International Journal of GEOMATE, April, 2025 Vol.28, Issue 128, pp.33-40
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2025.128.4781
Geotechnique, Construction Materials and Environment

PAVEMENT DESIGN INCORPORATING POLYMER-MODIFIED ASPHALT USING VARIOUS LABORATORY FATIGUE TESTS

*Van Bich Nguyen[1]

[1]Faculty of Transportation Engineering, Hanoi University of Civil Engineering (HUCE), Vietnam

*Corresponding Author, Received: 28 Oct. 2024, Revised: 03 Feb. 2025, Accepted: 09 Feb. 2025

ABSTRACT: Recently, there has been growing interest in pavements constructed with polymer-modified asphalt, largely driven by the significant increase in traffic volumes and loads. This study aims to improve the understanding of polymer-modified asphalt's detailed mechanical behaviour and to support the development of reliable pavement designs that incorporate it. This study employed styrene-butadiene-styrene (SBS), including one hard and one soft variant, to modify asphalt binders used in two distinct types of mixtures. A series of laboratory fatigue tests - including the beam wheel tracker fatigue test (BWTFT), 4-point bending test (4PBT), and indirect tensile fatigue test (ITFT) - were conducted, covering both unmodified and polymer-modified asphalt materials under various testing conditions. The findings indicate that data from the beam wheel tracker fatigue test can provide a way forward in pavement design, enabling the application of standard laboratory fatigue tests with a shift factor. Furthermore, the laboratory results suggest that polymer-modified asphalt pavements can be designed similarly to conventional asphalt pavements, but with an adjusted fatigue characteristic. This shift can be derived from data obtained through the BWTFT, 4PBT, or ITFT.

Keywords: Pavement design, Polymer-modified asphalt (PMA), Fatigue tests, Asphalt mixtures

1. INTRODUCTION

An asphalt pavement’s primary function is to facilitate the safe, smooth, and economical movement of traffic between different locations. However, various factors can negatively impact its performance, including increased traffic, extreme climate conditions, and the presence of heavy vehicles. These factors contribute to a decline in the pavement’s initial smoothness and serviceability, ultimately leading to premature deterioration [1]. The two primary failure modes in flexible pavements are permanent deformation (rutting) and fatigue cracking. Rutting, or the formation of a depression along the wheel path, results from internal strains within one or more layers of the pavement, whereas fatigue cracking in the bituminous layer arises from repeated tensile strains at the bottom of the asphalt layer due to traffic loading. In addition to traffic, environmental factors must also be considered when assessing asphalt pavement performance [2-4].

After years of research and development, it is now widely accepted that simple design considers only two critical locations in the structure: the bottom of the asphalt layer and the top of the subgrade, where maximum values of key parameters are observed [5]. The stress condition at the top of the subgrade is crucial, as the pavement must prevent the soil from being overstressed and deformed, with compressive strain often serving as the design criterion. In contrast, fatigue cracking in asphalt under repeated loading is mainly caused by tensile strain, which is typically used as the fatigue design criterion [3, 6-9].

Polymer modified asphalt (PMA) mixtures are now widely utilised in flexible pavement structures and overlays that accommodate high traffic volumes. The key benefits of incorporating polymer modifiers in asphalt mixtures include the reduction in both the extent and severity of permanent deformation and fatigue cracking, which in turn extends the service life of hot mix asphalt (HMA) pavements and overlays [10-13]. While numerous laboratory and field studies have confirmed the enhanced performance of PMA compared to conventional HMA mixtures, there has been limited effort to fully understand the detailed mechanical behaviour of PMA and to develop confident pavement design methods incorporating PMA based on relevant specifications and design guidance.

The fatigue test using a wheel tracker has been successfully employed by many researchers as it aims to replicate the realistic conditions experienced by an asphalt layer in a road. Its fundamental distinguishing feature is that the load is applied by a moving wheel. In early studies using the wheel tracker device, Van Dijk [14] and Rowe [15] utilised investigated the effects of a loaded wheel with a pneumatic tyre on an asphalt slab positioned on an elastic rubber foundation, with crack initiation and propagation detected using strain gauges attached to the underside of the slab specimen during the test. Based on the data from the beam wheel tracker fatigue test, a pathway for analysing pavement structures was proposed, along with recommended shift factors for converting laboratory test data into fatigue characteristics for pavement design. Liao, Chen and Tsou [16] conducted the wheel tracking fatigue test by applying a moving wheel load to an asphalt beam while monitoring the tensile strain induced at the bottom of the beam. The results of this test were utilised to compare the fatigue performance of asphalt mixtures with that of bitumen-filler mastics. In similar studies, Lacalle Jiménez [17] utilised the beam wheel tracker test to observe the differences in behaviour between hot and cold mix asphalt.

