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Investigation of permanent deformation characterisation of different asphalt mixtures

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ABSTRACT

Permanent deformation has emerged as a primary distress factor in asphalt pavements, largely driven by the recent rise in tyre pressures and axle loads. This deformation significantly impacts pavement performance, safety, and driving comfort, particularly when rutting depth exceeds a critical threshold. To address this issue, polymer-modified asphalt (PMA) mixtures have been widely adopted as an effective solution to resist permanent deformation (or rutting) under high temperatures. In this study, three different asphalt mixtures—one unmodified and two PMA mixtures—were selected for permanent deformation testing, which included the wheel tracking rutting test and the repeated load axial test under various conditions. The results were then compared, analysed, and discussed. The findings demonstrated a significant improvement in permanent deformation resistance in the PMA mixtures compared to conventional mixtures at both 45°C and 60°C. Furthermore, the results indicated that the use of PMA markedly enhanced both dynamic stability and strain rate, with the improvements becoming more pronounced at higher temperatures.

1 Introduction

Permanent deformation or rutting is considered as one of two main types of distress that occurs in asphalt pavements when subjected to traffic loading. The phenomenon occurring in asphalt mixtures is caused by a combination of shear deformation and poor mixture or pavement design [1]. The poor design may cause the aggregate skeleton to become more closely packed (i.e. densify) under traffic loading, while shear deformation may result in the formation of shoulders on either side of a rut due to the viscous behaviour of the material [2]. A number of factors affect permanent deformation in asphalt mixtures including aggregate gradation, type of aggregate, binder type and content, compaction level, compaction method, and temperature [3-7].

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When a wheel load is applied to a flexible pavement, it will create a deformation in the material elements. The magnitude of the deformation depends on the properties of the material, temperature, load level and loading time factors. As the load is removed, some of this deformation is then recovered but a part remains in the material. The recovered part is due to the elastic components of the material while the unrecovered part is due to the plastic and viscous components. The accumulation of deformation for each wheel load applied can result in high deformation in asphalt mixtures [8-10].

In the last few decades, as traffic has been significantly increasing in volumes, loads and tyre contact pressures, permanent deformation (rutting), a regular distress mode in asphalt pavements, has received an increased interest. In order to minimise this problem, polymer modified asphalt concrete mixtures have been widely used as an effective method in resisting permanent deformation (rutting) at high temperatures [11-15].

Qi, Sebaaly [16] investigated the permanent deformation behaviour of unmodified asphalt concrete mixtures as compared to the behaviour of asphalt concrete mixtures using a polyethylene modifier. The permanent deformation of the mixtures was tested at 40°C and 60°C in the laboratory with using a repeated load permanent deformation test. After that, the data for both modified and unmodified mixtures from the tests were analysed by using the VESYS model to predict the rutting development of typical pavement structures. The results indicated that the polymer modified mixtures exhibited higher resistance to rutting than the unmodified ones. This seems to be strongly supported by a number of subsequent studies. Moreover, it is highlighted that the structural layer coefficients of the polyethylene-modified asphalt mixtures were 75% - 85% higher than that of the unmodified mixtures. The structural coefficient concept was derived from the AASHTO road test based exclusively on results obtained from the performance of the various test sections and axle loadings.

In another study related to permanent deformation behaviour of unmodified and modified asphalt mixtures, Khodaii and Mehrara [17] determined the types of gradation with lower permanent deformation, and the amount of polymer to enhance the mechanical properties of samples made from those gradations. They found that coarse graded asphalt mixtures have more resistance to permanent deformation than dense graded ones, which can be caused by their lower dependency on mastic properties especially in the high temperature condition. The study showed that the mixtures modified with 5% SBS had the most improved mechanical behaviour compared with mixtures modified with 4% and 6% of SBS polymer.

In order to evaluate permanent deformation behaviour of asphalt mixtures incorporating PMA in the laboratory, one of most popular devices is the Laboratoire Central des Ponts et Chaussées (LCPC) wheel tracker, also known as French Rutting Tester. A study carried out by Özen [18] used this machine to investigate permanent deformation behaviour for hydrated lime and Styrene-Butadiene-Styrene (SBS) modified asphalt mixtures. In this study, control (C), 2% hydrated lime (2L), 5% SBS polymer (5SBS) and 2% hydrated lime-5% SBS (2L5SBS) mixtures were used. The results of the LCPC wheel tracker test indicated that 2L5SBS mixtures gave the best rutting resistance performance, followed by the 5SBS mixtures. This result is also similar to that given in previous studies [19-21] in that polymer modification increased rutting resistance of lime modified asphalt using the LCPC wheel tracking test.

