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Research Paper

Evaluation of fatigue behaviour of bituminous mixtures using a 4-point bending test

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ABSTRACT

One of the key structural failure modes found in bituminous pavement layer is flexural fatigue, resulting from repeated loading application of traffic-induced stresses. It is true that, in recent years, the 4-point bending test (4PBT) have been widely applied in order to characterise fatigue behaviour of asphalt mixtures. In this research paper, the test was used to investigate the fatigue characteristic of one unmodified and two quite different polymer modified asphalt mixtures. The 4PBT results indicated that under the same conditions, an increase trend in flexural stiffness as frequency increased from 1 Hz to 30 Hz for all three mixtures. The test results also presented an obvious difference in the initial stiffness loss behaviour of mixture types tested at 200 microstrain. In addition, in terms of fatigue lines, the 4PBT results showed the polymer modified mixtures have had a better fatigue performance in comparison with the performance of conventional mixtures as expected.

1 Introduction

Flexural fatigue is one of the main failure modes of bituminous pavement structures. Fatigue is also known as a phenomenon of fracture under repeated stress having a maximum value less than the tensile strength of the material. In flexible pavements, fatigue or cracking consists of two phases, crack initiation and crack propagation [1-4]. In general, crack initiation is described as the coalescence of micro cracks to form a macro crack under the repeated application of tensile strains. Crack propagation is the growth of the macro crack through the bituminous material under further application of tensile strains. However, it needs to be mentioned at this point that the fatigue behaviour of an asphalt mixture cannot be taken in isolation and the stiffness has to be considered as it determines the magnitude of the tensile strain experienced by the material [5-9].

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Fatigue damage often results in cracks that initiate at the bottom of the bituminous layers and then propagate to the pavement surface in thinner asphalt pavements (referred to as bottom-up fatigue cracking), whereas cracks start at the pavement surface and then propagate towards the bottom of bituminous layers in thicker asphalt pavements (top-down fatigue cracking). It is widely accepted that depending on the type of road structure, the materials and the progress of deterioration, cracks can take different orientations and patterns. They are often parallel to the direction of vehicle travel (longitudinal cracking) or perpendicular to the direction of travel (transverse cracking). Also, they can be single breaks in the pavement or double, branched or interlaced [10-12].

Recently, a large number of different testing methods have been developed to characterise and simulate fatigue behaviour of asphalt mixture materials. Fig. 1 shows common fatigue testing configurations used recently by many researchers [13]. Tension-compression, indirect tensile and flexural tests have all been successfully applied, as well as more complex configurations such as torsion or supported bending. Some general categories of most of the fatigue testing methods used in the past are summarised as presented in Fig. 1. It is widely accepted that the 4-point bending is one of the most common tests used to characterise fatigue behaviour of asphalt materials [14-22].

