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USING THE INDIRECT TENSILE FATIGUE TEST TO EVALUATE FATIGUE CHARACTERISATION OF ASPHALT MIXTURES

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Abstract

Fatigue cracking is a principal structural failure mode in asphalt pavement layers, resulting from repeated traffic-induced loading stresses. Therefore, understanding fatigue deterioration behaviour is crucial for ensuring effective pavement design. In recent years, the indirect tensile fatigue test has become one of the most commonly used methods for evaluating the fatigue behaviour of asphalt mixtures, owing to its simplicity and suitability for cylindrical specimens either produced in the laboratory or cored from pavement construction sites. In this research paper, the indirect tensile fatigue test was employed to assess the stiffness modulus and fatigue behaviour of one unmodified asphalt mixture (DBM50) and two polymer-modified mixtures (EME2 and SMA) in stress-controlled mode across various temperatures. The results indicated that the indirect tensile fatigue test worked well and it can be considered to characterise effectively fatigue behaviour of different asphalt mixtures in Vietnam. In addition, the test results revealed that the SMA mixtures exhibited the best performance at both 20 °C and 10 °C compared to other mixtures. Specially, the fatigue lines for DBM50 and SMA at 20 °C were positioned above those at 10 °C, while the fatigue lines for EME2 lines remained quite similar across both temperature levels.

Keywords: indirect tensile fatigue test (ITFT); asphalt mixtures; fatigue characterisation; stiffness modulus; fatigue lines.

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1. Introduction

Fatigue is identified as a major failure mechanism in pavement structures, causing the deterioration of pavement materials and eventually leading to the failure of the entire pavement structure. It is noted that Asphalt materials in roadways experience short-term loading every time a vehicle passes. If this loading is sufficiently high, it can cause a loss of material rigidity and potentially lead to failure [1, 2]. Therefore, understanding fatigue deterioration behaviour is crucial in pavement construction to ensure proper structural design and performance [3–8].

In terms of fatigue test methods for asphalt mixtures, many relevant test configurations have been introduced for fatigue testing, including tension-compression, indirect tensile and flexural tests (see Fig. 1). In the fatigue test methods mentioned, two standard tests, the indirect tensile fatigue test (ITFT) and the 4-point bending test (one of the flexural tests), have been widely used all over the world [9–26].

The ITFT, one type of direct axial test, is a straightforward fatigue test commonly used across Europe, particularly in the United Kingdom. While it is a simple test that works well with cylindrical specimens either produced in the laboratory or cored from real asphalt pavements, a notable drawback is the accumulation of permanent deformation, which can obscure the true extent of fatigue damage.

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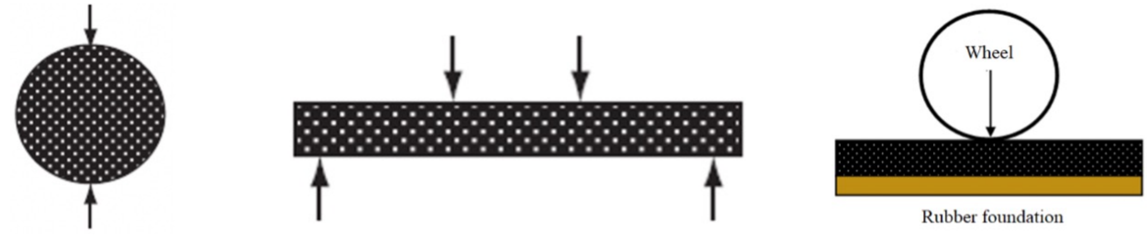


(a) Indirect tensile (b) 4 – point bending (c) Beam wheel tracker

Figure 1. Asphalt fatigue test configurations

Consequently, the ITFT is not capable of directly measuring fatigue behaviour, especially at high temperatures where viscoelastic effects become more significant [27–30].

The ITFT configuration has been applied to measure the stiffness modulus and fatigue behaviour of asphalt mixtures in both stress-controlled and strain-controlled modes. Nevertheless, the ITFT is frequently conducted in a load-controlled mode, where a repeated compressive load using a haversine waveform is used along the vertical diameter of the cylindrical specimen [31–33].