It clear that there are many methods for determining asphalt mixture rutting. The repeated load test is a test applying several thousand repetitions of a repeated load and recording the cumulative deformation as a function of the number of load cycles to identify the permanent deformation characteristics of asphalt mixtures. Behbahani, Ziari [22] carried out the repeated load uniaxial strain test on cylindrical specimens at 300 kPa loading stress at 45°C temperature with the loading pulse period of 2s selected in order to compare the rutting performance of mixtures modified by different polymer types. SBS and Ethylene Vinyl Acetate (EVA) modified mixtures were used in this study. The results concluded that increasing polymer content resulted in higher rutting resistance and SBS modified mixtures gave better rutting resistance compared to EVA modified ones.

As mentioned, the permanent deformation of asphalt mixtures is influenced by many factors. Therefore, there are many different methods to improve rutting resistance of asphalt mixtures. A large number of previous studies [12, 23-26] have indicated that adding polymer additives to PMA pavements has led to significant improvement in permanent deformation resistance compared to comparable control sections with unmodified mixtures.

This paper will show the performance of one unmodified (DBM50) and two PMA mixtures (EME2 and SMA) in terms of permanent deformation resistance using the wheel tracking test and the repeated load axial test (RLAT), followed by comparison, analysis and discussion.

2 Materials and testing programme

2.1 Materials

In this research paper, three types of asphalt mixtures were selected to evaluate their permanent deformation behaviour: a 20mm Dense Bitumen Macadam (DBM50), a 14mm “Enrobé à Module Élevé 2” (EME2), and a 10mm Stone Mastic Asphalt (SMA). The first mixture, DBM50, a conventional type of asphalt mixture, was selected as it is commonly used in the UK for base or binder course layers in pavement design. The second mixture, EME2, utilises a hard SBS polymer-modified binder and is similarly designed for application as a base or binder course layer. The third mixture, SMA, incorporates a much softer SBS-modified binder and is intended for use as a surface course material. The main properties of the selected asphalt mixtures are summarised in Table 1, with the binder contents in the mixtures determined based on recommendations from BS-EN standards [27-29]. The design particle size distribution for the DBM50, EME2, and SMA mixtures is illustrated in Fig. 1.

Table 1 – Main properties of asphalt mixtures

Mixture type	DBM50	EME2	SMA
Binder type	Unmodified	Hard SBS	Soft SBS
Nominal maximum aggregate size mixtures (mm)	20	14	10
Binder Penetration (0.1mm)	41	21	65
Binder content (%)	4.7	5.5	6.5

