not high enough to prevent the bitumen from recovering its original or at least a certain percentage of its original stage.

This explanation could explain why the % ξ increment occurs while the DL increases (before the failure point). However, more experiments are needed to understand this phenomenon fully. Furthermore, this research team recommends analyzing the whole DCC (up to the point of interest) instead of one specific point to precisely assess the bitumen fatigue performance. The finding from Figure 7 agrees with the study by Lv et al. [20].

The ranking analysis of the bitumen performance is also essential to decide which material should be used depending on the project characteristics. Table 8 illustrates the final rankings after

evaluating the results related to $\% \xi$, $\% \beta$, and $\% \delta$. When comparing the $\% \beta$ final rankings concerning those of $\% \xi$ (removing the influence of RPs and DLs on bitumen fatigue response), this research team confirms that the final rankings are the same. This finding does not mean that RP and DL do not influence asphalt binder performance because when these parameters change in Table 5, the ranking positions of the asphalt binders change. Hence, RP and DL influence bitumen response, but this effect is not high enough to change the final rankings, according to $\% \beta$ and $\% \xi$ assessment. Besides, the final rankings differ when comparing $\% \delta$ results regarding those of $\% \xi$ (deleting the effect of adding polymers). This finding proves that the influence of adding polymers into NA is high enough to change the final rankings, according to $\% \delta$ and $\% \xi$ data evaluation, as mentioned before.

Consistent with the findings in the previous paragraph, this research team can confirm that adding polymer into NA has more influence on bitumen fatigue performance than the RP and DL (S value), according to $\% \xi$, $\% \beta$, and $\% \delta$ evaluation. Even though previous research works have highlighted the importance of both parameters. For instance, Pérez-Jiménez et al. [47] confirmed the strong influence of RP on the fatigue performance of asphalt binders; Motamedi et al. [48] reported that S values have a considerable effect on bitumen fatigue life.

Future research works of this team will focus on a better understanding of the fatigue phenomenon related to $\% \xi$, $\% \beta$, and $\% \delta$ parameters. Future studies will also include the design of asphalt mixtures with SPBs and assessing the relationship between fatigue performance and the microstructure of asphalt binders. Moreover, the findings related to $\% \xi$, $\% \beta$, and $\% \delta$ parameters can change the factors to consider the convenient bitumen for one specific project and the criteria for evaluating the bitumen fatigue response.

5. Conclusions

This study proposed a new procedure to analyze the self-restoration capacity and fatigue performance of asphalt binders simultaneously utilizing LAS, LASH, and S-VECD methods. This proposal combines a new failure definition based on S values instead of N values and a new procedure to evaluate bitumen fatigue response and self-restoration capacity (all together) based on the area below the DCCs. This research work introduced two new parameters to assess the asphalt binder's response better. This study analyzed eight different bituminous materials to verify the efficiency of the new proposal. After analyzing all experimental results, the following conclusions can be drawn:

- The new procedure, with the three parameters, was effective for simultaneously evaluating the fatigue response and self-restoration activity of asphalt binders.
- Bitumen fatigue performance increased while increasing the S value where the RP was applied.
- The $\% R_s$ parameter failed to assess the actual fatigue response of asphalt binder effectively.
- The new procedure could evaluate the effect of adding polymer to the NA or the combined influence of DL and RP on bitumen fatigue performance. Moreover, the new proposal could simultaneously assess the combined effect of adding polymer to NA, DL, and RP.
- STPU was more stable to enhance the fatigue response of NA, but IPA1w caused the highest increment of NA fatigue performance.
- STPBs and IPABs showed their highest $\% \xi$ values containing 1.0% of STPU ($\% \xi = 207.54$) and 0.5% of IPA1w ($\% \xi = 232.64$), respectively. The results were obtained at DL = 75% of S_f and RP = 30 minutes in both cases.
- Adding the suitable SP, with its convenient content, to NA had a more significant influence on bitumen fatigue performance than the combined effect of DL and RP.