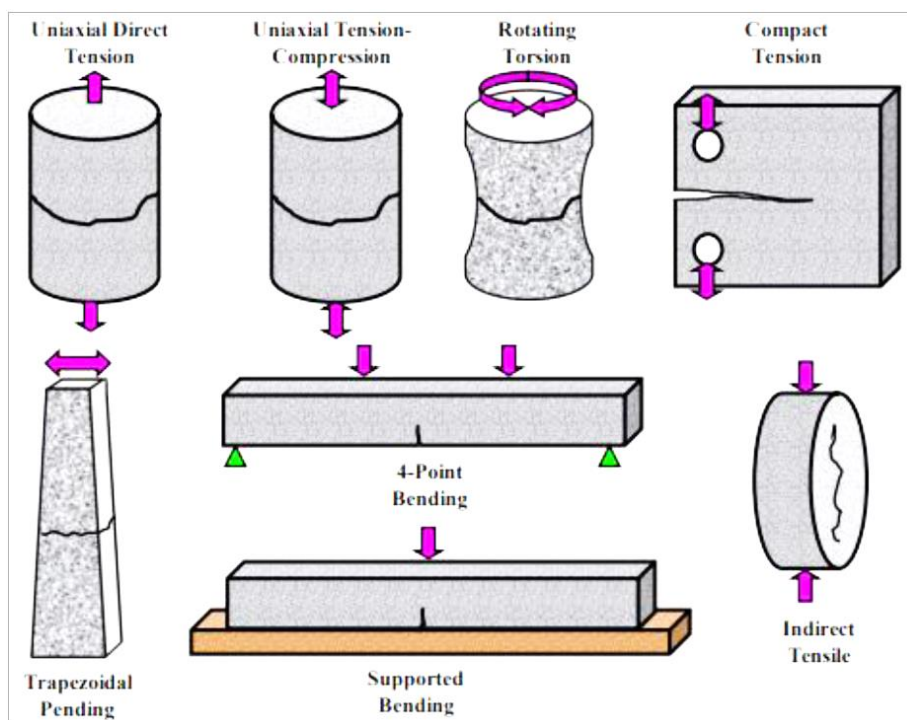


Fig. 1 - Common fatigue testing configurations [13]

This research paper is focused on use of a 4PBT to investigate the fatigue behaviour of some different asphalt mixture types including an unmodified asphalt mixture and two different polymer modified asphalt (PMA) mixtures. The results achieved from the tests have been evaluated, analysed and discussed using various approaches including flexural stiffness and fatigue-life characteristics.

2 Materials and testing methodology

2.1 Materials

This study focuses on examining the fatigue behaviour of three different asphalt mixtures: a 20mm Dense Bitumen Macadam (DBM50), a 14mm Enrobé à Module Élevé 2 (EME2), and a 10mm Stone Mastic Asphalt (SMA). The DBM50, which uses 40/60 pen unmodified bitumen, was selected because it is commonly used in pavement design in the UK and many European countries. The EME2 mixture, incorporating a hard SBS (Styrene-Butadiene-Styrene) polymer-modified binder, is designed for use as a base or binder course, while the SMA mixture, featuring a much softer SBS-modified binder, serves as a surface course material. This diverse selection of materials was chosen to provide a comprehensive investigation into the fundamental aspects of fatigue behaviour.

2.1.1 20mm Dense Bitumen Macadam

A conventional 20mm DBM50 mixture with a continuous grading was selected, using 40/60 bitumen as the binder, which is commonly applied globally. The binder content was 4.7% by mass, as recommended by BS-EN 4987 [23]. The aggregate material was limestone, with a nominal maximum particle size of 20mm.

2.1.2 14mm Enrobé à Module Élevé 2

A standard 14mm French EME2 mixture was chosen. Its gradation is quite similar to that of the DBM50, as both are intended for the same structural layer (either base or binder course). A hard SBS polymer-modified binder was used, with a binder content of 5.5% by mass, in accordance with BS-EN 13108 [24]. Limestone was also used as the aggregate, with a nominal maximum particle size of 14mm.

2.1.3 10mm Stone Mastic Asphalt

A standard 10mm SMA surface course was chosen for this paper. The mixture incorporated a soft SBS polymer-modified binder at a content of 6.5% and granite aggregate, with a particle size distribution designed according to BS-EN 13108 [25].

Fig. 2 presents the design particle size distribution for DBM50, EME2 and SMA mixtures.