To facilitate more reliable pavement design using PMA and to enhance the understanding of the fatigue cracking behaviour of asphalt mixtures, this research has conducted various fatigue tests, including two standard tests (the indirect tensile fatigue test and the 4-point bending test) and a non-standard fatigue machine, the beam wheel tracker fatigue test. These tests were performed under a range of conditions, covering both unmodified and PMA materials. The findings will be compared and analysed, and based on the outcomes, shift factors will be recommended for different cases.

The subsequent sections of the paper are organised as follows: Section 2 provides a summary of the laboratory testing programme. Section 3 presents the experimental results. Section 4 offers a comparison and discussion. Finally, Section 5 concludes the paper with key findings from the study.

2. RESEARCH SIGNIFICANCE

This study highlights that while material differences were similar at 20°C, a larger variation in the BWTFT at 10°C shows the PMA benefits are greater than anticipated based on the ITFT at lower design temperatures. The BWTFT data provide valuable insights for pavement design, and the study introduces shift factors to convert standard laboratory data to fatigue characteristics, addressing differences between BWTFT and other tests. The analysis suggests that shift factors at 20°C underestimate PMA advantages, which become more significant at lower temperatures.

3. LABORATORY TESTING PROGRAMME

3.1 Materials and Preparation

This study examines three types of asphalt mixtures: 20mm Dense Bitumen Macadam (DBM50), 14mm Enrobé à Module Élevé 2 (EME2), and 10mm Stone Mastic Asphalt (SMA). This particular selection of asphalt mixtures was carefully chosen to investigate the key factors influencing their fatigue behavior. The primary goal of this study is to improve the reliability of pavement designs that incorporate PMA mixtures. By examining these mixtures, the research aims to gain a deeper understanding of how different variables affect their performance under repeated loading, ultimately contributing to the development of more durable and efficient pavement designs.

For the first mixture, a standard 20mm continuously graded DBM50 was chosen. The binder used was 40/60 bitumen, commonly applied in the UK. The binder content was set at 4.7% by mass, in line with the recommendations of BS-EN 4987 [18]. Limestone aggregate, obtained from Tunstead Quarry in Buxton, UK, with a nominal maximum particle size of 20mm, was used. The particle size distribution for the design, alongside the standard's upper and lower limits, is shown in Fig. 1.

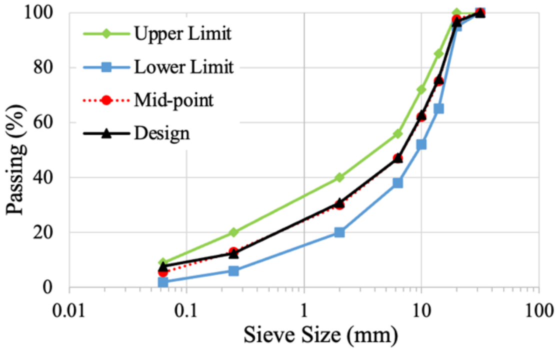

Fig. 1 DBM50 design particle size distribution

For the second mixture, a 14mm EME2 was chosen. Its gradation is quite similar to that of the DBM50, as it is intended for the same structural layer (base or binder course). A hard SBS polymer-modified binder (21 pen) was utilised, with a binder content of 5.5% by mass, in accordance with BS-EN 13108 [19]. The aggregate used was also limestone, sourced from Tunstead Quarry, featuring a nominal maximum particle size of 14mm (Fig. 2).

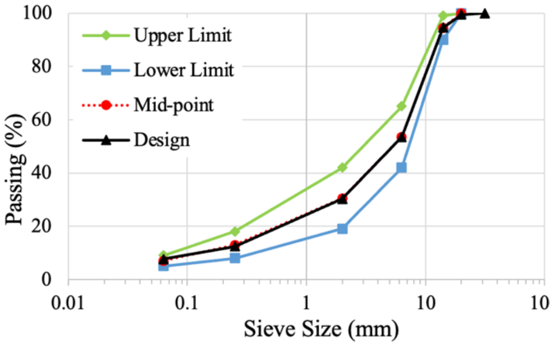

Fig. 2 EME2 design particle size distribution

For the third mixture, a standard 10mm Stone Mastic Asphalt (SMA) surface course was selected for this study. This mixture employed a soft SBS polymer-modified binder (65 pen) at a content of 6.5%, as specified in BS-EN 13108 [20], and utilised granite aggregate with a design particle size distribution shown in Fig. 3.

3.2 Experimental Programme

3.2.1 Indirect tensile fatigue test (ITFT)

The ITFT method is commonly employed to evaluate the stiffness modulus and fatigue performance of asphalt mixtures in both stress-controlled and strain-controlled modes, with this project specifically utilising the stress-controlled mode. The specimens, which were prepared to final dimensions of 100 mm in diameter and 40 mm in height, were created as previously outlined. It is crucial to note that prior to the ITFT, the indirect tensile stiffness test (ITST) was carried out to assess the stiffness of the specimens at various stress levels. Following this, the specimens underwent the ITFT to ascertain the number of load applications until failure at the same stress level used during the ITST. Additionally, before commencing the ITFT, the specimens were conditioned in a Nottingham Asphalt Tester (NAT) cabinet for a minimum of four hours at the designated testing temperature.