6. Patents

This section is not mandatory but may be added if there are patents resulting from the work reported in this manuscript.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: DCCs related to LASH tests of all bitumens at 25% of S_f : (a) RP1; (b) RP5; (c) RP15; (d) RP30; Figure S2: DCCs related to LASH tests of all bitumens at 50% of S_f : (a) RP1; (b) RP5; (c) RP15;

(d) RP30; Figure S3: DCCs related to LASH tests of all bitumens at 75% of S_f : (a) RP1; (b) RP5; (c) RP15; (d) RP30; Figure S4: DCCs related to LASH tests of all bitumens at 125% of S_f : (a) RP1; (b) RP5; (c) RP15; (d) RP30; Figure S5: DCCs of bitumens linked with cLAS test results; Figure S6: DCCs of NA related to LASH (25%, 50%, 75%, and 125% of S_f) at: (a) RP1; (b) RP5; (c) RP15; (d) RP 30 (including the DCC of cLAS as reference); Figure S7: DCCs of STPB0.5 related to LASH (25%, 50%, 75%, and 125% of S_f) at: (a) RP1; (b) RP5; (c) RP15; (d) RP 30 (including the DCC of cLAS as reference); Figure S8: DCCs of STPB1.0 related to LASH (25%, 50%, 75%, and 125% of S_f) at: (a) RP1; (b) RP5; (c) RP15; (d) RP 30 (including the DCC of cLAS as reference); Figure S9: DCCs of STPB1.5 related to LASH (25%, 50%, 75%, and 125% of S_f) at: (a) RP1; (b) RP5; (c) RP15; (d) RP 30 (including the DCC of cLAS as reference); Figure S10: DCCs of IPAB0.5 related to LASH (25%, 50%, 75%, and 125% of S_f) at: (a) RP1; (b) RP5; (c) RP15; (d) RP 30 (including the DCC of cLAS as reference); Figure S11: DCCs of IPAB1.0 related to LASH (25%, 50%, 75%, and 125% of S_f) at: (a) RP1; (b) RP5; (c) RP15; (d) RP 30 (including the DCC of cLAS as reference); Figure S12: DCCs of IPAB1.0 related to LASH (25%, 50%, 75%, and 125% of S_f) at: (a) RP1; (b) RP5; (c) RP15; (d) RP 30 (including the DCC of cLAS as reference); Figure S13: DCCs of IPAB1.0 related to LASH (25%, 50%, 75%, and 125% of S_f) at: (a) RP1; (b) RP5; (c) RP15; (d) RP 30 (including the DCC of cLAS as reference).