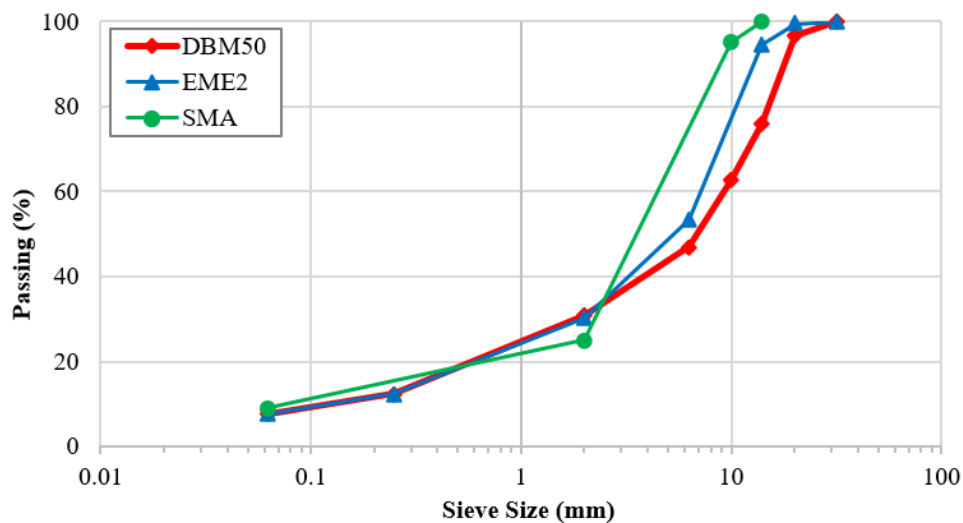


Fig. 2 – Design particle size distribution for the DBM50, EME2 and SMA mixture

2.2 Testing methodology

2.2.1 Test introduction

Nowadays, the 4PBT is widely applied for measuring the stiffness modulus and assessing the fatigue resistance of asphalt pavement materials. This test simulates well a pavement fatigue failure under traffic loading because repeated loading causes tension in the bottom zone of the specimen. Fracture generally occurs in the area of constant maximum value of bending moment between the two inner clamps [15].

2.2.2 Specimen Preparation

The dimensions of the asphalt beams used in this research were 380mm long, 50mm width and 50mm height. The beams were cut from large asphalt slabs with dimensions of 500x500x70mm and trimmed from the bottom and top to leave the 50mm thickness (Fig. 3).

2.2.3 Configuration

The 4PBT applies a continuous sinusoidal waveform to a prismatic specimen by means of two load points named inner clamps (see Fig. 4). The beam specimen is restrained at 4 points by means of four clamps including two outside that remain static (only shift horizontally) and two clamps that deflect according to the loads applied [15]. Free translation and rotations are allowed at all loading levels and reaction points.



Fig. 3 – Large Slab and Beam Specimens for 4PBT

In the 4PBT, initial stiffness is often defined as that between the 50th and the 100th load application. Traditionally, fatigue failure is the moment when the stiffness modulus has decreased to half of its initial value (50%) [15, 26].

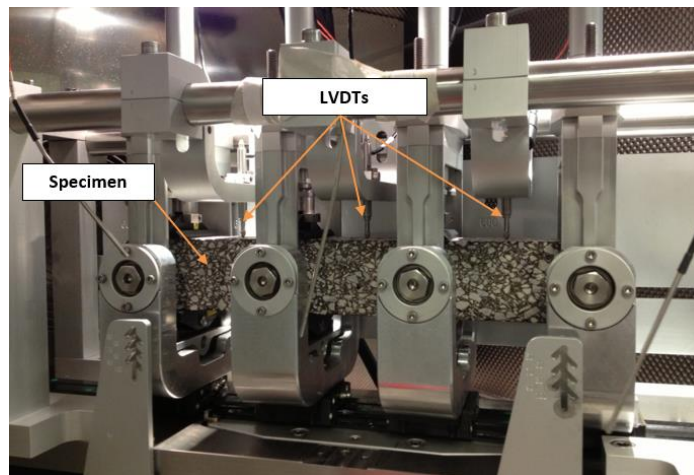


Fig. 4 – 4-Point Bending Test Configuration

The deformation of the specimen is measured at the bottom between the two inner clamps as defined in accordance with BS EN 12697-26 and BS EN 12697-24 [27, 28]. The deformation is calculated by means of three LVDTs placed at three different points (see Fig. 3). Total deformation is given by the following equation

$$D = \left[LVDT_1 - \left(\frac{LVDT_2 + LVDT_3}{2} \right) \right] \times 2 \quad (1)$$

In the project, the 4PB tests using a Coopers four-point bending machine at the technical centre of Tarmac were carried out at 20°C and 30Hz frequency in strain control mode. Strain levels applied varied from 100 to 400 $\mu\epsilon$ depending on the type of asphalt mixture.