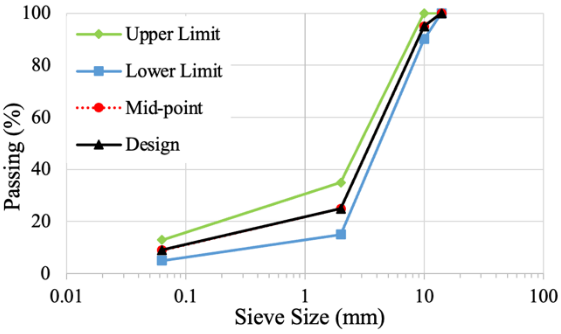

Fig. 3 SMA design particle size distribution

In this study, the ITFT was executed in stress-controlled mode within the NAT at temperatures of 20°C and 10°C. The temperatures encountered in road pavements vary significantly, ranging from -40°C to +70°C globally, depending on the location and climate zone. In the UK, a fatigue design temperature of 20°C is typically used. However, in practice, fatigue damage is more likely to occur at lower temperatures. For this reason, this study has selected test temperatures of 20°C and 10°C.

In accordance with British standards [21], the test was performed with a repeated constant loading time of 124 ± 4 ms and a pulse repetition time of 1.5 ± 0.1 s. Failure was deemed to occur when the total vertical deformation of the specimen reached 10 mm. A schematic representation of the ITFT is illustrated in Fig. 4.

3.2.2 4-Point bending test (4PBT)

The 4PBT is commonly employed to evaluate the stiffness modulus and fatigue resistance of asphalt pavement materials. This test effectively simulates pavement fatigue failure under traffic loads, as repeated loading induces tension in the lower section of the specimen. Fracture typically occurs in the region of constant maximum bending moment between the two inner clamps [22].

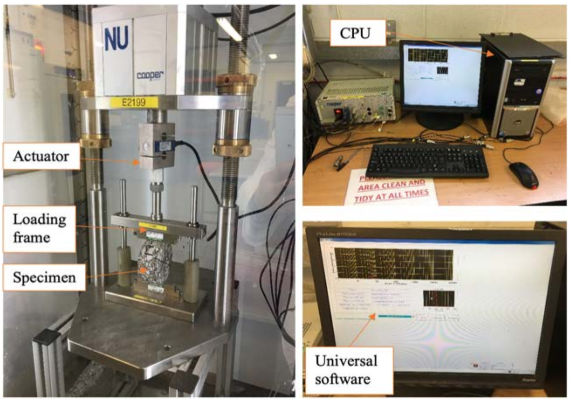

Fig. 4 Configuration of the ITFT

In this study, the asphalt beams measured 380 mm in length, 50 mm in width, and 50 mm in height. These beams were cut from larger asphalt slabs measuring 500 mm x 500 mm x 70 mm and were trimmed to maintain a thickness of 50 mm.

The 4PBT employs a continuous sinusoidal waveform applied to a prismatic specimen via two load points, known as the inner clamps (see Fig. 5). The beam specimen is supported at four points with the assistance of four clamps, including two static outer clamps that only shift horizontally, while the inner clamps move in response to the applied loads [22]. At all loading levels and reaction points, free translation and rotation are permitted.

In the context of the 4PBT, initial stiffness is typically defined as the stiffness measured between the 50th and 100th load applications. Traditionally, fatigue failure is identified as the point at which the stiffness modulus has reduced to 50% of its initial value [22, 23].

The deformation of the specimen is recorded at the bottom between the two inner clamps, as specified by BS EN 12697-26 and BS EN 12697-24 [24, 25]. In this research, the 4PBTs were conducted using a Cooper 4-point bending machine at temperatures of 20°C and a frequency of 30 Hz in strain control mode. The strain levels applied ranged from 100 to 400 $\mu\varepsilon$, depending on the specific asphalt mixture used.