In this study, the ITFT was used to investigate the fatigue behaviour of selected different types of flexible pavement including one unmodified and two polymer-modified asphalt mixtures. The main aim of this paper is to characterise fatigue behaviour of the selected various asphalt mixtures based on the ITFT test, after which analysis, discussion and conclusion will be included.

2. Materials and testing programme

2.1. Materials

In this research, three asphalt mixtures were selected to examine fatigue behaviour using the Indirect Tensile Fatigue Test (ITFT): a 20 mm Dense Bitumen Macadam (DBM50), a 14 mm Enrobé à Module Élevé 2 (EME2), and a 10 mm Stone Mastic Asphalt (SMA). The DBM50 mixture, containing 40/60 penetration grade bitumen, is representative of typical UK pavement base or binder course layers. The EME2 mixture employs a hard Styrene-Butadiene-Styrene (SBS) polymer-modified binder (21 pen) and is also intended for base or binder course layers. In contrast, the SMA mixture, which utilizes a softer SBS-modified binder (65 pen), serves as a surface course material. The selection of these diverse materials was intentional, as the authors aimed to explore a wide range of fatigue behaviour characteristics.

a. 20 mm Dense Bitumen Macadam (DBM50)

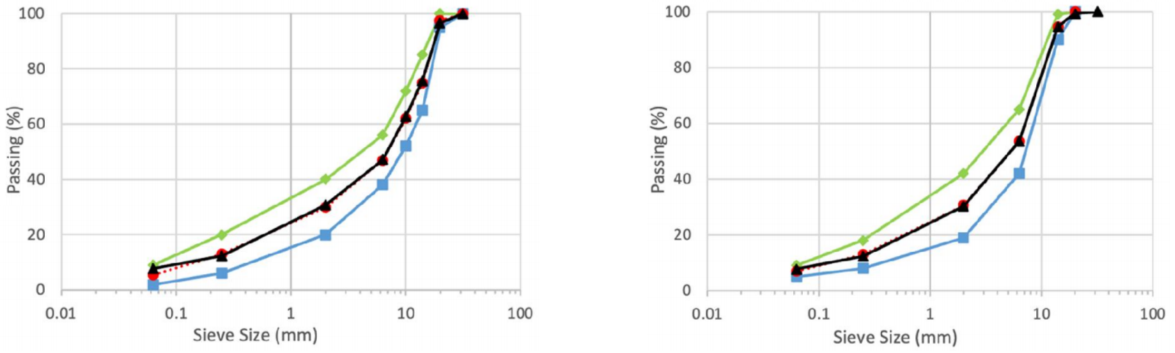
A conventional continuously graded 20 mm DBM50 was chosen, utilizing 40/60 penetration grade bitumen, a commonly used binder grade worldwide. The binder content was set at 4.7% by mass, as recommended by BS-EN 4987 [34]. The aggregate used was limestone from Buxton, UK, with a nominal maximum particle size of 20 mm.

b. 14 mm Enrobé à Module Élevé 2 (EME2)

A standard French 14 mm EME2 was chosen due to its comparable gradation to the DBM50, as it is intended for use in the same structural layer (base or binder course). A hard SBS polymer-modified binder, according to BS-EN 13108 specifications [35], was employed at a binder content of 5.5% by mass. Additionally, the aggregate was limestone obtained from a UK quarry, featuring a nominal maximum particle size of 14 mm.

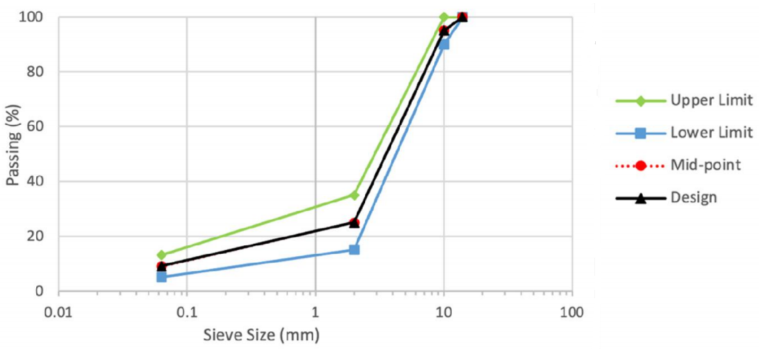
c. 10 mm Stone Mastic Asphalt (SMA)

For this study, a standard 10 mm SMA surface course was chosen. The mixture incorporated a soft SBS polymer-modified binder at a concentration of 6.5%, and granite aggregate with a particle size distribution designed in accordance with BS-EN 13108 standards [36]. Fig. 2 illustrates the design particle size distributions for the DBM50, EME2, and SMA mixtures.