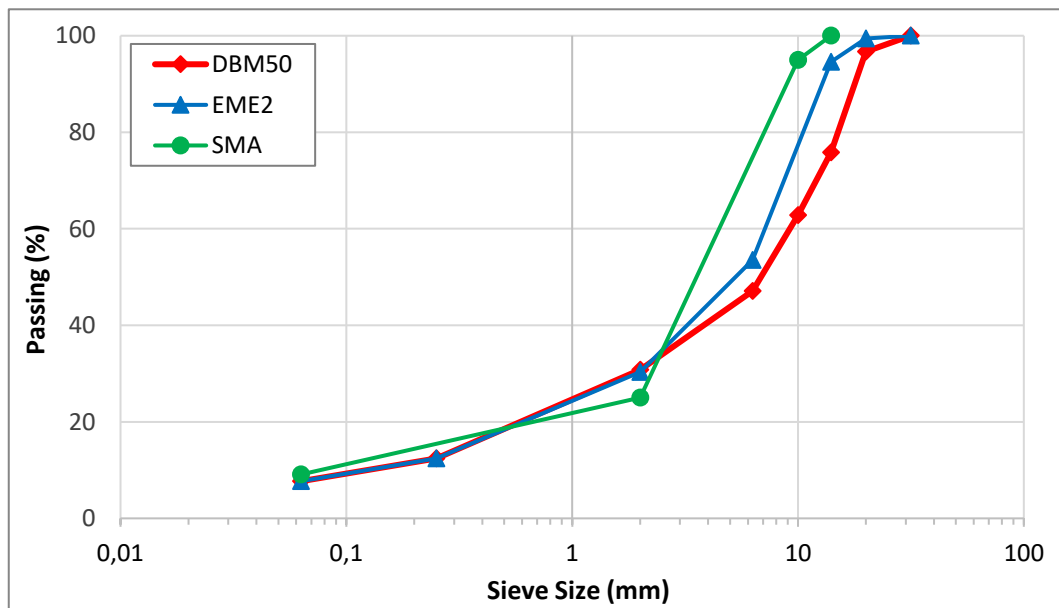


Fig. 1 – Design particle size distribution for the DBM50, EME2 and SMA mixture

2.2 Testing programme

2.2.1 Wheel tracking rutting test

In this research, six slabs comprising DBM50, EME2, and SMA mixtures were produced for the purpose of predicting permanent deformation. Two slabs were prepared for each mixture type, and they were subjected to wheel tracking tests at elevated temperatures of 45°C and 60°C (as shown in Fig. 2). Each slab underwent testing in the wheel tracking machine at the specified temperatures, following the BSI [30]. The tests were conducted for a duration of 10,000 cycles (equivalent to 20,000 passes).

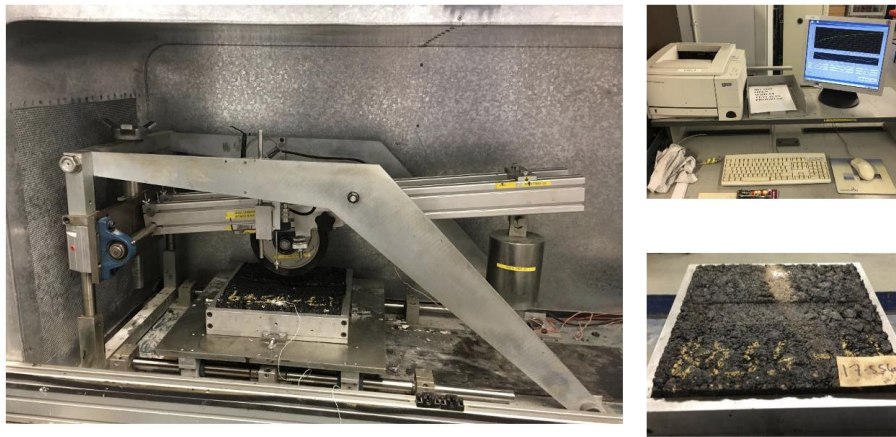


Fig. 2 – Wheel tracking rutting test configuration

2.2.2 Repeated load axial test (RLAT)

The Repeated Load Axial Test (RLAT) involves applying vertical stress cyclically to four core samples, which were extracted from the outer section of each slab previously tested in the wheel tracking test at identical temperatures (Fig. 3). According to BSI [31], the stress is applied to the sample for one second, followed by a one-second rest period. The cores had dimensions of 100mm in diameter and 50mm in height, after trimming 10mm from the top. In this study, the stress level was set at 300kPa, and the test temperatures matched those of the wheel tracking rutting test, 45°C and 60°C. The duration of the test was 5,000 cycles (equivalent to 10,000 seconds).