3 Results, analysis and discussion

3.1 Flexural stiffness

Flexural stiffness results for the three types of asphalt mixture were obtained at 20°C at the 100th cycle and 50 microstrain in frequency sweep mode as shown in Fig. 5. Error bars representing plus and minus one standard error are also presented in

the figure. In general, the test shows an increase trend in flexural stiffness as frequency increases from 1 Hz to 30 Hz for all three mixtures under the same conditions of temperature and strain level. This is in agreement with Maggiore [15]. The DBM50 and EME2 flexural stiffness curves are quite close as stiffness value increases from about 5,000 MPa at 1 Hz frequency to approximately 12,000 MPa at 30 Hz. In fact, the curves are almost identical at low frequency (under 5 Hz) and become more distinct at higher frequency as seen from the figure. On the other hand, the SMA flexural stiffness values are much lower in comparison with DBM50 and EME2, increasing from around 1,200 MPa at 1 Hz to about 4,600 MPa at 30 Hz.

In addition, it is widely accepted that master curves can be constructed from four-point bending test results to estimate the modulus of an asphalt mixture under various combinations of loading speed and temperature, thus providing valuable input to the pavement design process [29, 30]. Due to time constraints, the development of these curves based on the varied frequency test will be included in future publications.

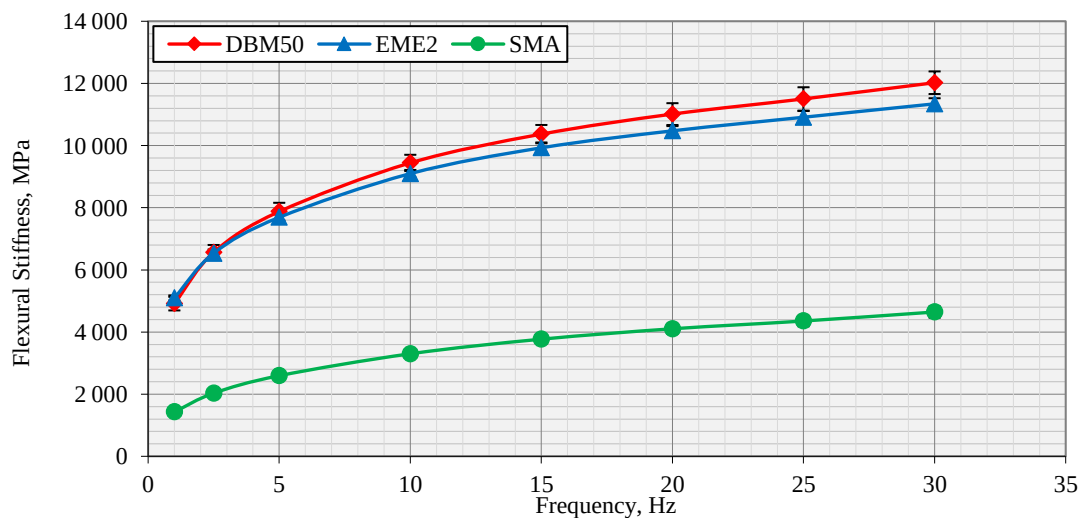


Fig. 5 – Flexural stiffness for DBM50, EME2 and SMA mixtures against frequency at 20°C at the 100th cycle and 50 microstrain

It is obvious that the stress-strain distribution in the beam in a 4PBT is complex and not uniform. An asphalt stiffness modulus, although representing an approximately linear relationship between stress and strain, does not have a unique value [14]. In the 4PB fatigue tests, the initial stiffness is defined as the measured stiffness at the 100th cycle.

Fig. 6 presents a comparison of initial flexural stiffness for the three mixture types at different strain levels using the 4PBT with the standard error bars included.