Author Contributions: Conceptualization, S.L., D.G. and M.B.C.; methodology, M.B.C.; software, M.B.C., validation, M.B.C., formal analysis, M.B.C.; investigation, S.C., D.L. and W.Z.; resources, S.L., D.G., C.-H.L. and M.B.C.; data curation, M.B.C.; writing—original draft preparation, M.B.C. and C.-H.L.; writing—review and editing, M.B.C. and C.-H.L.; visualization, S.L., D.G. and M.B.C.; supervision, S.L., D.G. and M.B.C.; project administration, S.L., D.G. and M.B.C.; funding acquisition, S.L., D.G., C.-H.L. and M.B.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Key Laboratory of Road Structure and Material of Ministry of Transport (Changsha), Changsha University of Science & Technology, grant number kfj220305.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. H. Zakeri, F.M. Nejad, A. Fahimifar, Image Based Techniques for Crack Detection, Classification and Quantification in Asphalt Pavement: A Review., *Archives of Computational Methods in Engineering*. 24 (2017) 935–977. <https://doi.org/10.1007/s11831-016-9194-z>.
2. L. Zhang, I. Hoff, X. Zhang, J. Liu, C. Yang, F. Wang, A Methodological Review on Development of Crack Healing Technologies of Asphalt Pavement., *Sustainability* (Switzerland). 15 (2023). <https://doi.org/10.3390/su15129659>.
3. C. Shi, X. Cai, X. Yi, T. Wang, J. Yang, Fatigue crack density of asphalt binders under controlled-stress rotational shear load testing., *Construction and Building Materials*. 272 (2021) 121899. <https://doi.org/10.1016/j.conbuildmat.2020.121899>.
4. C. Wang, Y. Chen, L. Song, Investigating the Crack Initiation and Propagation of Asphalt Binder in Linear Amplitude Sweep Test., *Journal of Materials in Civil Engineering*. 32 (2020) 1–10. [https://doi.org/10.1061/\(asce\)mt.1943-5533.0003470](https://doi.org/10.1061/(asce)mt.1943-5533.0003470).
5. Z. Zhang, M. Oeser, Energy dissipation and rheological property degradation of asphalt binder under repeated shearing with different oscillation amplitudes., *International Journal of Fatigue*. 152 (2021) 106417. <https://doi.org/10.1016/j.ijfatigue.2021.106417>.
6. Y. Yan, D. Hernando, B. Park, C. Allen, R. Roque, Understanding asphalt binder cracking characterization at intermediate temperatures: Review and evaluation of two approaches., *Construction and Building Materials*. 312 (2021). <https://doi.org/10.1016/j.conbuildmat.2021.125163>.
7. F. Ma, W. Dong, Z. Fu, R. Wang, Y. Huang, J. Liu, Life cycle assessment of greenhouse gas emissions from asphalt pavement maintenance: A case study in China., *Journal of Cleaner Production*. 288 (2021) 125595. <https://doi.org/10.1016/j.jclepro.2020.125595>.
8. C. Wang, L. Xue, W. Xie, W. Cao, Investigation on self-healing of neat and polymer modified asphalt binders., *Archives of Civil and Mechanical Engineering*. 20 (2020). <https://doi.org/10.1007/s43452-019-0006-8>.
9. C. Wang, C. Castorena, J. Zhang, Y. Richard Kim, Application of Time-Temperature Superposition Principle on Fatigue Failure Analysis of Asphalt Binder, *Journal of Materials in Civil Engineering*. 29 (2017) 1–9. [https://doi.org/10.1061/\(asce\)mt.1943-5533.0001730](https://doi.org/10.1061/(asce)mt.1943-5533.0001730).