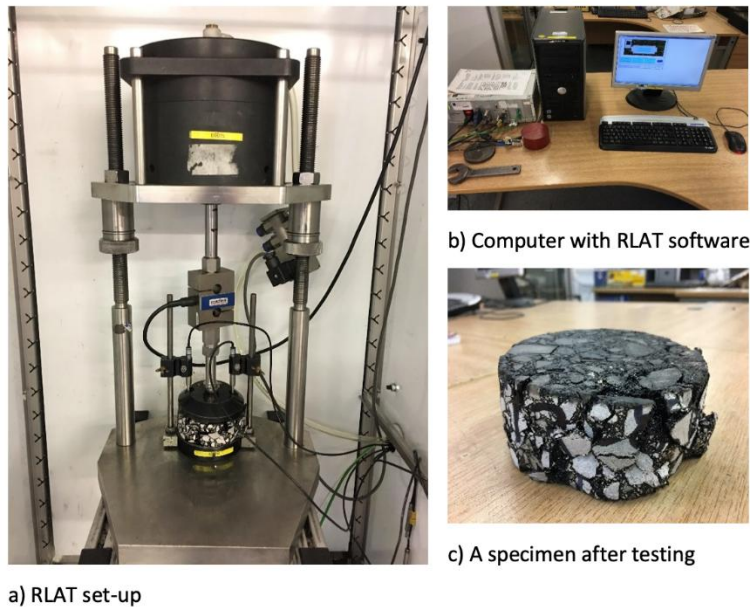


Fig. 3 – RLAT configuration

3 Permanent deformation indication

3.1 Dynamic stability

Dynamic stability (DS), a testing indicator, can be used to evaluate the high temperature stability of asphalt mixtures [32–34]. DS is calculated by the following equation:

$$DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \quad (1)$$

where DS is dynamic stability, passes/mm;
 t_1 and t_2 are time after 45 and 60 min, respectively;
 d_1 and d_2 are deformation or rut depth at time t_1 and t_2 , respectively as illustrated by Fig. 4;
 N is the number of wheel passes over the specimen per minute;

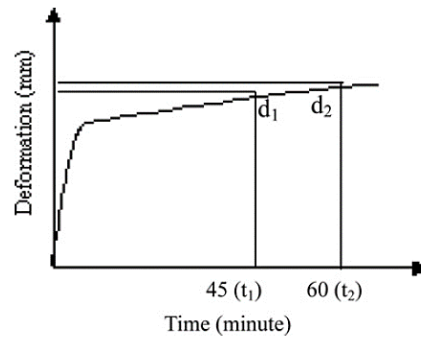


Fig. 4 – Diagram of deformation versus time

The higher the DS of asphalt mixtures the better the performance in terms of resistance to rutting at high temperature [32]. It is agreed by some studies that specific DS values depend on the highest expected temperature and the highest expected traffic load. Another study conducted by Poulikakos and Partl [35] proposed that for asphalt mixtures experiencing light and medium traffic volume, DS should be 800, and 3000 for heavy traffic highways at 60°C.

3.2 Permanent strain curve

In general, previous studies have found that the typical plot of the total cumulative permanent strain versus the number of load repetitions includes three distinct stages: Primary, secondary, and tertiary [36–38]. In the primary stage, permanent strain accumulates rapidly due to a combination of adjustment of loading platens and material densification. However, permanent strain per load cycle tends to decrease gradually. The secondary stage takes place when the strain rate reaches approximately a steady state response, and the permanent strain increases in proportion to the load cycles. Finally, the tertiary stage starts when the rate of deformation increases markedly representing specimen failure. The typical three-stage curve of cumulative permanent strain versus the number of load repetitions is shown in Fig. 5.

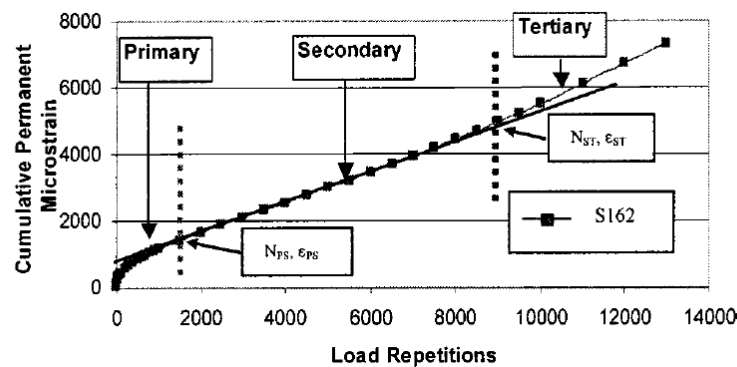


Fig. 5 – Typical three-stage curve of cumulative permanent strain versus the number of load repetitions [38]

3.3 Strain rate

The strain rate (microstrain per cycle) during the secondary stage can be used to gain a better understanding of the permanent deformation resistance performance of the asphalt mixtures. This rate gives a more reliable indication of the permanent deformation of the asphalt mixtures as it does not depend on the initial densification stage. The strain rate