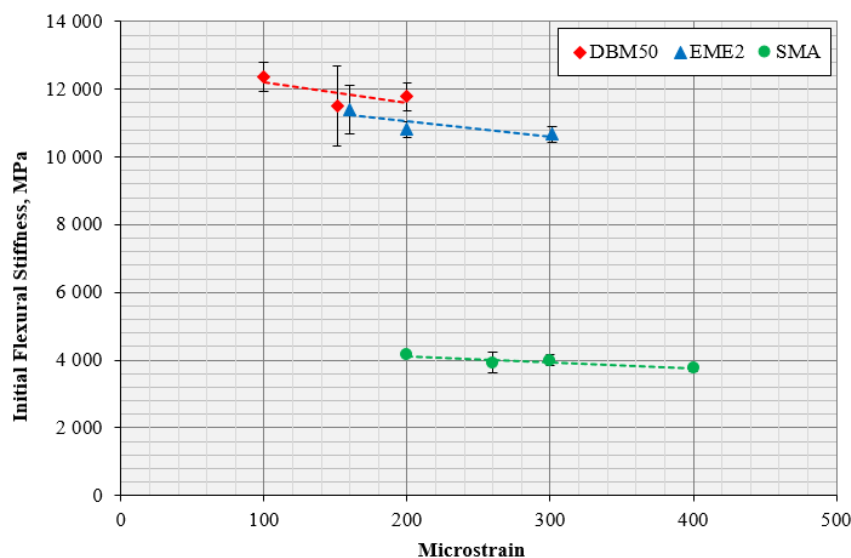


Fig. 6 – Comparison of initial flexural stiffness for three mixture types at different strain levels tested at 20°C and 30 Hz

It can be seen from the figure that the initial stiffness value of DBM50 mixture is the highest (around 12,000 MPa), followed by EME2 with a stiffness value of about 11,000 MPa, while the SMA mixture shows the lowest initial stiffness with a value of around 4,000 MPa at the strain levels tested. Moreover, initial stiffness tends to decrease slightly as strain level increases as shown in the figure. The level of the decrease in initial stiffness is different between the asphalt mixtures as shown by the various slopes of the trend lines. This is consistent with a study carried out by Dehghan and Modarres [31] which indicated a decreasing trend in initial flexural stiffness of different asphalt mixtures incorporating fibres as strain level increased from 300 to 500 and then 700 microstrain using the 4PBT.

In order to compare the flexural stiffness variation versus the number of cycles between two PMA mixtures (EME2 and SMA) and one unmodified mixture (DBM50) using the 4PB test, the 200 microstrain level was selected for the comparison, and the result is shown in Fig. 7. It is found that at the same strain level of 200 microstrain, the SMA mixture using higher PMB content shows much the best performance with approximately 5.7 million cycles to failure compared to 0.35 and 0.055 million cycles for EME2 and DBM50, respectively.

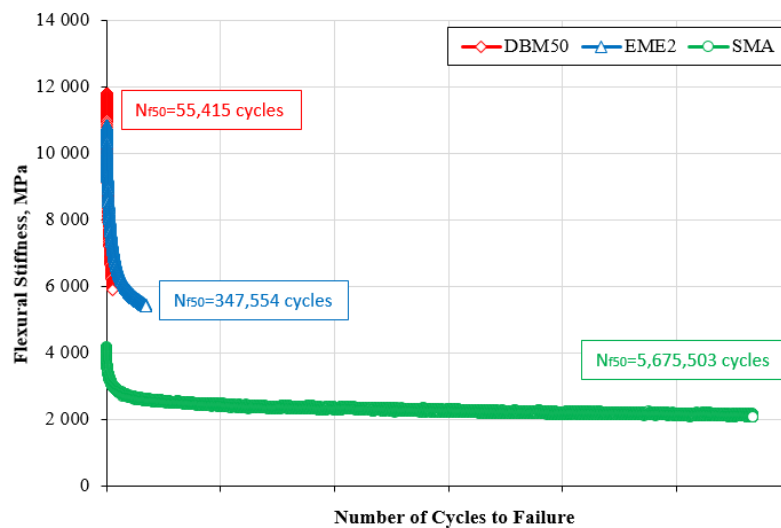


Fig. 7 – Variation of flexural stiffness with cycles for DBM50, EME2 and SMA mixtures at 200 microstrain