10. M. Ameri, A. Mansourkhaki, D. Daryaei, Evaluation of fatigue behavior of asphalt binders containing reclaimed asphalt binder using simplified viscoelastic continuum damage approach., *Construction and Building Materials*. 202 (2019) 374–386. <https://doi.org/10.1016/j.conbuildmat.2019.01.021>.
11. R. Roque, Y. Yan, G. Lopp, Cracking Performance Evaluation of Asphalt Binders At Intermediate Temperature., University of Florida and Florida Department of Transportation. Contract No. BDV31-977-83. Final Report., 2020.
12. R.A. Schapery, Correspondence principles and a generalized J integral for large deformation and fracture analysis of viscoelastic media., *International Journal of Fracture*. 25 (1984) 195–223. <https://doi.org/10.1007/BF01140837>.
13. S.W. Park, Y.R. Kim, R.A. Schapery, A viscoelastic continuum damage model and its application to uniaxial behavior of asphalt concrete., *Mechanics of Materials*. 24 (1996) 241–255. [https://doi.org/10.1016/S0167-6636\(96\)00042-7](https://doi.org/10.1016/S0167-6636(96)00042-7).
14. W. Xie, C. Castorena, C. Wang, Y.R. Kim, A framework to characterize the healing potential of asphalt binder using the linear amplitude sweep test., *Construction and Building Materials*. 154 (2017) 771–779. <https://doi.org/10.1016/j.conbuildmat.2017.08.021>.
15. C. Wang, Y. Chen, W. Cao, A chemo-rheological approach to the healing characteristics of asphalt binders under short- and long-term oxidative aging, *Construction and Building Materials*. 221 (2019) 553–561. <https://doi.org/10.1016/j.conbuildmat.2019.06.115>.
16. M. Aurilio, Evaluating the Effect of a Self-Healing Elastomer on the Self-Healing Properties of Asphalt Cement. [Master thesis of Applied Science in Civil Engineering], University of Waterloo. Waterloo, Ontario, Canada, 2020.
17. M. Aurilio, H. Baaj, Examining the effects of a self-healing elastomer on the properties of bitumen., in: RILEM International Symposium on Bituminous Materials, RILEM Bookseries 27, 2022: pp. 857–863. https://doi.org/10.1007/978-3-030-46455-4_109.
18. R.M. Aurilio, M. Aurilio, H. Baaj, The effect of a chemical warm mix additive on the self-healing capability of bitumen, *Journal of Testing and Evaluation*. 50 (2022). <https://doi.org/10.1520/JTE20210207>.
19. H. Almutairi, H. Baaj, Evaluating Self-Healing Behaviour of Asphalt Binders Modified with Phase-Change Materials, Polymers and Recycled Glass Powder., *Polymers*. 15 (2023). <https://doi.org/10.3390/polym15081934>.
20. S. Lv, D. Ge, Z. Wang, J. Wang, J. Liu, Z. Ju, X. Peng, X. Fan, S. Cao, D. Liu, W. Zhang, M. Borges Cabrera, Performance Assessment of Self-Healing Polymer-Modified Bitumens by Evaluating the Suitability of Current Failure Definition, Failure Criterion, and Fatigue-Restoration Criteria., *Materials*. 16 (2023). <https://doi.org/10.3390/ma16062488>.
21. S. Lv, D. Ge, S. Cao, D. Liu, W. Zhang, C. Li, Development of a Framework for Assessing Bitumen Fatigue Cracking Performance under Different Temperatures and Aging Conditions., *Buildings*. 14 (2024). <https://doi.org/https://doi.org/10.3390/buildings14020311>.
22. R.A. Yousif, S.A. Tayh, I.F. Al-Saadi, A.F. Jasim, Physical and Rheological Properties of Asphalt Binder Modified with Recycled Fibers, *Advances in Civil Engineering*. 2022 (2022). <https://doi.org/10.1155/2022/1223467>.
23. X. Li, D. Guo, M. Xu, C. Guo, D. Wang, REOB/SBS Composite-Modified Bitumen Preparation and Modification Mechanism Analysis., *Buildings*. 13 (2023) 1601. <https://doi.org/10.3390/buildings13071601>.
24. W. Zhang, L. Zou, F. Chen, C. Yang, Y. Li, X. Yan, J. Zang, J. Liu, Evaluation method of storage stability of SBS modified bitumen based on dynamic rheological properties., *Construction and Building Materials*. 323 (2022). <https://doi.org/10.1016/j.conbuildmat.2022.126615>.
25. Y. Li, W. Li, A. Sun, M. Jing, X. Liu, L. Wei, K. Wu, Q. Fu, A self-reinforcing and self-healing elastomer with high strength, unprecedented toughness and room-temperature reparability., *Materials Horizons*. 8 (2020) 267–275. <https://doi.org/10.1039/d0mh01447h>.
26. D.P. Wang, Z.H. Zhao, C.H. Li, Universal Self-Healing Poly(dimethylsiloxane) Polymer Crosslinked Predominantly by Physical Entanglements, *ACS Applied Materials and Interfaces*. 13 (2021) 31129–31139. <https://doi.org/10.1021/acsami.1c06521>.
27. S. Yang, J. Ji, H. Tao, Y. Muhammad, J. Huang, S. Wang, Y. Wei, J. Li, Fabrication of urea formaldehyde–epoxy resin microcapsules for the preparation of high self-healing ability containing SBS modified asphalt, *Polymer Composites*. 42 (2021) 4128–4137. <https://doi.org/10.1002/pc.26135>.
28. AASHTO T240; Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test). AASHTO: Washington, DC, USA., (2023).
29. AASHTO R28-12; Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV). AASHTO: Washington, DC, USA., (2015).