(microstrain/cycle) over the steady state stage of the cumulative permanent strain curve can be calculated between 1800 and 3600 pulses as suggested by Brown and Gibb [39]. In this study, the slope of the steady state stage is determined as follows:

$$\text{Strain Rate } (\mu\epsilon/\text{cycle}) = \frac{(\epsilon_{3600} - \epsilon_{1800})}{1800} \times 10^6 \quad (2)$$

where ϵ_{3600} is the accumulative strain at 3600 pulses;
 ϵ_{1800} is the accumulative strain at 1800 pulses;

4 Results, analysis and discussion

4.1 Wheel tracking rutting test

Fig. 6 and Fig. 7 show the rut depth results of wheel tracking test for one unmodified mixture (DBM50) and two PMA mixtures (EME2 and SMA) at 45°C and 60°C, respectively. As can be seen from the graphs, none of the asphalt mixtures reached 10mm rut depth during the loading period of 20,000 passes (10,000 cycles) at either 45°C or 60°C test temperatures.

It can be seen from the graphs that the rut depth of the DBM50 mixture increased significantly as the number of load cycles increased, while the PMA mixtures (EME2 and SMA) showed much lower permanent deformation increase. In particular, after the first 2000 cycles, the permanent deformation increase rate of the PMA mixtures was very low, even at a temperature of 60°C. Moreover, it is found that the difference between the rut depths of the PMA mixture specimens and the unmodified mixture specimens increased continuously from the first cycle to the end of the test at 10,000 cycles.

A comparison between the two PMA mixtures used in the test, EME2 and SMA, shows that the mixtures presented relatively similar performance in rutting resistance at a temperature of 45°C, and SMA only showed a small improvement over the later cycles compared to EME2 as illustrated in Fig. 6. At the increased temperature of 60°C, the improvement in rutting resistance of SMA in comparison with EME2 became more obvious (see Fig. 7). It can be highlighted that the SMA mixture showed the best performance under the wheel tracking test compared to either DBM50 or EME2 mixtures. This is consistent with previous studies [40, 41] that have indicated that properly designed SMA mixtures are rut resistant at high temperatures.

The DS of DBM50, EME2 and SMA mixtures used in the wheel tracking rutting test at both 45°C and 60°C temperatures is shown in Fig. 8. In comparison with the unmodified mixture (DBM50), at a temperature of 45°C the DS values of EME2 and SMA increased by 2.14 and 3.00 times, respectively; when the test temperature went up to 60°C, the values increased by 3.07 and 3.91 times, respectively. This suggests that in terms of the dynamic stability, the higher the temperature, the higher the permanent deformation resistance of the PMA mixtures in comparison with the unmodified mixture.

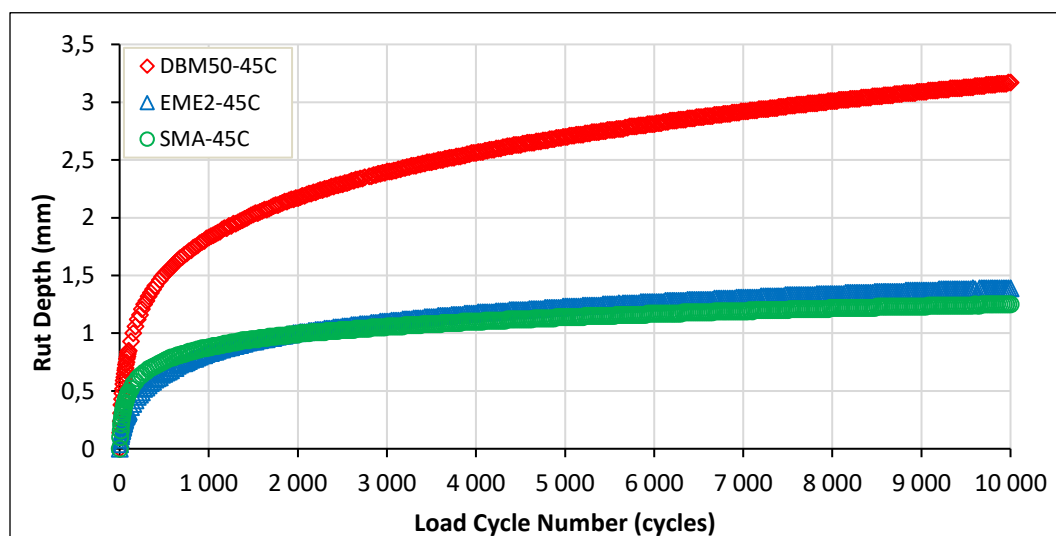


Fig. 6 – Wheel tracking rutting test results at 45°C for DBM50, EME2 and SMA mixtures

