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A novel fatigue test method for bitumen-stone combinations under cyclic tension-compression loading

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ABSTRACT

Asphalt pavement distress is closely linked to the fatigue performance of asphalt mixtures. Traditional fatigue tests like the dynamic shear rheometer (DSR) cannot assess failure between bitumen and stone, while methods like the four-point bending (4PB) test are complex and require specialised equipment. This study introduces a simplified bonding fatigue (BF) test method using a universal testing machine for bitumen-stone combinations, along with three evaluation indices. Two loading modes are applied to evaluate the fatigue properties of one neat bitumen and five modified binders. The accuracy of the BF experiment is validated against the 4PB test. Results indicate that the BF experiment effectively characterises the performance degradation process and bearing capacity during the yielding stage of samples under fatigue loading. While gilsonite and high-density polypropylene significantly increase the fatigue life, they cause brittle failure without a yielding period. 18 % crumb rubber-modified bitumen and 4.5 % SBS-modified bitumen exhibit superior fatigue life with an extended yield period, making them ideal for fatigue resistance. Correlation analyses with the 4PB experiments confirm that the BF experiment accurately evaluates the bonding fatigue performance of bitumen-stone combinations. Given its simplified sample preparation and equipment needs, the BF test is a viable alternative to the 4PB test.

1. Introduction

The UK's road infrastructure network is essential to the national economy and quality of life. It carries 70 % of freight and 90 % of passenger traffic, with a total asset value of £750 billion [1]. The surfacing material for most roads in the UK (95 % of the UK's Strategic Motorway Network and local authority networks) and worldwide is asphalt mixtures. As asphalt pavements are put into service over time, a variety of damages can occur due to vehicle loading and environmental effects, including ravelling, potholes, and cracking. Among the various mechanisms of asphalt pavement distress, bonding failure between bitumen and aggregate under fatigue loading is considered one of the leading causes of many road distresses [23]. Due to traffic loading and environmental influences (e.g. moisture damage and oxidative ageing), microcracks usually start to appear at the adhesion interface between asphalt binders and stone materials and progressively develop into large cracks with the increase of pavement service life, which further lead to the degradation of pavement function. The bonding fatigue resistance between bitumen and stone is considered one of the most critical characteristics that affects the service life of asphalt pavement to a great extent. Therefore, studying the bonding fatigue properties between bitumen and stone is essential for realising a resilient road by 'providing reliable infrastructure and protection against natural and man-made threats' [4].

Extensive efforts have been devoted to accurately measuring the bonding property of bitumen, and a variety of experimental methods have been used to evaluate the bond strength between bitumen and stones. Most of these experiments have been designed to test the maximum bonding strength of bitumen-stone combinations, such as the widely used binder bond strength (BBS) experiments [5678910111213] reported in published papers in recent years. This experimental method is simple and easy to operate and can quickly measure the adhesion strength between bitumen and stones [141516]. However, in practice, the vehicle loading mode on asphalt pavement is mainly a continuous fatigue damage load lower than the maximum bonding strength of bitumen-stone rather than a single destructive load. Therefore, applying

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fatigue loading below the bonding capacity of bitumen-stone combinations can better simulate the real pavement stress situation and more accurately predict the bonding fatigue life of asphalt pavement.

Currently, commonly used fatigue performance testing methods are generally classified by the material scale they focus on: asphalt binder and asphalt mixture. For asphalt binders, rheological fatigue tests such as the dynamic shear rheometer (DSR) and bending beam rheometer (BBR) are commonly used [17]. For asphalt mixtures, various fatigue testing methods are applied, including the four-point bending (4PB) fatigue test [1819], semi-circular bending (SCB) test [2021], indirect tensile (IDT) fatigue test [2223] and the direct tension fatigue test [242526]. These experiments have been applied extensively for many years. While DSR and BBR offer fast and convenient fatigue testing with precise sample response, these methods assess only the intrinsic fatigue performance of the binder material itself. They do not capture the bonding fatigue properties of bitumen-stone combinations. Moreover, the pure shear loading in DSR tests significantly differs from the complex stress conditions found in real pavements, which leads to the DSR-based bitumen fatigue testing methods failing to accurately represent the fatigue loads experienced by asphalt pavements [2728]. On the other hand, fatigue tests for asphalt mixtures better simulate actual pavement loading in terms of test objects and loading modes, but they have drawbacks, including complex sample preparation, lengthy testing cycles, and costly equipment requirements [2930].

In view of the advantages and disadvantages of the above two types of fatigue experiments, there is a need for an experimental method that can achieve easy sample preparation, rapid and convenient testing and also ensure that the test samples and test method are close to the real pavement loading situation. Based on this research gap, a novel bonding fatigue (BF) test is proposed in this study to measure the bonding fatigue performance of bitumen-stone combinations under cyclic tension–compression loading using the universal testing machine (UTM). The testing procedure and the evaluation indices are described and analysed in detail. The fatigue properties of one neat bitumen and five modified bitumen binders are evaluated using the BF and 4PB tests, respectively. Finally, the promising application of this newly proposed BF test protocol in testing the bonding fatigue performance of bitumen-stone is validated by comparing the fatigue resistance results of the two experiments.

2. Objectives

The objectives of the study are as follows:

(1) To introduce a BF test method for the bonding fatigue properties of bitumen-stone under cyclic tensile-compressive loading based on the UTM, which has the following advantages: the sample preparation is more accessible than that of the testing for asphalt mixtures, and the test samples and the loading mode are in line with the actual asphalt pavement conditions.
(2) To evaluate the fatigue properties of one neat bitumen and five modified bitumen binders by performing the BF test under two loading modes: cyclic tension–compression loading and cyclic tension loading (without compression).
(3) To verify the applicability and accuracy of the BF experiment in evaluating the fatigue characteristics of bitumen-stone combinations by comparing the BF experimental results of the above-mentioned bitumen binders with the 4PB test results on the corresponding asphalt mixtures.

3. Materials

3.1. Bitumen and stone materials

In this study, one neat bitumen and five modified bitumen binders are selected for the testing, including SBS-modified bitumen (SBSMB), high-density polypropylene-modified bitumen (PEMB), gilsonite-modified bitumen (GMB), crumb rubber-modified bitumen (CRMB), and terminal blend (TB) rubberised bitumen. Compared to the traditional CRMB, the TB rubberised bitumen has a lower viscosity and better storage stability due to its specialised producing process, during which the crumb rubber is devulcanised at high temperatures and mixed with asphalt binder at high shear speed with an extended period during the modification. The dosages of modifiers and the physical properties of these binders are listed in Table 1.

Basalt is the stone material for bonding with bitumen in the BF tests, as it is commonly used in pavement. Basalt boulders were cut into small slabs of the same size, and the surface of the stone slabs was polished in the same process using a polishing machine to achieve the same surface roughness for experimental purposes.