(a) DBM50

(b) EME2



(c) SMA mixture

Figure 2. Design particle size distribution for all mixtures

2.2. *Testing programme*

a. Indirect Tensile Stiffness Modulus (ITSM) Test

The ITSM is a simple, non-destructive, quick and inexpensive test to determine the resilient modulus of asphalt mixtures. In addition, the test can be easily carried out by using the Nottingham Asphalt Tester (NAT) equipment provided by the Nottingham Transportation Engineering Centre (NTEC).

The cylindrical specimens used for the ITSM test and then for the ITFT were cored from slabs manufactured in the laboratory. The processes of design, mixing and compaction of the mixture were reported above. After cylindrical cores of 100 mm in diameter were taken from each slab (306 × 306 × 60 mm), they were cut and trimmed from the top and bottom surfaces to have final dimensions of 100 mm in diameter and 40 mm in height. The process of coring and trimming specimens is described in Fig. 3.

Prior to testing, all cylindrical specimens were conditioned for at least 4 hours at temperatures of 20 or 10 °C, the temperatures at which the ITFT was conducted.

The ITSM test for mixture specimens is defined in BS EN 12697-26 and was used to investigate the stiffness modulus of DBM50, EME2 and SMA mixtures [37]. The NAT machine was used for

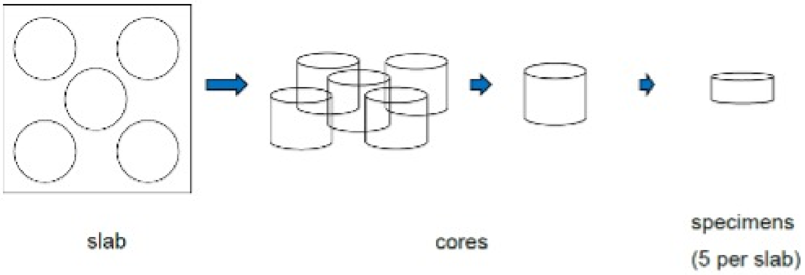


Figure 3. Coring and trimming process for ITFT specimens

the tests. Following BS EN 12697-26, a pulsating load is used centrally between the upper and lower platens and the peak transient deformation along the horizontal diameter is measured (see Fig. 4). The target horizontal deformation was 5 ± 2 µm with an assumed Poisson's ratio of 0.35 and a target rise time of 124 ± 4 ms.

The testing system needs at least ten conditioning pulses to adjust the load value to obtain the target horizontal strain and rise time, followed by five further load pulses. The load and horizontal strain were measured and stored for each load pulse to calculate the stiffness modulus values. These measurements were carried out in two orthogonal orientations. The stiffness modulus value achieved was calculated as the average value of the two tests. The equation for calculating the stiffness modulus is as follows:

$$E = \frac{F \times (\nu + 0.27)}{(z \times h)} \tag{1}$$

where E is the stiffness modulus measured in the test (MPa); F is the peak applied vertical load (N); z is the horizontal deformation amplitude achieved during the load cycle (mm); h is the mean thickness of the sample (mm); ν is the Poisson's ratio.

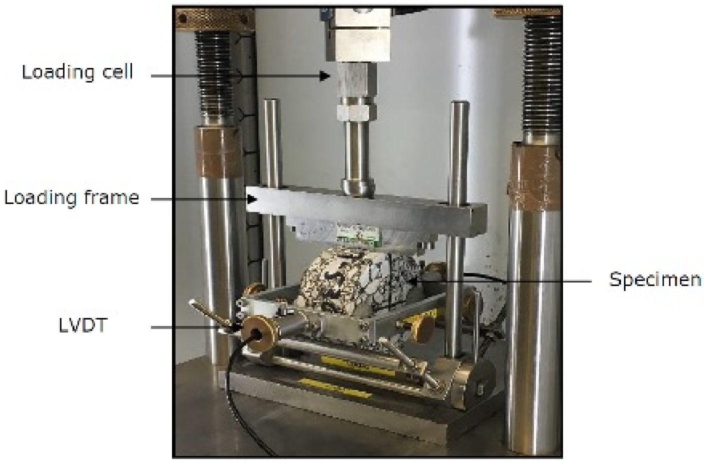


Figure 4. ITSM Test Configuration using NAT

b. Indirect Tensile Fatigue Test (ITFT)