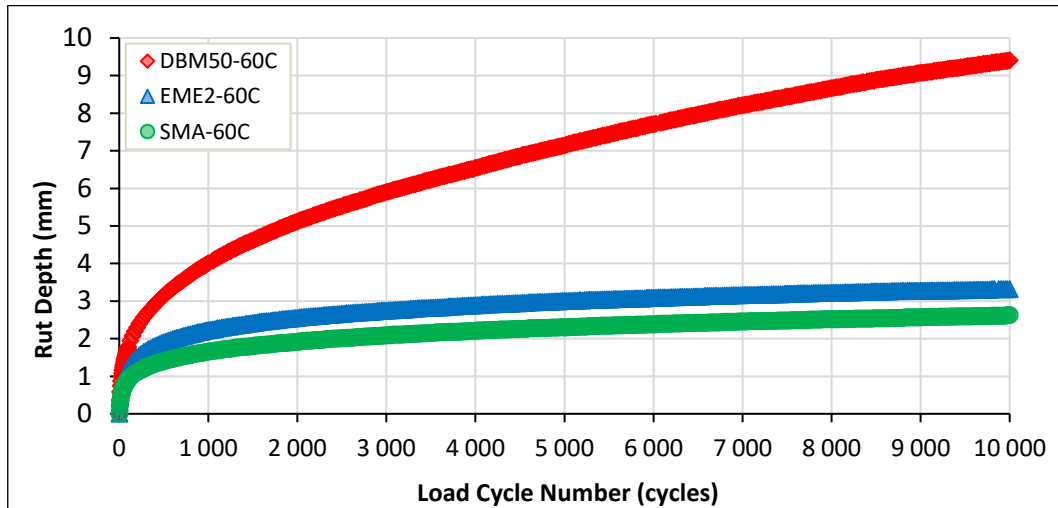


Fig. 7 – Wheel tracking rutting test results at 60°C for DBM50, EME2 and SMA mixtures

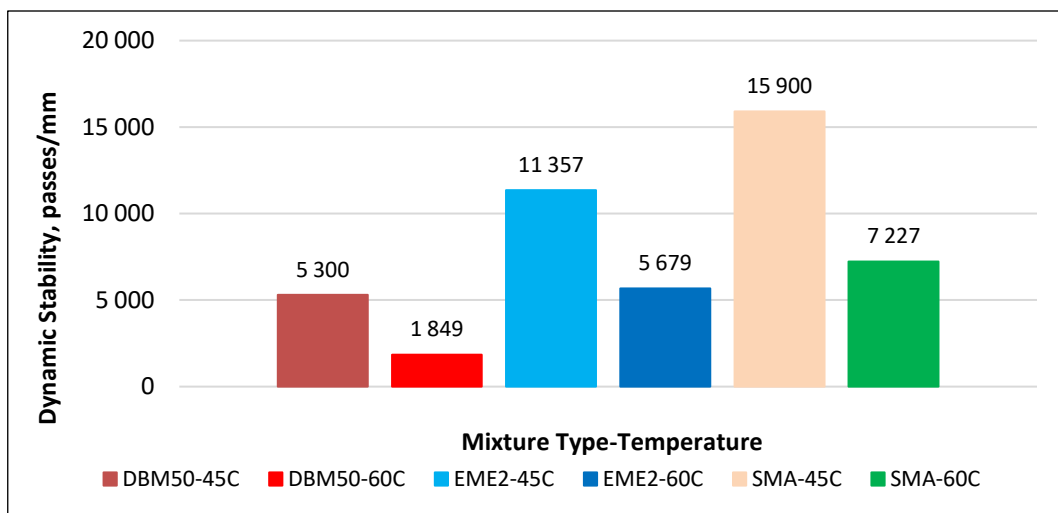


Fig. 8 – Dynamic Stability of DBM50, EME2 and SMA mixtures at 45°C and 60°C

4.2 RLAT

Fig. 9 and Fig. 10 present the results obtained from the RLAT for one unmodified mixture (DBM50) and two PMA mixtures (EME2 and SMA) tested at 45°C and 60°C, respectively, where permanent axial strain is plotted against the number of pulses. In these figures, each resulting permanent strain curve was averaged from four specimens tested in the RLAT. In terms of the typical three-stage curve of the plot of permanent strain versus number of load repetitions, in this study, during the loading period of 5000 pulses at 300kPa stress level, only DBM50 specimens tested at 60°C reached the tertiary stage, while others did not.