3.2. Asphalt mixture gradation

In this paper, basalt is used as the coarse aggregate for the asphalt mixture, and limestone is selected as the fine aggregate and filler. A typical AC-13 dense gradation is chosen for all bitumen binders except for CRMB. The target air void is 4.0 %, and the asphalt content is 4.8 %. For CRMB, a gap-graded mix gradation (ARAC-13), recommended for use in Arizona State, USA [31], is applied in this study due to the particle size of the rubber, which will impact the gradation. The ARAC-13 gradation is similar to the SMA gradation, with more coarse aggregates, less fine aggregates, and a high VMA with a high asphalt content. In addition, no filler is added to ARAC-13, the passing rate of 0.075 mm sieve is strictly controlled to less than 3 %, and the asphalt content is 6.1 %. The passing rate of each sieve in AC-13 and ARAC-13 gradations is shown in Table 2.

The bitumen is mixed with aggregates at 150 °C for neat bitumen and 170 °C for modified bitumen. The loose asphalt mixture is conditioned in the oven at 163 °C for 2 h to simulate the short-term ageing in the field. After ageing, the 4PB test specimens are prepared using an asphalt slab compactor. Then, the asphalt slabs are cut into beams with the dimensions of 385 × 65 × 50 mm.

4. Methods

4.1. Bonding fatigue (BF) test

The UTM tester is used for the BF test for the cyclic tension–compression loading. The specific preparation procedure for the sample is as follows:

(1) The stone slabs are cleaned with ultrasonic water bathing for 10 min to remove any contamination from the surface and ensure that the internal pores are also cleaned.
(2) Cleaned stone slabs (Fig. 1-**a**) and neat bitumen are heated in the oven at 150 °C and modified bitumen is heated at 170 °C for an hour to evaporate the moisture inside the voids of the stones and

Table 1
Conventional physical properties of the selected bitumen binders.

	Binder Properties Penetration (25℃)/0.1 mm	Softening Point/℃	Ductility /cm	Brookfield Viscosity at 135℃/Pa·s
Neat bitumen	64.3	47.2	44.2 (10℃)	0.356
4.5 % SBSMB	55.0	87.7	41.0 (5℃)	2.109
18 % CRMB	47.9	68.7	7.6 (5℃)	8.977
10 % TB rubberised bitumen	88.0	49.8	12.0 (5℃)	0.890
12 % GMB	43.2	53.6	13.3 (5℃)	0.548
8 % PEMB	45.6	58.6	10.3 (5℃)	0.750

Table 2
Aggregate gradation.

Sieve size (mm)	16.0	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
Passing rate (%)	AC-13	100	96.4	75.5	47.1	34.7	24.8	17.6	12.4	8.9	0.2
	ARAC-13	100	90.0	70.0	35.0	18.0	—	—	—	—	1.5

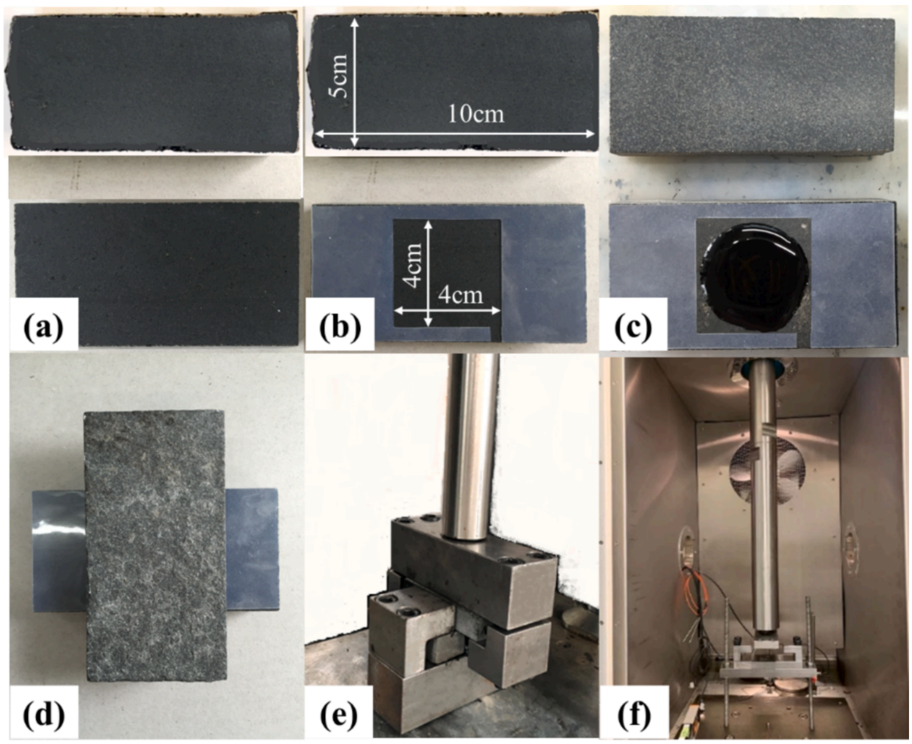

Fig. 1. (a)~(d) Sample preparation in the BF test and, (e) fixtures and sample loading and (f) environmental chamber.

to allow the bitumen to flow. After heating, a silicone rubber mould is put on the bottom slab (Fig. 1-**b**), and about 2 g of liquid bitumen is dropped down in the centre of the slab (Fig. 1-**c**). The top slab is then placed on the bottom slab in a cross shape (Fig. 1-**d**). The silicone rubber mould is customised and gouged out in the middle. A slit at the edge is made so that when the top slab is placed, excess hot bitumen can flow out through the small opening, and the thickness of the bitumen film can be accurately controlled at 0.5 mm (which is the thickness of the silicone rubber mould).

(3) The stone-bitumen-stone sample is cured in the dry condition at 25 °C for 24 h before testing. The top and bottom fixtures are mounted cross-shapely on the UTM loading platform. In the BF test, the samples are subjected to vertical cyclic loading (Fig. 1-**e**) at 25℃ in the environmental chamber of the UTM (Fig. 1-**f**). Three replicates are tested for each sample.

In the BF test, the loading waveform is a square wave in the cyclic tension–compression loading, in which the maximum tensile and compression force is 0.6 kN, and the loading cycle is 1 s, i.e., the tensile and the compression last for 0.5 s each. In this study, the cyclic tension fatigue test (without compression) is also performed for the same loading cycles: a 0.5 s tension duration followed by a 0.5 s loading interval (i.e., 0.5 s without any load) per cycle. The two loading modes used in the BF tests are shown in Fig. 2.