The ITFT is commonly used in the United Kingdom to characterise the stiffness and fatigue properties of asphalt mixtures, owing to its simplicity and its compatibility with cylindrical specimens either manufactured in the laboratory or cored from actual asphalt pavements [27]. However, a significant drawback of this method is the accumulation of permanent deformation, which can obscure the true extent of fatigue damage. Consequently, the ITFT is unable to directly assess fatigue behaviour, particularly at elevated temperatures where viscous behaviour plays a more significant role [28, 29]. The ITFT configuration is widely employed to evaluate the stiffness modulus and fatigue behaviour of asphalt mixtures in both stress-controlled and strain-controlled modes. For this project, the stress-controlled mode was chosen for the ITFTs. The specimens with final dimensions of 100 mm in diameter and 40 mm in height were made as described above.

It is noted that before the ITFT, the indirect tensile stiffness test (ITST) was used to measure the stiffness of specimens at different stresses. These specimens were then subjected to the ITFT to indicate the number of load applications to failure at the same stress level as in the ITST. For the ITFT, before starting the test, specimens are also conditioned in the NAT cabinet for at least 4 hours at the testing temperature.

In this study, the ITFT was conducted under stress-controlled mode in the NAT at 10 and 20 °C. Based on the British standard [38], this test was carried out at 124 ± 4 ms of repeated constant loading time and 1.5 ± 0.1 s of a pulse repetition time. When the total vertical deformation of the specimen reaches 10 mm, failure is deemed to have occurred. A schematic of the ITFT is shown in Fig. 5.

Figure 5. Schematic of ITFT at NTEC

According to [38], the maximum tensile horizontal strains at the centre of the specimen ($\varepsilon_{x,\max}$) are graphed against the number of cycles to failure (N_f) with logarithmic scales on both x and y axes. At the centre of each specimen, the initial maximum tensile strain is calculated from the following equation:

$$\varepsilon_{x,\max} = \frac{\sigma_{x,\max} \times (1 + 3\nu)}{S_m} \times 1000 \tag{2}$$

where $\sigma_{x,\max}$ is the maximum tensile stress at the centre of each specimen (kPa); ν is Poisson's ratio (assumed to be 0.35); S_m is the indirect tensile stiffness modulus at the maximum stress $\sigma_{x,\max}$ (MPa).

Using data from five specimens per material set at each temperature level, linear regression analysis employing the characteristic Least Squares (R^2) method is performed to derive the best-fit equation for each fatigue test. [39] found that the most suitable empirical relationship for regression analysis is given by the following expression:

$$N_f = K_1 \left(\varepsilon_i\right)^{K_2} \tag{3}$$

where N_f is the number of cycles to failure at a particular level of initial strain; ε_i is the initial tensile strain; K_1 and K_2 are material coefficients.

3. Results, analysis and discussion

3.1. ITSM results

Fig. 6 presents stiffness modulus data for DBM50, EME2, and SMA mixtures measured by the ITSM test at 20 °C and 10 °C. Error bars in the graph represent plus and minus one standard deviation from five ITSM specimens.

As illustrated in the figure, the stiffness values of DBM50 and EME2, as measured by the ITSM, are quite similar, while SMA stiffness values are lower at both temperatures. This is logical because the DBM50 mixture included 40/60 pure bitumen with 20 mm limestone aggregates, and the EME2 mixture used the hard PMA (measured pen 21) with 14 mm limestone aggregates. In constrast, a smaller maximum aggregate size of 10 mm granite stones and a much softer binder were used for the SMA mixture. As expected, the results also confirm that the stiffness modulus of asphalt mixtures depends on temperature. In this study, as the test temperature decreases from 20 °C to 10 °C the stiffness values of DBM50, EME2, and SMA mixtures increase by 1.80, 1.79, and 2.47 times, respectively.