Fig. 8 presents the results of stiffness reduction for DBM50, EME2 and SMA mixtures at 200 microstrain and 20°C by normalising both axes and by averaging data from several specimens in each case. The forms shown in the figure seem to include only the first two phases of the full three-phase stiffness reduction curve illustrated in numerous publications [16, 32, 33]. Obviously, the last phase of the overall stiffness reduction curve, final failure, did not occur in the specimens because a stiffness reduction up to 50% of the initial stiffness was defined as failure or fatigue life – N_{f50} of the 4PBT specimens [34].

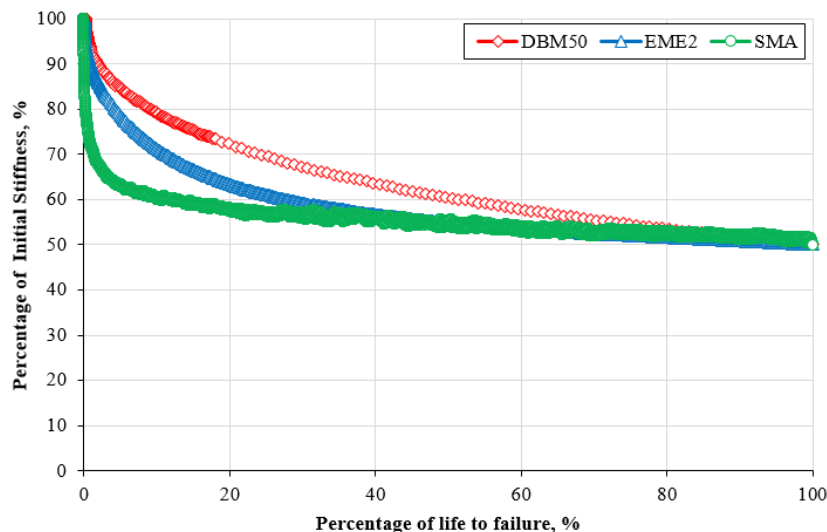


Fig. 8 – Stiffness reduction for DBM50, EME2 & SMA mixtures at 200 microstrain during 4PBT tested 20°C and 30 Hz

It can be seen from Fig. 8 that there is a very clear difference in the initial stiffness loss behaviour of DBM50, EME2 and SMA mixtures using the 4PBT at 200 microstrain and 20°C. While the SMA shows a significant decrease in stiffness in the first phase before flattening off in the second phase, the DBM50 mixture experienced gradual stiffness reduction through both the first and second phases. The stiffness reduction behaviour of EME2 is between that of SMA and DBM50, as presented in the figure.

3.2 4PBT fatigue life

All fatigue life results for DBM50, EME2 and SMA mixtures using the 4PBT at various strain levels in this study are summarised in Table 1.

Table 1 - 4PBT fatigue lives of DBM50, EME2 and SMA at various strain levels

Mixture Type	Strain Level (microstrain)	Cycles to Failure (N_{50})
DBM50	200	50,746
	200	63,500
	200	52,000
	150	100,797
	150	144,000
	150	258,047
	100	2,162,500
	100	1,237,500
	100	877,500
EME2	300	33,083
	300	27,016
	300	34,868
	200	408,253
	200	400,000
	200	234,410
	160	1,864,148
	160	2,405,937
	160	544,000
SMA	400	51,663
	400	55,668
	400	58,500
	300	348,000
	300	267,500
	300	783,000
	260	1,418,500
	260	1,007,483
	260	754,772
	200	5,675,503

Fig. 9 illustrates a comparison of the average number of cycles to failure for the three mixture types at various strain levels. Error bars in the figure represent plus and minus one standard deviation for three 4PBT beams. As can be seen from

the figure, for the same mixture, the number of cycles to failure (N_{f50}) increases rapidly as the strain levels decrease. It is noted that at the low strain levels (e.g. 100 – 200 microstrain) the 4PBT results in a very large number of cycles for all the mixtures tested, especially for the SMA mixture.