It is worth mentioning that the tension and compression forces are determined based on the ratio of the maximum pull-off force of the bitumen-stone combination samples, which can be obtained by conducting a pull-off test using the same setup and loading device [13]. In

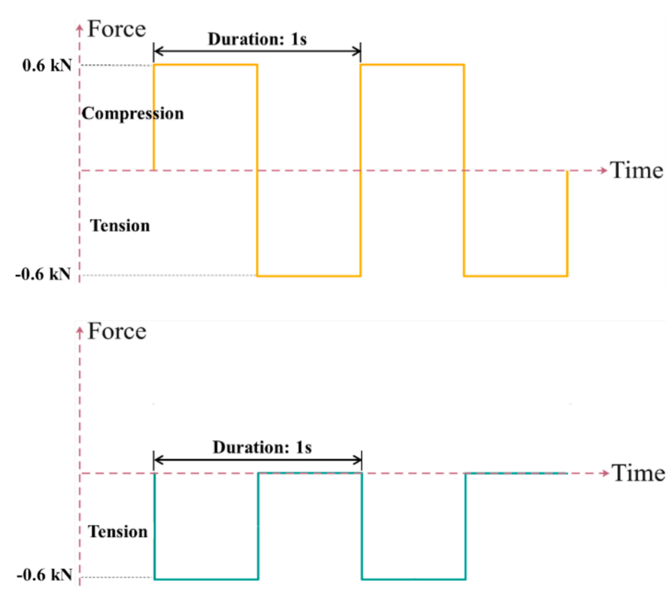

Fig. 2. The loading waveforms for (a) cyclic tension–compression loading mode and (b) cyclic tension loading mode in the BF test.

the preliminary tests, the tension and compression forces of ± 0.2 kN, ±0.4 kN, ±0.6 kN, ±0.8 kN, and ± 1.0 kN were selected based on 20 %-30 % of the average pull-off strength value of the bitumen-stone samples at 25 °C. This proportion aligns with fatigue design practices, where pavement design stress levels are often set at 20 %-40 % of the asphalt mixture's ultimate flexural strength [32]. The results showed that the time required from the start of loading to final damage was too long for the bitumen-stone samples at the loading of ± 0.2 kN and ± 0.4 kN due to the small tensile load. Especially for some modified bitumen binders, the samples remained undamaged even after the continuous loading of 50 h, which greatly reduces the experimental efficiency and increases the cost. However, higher fatigue loading (±0.8 kN and ± 1.0 kN) could lead to rapid damage to the samples and large variability of the data, which is not conducive to experimental analysis. Therefore, 0.6 kN was selected as the tension and compression loads for various bitumen-stone samples in the BF experiment.

4.2. Four-point bending (4PB) mixture fatigue test

4PB fatigue testing is widely employed to evaluate the fatigue performance of asphalt mixtures. In this study, the 4PB tests are conducted in strain-controlled mode with a microstrain level of 800, at a frequency of 10 Hz and a temperature of 25 °C. For asphalt mixtures with neat bitumen, the fatigue life was evaluated using the N_{f50} criterion, where fatigue life is defined as the number of load cycles required for the initial stiffness modulus to decrease by 50 % [33].Given that the loading process requires time to stabilise at the beginning of the test, the initial stiffness modulus was defined as the value at the 50th load cycle. However, for mixtures with modified binders, the N_{fNM} (normalised modulus) criterion [193435] was applied, as it has been shown to provide a more accurate assessment of fatigue performance in these materials. The N_{fNM} criterion involves a normalised evaluation approach, introducing the concept of "Normalised Modulus × Cycles (*NM*)," calculated as shown in Equation (1):

$$NM = \frac{S_i \times N_i}{S_0 \times N_0} \quad (1)$$

where:

NM – the normalised modulus-load cycle.

S_i – the stiffness modulus at the i_{th} load cycle.

N_i – the number of load cycles.

S_0 – the initial stiffness modulus.

N_0 – the initial load cycle count.

Here, S_0 and N_0 represent the initial state of the samples, set as the stiffness and cycle count at the 50th cycle for data stability. The variation of NM with loading cycles is illustrated in Fig. 3-**a**. In the N_{fNM} method, the fatigue life of the specimen is defined as the cycle count corresponding to the maximum NM value.

Some researchers [3435] argue that a 50 % reduction in a specimen's modulus, as used in the N_{f50} criterion, does not represent complete fatigue failure but rather the initial stage of crack formation. Full fatigue life should encompass the entire process, including crack development and propagation until the final fracture. Therefore, N_{f50} may underestimate the actual fatigue life of modified asphalts. Furthermore, the subjectivity in selecting the initial stiffness modulus can lead to significant variability in calculated fatigue life, complicating accurate comparisons between asphalt mixtures. The N_{fNM} criterion was therefore chosen for this study due to its ability to evaluate cumulative energy dissipation, making it more sensitive to the distinct fatigue behaviour of modified asphalts, especially polymer-modified types. Unlike N_{f50}, which only considers modulus reduction, N_{fNM} captures nonlinear trends in energy dissipation, allowing for a more precise determination of the failure point.

A beam fatigue apparatus (BFA) from IPC, Australia, is used to measure the fatigue performance of the mixtures. The BFA tester adopts high-precision displacement and force sensors and is equipped with a temperature-controlled environmental chamber (−20℃~60℃), as shown in Fig. 3-**b a, 3-c**.

5. Results

5.1. Curve analysis of the BF test under different loading conditions

In this section, the experimental curves in the BF tests are analysed by performing fatigue tests on bitumen-stone samples under cyclic tension–compression loading and cyclic tensile loading (without compression). The two loading methods and the experimental indices are specified below, respectively.

5.1.1. BF test under cyclic tension–compression loading

Fatigue testing under cyclic tension–compression loading is carried out according to the loading pattern in Fig. 2-**a**, with tensile and compressive values of 0.6 kN. The mechanical response of the samples subjected to cyclic tension–compression loading is illustrated in Fig. 4. The positive part of the Y-axis in Fig. 4-**a** represents the response of the sample under compression, and the negative portion represents its response under tension. Damage usually occurs due to tension stress in tension–compression loading. Therefore, the data points for the sample's response under tension are collected separately and plotted in Fig. 4-**b**. It should be noted that, due to data being recorded every 0.1 s during the experiment, Fig. 4-**a** contains a large number of raw data points. To enhance readability and focus on the specimen's critical response under load, the Fig. 4-**b** is simplified by selectively removing data points that did not significantly reflect changes in the specimen's response.This approach clarifies the visual interpretation of the data without compromising the accuracy of the results presented. The same approach was applied to Fig. 5 and Fig. 6 below.