The ITSM results for the DBM50 and SMA mixtures in this research are consistent with the outcomes reported by Nejad et al. [33], who investigated the asphalt stiffness modulus of both SMA and Hot Mix Asphalt (HMA) mixtures using different aggregate gradations at various loads and three temperature levels. Both studies indicated that the DBM50 and HMA mixtures had an average stiffness significantly higher than that of the SMA mixtures at all test temperatures. Additionally, they confirmed that decreasing the ITSM temperature results in an increased stiffness modulus.

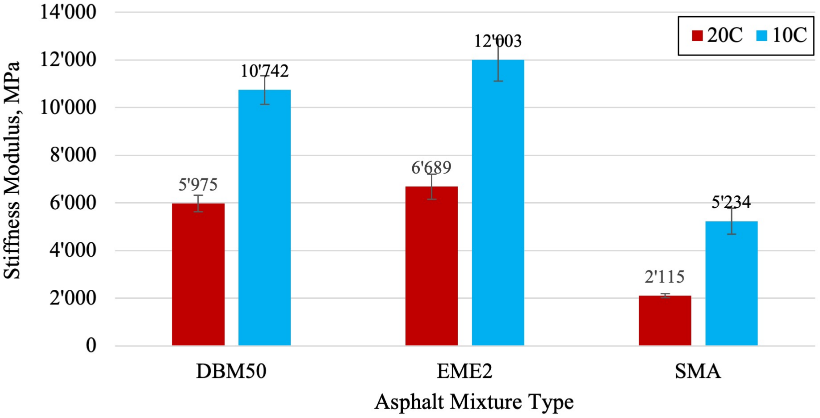


Figure 6. Stiffness Modulus for DBM50, EME2 and SMA mixtures at 20 °C and 10 °C

3.2. ITFT results, analysis and discussion

The fatigue results for DBM50, EME2 and SMA mixtures using the ITFT are shown in Fig. 7. In addition, the summary ITFT data including fatigue equations with their R^2 values, the strains at 10^6

cycles as well as the number of load applications to failure at 100 microstrain for all mixture types at test temperatures of 20 and 10 °C are shown in Table 1 although it is appreciated that both strains at 10^6 cycles and N_f at 100 microstrains involve significant extrapolation from limited data.

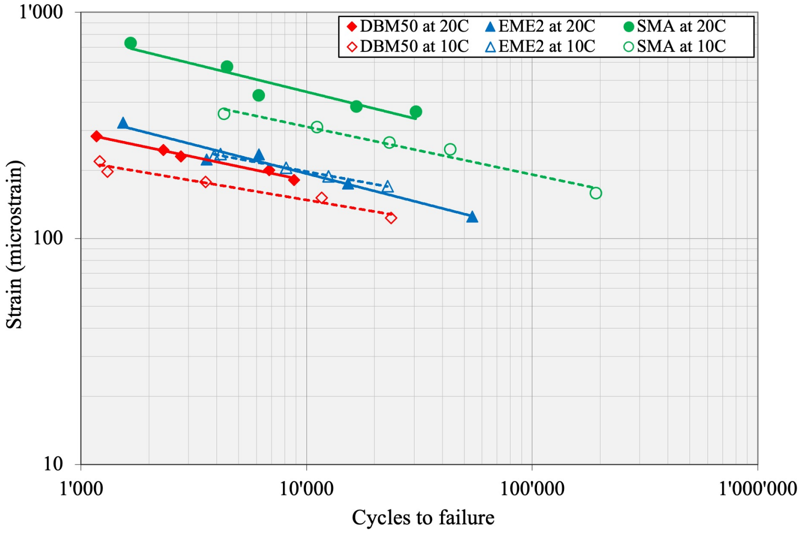


Figure 7. ITFT fatigue lines of DBM50, EME2 and SMA mixtures at 20 °C and 10 °C

As presented in Table 1, the high values of R^2 for all mixtures (above 0.90) suggest that the empirical relationship between the number of load applications to failure and the initial maximum strain (Eq. (3)) at the centre of specimen accurately fits the experimental data. Since fatigue failure typically occurs within the 30-200 microstrain range [28], the number of load applications to failure at 100 microstrain has been extrapolated from the fatigue equations for comparison purposes.