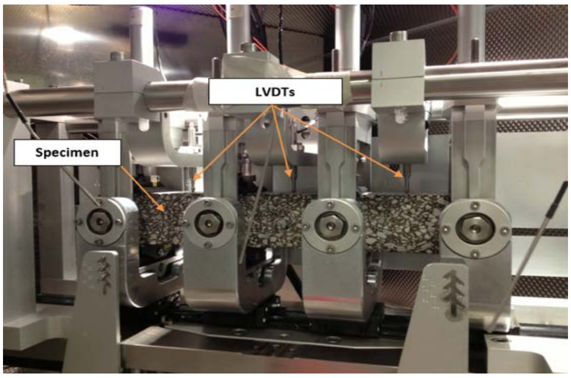

Fig. 5 Configuration of the 4PBT

3.2.3 Beam wheel tracker fatigue test (BWTFT)

In this project, the BWTFT was conducted on asphalt beam mixtures at a temperature of 20°C and 10°C within a controlled environment. A cam system was employed to move the specimen back and forth relative to the wheel at a frequency of 0.4 Hz, as illustrated in Fig. 6. Two strain gauges were attached, one to the bottom of each vertical face, and these gauges were connected to a computer system using National Instruments equipment. Additionally, a camera was utilised to directly observe crack progression, with the faces painted white to enhance visibility.

The asphalt beams used in this research were 306 mm long, 50 mm wide, and 35 mm high. They were cut from roller-compacted slabs measuring 306 mm x 306 mm x 50 mm, and trimmed at the bottom to achieve the required thickness of 35 mm. The test beam was placed at the centre of a steel mould measuring 306 mm x 306 mm x 80 mm and rested on two layers of rubber pads, totalling 20 mm in thickness, supported by a steel base plate. These rubber pads served as an elastic foundation for the asphalt beam. In addition, two steel end restraints were used to secure both ends of the test beam, preventing vertical movement and simulating the behaviour of a continuous beam.

During the BWTFT, a wheel load was applied to the moving asphalt beam while monitoring the tensile strains along its sides. The solid tyre wheel used in this study had an outer diameter of 200 mm and a width of 50 mm, with a travel distance of 225 mm. Various load levels, ranging from 0.76 to 1.50 kN, were applied. Before starting the test, the beams with attached gauges were conditioned at the test temperature for at least four hours. The tests continued until a visible crack propagated through the entire thickness of the beam [26].

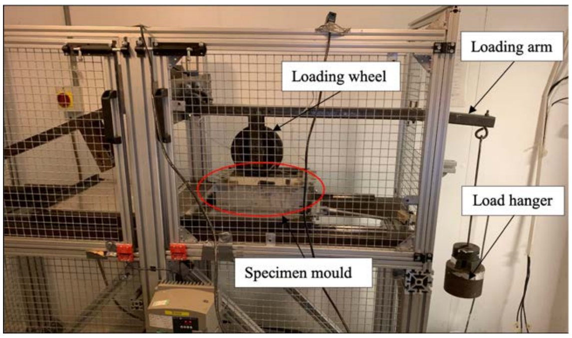

Fig. 6 Configurtation of the BWTFT

4. EXPERIMENTAL RESULTS

4.1 ITFT Results

The fatigue results for the DBM50, EME2, and SMA mixtures obtained from the ITFT are presented in Fig. 7. Additionally, Table 1 summarises the ITFT data, which includes fatigue equations along with their R² values, and the number of cycles to failure (N_f) at 100 microstrain for all types of mixtures at testing temperatures of 20°C and 10°C. It should be noted that the N_f at 100 microstrain is derived from significant extrapolation of limited data. The outcomes of the ITFT were comprehensively presented in the research carried out by [27].

Table 1. Fatigue results for all mixtures tested using the ITFT [27].

Mixture Type	Temp (°C)	Equation based on N_f	N_f@ $100\mu\varepsilon$	R^2
DBM50	20	$\boldsymbol{N_f = 5.365 \times 10^{14}\varepsilon^{-4.76}}$	160,535	0.98
	10	$\boldsymbol{N_f = 5.709 \times 10^{16}\varepsilon^{-5.88}}$	98,301	0.96
EME2	20	$\boldsymbol{N_f = 8.532 \times 10^{12}\varepsilon^{-3.91}}$	131,538	0.96
	10	$\boldsymbol{N_f = 2.627 \times 10^{16}\varepsilon^{-5.41}}$	406,874	0.99
SMA	20	$\boldsymbol{N_f = 5.831 \times 10^{14}\varepsilon^{-4.07}}$	4,322,580	0.90
	10	$\boldsymbol{N_f = 5.751 \times 10^{15}\varepsilon^{-4.72}}$	2,117,110	0.97

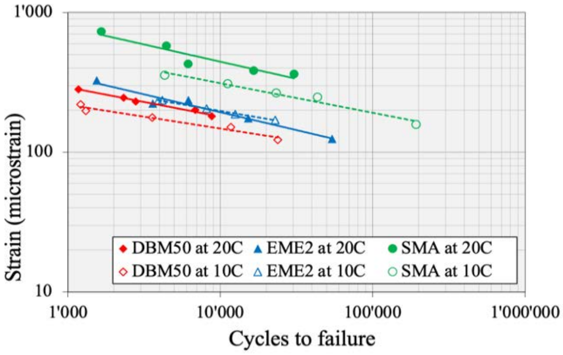

Fig. 7 ITFT fatigue lines of DBM50, EME2 and SMA mixtures at 20 and 10°C [27]

4.2 4PBT Results

The results of the fatigue tests for the DBM50, EME2, and SMA mixtures conducted using the Four-Point Bending Test (4PBT) at 20°C and 30 Hz are illustrated in Fig. 8. Table 2 presents the fatigue equations for each mixture, along with their corresponding R² values. These equations demonstrate a high level of accuracy for all mixtures, as indicated by R² values exceeding 0.90. Additionally, the table provides the number of cycles to failure (N_f) at 100 microstrain for each type of mixture tested at 20°C.