As shown in Fig. 4-**a**, at the beginning of the loading period, the mechanical response of the sample reaches the maximum tensile force and compression force in each cyclic loading, which does not decrease with the increase of the fatigue cycles. As the number of fatigue loads increases, it is found that in the compressive force response region

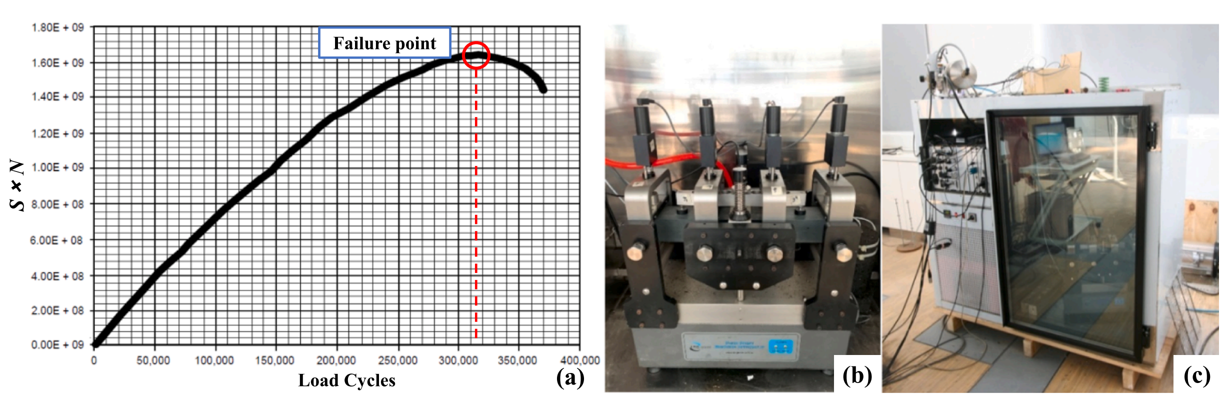

Fig. 3. (a) S × N versus Load Cycles [19], (b) the beam fatigue apparatus for the 4PB test and (c) the environmental chamber.

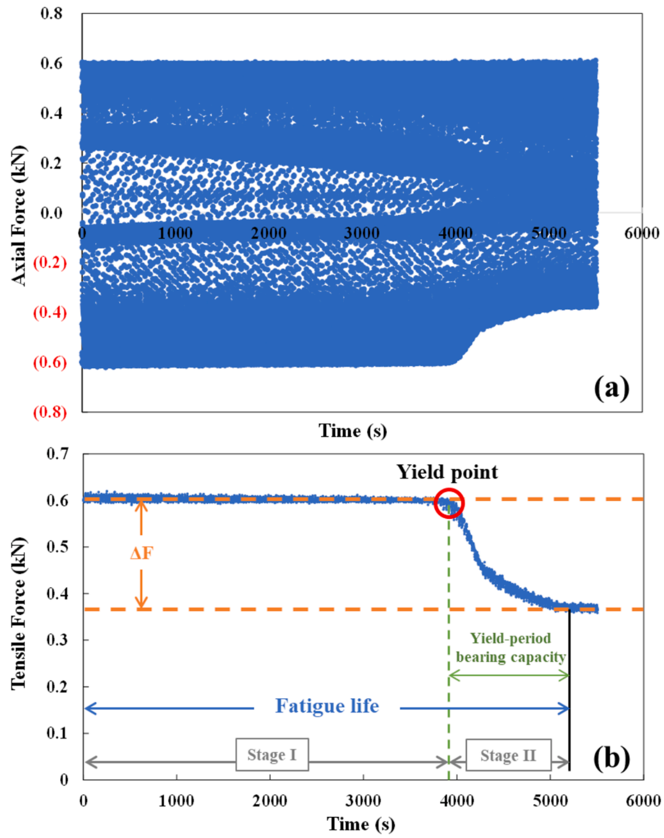

Fig. 4. (a) Raw data in the BF test and (b) the tensile force that the sample can withstand during the fatigue loading and the description of indicators.

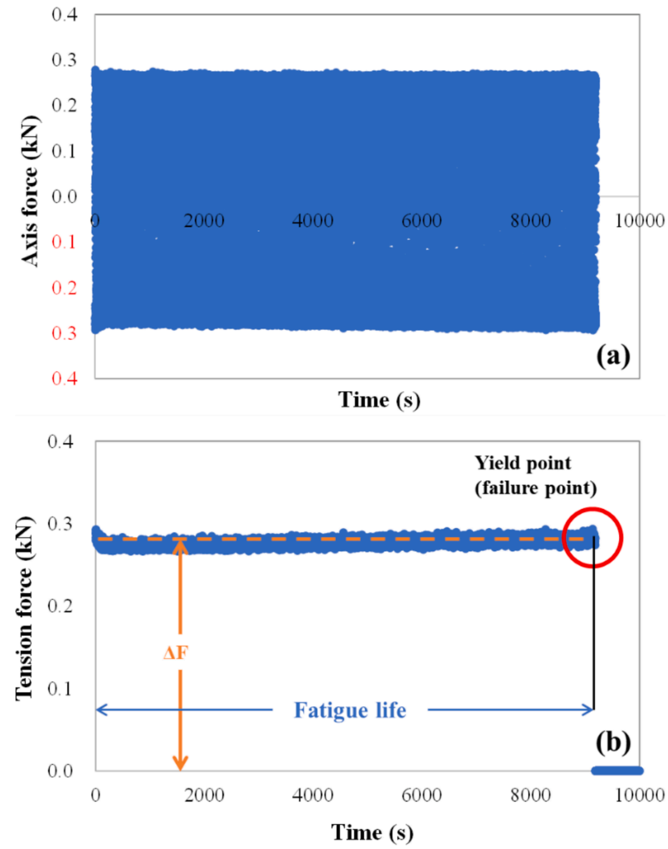

Fig. 5. (a) Raw data of the samples with brittle damage in the BF test and (b) the tensile force that the sample can withstand during the fatigue loading and the description of indicators in the case of brittle damage.

(positive part of the Y-axis), the mechanical response of the sample reaches the maximum compression (0.6 kN) in each loading cycle, and the curve formed by the maximum value of the data in the positive part of the Y-axis does not change with loading, indicating that the samples are still able to fully withstand the compressive loads without damage. However, in the tensile force response region (negative part of the Y-axis), there is an inflection point and a gradual decrease in the bearable tensile force, which indicates that bonding damage starts to occur under fatigue loading.

As illustrated in Fig. 4-**b**, Stage I is the period from the beginning of loading until the bearable tensile force begins to decrease, and this inflection point is defined as the 'yield point' in the BF test. As the cyclic loading continues, the tensile force that the bitumen-stone sample can withstand gradually decreases and eventually stabilises around a value (the ultimate bearable tensile force) or zero. The difference between the initial tension force and the ultimate bearable tensile force is recorded as ΔF, and this stage is considered the yielding stage (Stage II) of the sample under fatigue loading.

The number of loading cycles during the phase from the beginning of loading to the point where the bearable tensile force drops to a stable value (Stage I + Stage II) is defined as the fatigue life of the sample. The number of loading cycles in which the sample is loaded at the yielding stage (Stage II) is defined as the yield-period bearing capacity. The yield-period bearing capacity represents the yielding resistance of the bitumen-stone sample in the repeated fatigue from cracking to complete failure. This indicator reflects the 'toughness' and energy dissipation capacity of the bitumen-stone. The higher the yield-period bearing capacity of the sample, the slower it will be in the performance decline period, which can reduce the frequency of road maintenance while improving maintenance efficiency, thus extending the service life of the pavement and reducing road maintenance expenditures.