As can be seen from the data, the SMA mixture with a soft PMB binder and also its higher binder content shows the best performance at both 20 and 10 °C compared to the EME2 and conventional DBM50 mixtures. It is also reported that the DBM50 and SMA fatigue lines at 20 °C lie above those at 10 °C, while fatigue lines of EME2 mixtures at 20 and 10 °C are similar. For the DBM50 and SMA mixtures, the distinctive performance at different temperatures can be explained in that decreasing test temperature causes an increase of stiffness modulus in asphalt mixtures and higher stiffness results in low strain. At the 100 microstrain level (see Table 1), at 20 °C the SMA mixture shows approximately 33 and 27 times higher fatigue life compared to EME2 and DBM50, respectively, and these become 5.2 and 21.5 times when the test temperature is 10 °C.

In terms of fatigue lines, the results of this research are quite consistent with several previous studies. The findings by Nejad et al. [33] indicated that the average values of K_1 and K_2 were approximately 2.5×10^{15} and -4.25 for HMA mixtures and 2.3×10^{12} and -3.35 for SMA mixtures at 25 °C. These can be compared to the DBM50 ($K_1 = 5.4 \times 10^{14}$, $K_2 = -4.76$) and SMA ($K_1 = 5.83 \times 10^{14}$, $K_2 = -4.07$) results tested at 20 °C in this paper. While the results are generally consistent and reasonable, there are some slight differences. These differences may be attributed to the minor variation in test temperatures (25 °C and 20 °C) and other influencing factors such as binder content, gradation type, etc. The findings appear to be supported by Khalid [32], who conducted ITFT tests on five mixture types, including DBM and modified-SMA. However, the fatigue parameters K_1 and K_2 observed in this research differ significantly from those in the aforementioned studies, particularly for the DBM fatigue lines. This discrepancy may be explained that the DBM mixture in Khalid's study used a maximum aggregate size of 10 mm, while the DBM50 in this paper used a nominal maximum particle size of 20 mm.

Table 1. Summary fatigue results for all mixtures tested using the ITFT

Mixture Type	Test Temp.	Equation based on ε	ε@10^6 cycles	Equation based on N_f	N_f@$100\mu\varepsilon$	R^2
DBM50	20 °C	$\varepsilon = 1239.4\,N_f^{-0.21}$	68.1	$N_f = 5.365\times10^{14}\varepsilon^{-4.762}$	160,535	0.98
	10 °C	$\varepsilon = 705.7\,N_f^{-0.17}$	67.4	$N_f = 5.709\times10^{16}\varepsilon^{-5.882}$	98,301	0.96
EME2	20 °C	$\varepsilon = 2043.4\,N_f^{-0.256}$	59.5	$N_f = 8.532\times10^{12}\varepsilon^{-3.906}$	131,538	0.96
	10 °C	$\varepsilon = 1090.4\,N_f^{-0.185}$	84.6	$N_f = 2.627\times10^{16}\varepsilon^{-5.405}$	406,874	0.99
SMA	20 °C	$\varepsilon = 4289.1\,N_f^{-0.246}$	143.3	$N_f = 5.831\times10^{14}\varepsilon^{-4.065}$	4,322,580	0.90
	10 °C	$\varepsilon = 2193.1\,N_f^{-0.212}$	117.2	$N_f = 5.751\times10^{15}\varepsilon^{-4.717}$	2,117,110	0.97

4. Conclusions

In this research, the ITSM and ITFT tests have been carried out for DBM50, EME2, and SMA mixtures under various loading or strain conditions at test temperatures of 20 and 10 °C. Based on the results presented in this paper, the following conclusions are offered:

- The ITSM results for all mixtures under various conditions confirmed that the stiffness modulus is temperature-dependent, showing that as the test temperature increases, the stiffness modulus decreases.

- It is crucial to emphasise that the ITFT is simple to conduct and well-suited for characterising the stiffness and fatigue properties of asphalt materials especially for pavement construction sites. Therefore, the test should be considered to be widely applied in Vietnam. However, before using the test in Vietnam, some ITFT parameters will need to be calibrated based on Vietnamese standards.

- The SMA mixtures using a higher polymer-modified binder content showed the best performance at both 20 °C and 10 °C compared to the EME2 and conventional DBM50 mixtures.

- It is also noted that the DBM50 and SMA fatigue lines at 20 °C lay above those at 10 °C, while the EME2 lines at 20 and 10 °C were quite similar. This is quite consistent with the results conducted by many researchers in the past [27, 30, 40].

