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Influence of surface layer bitumen on the performance evolution of base layer over service time

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A R T I C L E I N F O

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A B S T R A C T

In conjunction with the aggregates, bitumen is commonly applied for surface and base layers of asphalt pavements. A large number of studies concentrated more on the surface layer performance influenced by different types of bitumen and service time. However, the performance evolution of base layer bitumen properties influenced by surface layer bitumen over time remains understudied. To contribute to this gap, this study aims to investigate the influence of surface layer bitumen type on base layer performance with varying service time. Four road segments with two-layer structure (surface layer and base layer) serviced for 4, 6, 7 and 9 years were studied. The surface layer was paved with neat bitumen with Pen 70/100 and polymer modified bitumen (PMB), and the base layer was applied with soft bitumen with Pen 160/220. Physical properties, chemical structure, intermediate-temperature rheological properties, permanent deformation resistance, anti-rutting ability and recovery properties of the field bitumen were analysed and compared with the reference bitumen. The temperature- and frequency-dependent characteristics of asphaltic core samples, as well as the reference mixtures, were characterised. The statistical analyses were performed to quantitatively evaluate the significance of service time and bitumen type of surface layer to base layer performance using mean absolute percentage errors (*MAPEs*), Pearson correlation coefficient and eta squared. The results showed that the performance of the surface layer was greatly related to service time, and PMB presented better durability and anti-ageing properties than 70/100. Notably, the bitumen type of the surface layer played an important role in base layer performance except for service time, especially in penetration, phase angle and J_{nr} with eta squared of 0.925, 0.976 and 0.988. Moreover, the ageing speed of the base layer was highly determined by the bitumen type of the surface layer. The findings imply that a better bitumen type of surface layer can enhance the durability of both surface and base layers, resulting in significant improvement in lifespan of asphalt pavement.

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1. Introduction

Bitumen ageing is an inevitable topic of asphalt pavement since many factors that are hardly avoided can be the inducements, including thermal-oxidative ageing, ultraviolet radiation, moisture or environmental chemical erosion [1–5], resulting in bitumen stiffening and brittleness. Asphalt pavement with aged bitumen is easily cracked and deformed with the coordinated effect of temperature and heavy traffic loading, which in turn leads to various deterioration and distress including rutting, transverse cracking, potholes and weathering [6–9]. Therefore, bitumen ageing has received continuous and widespread concern in the field of asphalt pavement.

The ageing forms of bitumen are divided into laboratory ageing and in-field ageing. In-field ageing refers to the oxidative reaction of bitumen during the manufacturing, transportation, layering, compaction and servicing processes [10–13]. Laboratory ageing is proposed to simulate in-field ageing in the laboratory, which is categorised into two stages: short-term ageing and long-term ageing, corresponding to the processes of manufacturing, transportation, layering and compaction and the process of servicing period, respectively [14–19]. As the laboratory ageing method is more convenient to conduct than in-field ageing, it has been used extensively for bitumen ageing research [20–22]. Many studies focused on laboratory ageing of bitumen, whereas only a few studies investigated the development of bitumen properties under in-field ageing [12,23–26]. The findings of laboratory ageing and in-field ageing on bitumen are similar, leading to stiffer and more brittle bitumen with more oxygen-contained chemical groups, more prone to elasticity, better rutting resistance, worse fatigue resistance and adhesion. However, the ageing degrees of bitumen caused by laboratory and in-field ageing are different, which indicates that laboratory ageing cannot accurately characterise in-field ageing under complex conditions [1,27–30].

In most countries, bitumen is used not only for the surface layer of asphalt pavement but also for the base layer [31–33]. However, the bitumen requirements for the surface layer and base layer are different. Generally, the requirement of surface layer bitumen is stricter than that of base layer bitumen as the surface layer directly withstands the compressive and shear stresses of vehicles and is exposed to external environments including rainfall, sunshine, temperature, snow and de-icing salts [33]. In the case of Norway, neat bitumen with penetration of 70/100 and polymer modified bitumen are commonly used for the surface layer, and soft bitumen with penetration of 160/220 and 330/430 is applied for the base layer [31,34].