4.3 BWTFT Results

Fig. 9 presents the strain-life characteristics for all three asphalt materials tested at 20°C and 10°C, with failure defined as the stage at which crack propagation was fully complete, as monitored by a camera. The initial strain is identified as the maximum strain (recorded at the bottom of the beam) during the 100th loading cycle, calculated as 1.4 times the peak-to-trough strain observed. This is due to the positioning of the strain gauges, which were located 5 mm from the bottom edge of the beam in the tests.

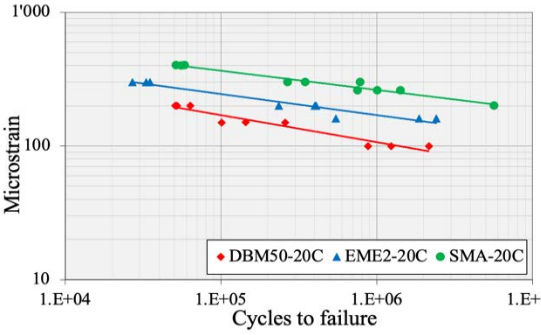

Fig. 8 4PBT fatigue lines for DBM50, EME2 and SMA mixtures at 20°C and 30Hz [4]

Table 2. Result data for all mixtures at 20°C and 30 Hz using the 4PBT [4]

Mixture Type	Equation based on N_{f50}	N_f @ $100\mu\varepsilon$	R^2
DBM50	$N_{f50} = 1.1118 \times 10^{16}\ \boldsymbol{\varepsilon}^{-4.95}$	1,399,673	0.94
EME2	$N_{f50} = 1.6906 \times 10^{20}\ \boldsymbol{\varepsilon}^{-6.39}$	30,844,829	0.94
SMA	$N_{f50} = 8.6712 \times 10^{22}\ \boldsymbol{\varepsilon}^{-6.99}$	895,504,354	0.96

A significant observation from this figure is that the strain levels are notably higher than those typically found in other standard fatigue tests. In fact, they are closely aligned with the strain levels used in real pavement design, indicating that this testing method might be realistic enough to eliminate the need for applying a transfer function (shift factor) before its application. The findings related to the BWTFT were detailed in the research conducted by [26].

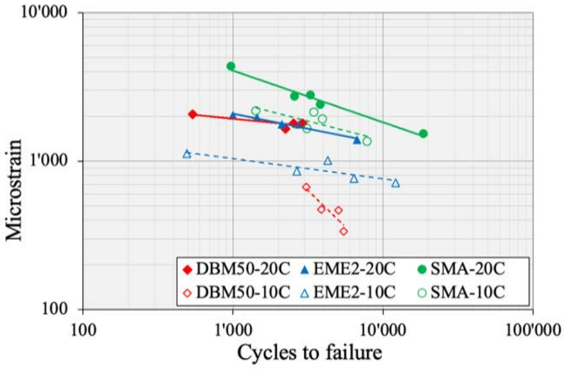

Fig. 9 Initial strain versus number of cycles to failure for BWTFTs at 20°C and 10°C [26]

5. COMPARISON AND DISCUSSION ON PAVEMENT DESIGN

5.1 Comparison of Three Fatigue Tests

As illustrated in this paper, three different fatigue tests have been undertaken for DBM50, EME2 and SMA mixtures under various loading or strain conditions at 20 and 10°C. A summary of the fatigue lines derived from these tests is shown in Fig. 10. In terms of strain-life characteristics, uncertainty is acknowledged since the fatigue lines shown in the figure are derived from only 4-10 individual specimens compared to the 18 minimum recommended by standards [25, 28].