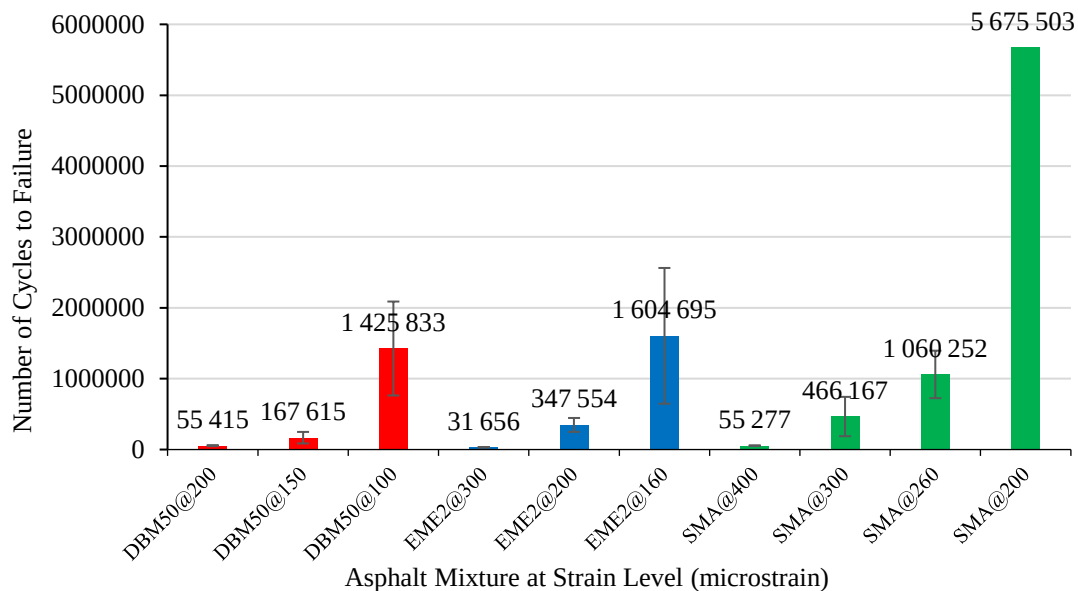


Fig. 9 – Comparison of average number of cycles to failure for three mixture types at various strain levels

The fatigue line results for DBM50, EME2 and SMA mixtures using the 4PBT at 20°C and 30 Hz are presented in Fig. 10, while the fatigue equations for the mixtures and their R^2 values are shown in Table 2.

Table 2 - Summary result data for all mixtures at 20°C and 30 Hz using the 4PBT

Mixture Type	Equation based on ϵ	ϵ @ 10^6 cycles	Equation based on N_{f50}	N_f @ $100\mu\epsilon$	R^2
DBM50	$\epsilon = 1743 N_f^{-0.202}$	106.98	$N_{f50} = 1.1118 \times 10^{16} \epsilon^{-4.950}$	1,399,673	0.94
EME2	$\epsilon = 1499 N_f^{-0.157}$	171.32	$N_{f50} = 1.6906 \times 10^{20} \epsilon^{-6.394}$	30,844,829	0.94
SMA	$\epsilon = 1906.1 N_f^{-0.143}$	246.33	$N_{f50} = 8.6712 \times 10^{22} \epsilon^{-6.993}$	895,504,354	0.96