Different bitumen-stone combinations may have similar bonding fatigue lives. However, there is a clear difference in their yield-period capacity: some bitumen-stone combinations have a long yielding stage, while others show 'brittle' damage, i.e., there is no yielding stage, and the yield point is the failure point (as the example shown in Fig. 5). In the BF experiments, under the premise of having the same fatigue life, the samples with higher yield-period bearing capacity are considered to have better fatigue performance. This is because the period between the start of the decline in pavement performance and the complete destruction of the pavement can be an 'early warning' and act as a 'buffer' for road maintenance, helping to prevent and control the early road damage and avoiding the occurrence of large-scale pavement distress in the same road section during the same period and severe road traffic disruption. The bitumen-stone combinations without the yielding stage (i.e., samples with brittle damage) do not have such a 'performance decline warning' function.

In summary, it can be concluded that in evaluating the bonding fatigue performance of bitumen-stone combinations, not only is the 'fatigue life' needed as an indicator, but the yield-period bearing capacity should also be considered as an evaluation index. Based on the above analysis, three indices characterising the fatigue performance of bitumen-stone combinations are proposed in the BF test: the fatigue life (N_f), yield-period bearing capacity (N_{YP}) and yield fatigue ratio (R), which is the ratio of N_{YP} to N_f. These three indices need to be considered when evaluating the fatigue performance of bitumen-stone combinations to obtain the fatigue response of the samples at each stage of damage and to characterise the fatigue performance comprehensively.

5.1.2. BF test under cyclic tensile loading (without compression)

Fig. 6 shows the mechanical response of the bitumen-stone combinations under cyclic tension loading, with a maximum tensile force of 0.6 kN and a loading cycle of 1 s (tensile force lasts for 0.5 s and the

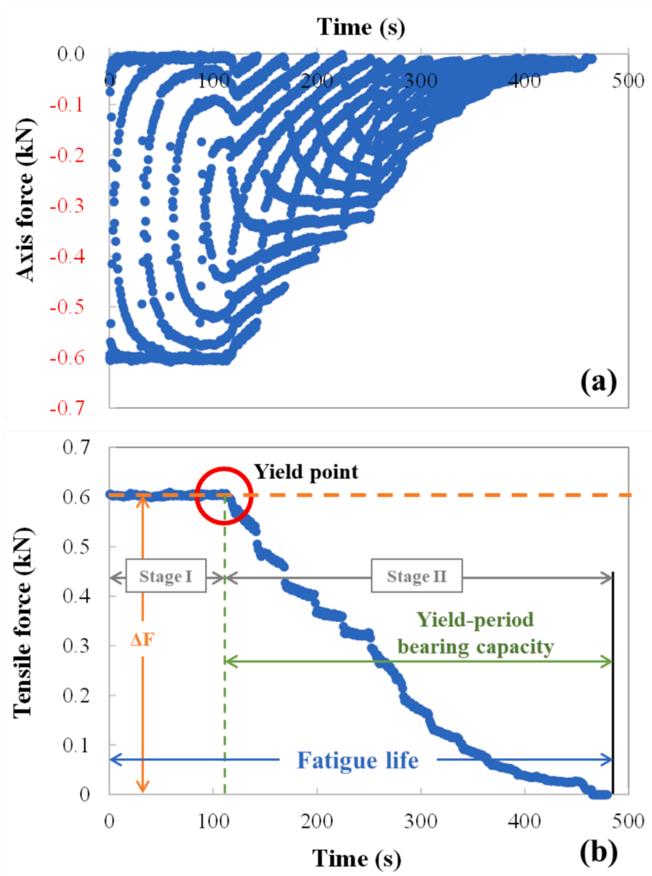

Fig. 6. (a) Raw data in the BF test under cyclic tensile loading (without compression) and (b) the tensile force that the sample can withstand during the fatigue loading and the description of indicators.

interval is 0.5 s).

As shown in Fig. 6, the mechanical response of the bitumen-stone combinations under cyclic tension loading (without compression) is similar to that under cyclic tension–compression loading, and the indicators are defined similarly. However, the removal of the compression in fatigue loading leads to a significant advance in the occurrence of the yield point of the sample and a dramatic reduction in the fatigue life (N_f) and yield-period bearing capacity (N_{YP}). In addition, it can be observed that during the yielding stage, the bearable tensile force gradually decreases from the initial tensile force to zero and does not ultimately maintain a constant bearable tensile force' as in the case of BF experiments under tension–compression loading. It is also worth mentioning that brittle damage without a yielding stage occurs in the BF tests under cyclic tension loading.

5.2. *Evaluation of fatigue performance of various bitumen-stone combinations using the BF experiments*

In this section, the fatigue properties of the six bitumen-stone combinations, as listed in Table 1, are evaluated and compared using BF experiments under cyclic tension–compression and cyclic tension loading (without compression), respectively.

5.2.1. *Fatigue performance under cyclic tension–compression loading*

The comparison of the fatigue properties of various bitumen-stone combinations under cyclic tension–compression loading is shown in Fig. 7.

As presented in Fig. 7, there is a significant difference in fatigue performance between various bitumen-stone combinations. Overall, the fatigue life of each bitumen under cyclic tension–compression in the BF test is ranked as follows: 12 % GMB > 4.5 % SBSMB > 8% PEMB > 18 % CRMB > neat bitumen > 10 % TB rubberised bitumen. Due to the high modulus, the overall fatigue life of 12 % GMB and 8 % PEMB is far greater than that of the other bitumen binders. Previous studies have reported that bitumen with high modulus, such as GMB, has significantly higher adhesion strength with stones [11123637]. However, 12 % GMB and 8 % PEMB samples show brittle damage with no yielding stage under the fatigue loading. In addition, it is found that their bearable tensile force is reduced to zero ($\Delta F = 0.6$ kN) once the samples are damaged in Stage II of the loading. On the other hand, the samples with other bitumen binders show a low final bearable tensile force (ΔF around 0.4kN to 0.5kN), indicating that a certain bonding capacity can be maintained at each cycle of pressure.

4.5 % SBSMB and 18 % CRMB samples also showed good fatigue resistance (N_f) and yield-period bearing capacity (N_{YP}), as well as yield fatigue ratio (R) in tension–compression fatigue loads due to their excellent toughness and elastic properties. It is worth mentioning that although the fatigue life (N_f) of CRMB samples is longer than that of the neat bitumen samples. Its yield point in the BF experiment appears earlier than that of the neat bitumen, indicating that the 18 % CRMB-