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References

[1] Di Benedetto, H. (2003). Fatigue of bituminous mixtures: different approaches and RILEM group contribution. In *Sixth International RILEM Symposium on Performance Testing and Evaluation of Bituminous Materials*, RILEM Publications SARL.

[2] Rooholamini, H., Karimi, A., Safari, J. (2021). A statistical fatigue life prediction model applicable for fibre-reinforced roller-compacted concrete pavement. *Road Materials and Pavement Design*, 24(1):103–120.

[3] Di Benedetto, H., de La Roche, C., Baaj, H., Pronk, A., Lundström, R. (2004). Fatigue of bituminous mixtures. *Materials and Structures*, 37(3):202–216.

[4] Nguyen, V. B., Thom, N. (2020). Using a beam wheel tracker fatigue test to evaluate fatigue performance of asphalt mixtures. *Road Materials and Pavement Design*, 22(12):2801–2817.

[5] Bharath, G., Reddy, K. S., Tandon, V., Reddy, M. A. (2019). Aggregate gradation effect on the fatigue performance of recycled asphalt mixtures. *Road Materials and Pavement Design*, 22(1):165–184.

[6] Tuan, N. Q. (2021). Mechanical properties of bituminous mixtures under sinusoidal cyclic loadings: Experiment and modelling. *Journal of Science and Technology in Civil Engineering (STCE) - NUCE*, 15 (2):67–76.

[7] Le Xuan, Q., Nguyen Mai, L., Nguyen Quang, T., Hornych, P. (2022). Longitudinal strain analysis in asphalt pavement under full-scale moving loads. *Transport and Communications Science Journal*, 73(4): 359–370.

[8] Nguyen Thu, T., Tran Ngoc, H., Pham Huy, K., Bui Xuan, C., Bui Ngoc, K. (2021). Research on the effects of sulfur on characteristics of sulfur bituminous binder (SBB) and hot mix asphalt – sulfur (HMAS). *Transport and Communications Science Journal*, 72(1):33–45.

[9] Thom, N. (2014). *Principles of pavement engineering*. Second edition, London: ICE Publishing.

[10] Choi, Y., Thom, N. H., Collop, A. (2005). Fatigue damage accumulation measured using different laboratory techniques. In *4th International Symposium on Maintenance and Rehabilitation of Pavements and Technological Control*, Belfast.

[11] Lacalle Jiménez, H. I. (2017). Airfield pavement design with cold recycled materials. PhD thesis, University of Nottingham, United Kingdom.

[12] Liao, M.-C., Chen, J.-S., Tsou, K.-W. (2012). Fatigue Characteristics of Bitumen-Filler Mastics and Asphalt Mixtures. *Journal of Materials in Civil Engineering*, 24(7):916–923.

[13] Ojum, C. K. (2015). The design and optimisation of cold asphalt emulsion mixtures. PhD thesis, University of Nottingham, United Kingdom.

[14] Jiang, Y., Deng, C., Xue, J., Liu, H., Chen, Z. (2018). Investigation of the fatigue properties of asphalt mixture designed using vertical vibration method. *Road Materials and Pavement Design*, 21(5):1454–1469.

[15] Chen, A., Airey, G. D., Thom, N., Li, Y. (2022). Characterisation of fatigue damage in asphalt mixtures using X-ray computed tomography. *Road Materials and Pavement Design*, 24(3):653–671.

[16] Žák, J., Monismith, C. L., Jarušková, D. (2014). Consideration of fatigue resistance tests variability in pavement design methodology. *International Journal of Pavement Engineering*, 16(1):91–96.

[17] Zokaei, M., Hesami, S. (2024). Prediction of fatigue crack behaviour of carbon fibre reinforced asphalt using fracture testing and modelling of the adhesive zone CZM. *International Journal of Pavement Engineering*, 25(1).

[18] Bell, H. P., Howard, I. L., Freeman, R. B., Brown, E. R. (2012). Evaluation of remaining fatigue life model for hot-mix asphalt airfield pavements. *International Journal of Pavement Engineering*, 13(4):281–296.

[19] Lytton, R. L., Zhang, Y., Gu, F., Luo, X. (2018). Characteristics of damaged asphalt mixtures in tension and compression. *International Journal of Pavement Engineering*, 19(3):292–306.