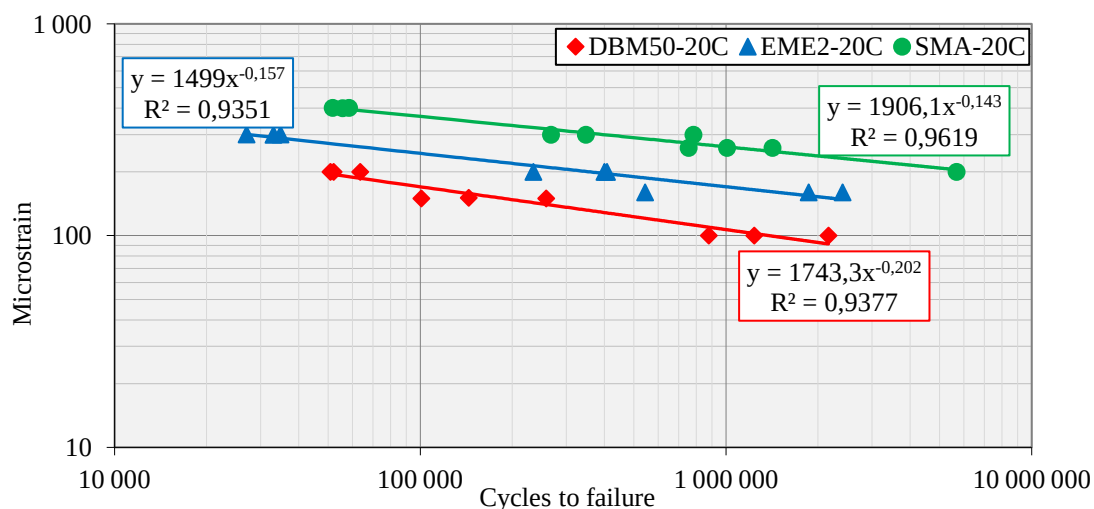


Fig. 10 – 4PBT fatigue lines for DBM50, EME2 and SMA mixtures at 20°C and 30Hz

The fatigue equations of the mixtures indicate a high degree of accuracy for all mixtures as their R^2 values are all above 0.90. In addition, the table shows the strains at 10^6 cycles as well as the number of cycles to failure at 100 microstrain for each mixture type using the 4PBT at a test temperature of 20°C although it is appreciated that both strain at 10^6 cycles and N_f at 100 microstrain involve significant extrapolation from limited data.

As can be seen from Fig. 10 and Table 2, as expected, the fatigue performance of the SMA mixture using higher PMB content is the best compared to EME2 and DBM50 since its fatigue line lies above the others, while the fatigue line for conventional DBM50 is in the lowest position. Moreover, at the 100 microstrain level, both the SMA and EME2 mixtures present a massive improvement with approximately 640 and 22 times higher fatigue life compared to the conventional DBM50 mixture when using the 4PBT at 20°C and 30 Hz as shown in Table 2.

4 Conclusions

The 4-point bending test have been successfully used to investigate fatigue behaviour of asphalt pavements all over the world. In this study, the test was effectively applied for selected asphalt mixture including an unmodified DBM50 and two PMAs (EME2 and SMA) at 20°C and 30 Hz in strain control mode. The following main points are concluded from this research:

- In terms of flexural stiffness, the 4PBT showed an increase trend in flexural stiffness as frequency increased from 1 Hz to 30 Hz for all three mixtures under the same conditions of temperature and strain level.
- In terms of initial flexural stiffness measured by the 4PBT, it is reported that the average initial stiffness value of DBM50 mixture was the highest (about 12,000 MPa), followed by EME2 with a stiffness value of 11,000 MPa, and the SMA initial stiffness value of 4,000 MPa at the strain levels tested. Furthermore, it was found that initial stiffness tended to decrease slightly as strain level increased.
- In terms of stiffness reduction, the 4PBT illustrated an obvious difference in the initial stiffness loss behaviour of DBM50, EME2 and SMA mixtures at 200 microstrain. The SMA showed a significant decrease in stiffness compared to its initial stiffness in the first fatigue phase before flattening off in the second phase, while the DBM50 stiffness reduced gradually through both the first and second phases. The EME2 stiffness reduction behaviour lay between those of SMA and DBM50.
- In terms of fatigue lines, as expected the SMA mixture using higher PMB content showed the best performance, followed by the EME2 mixture in comparison with the performance of conventional DBM50 mixture.

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