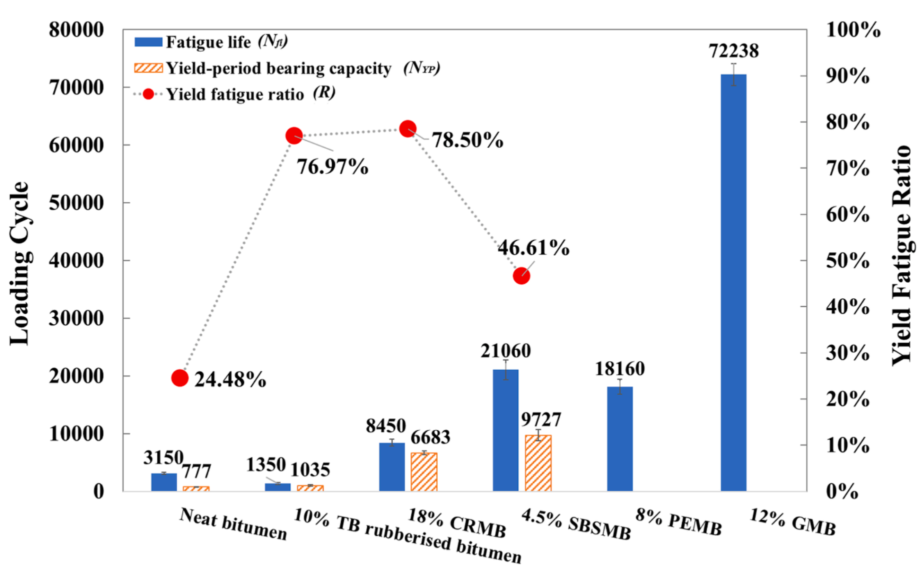

Fig. 7. Fatigue properties of various bitumen-stone combinations under cyclic tension–compression loading.

stone samples start to crack earlier than the neat bitumen samples, but show a more extended yielding stage. This is because the bond strength of CRMB to stone is lower than that of neat bitumen, as reported in previous studies [12]. The rubber particles in the bitumen have good elastic properties. When vertical tensile load is applied to the bitumen-stone samples in the BF test, they can absorb the externally applied work through deformation, reducing the damage to the sample. Even if microcracks occur at the early stage, the CRMB samples can still withstand the fatigue loading (less than the maximum bond strength) for an extended period and, thus, exhibit a more prolonged yielding stage than the neat bitumen samples.

TB rubberised bitumen exhibits the lowest fatigue life, primarily due to the desulfurisation pyrolysis process at high temperatures (≥220℃), which weakens the material's structural integrity and adhesive properties. During this process, sulfur-sulfur (S-S) and sulfur-carbon (S-C) bonds, crucial for the cross-linked network in rubber-modified bitumen, are broken. These bonds act as "bridges" between polymer chains, providing enhanced strength and elasticity; thus, their breakage disrupts the cross-linked structure, reducing molecular connections and weakening the material's resistance to mechanical stress. This bond degradation also leads to the fragmentation of long macromolecular chains into shorter segments, diminishing the cohesive strength since shorter chains lack the stability of interconnected macromolecules. Additionally, the reduced S-S and S-C bonds decrease intermolecular interactions, such as van der Waals forces, further compromising the material's cohesion and making it more prone to cracking and deformation under cyclic loading. Pyrolysis also causes rubber particles to break down into smaller fragments, producing carbon ash that impairs the bitumen-stone interface adhesion [3839], facilitating detachment of bitumen from the aggregate and lowering bonding fatigue performance. Despite these adverse effects, TB rubberised bitumen's high penetration and deformability allow it to re-bond to the stone under compressive cyclic loading, resulting in a relatively extended yielding stage and a higher yield fatigue ratio (*R*).

Based on fatigue life and yield-period bearing capacity indices, among the six bitumen selected in this study, 18 % CRMB and 4.5 % SBSMB are the preferred binders based on fatigue resistance. The bitumen-stone samples prepared with these two can withstand both prolonged fatigue loading and show good yield-period bearing capacity during the yielding stage after cracks occur, avoiding brittle fracture of the samples. From a macro perspective, this creates a 'window period' for pavement status monitoring and maintenance. It allows maintenance and repairs to be carried out after road damage is detected but before the condition significantly deteriorates. To some extent, this postpones the need for major road reconstructions (complete milling and resurfacing).

5.2.2. Fatigue performance under cyclic tension loading (without compression)

The comparison of the fatigue properties of various bitumen-stone combinations under cyclic tension loading is shown in Fig. 8.

As shown in Fig. 8, the bonding fatigue life (N_f) of various bitumen-stone samples under cyclic tension loading (without compression) is ranked as follows: 12 % GMB > 4.5 % SBSMB > neat bitumen > 18 % CRMB > 8% PEMB > 10 % TB rubberised bitumen. With the exception of PEMB and neat bitumen, this ranking is consistent with the test results under cyclic tension–compression loading in Fig. 7. The comparison between Fig. 7 and Fig. 8 shows that the damage will occur in a very short period under repeated tension only. The reduction in fatigue life is more than 80 % compared with the results under cyclic tension–compression loading and even by 98.2 % for 8 % PEMB.

The samples with 18 % CRMB and 8 % PEMB, which have a significant advantage in fatigue resistance over neat bitumen under tension–compression loading, exhibit a lower fatigue life than neat bitumen under cyclic tension loading. In addition, the yield point at which damage occurs in the bitumen-stone samples is significantly advanced, and the yield-period bearing capacity (N_{YP}) is significantly curtailed without the compression force during fatigue loading.

The significant difference in fatigue life of 8 % PEMB under cyclic tension–compression and pure tensile loads can be attributed to the impact of polyethylene on the internal structure and stress distribution of bitumen. Under cyclic tension–compression loading, the alternating tensile and compressive forces allow the PEMB to dissipate stress more effectively through viscoelastic and plastic deformation mechanisms. PE enhances the bitumen matrix, distributing and alleviating local stress concentrations, thereby enabling the PEMB to maintain a high fatigue life under repeated cyclic loading. However, under cyclic tensile loading, the tensile stresses concentrate directly within the tensile strength limits of bitumen, with no compressive component to assist in stress dissipation. In such cases, the increased stiffness imparted by PE modification can reduce the bitumen's ability to distribute strain, making it more prone to brittle damage under tension, leading to microcrack propagation and premature failure. Thus, while PE modification improves fatigue life under cyclic tension–compression loads, its brittle nature under cyclic tensile conditions, due to the lack of compressive buffering, significantly reduces the fatigue life of PEMB. For 18 % CRMB, the drastic difference in fatigue performance under different loading modes is likely related to the toughening effect of rubber particles and their stress distribution characteristics. The high

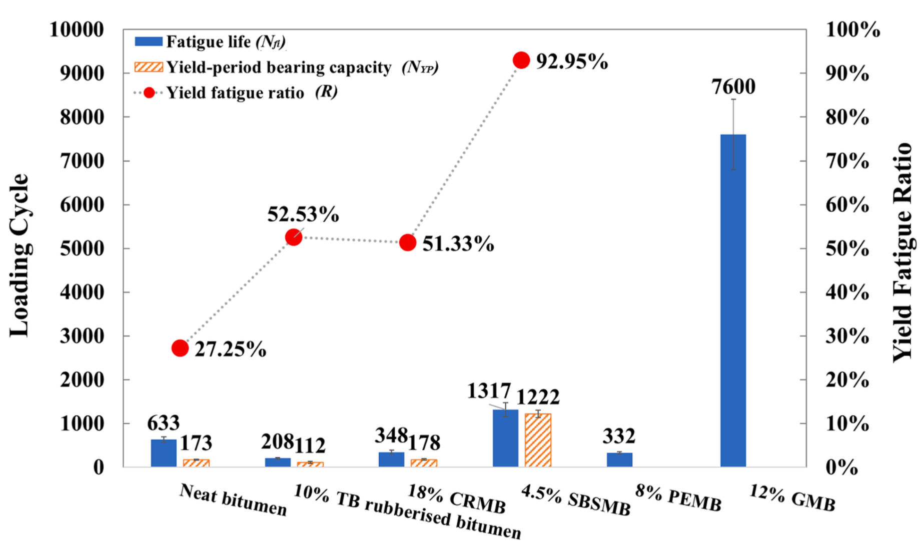

Fig. 8. Fatigue properties of various bitumen-stone combinations under cyclic tension loading (without compression).