As can be seen from the graphs, it is obvious that in comparison with the DBM50 mixture, the PMA mixtures (EME2 and SMA) showed much better performance in permanent deformation resistance at both 45°C and 60°C. Moreover, when the test temperature increased from 45°C to 60°C, while the DBM50 mixture reached failure at around 3500 cycles, the axial strains of PMA mixtures increased only gradually. This confirms that the PMA mixtures are able to bring more improvement in permanent deformation resistance to asphalt pavements.

Fig. 11 shows the strain rate of DBM50, EME2 and SMA mixtures obtained from the RLAT at both 45°C and 60°C. Obviously, the PMA mixtures (EME2 and SMA) gave much lower strain rate compared to that of the unmodified mixture (DBM50) at test temperatures. This implies that the DBM50 mixture will reach the tertiary stage more quickly than the EME2 and SMA mixtures, and that adding polymers to the PMA mixtures will delay the deterioration in asphalt mixtures, leading to longer service life of asphalt pavements. In terms of the strain rate, as presented in Fig. 11, the SMA mixture experienced

the best performance in permanent deformation resistance at the high temperatures again when compared to the DBM50 and EME2 mixtures. The results are completely consistent with outcomes achieved from the wheel tracking test.

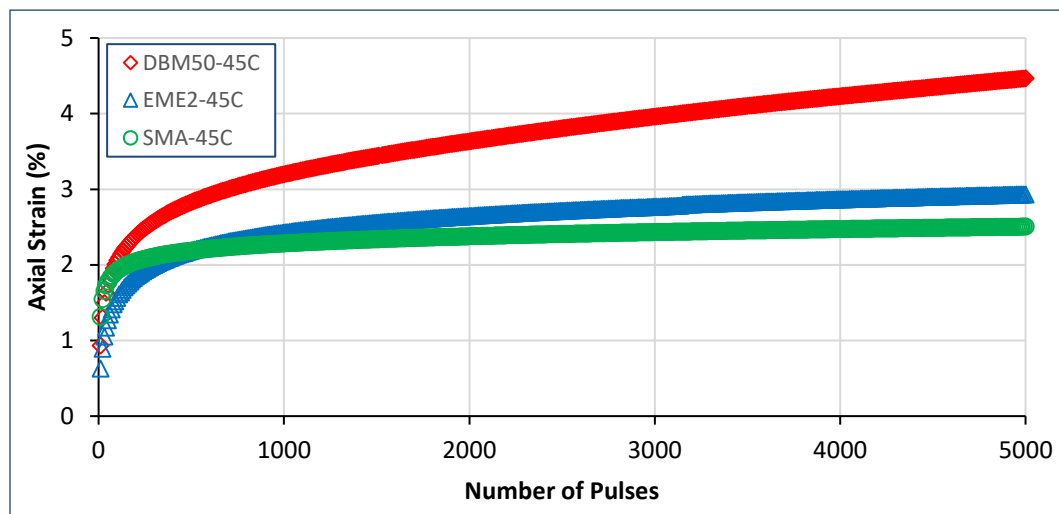


Fig. 9 – RLAT results for all mixtures tested at 45°C