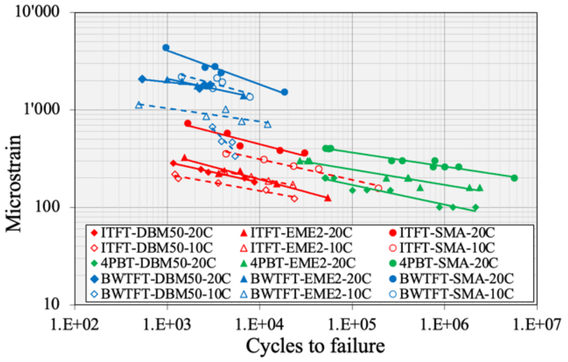

Fig. 10 Comparison of fatigue lines for three mixture types using different tests at 20 and 10°C

It can be seen from Fig. 10, in general fatigue lines derived from the BWTFT are located at the highest positions compared to those obtained from the 4PBT and the ITFT. In contrast, the ITFT fatigue line positions are the lowest, while the 4PBT results lie in between. It is highlighted that the performance of SMA mixtures using PMB with its higher binder content was the best compared to the EME2 and DBM50 at both 20 and 10°C test temperature in all fatigue tests conducted. At 20°C, fatigue performances of the EME2 and DBM50 mixtures were quite similar in the BWTFT and ITFT, while the EME2 mixture experienced better fatigue performance in the 4PBT. Moreover, it is noted that all 10°C fatigue lines lie below the 20°C corresponding lines as expected in the BWTFT and ITFT, except the EME2 fatigue lines taken from the ITFT.

It is acknowledged that the selection of stress- or strain-controlled testing, along with other factors such as binder content and the volumetric composition of the mixture, may influence the comparability of results. However, the primary focus of this study is on the fatigue characteristics of various asphalt mixtures incorporating PMA, with the goal of enhancing the reliability of pavement design. Therefore, the differences in the control methods of the fatigue tests are considered acceptable.

5.2 Discussion on Pavement Design

One of the key reasons for carrying out the different tests in this study is to observe whether the difference between materials remains similar in all fatigue tests or not. The experimental results illustrate that generally the difference remains relatively similar in all tests, although the difference appears slightly greater with the BWTFT at a test temperature of 10°C. This therefore may lead to the conclusion that design of pavements using PMA could be conducted in the same way as ordinary asphalt pavements but with a shifted fatigue characteristic, and the shift could be derived from one of the fatigue tests. To indicate the shifted fatigue characteristic, all fatigue lines have been assumed to have a realistic slope of 0.25 bearing in mind the low number of tests conducted for each line (Fig. 11). Based on the figure, the shifted characteristics are calculated for PMAs in relation to the DBM50 derived from all fatigue tests at 20 and 10°C as shown in Table 3.

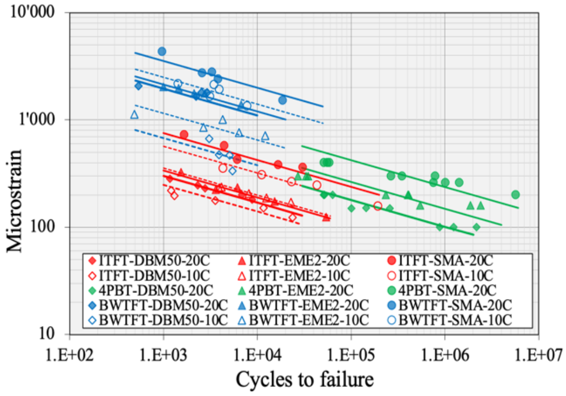

Fig. 11 Fatigue lines adjusted with a slope of 0.25 for all mixtures using different tests at 20 and 10°C

Table 3. Shifted fatigue characteristic for PMAs in relation to conventional DBM50 derived from all tests at 20 and 10°C

PMA material		EME2		SMA	
Design temp. (°C)		20	10	20	10
Shifted fatigue characteristic using BWTFT	On strain scale	1.1	1.7	1.8	3.7
	On N_f scale	1.5	9	11	190
Shifted fatigue characteristic using ITFT	On strain scale	1.1	1.4	2.5	2.3
	On N_f scale	1.5	4	39	28
Shifted fatigue characteristic using 4PBT	On strain scale	1.5	-	2.3	-
	On N_f scale	5	-	28	-

As can be seen from Table 3, at 20°C, based on the three tests the shifted factor is 1.1 – 1.5 on the strain scale (about 1.5 – 5 on the load applications scale) for EME2 and 1.8 – 2.5 on the strain scale (about 11 – 39 on the load applications scale) for SMA while at 10°C, the factor is 1.4 – 1.7 on the strain scale (about 4 – 9 on the load applications scale) for EME2 and 2.3 – 3.7 on the strain scale (about 28 – 190 on the load applications scale) for SMA using the BWTFT and ITFT.

Based on the shifted factors indicated in this table, it is noticeable that while the difference between materials at 20°C is relatively similar among the three tests, the greater difference found in the BWTFT (i.e. the most realistic test) at 10°C implies that the advantage of PMA is rather greater than pavement designers would have expected based on the ITFT at lower design temperature.