elasticity of rubber particles provides a cushioning effect, enabling effective stress dispersion and absorption during alternating tensile and compressive forces. This process reduces stress concentrations, delays crack initiation and propagation, and ultimately extends the fatigue life of CRMB under cyclic tension–compression. Under cyclic tensile loading, this toughening effect is relatively weakened. Similar to PEMB, without compressive forces to help relieve stress concentrations, tensile stresses act directly on the relatively weaker interfacial areas within the CRMB. Although rubber particles have good elasticity, their toughening effect is limited under pure tensile conditions. At high rubber content (e.g., 18 %), the interfacial adhesion may be insufficient to resist pure tensile stresses, making the bitumen more susceptible to microcrack formation and accelerated fatigue damage.

The fatigue performance of samples with 4.5 % SBSMB under cyclic tension also decreases considerably. In contrast, the yield fatigue ratio *(R)* increases significantly, indicating that the 4.5 % SBSMB sample cracks at a very early stage under tension only, and the performance decline process is dominated by the damage stage (Stage II). Due to SBS's excellent elastic and tensile properties, the samples still show good fatigue performance under cyclic tensile loading compared with the samples with other bitumen binders.

As seen in Fig. 7 and Fig. 8, the data variability in the BF test is generally low for most bitumen binders, except for the 12 % GMB, which exhibits greater variation. This indicates that the BF test demonstrates good repeatability in evaluating bitumen-stone fatigue performance. Moreover, the comparison of the results of the two loading modes illustrates the critical role of the instantaneous pressure action in extending the fatigue life of bitumen-stone combinations in tension–compression fatigue loading tests. Assuming that the non-tensile loading period (i.e., 0.5-second no-load interval or 0.5-second compressive loading period) in each loading cycle is considered as a short-term (transient) healing period within a cycle (the compressive loading period can be regarded as a healing period with an applied external force), it can be seen that compressive loading during the 'transient healing phase' has an essential contribution to increasing the fatigue life of samples during the cyclic tensile-compressive load.

It is also worth mentioning that even under tension fatigue loading (without compression), the yield fatigue ratio (R) of 18 % CRMB and 4.5 % SBSMB remains high. The 12 % GMB still shows an excellent bonding fatigue life, which even exceeds the fatigue life of some other bitumen with transient healing compressive loads (i.e., tension–compression fatigue loading).

5.3. *Evaluation of fatigue performance of various asphalt mixtures using the 4PB experiments*

Since the BF test is a newly proposed experimental method, its accuracy in evaluating the fatigue performance of bitumen-stone combinations needs to be validated by other fatigue experiments that are more widely used and have been proven to be able to reflect the real characteristics of asphalt materials in engineering. In this paper, the asphalt 4PB experiment is chosen to verify the evaluation accuracy of the BF test. Considering the repeated sinusoidal loading applied in the 4PB experiment, the results of the BF experiment under cyclic tension–compression loading are selected for the correlation analysis of the two experiments. In addition, due to the large variability of the data of cycle numbers where the yield point occurs and the yield-period bearing capacity (N_{YP}) and that the main evaluation index in the fatigue test is the overall fatigue life of the samples, the fatigue life (N_f) is selected as the main evaluation index in the BF experiment for the correlation analysis with 4PB test.

The 4PB experimental results for the six asphalt mixture specimens are presented in Table 3.

The fatigue life from the BF experiments under cyclic tension–compression loading is plotted against the fatigue life data in the 4PB test, and a correlation analysis is performed, as shown in Fig. 9**-a**.

Table 3
4PB experimental results for the asphalt mixture specimens.

Bitumen Type	Sample	Fatigue Life (Cycles)	Average	STDEVP	COV
Neat bitumen	1	24,140	23,953	398	1.66 %
	2	23,400			
	3	24,320			
4.5 % SBSMB	1	371,850	381,340	12,048	3.16 %
	2	398,340			
	3	373,830			
18 % CRMB	1	245,180	238,860	18,677	7.82 %
	2	213,490			
	3	257,910			
10 % TB rubberised bitumen	1	155,990	144,323	12,865	8.91 %
	2	150,580			
	3	126,400			
12 % GMB	1	57,620	82,557	18,627	22.56 %
	2	102,380			
	3	87,670			
8 % PEMB	1	242,310	266,650	17,247	6.47 %
	2	277,450			
	3	280,190			

Fig. 9**-a** shows no significant correlation between the fatigue life indices in the BF experiment for bitumen-stone combinations and the 4PB experiment for asphalt mixtures ($R^2 = 0.0202$). However, it can be observed that data point in the top left corner of the graph deviate from the straight line fitted to all the data points, whereas the fatigue life of the BF test and the 4PB test as presented by the other data points seem to show a good linear correlation. It was found that the data point that deviated from the fit was for the 12 % GMB. According to the experimental experience, 12 % GMB will cause brittle fracture of the sample in both the 4PB and BF tests due to the high modulus of bitumen, resulting in high variability of the experimental data. Therefore, in the following, the data of samples with 12 % GMB are excluded during the correlation analysis of fatigue life indexes between the BF and 4PB test, as shown in Fig. 9**-b**. The fatigue life indices in the BF and 4PB tests show a certain linear correlation ($R^2 = 0.7640$) after the samples with 12 % GMB are excluded. This indicates that the results of the BF and the 4PB experiments are essentially consistent in evaluating the fatigue performance of the bitumen-stone combinations and mixtures, except for samples with high-modulus bitumen, which is prone to sudden changes in load response and brittle damage in the fatigue tests.

Additionally, it is worth mentioning that the fitted linear regression line in Fig. 9**-b** does not pass through the origin. This may be attributed to the following reasons: (1) Measurement error or systematic error: The data may contain measurement or systematic errors, which can lead to deviations in the linear fit, preventing it from intersecting the origin; (2) Exclusion of the origin's influence: When the experimental data do not include values near the origin, the fitting process may naturally exclude the influence of the origin, resulting in a shift of the fitted line.

The main reason for the inconsistency in the results between the BF and 4PB tests is as follows: the repeated flexural bending force applied on the asphalt mixture samples in the 4PB test is different from the vertical tension–compression force conducted at the bitumen-stone interface in the BF test. At the microscopic level, the loading forces on the bitumen-aggregate contact surface in the 4PB experiments are complex. The magnitude of the forces decomposed into directions perpendicular or parallel to the bitumen-aggregate contact interface are neither equal nor regular. However, the samples in the BF test are only subjected to tension–compression loading perpendicular to the bitumen-stone contact surface, and the tensile and compressive forces remain constant in each loading cycle. Due to the repeated direct tensile forces, the damage of the samples occurs more rapidly in the BF test than in the 4PB test.