30. AASHTO T48-06; Standard Method of Test for Flash and Fire Points by Cleveland Open Cup. AASHTO: Washington, DC, USA., (2015).
31. AASHTO T316; Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer. AASHTO: Washington, DC, USA., (2022).
32. AASHTO T315-20; Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR). AASHTO: Washington, DC, USA., (2020).
33. AASHTO T313-12; Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR). AASHTO: Washington, DC, USA., (2015).
34. AASHTO M320-10; Standard Specification for Performance-Graded Asphalt Binder. AASHTO: Washington, DC, USA., (2015).
35. W. Cao, C. Wang, A new comprehensive analysis framework for fatigue characterization of asphalt binder using the Linear Amplitude Sweep test., *Construction and Building Materials*. 171 (2018) 1–12. <https://doi.org/10.1016/j.conbuildmat.2018.03.125>.
36. C. Wang, C. Castorena, J. Zhang, Y.R. Kim, Unified failure criterion for asphalt binder under cyclic fatigue loading., *Road Materials and Pavement Design*. 16 (2015) 1–25. <https://doi.org/10.1080/14680629.2015.1077010>.
37. F. Safaei, C. Castorena, Temperature effects of linear amplitude sweep testing and analysis., *Transportation Research Record*. 2574 (2016) 92–100. <https://doi.org/10.3141/2574-10>.
38. F. Canestrari, A. Virgili, A. Graziani, A. Stimilli, Modeling and assessment of self-healing and thixotropy properties for modified binders, *International Journal of Fatigue*. 70 (2015) 351–360. <https://doi.org/10.1016/j.ijfatigue.2014.08.004>.
39. G. Leegwater, A. Tabokovic, O. Baglieri, F. Hammoum, H. Baaj, Terms and Definitions on Crack-Healing and Restoration of Mechanical Properties in Bituminous Materials., in: (Paper Presentation) RILEM International Symposium on Bituminous Materials, Lyon, France, December 14–16, 2020: pp. 14–16.
40. C. Wang, G. Gong, Y. Chen, Y. Sun, Estimating the Healing Characteristic of Asphalt Binder Using the LASH Test. *J. Mater. Civ. Eng.* 2022, 34, 04021421., *Journal of Materials in Civil Engineering*. 34 (2022). [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0004049](https://doi.org/10.1061/(ASCE)MT.1943-5533.0004049).
41. C. Wang, G. Gong, Z. Ren, Addressing the healing compensation on fatigue damage of asphalt binder using TSH and LASH tests., *International Journal of Fatigue*. 167 (2023). <https://doi.org/10.1016/j.ijfatigue.2022.107292>.
42. R. Botella, F.E. Pérez-Jiménez, T. López-Montero, R. Miró, Cyclic testing setups to highlight the importance of heating and other reversible phenomena on asphalt mixtures., *International Journal of Fatigue*. 134 (2020) 105514. <https://doi.org/10.1016/j.ijfatigue.2020.105514>.
43. H. Lv, H. Liu, C. Zhang, Y. Wang, M. Han, Y. Tan, Characterization of the healing potential of asphalt binders with separation of thixotropy after cyclic loading., *Construction and Building Materials*. 370 (2023). <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2023.130686>.
44. L.F. d. A.L. Babadopoulos, G. Orozco, C. Sauzéat, H. Di Benedetto, Reversible phenomena and fatigue damage during cyclic loading and rest periods on bitumen., *International Journal of Fatigue*. 124 (2019) 303–314. <https://doi.org/10.1016/j.ijfatigue.2019.03.008>.
45. X. Ma, Y. Wang, J. Hou, Y. Sheng, W. Zheng, S. Wu, Study on Thixotropic Properties of Asphalt Mastics Based on Energy Viewpoint., *Coatings*. 13 (2023). <https://doi.org/10.3390/coatings13030650>.
46. D. Sun, T. Lin, X. Zhu, L. Cao, Calculation and evaluation of activation energy as a self-healing indication of asphalt mastic, *Construction and Building Materials*. 95 (2015) 431–436. <https://doi.org/10.1016/j.conbuildmat.2015.07.126>.
47. F.E. Pérez-Jiménez, R. Miró, R. Botella, T. López-Montero, A.H. Martínez, The Effect of Temperature, Rest Periods and Ageing on the Response of Bituminous Materials in Fatigue Tests: Considerations and Proposals on Analytical Dimensioning Models., *Materials*. 15 (2022). <https://doi.org/10.3390/ma15030790>.
48. M. Motamedi, G. Shafabakhsh, M. Azadi, Evaluating Fatigue-Damage of Asphalt Binder and Mastic Modified with Nano-Silica and Synthesized Polyurethane Using VECD Method., *Journal of Materials in Civil Engineering*. 32 (2020) 1–10. [https://doi.org/10.1061/\(asce\)mt.1943-5533.0003280](https://doi.org/10.1061/(asce)mt.1943-5533.0003280).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.