On the other hand, if the BWTFT can be taken to be approximately representative of a pavement layer, this suggests that it may be acceptable to use the standard laboratory fatigue (ITFT or 4PBT) data with a shift factor in pavement design. Based on Fig. 11, the shift factors calculated for the ITFT and 4PBT at design temperatures of 20 and 10°C are shown Table 4. The calculation and assumption made for the shift factors in the table are the same as those used in Table 3.

Table 4. Shift factor for the ITFT and 4PBT in relation to the BWTFT for all materials at 20 and 10°C

Material		DBM50		EME2		SMA	
Design temp. (°C)		20	10	20	10	20	10
Shift factor for ITFT	On strain scale	6.5	2.7	6.3	3.3	4.7	4.4
	On N_f scale	1,790	50	1,580	120	490	370
Shift factor for 4PBT	On strain scale	3.4	-	2.6	-	2.7	-
	On N_f scale	130	-	45	-	50	-

As can be seen from the table, if the design temperature is 20°C and the ITFT data is used, the shift factor is 4.7 – 6.3 on the strain scale (about 490 – 1,580 on the load applications scale) for PMAs and 6.5 on the strain scale (about 1,790 on the load applications scale) for conventional DBM50 while if the 4PBT data is used, the shift factor decreases to 2.6 – 2.7 on the strain scale (about 45 – 50 on the load scale) for PMAs and 3.4 on the strain scale (about 130 on the load scale) for conventional material. Meanwhile, if the design temperature decreases to 10°C, the shift factor used for the ITFT is 3.3 – 4.4 on the strain scale (about 120 – 370 on the load scale) for PMAs and 2.7 on the strain scale (about 50 on the load scale) for conventional material as indicated in Table 4.

At 20°C, it is clear that the shift factor for PMAs is similar or even lower when compared to that for the conventional material and this suggests that relying on 20ºC tests may give an underestimate of the benefit of PMAs. Meanwhile, at 10ºC, the picture is very different, where the shift factor for PMAs is significantly greater as shown in the table. This, therefore, indicates that the advantage of PMAs becomes more evident in the case of lower design temperature.

6. CONCLUSIONS

In this study, three different fatigue tests, the ITFT, 4PBT and BWTFT, have been carried out for DBM50, EME2 and SMA mixtures under various loading or strain conditions at test temperatures of 20ºC and 10ºC. Based on the analysis and discussion presented in this paper, the following conclusions are offered:

This study demonstrates that fatigue lines derived from the BWTFT consistently occupy higher positions compared to those obtained from the 4PBT and ITFT, indicating more favorable fatigue performance. Specifically, the SMA mixture with higher PMB content exhibited superior fatigue performance across all tests (BWTFT, ITFT, and 4PBT) at both 20°C and 10°C, outperforming the EME2 and DBM50 mixtures. As expected, fatigue lines at 10°C are lower than those at 20°C in both the BWTFT and ITFT, except for the EME2 mixture from the ITFT.

The findings suggest that pavement design using PMA can be conducted in the same manner as ordinary asphalt, with an adjusted fatigue characteristic. This shift in fatigue performance can be quantified using data from the BWTFT, ITFT, or 4PBT. Notably, the greater difference observed in the BWTFT results at lower temperatures reveals that the advantages of PMA may be more pronounced than anticipated when based on the ITFT at typical design temperatures.

While this study does not offer an in-depth analysis, it establishes that BWTFT data provides a practical tool for pavement design. The shift factors derived from the BWTFT, relative to the ITFT and 4PBT results, offer a more accurate representation of the fatigue performance of PMAs. It is recommended that these shift factors be incorporated into design practices. The analysis further suggests that relying solely on 20°C test results may lead to an underestimate of the benefits of PMAs, with these benefits becoming more apparent when lower design temperatures are used.

7. ACKNOWLEDGMENTS

The author would like to acknowledge the facilities provided by the University of Nottingham, United Kingdom.

8. REFERENCES

[1] Jihanny, J., Subagio, B.S., Yang, S.-H., Karsaman, R.H., and Hariyadi, E.S., The overload impact on design life of flexible pavement. International Journal of GEOMATE, 2021, 20, (78), pp. 65-72

[2] Al-Mosawe, H., Prediction of Permanent Deformation in Asphalt Mixtures. PhD Dissertation, University of Nottingham, 2016

[3] Brown, S.F., An introduction to asphalt pavement design in the UK, in Editor (Ed.). Book An introduction to asphalt pavement design in the UK (Thomas Telford Ltd, 2013, edn.), pp. 189-202

[4] Nguyen, V.B., Evaluation of fatigue behaviour of bituminous mixtures using a 4-point bending test. Journal of Materials and Engineering Structures, 2024, 11, (3), pp. 223-233

[5] Putri, E.E., Liew, S., Mannan, M.A., Chan, R.A., Buking, R., and Tirau, L.S., Stormpav Pavement Using Different Wheel Loads. International Journal of GEOMATE, 2022, 22, (89), pp. 1-8