In summary, the BF test can be considered an alternative to the 4PB test, with a simplified sample preparation and loading method, a more straightforward interaction between bitumen and stone and a more

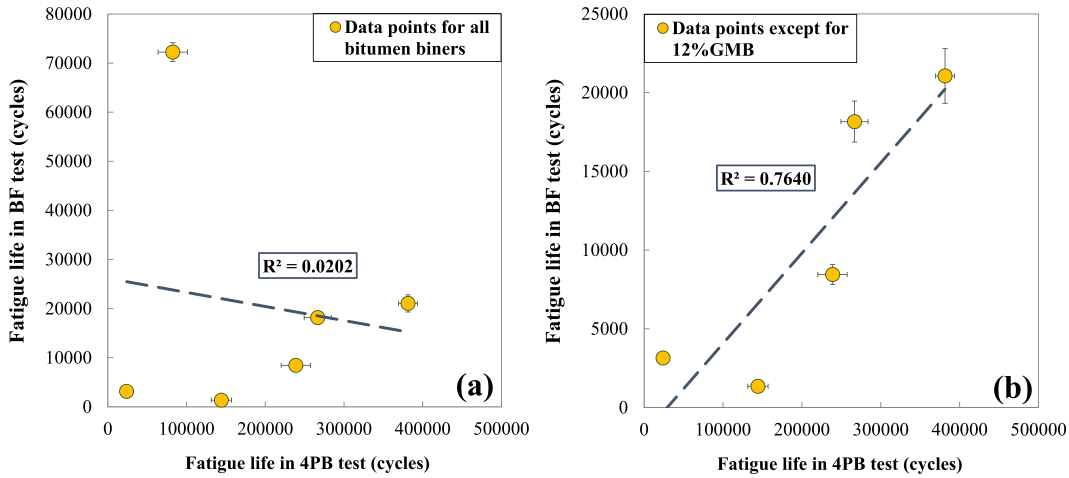

Fig. 9. Correlation analysis between BF and 4PB fatigue test results: (a) data points of six bitumen binders and mixes and (b) data points of 12 % GMB and mix excluded.

explicit analysis of the results. In addition, the experimental curves in the BF test can fully reflect the changes in the deterioration of properties during the damage process of the samples. The correlation analysis between the two experimental data also proves the accuracy and reliability of the BF test in evaluating the fatigue performance of bitumen-stone combinations.

6. Conclusions

This study introduced a novel test (BF test) based on the UTM testing machine to evaluate the fatigue performance of bitumen-stone combinations under cyclic loading perpendicular to the bitumen-stone bonding interface. The corresponding quantitative methods and fatigue performance evaluation indices are proposed. Two loading modes, cyclic tension–compression and cyclic tension loading (without compression), are applied in the BF test to evaluate the fatigue performance of one neat bitumen and five modified bitumen binders. The fatigue properties of the corresponding asphalt mixtures are also tested using the 4PB experiment, and the results of the two experiments are compared to verify the accuracy of the BF test in evaluating the fatigue properties of bitumen-stone combinations. The conclusions in this paper are summarised as follows:

(1) Based on the bearable tensile force-loading time curves obtained in the experiment, three evaluation indices are proposed for evaluating the fatigue of bitumen-stone combinations, including the fatigue life (N_f), yield-period bearing capacity (N_{YP}) and yield fatigue ratio (R). Among them, the indicator N_{YP} represents the number of loading cycles the sample can withstand from the start of small cracks to complete destruction. It reflects the characteristic of 'cracked but not completely damaged', which is also an important indication of fatigue damage resistance.

(2) The results of the BF test under cyclic tension–compression loading show that the fatigue life of all modified bitumen is better than that of the neat bitumen, except for the TB rubberised bitumen. Samples prepared with 12 % GMB and 8 % PEMB present superior bonding fatigue performance. However, both do not show a yielding stage during fatigue loading and exhibit brittle damage. The indices fatigue life (N_f) and yield-period bearing capacity (N_{YP}) indicate that 18 % CRMB and 4.5 % SBSMB have both better fatigue load resistance and more extended yielding periods, which provide 'extended time' for road performance monitoring and maintenance, avoiding large-scale clustered pavement damage over the same period.

(3) Under cyclic tensile loading (without compression), the fatigue life (N_f) and yield-period bearing capacity (N_{YP}) of the various bitumen binders decrease significantly. The fatigue performance of 18 % CRMB and 8 % PEMB declined to a level inferior to that of the neat bitumen, but 12 % GMB still exhibited excellent fatigue characteristics. However, when using high-modulus modified bitumen, care needs to be taken to monitor the health of pavements regularly and to be wary of large-scale low-temperature cracking of the roads to avoid traffic problems due to the need for extensive maintenance.

(4) The correlation analysis shows that the fatigue life (N_f) index under cyclic tension–compression loading in the BF experiment and the fatigue life index in the 4PB experiment show a fair linear correlation ($R^2 = 0.7640$) after excluding the data with high variability brought by samples with high-modulus bitumen. Considering the difference in loading methods and sample types between the two experiments, this correlation shows that the BF experiment can accurately reflect the fatigue performance of bitumen-stone combinations under repeated tension–compression loads. Compared with the 4PB experiment of asphalt mixtures, the BF test has the advantages of simplified sample preparation and loading methods, lower testing equipment requirements, and straightforward experimental analysis. Moreover, it can more comprehensively evaluate the performance degradation process of bitumen-stone samples under bonding fatigue loading, which shows promising feasibility and application in assessing the fatigue properties of bitumen-stone combinations.

In future research, several key areas should be addressed to enhance the accuracy and practical relevance of the BF test for bitumen-stone fatigue performance. First, additional experimental data spanning a wider range of bitumen and stone types is essential to validate the robustness of this method across diverse material combinations. Second, an ideal test should incorporate essential hot mix asphalt (HMA) properties (such as volumetrics, aggregate gradation, and shape) to better reflect the complex composite nature of asphalt mixtures under realistic loading conditions. Including these properties would enable the BF test to more accurately capture the interactions observed in actual pavements. Additionally, the impact of various factors, including moisture and ageing on the fatigue performance of bitumen-stone combinations under cyclic vertical loading should be considered to establish a clearer link between laboratory results and field conditions. Addressing these factors will help refine the BF test, making it a more comprehensive tool for assessing bonding fatigue performance and aligning it more closely with the long-term durability and behaviour of real-world asphalt pavements.

CRediT authorship contribution statement

Lu Zhou: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gordon Airey:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition. **Yuqing Zhang:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Weidong Huang:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Chonghui Wang:** Writing – review & editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.matdes.2024.113577.

Data availability

Data will be made available on request.

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