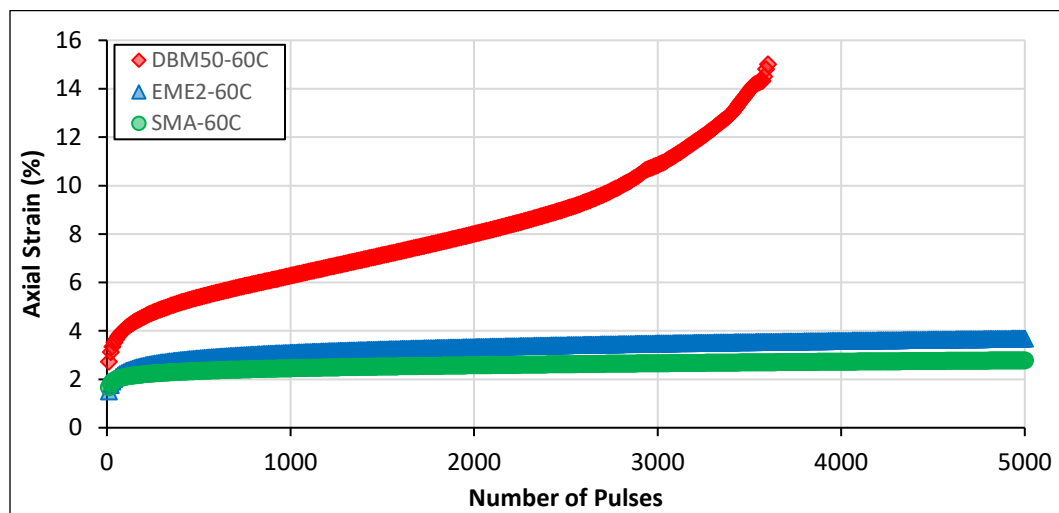


Fig. 10 – RLAT results for all mixtures tested at 60°C

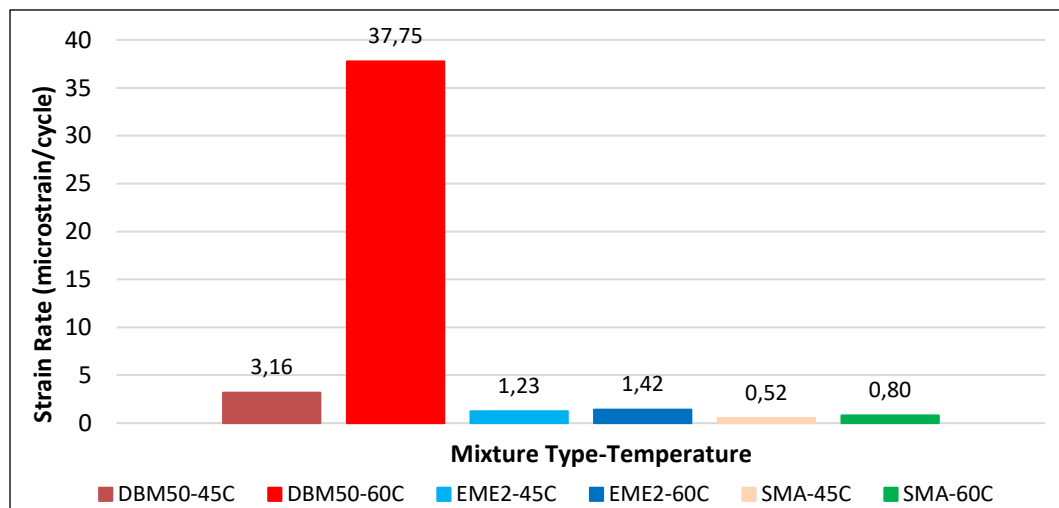


Fig. 11 – Strain rate of DBM50, EME2 and SMA mixtures at 45°C and 60°C

5 Conclusions

The PMA mixtures present excellent performance in permanent deformation resistance at moderate and high temperatures compared to the conventional mixture in this chapter. The wheel tracking test and RLAT results were used to investigate and analyse the permanent deformation resistance of asphalt mixtures incorporating PMA, followed by discussion about the correlation between binders and mixtures in terms of rutting performance. The following conclusions can be drawn from this research:

- The wheel tracking test results indicated that the rut depth of PMA mixtures (EME2 and SMA) was significantly lower than that of the unmodified mixture (DBM50) at both 45°C and 60°C.
- The use of PMA caused a significant improvement in the dynamic stability of asphalt mixtures, and the improvement became more obvious at higher temperature.
- The repeated load axial test (RLAT) results confirmed the improvement in permanent deformation resistance of the PMA mixtures at both 45°C and 60°C.
- In terms of the strain rate obtained from the RLAT, the PMA mixtures showed much lower strain rates compared to the conventional DBM50 mixture at test temperatures.

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