[6] Torio-Kaimo, L., Sargado, J.M., and Peckley Jr, D., Flexible Pavement Design Using Mechanistic-Empirical Pavement Design Guide in the Philippines. International Journal of GEOMATE, 2019, 17, (64), pp. 9-17

[7] Rahmawati, A., and Adiyasa, M., Analysis of remaining service life for flexible pavement using mechanistic-empirical methods. International Journal of GEOMATE, 2021, 21, (85), pp. 145-153

[8] Wasanta, T., Subagio, B.S., Wibowo, S.S., and Hariyadi, E.S., Comparative Analysis of Overlay Thickness Using the Asphalt Institute's and MEPDG with KENLAYER. International Journal of GEOMATE, 2024, 26, (118), pp. 57-64

[9] Siahaya, L., Subagio, B.S., and Susilo, A.J., Development of Flexible Pavement Structure Using the Local Materials of Sarmi, Papua, Indonesia-based on Indonesia National Specification. International Journal of GEOMATE, 2023, 24, (103), pp. 34-41

[10] Von Quintus, H.L., Mallela, J., and Buncher, M., Quantification of effect of polymer-modified asphalt on flexible pavement performance. Transportation Research Record, 2007, 2001, (1), pp. 141-154

[11] Raad, L., Saboundjian, S., Sebaaly, P., Epps, J., Camilli, B., and Bush, D., Low temperature cracking of modified AC mixes in Alaska. Transportation Research Record, 1998, 1629, (1), pp. 117-126

[12] Wegman, D., Weigel, J., and Forsberg, A., Collaborative evaluations of low-temperature Superpave performance-graded asphalt binders.

Transportation Research Record, 1999, 1661, (1), pp. 75-82
[13] Zubeck, H., Raad, L., Saboundjian, S., Minassian, G., and Ryer, J., Performance of polymer-modified asphalt-aggregate mixtures in Alaska. Journal of Cold Regions Engineering, 2002, 16, (4), pp. 170-190
[14] Van Dijk, W., Practical fatigue characterization of bituminous mixes. Journal of the Association of Asphalt Paving Technologists, 1975, 44, pp. 38-72
[15] Rowe, G.M., Application of the dissipated energy concept to fatigue cracking in asphalt pavements. PhD Dissertation, University of Nottingham, 1996
[16] Liao, M.-C., Chen, J.-S., and Tsou, K.-W., Fatigue characteristics of bitumen-filler mastics and asphalt mixtures. Journal of Materials in Civil Engineering, 2011, 24, (7), pp. 916-923
[17] Lacalle Jiménez, H.I., Airfield pavement design with cold recycled materials. PhD Dissertation, University of Nottingham, 2017
[18] BSI, Coated Macadam (asphalt concrete for roads and other paved areas). BS EN 4987-1:2005, 2005 (British Standards Institution)
[19] BSI, Published Document – Guidance on the use of BS EN 13108, Bituminous mixtures – Material specifications. PD 6691:2015+A1:2016, 2016 (British Standards Institution)
[20] BSI, Bituminous mixtures – Material specifications. Part 5: Stone Mastic Asphalt. BS EN 13108-5:2016, 2016 (British Standards Institution)
[21] BSI, Method for the determination of the fatigue characteristics of bituminous mixtures using indirect tensile fatigue. British Standard Draft for Development. DD 226:1996, 1996 (British Standards Institution)
[22] Maggiore, C., A Comparison of Different Test and Analysis Methods for Asphalt Fatigue. PhD Dissertation, University of Nottingham, 2014
[23] Di Benedetto, H., De La Roche, C., and Francken, L., Fatigue of bituminous mixtures: different approaches and RILEM interlaboratory tests. Mechanical tests for bituminous materials, 5th mtbm rilem, 1997, pp. 15-26
[24] BSI, Bituminous mixtures–Test methods for hot mix asphalt–Part 26: Stiffness. BS EN 12697-26: 2012, 2012 (British Standards Institution)
[25] BSI, Bituminous mixtures–Test methods for hot mix asphalt–Part 24: Fatigue. BS EN 12697-24: 2012, 2012 (British Standards Institution)
[26] Nguyen, V.B., and Thom, N., Using a beam wheel tracker fatigue test to evaluate fatigue performance of asphalt mixtures. Road Materials and Pavement Design, 2021, 22, (12), pp. 2801-2817
[27] Nguyen, V.B., Using the indirect tensile fatigue test to evaluate fatigue characterisation of asphalt mixtures. Journal of Science and Technology in Civil Engineering (JSTCE)-HUCE, 2024, 18, (3), pp. 92–101
[28] BSI, Bituminous mixtures–Test methods for hot mix asphalt–Part 24: Fatigue. BS EN 12697-24: 2004, 2004 (British Standards Institution)