[20] Li, T., Liu, P., Du, C., Schnittcher, M., Hu, J., Wang, D., Oeser, M. (2020). Microstructural analysis of the effects of compaction on fatigue properties of asphalt mixtures. *International Journal of Pavement Engineering*, 23(1):9–20.

[21] Ling, M., Fuentes, L., Liu, H., Khalili, M., Walubita, L. F. (2022). Evaluating fatigue resistance based on viscoelastic properties of asphalt mixtures. *International Journal of Pavement Engineering*, 24(2).

[22] Seitllari, A., Kutay, M. E. (2023). Investigation of the fatigue life relationship among different geometry combinations of the 3-point bending cylinder (3PBC) fatigue test for asphalt concrete. *International Journal of Pavement Engineering*, 24(1).

[23] Jia, H., Sheng, Y., Chen, H., Guo, P., Ma, Q., Li, Y., Xiong, R. (2023). Effect of long-term aging on the fatigue properties of aramid fibres reinforced asphalt mixture. *International Journal of Pavement Engineering*, 24(1).

[24] Ozer, H., Al-Qadi, I. L., Singhvi, P., Bausano, J., Carvalho, R., Li, X., Gibson, N. (2018). Prediction of pavement fatigue cracking at an accelerated testing section using asphalt mixture performance tests. *International Journal of Pavement Engineering*, 19(3):264–278.

[25] Saleh, M. (2012). Calibration and Validation of the Shell Fatigue Model Using AC10 And AC14 Dense Graded Hot Mix Asphalt Fatigue Laboratory Data. *Engineering Journal*, 16(5):127–136.

[26] Chuong, L. H., Trang, U. Q., Lam, N. (2019). Asphalt concrete testing device: Studying and designing based on the properties of asphalt concrete. *Journal of Science and Technology in Civil Engineering (STCE) - NUCE*, 13(1):60–65.

[27] Maggiore, C. (2014). A comparison of different test and analysis methods for asphalt fatigue. PhD thesis, University of Nottingham, United Kingdom.

[28] Read, J. M. (1996). Fatigue cracking of bituminous paving mixtures. PhD thesis, University of Nottingham, United Kingdom.

[29] Cocurullo, A., Airey, G. D., Collop, A. C., Sangiorgi, C. (2008). Indirect tensile versus two-point bending fatigue testing. *Proceedings of the Institution of Civil Engineers - Transport*, 161(4):207–220.

[30] Hartman, A. M., Gilchrist, M. D., Walsh, G. (2001). Effect of mixture compaction on indirect tensile stiffness and fatigue. *Journal of transportation engineering*, 127(5):370–378.

[31] Wen, H., Bhusal, S. (2013). A Laboratory Study to Predict the Rutting and Fatigue Behavior of Asphalt Concrete Using the Indirect Tensile Test. *Journal of Testing and Evaluation*, 41(2):299–304.

[32] Khalid, H. A. (2000). A comparison between bending and diametral fatigue tests for bituminous materials. *Materials and Structures*, 33(7):457–465.

[33] Nejad, F. M., Aflaki, E., Mohammadi, M. A. (2010). Fatigue behavior of SMA and HMA mixtures. *Construction and Building Materials*, 24(7):1158–1165.

[34] BS EN 4987-1:2005. *Coated Macadam (asphalt concrete for roads and other paved areas)*. British Standards Institution.

[35] BS EN 12697-35:2016. *Bituminous mixtures - Test methods for hot mix asphalt - Part 35: Laboratory mixing*. British Standards Institution.

[36] BS EN 13108-5:2016. *Bituminous mixtures - Material specifications. Part 5: Stone Mastic Asphalt*. British Standards Institution.

[37] BS EN 12697-26:2012. *Bituminous mixtures-Test methods for hot mix asphalt-Part 26: Stiffness*. British Standards Institution.

[38] DD 226:1996. *Method for the determination of the fatigue characteristics of bituminous mixtures using indirect tensile fatigue*. British Standard Draft for Development, British Standards Institution.

[39] Pell, P. S. (1973). Characterization of fatigue behavior. *Highway Research Board Special Report*, (140).

[40] Cheng, H., Liu, J., Sun, L., Liu, L., Zhang, Y. (2021). Fatigue behaviours of asphalt mixture at different temperatures in four-point bending and indirect tensile fatigue tests. *Construction and Building Materials*, 273:121675.