In summary, most studies concentrated on the bitumen and mixture properties of the surface layer over service time, as the surface layer suffers the heaviest traffic loading and is directly exposed to external environments. However, the base layer, also one of the most significant layers, has been paid less attention to, especially the correlation between surface layer performance and base layer performance. Based on the given background, this study aims to investigate the influence of surface layer bitumen type on the performance evolution of the base layer and the bitumen and mixture property development of both surface and base layers from in-service asphalt pavements over service time. The physical properties, chemical functional group, rheological properties, permanent deformation resistance and anti-rutting performance of the surface layer and base layer bitumen were analysed and compared with reference bitumen, and the mechanical properties of asphalt mixtures of surface and base layers were also characterised and compared with reference mixtures. The performance evolution of base layer bitumen and asphalt mixtures over different service time and with bitumen types of the surface layer was quantificationally assessed by the mean absolute percentage error (*MAPE*), Pearson correlation coefficient and eta squared.

2. Materials and testing programs

2.1. The reference bitumen

Three types of bitumen, polymer-modified bitumen (PMB) containing styrene butadiene styrene, neat bitumen with Pen 70/100 (70/100) and soft bitumen with Pen 160/220 (160/220), were considered in this study. PMB and 70/100 were generally applied to the in-service surface layer based on different traffic volumes, and 160/220 was used to construct the in-service base layers of asphalt pavements in Norway. The three types of bitumen were acquired from manufacturers, and the physical properties of the bitumen were tested in the laboratory, as shown in Table 1.

The reference bitumen without ageing or servicing was compared with the bitumen from the in-service asphalt pavements to evaluate the property changes due to the surface layer bitumen type, service time, etc.

2.2. The reference asphalt mixtures

The reference asphalt mixtures had the same mixture types as the core samples from the fields, with Asphalt Concrete (AC 11) for

Table 1
Physical properties of the three bitumen.

Bitumen	Penetration [0.1 mm] EN 1426:2015	Softening point [°C] EN 1427:2015
70/100	72	48.0
PMB	72	64.6
160/220	189	38.2

the surface layer and Asphalt Gravel (AG 16) for the base layer. The crushed rock used for aggregate in the study was supplied by the company Franzefoss (Heimdal, Norway). The Abrasion value, Micro-Deval coefficient and Los Angeles value of the aggregates are respectively 7.8 %, 14.2 %, 18.2 %, fulfilling the corresponding standards (Statens Vegvesens Rapporter Nr. 670). The aggregate gradation is illustrated in Fig. 1.

The reference asphalt mixtures fabricated in the laboratory were made in accordance with the mixture types of field samples. The air voids and binder contents are presented in Table 2. Four replicate specimens of each mixture type were prepared for subsequent testing.

The reference asphalt mixtures were compared to the in-service asphalt mixtures to investigate the effect of external conditions on mixture properties.

2.3. In-service bitumen and asphalt mixtures

Four road segments have been in service for 4, 6, 7 and 9 years, respectively, as outlined in Table 3. The service conditions for each of the four segments are detailed in Table 4. Two of the road segments have a surface layer bitumen of 70/100, while the other two contain PMB. All four segments have the same bitumen type of 160/200 in their base layers. The pavement structure for these segments consists of a 50 mm surface layer and a 130 mm base layer, which is commonly used for road construction in Norway. The air voids of field samples increase due to the ageing effect during service.

To obtain the asphalt mixtures and bitumen from the in-service asphalt pavements, three steps were carried out [35,36]. Firstly, field cores were drilled from the in-service asphalt pavements. Then, specimens from the surface and base layers were distinguished and sawn at the exact positions of the field cores, which were the middle of the surface layer and the top of the base layer. Finally, the bitumen of the surface and base layers was extracted from the surface and base specimens using a dichloromethane solution following EN 12697–3. To avoid the dissolution of the extraction solvent, the extracted bitumen was dried in a heating cabinet until its weight remained unchanged.

In order to evaluate bitumen and mixture properties developed over service time, the surface layer of segments 1, 2, 3 and 4 are coded as 70/100–4 years, PMB-6 years, 70/100–7 years and PMB-9 years, respectively. In the same way, the base layer of segments 1, 2, 3 and 4 are named 160/220–4 years, 160/220–6 years, 160/220–7 years and 160/220–9 years. A total of eight aged/serviced bitumen and mixtures were studied in this research, as well as three reference bitumen and mixtures.

2.4. Testing program

2.4.1. Ring-ball test and needle penetration test

To evaluate the influence of field ageing on bitumen physical properties, ring and ball and needle penetration tests were performed in accordance with EN 1426:2015 and EN 1427:2015 [37,38]. As a result, the penetration and softening point of bitumen were acquired. Three measurements for penetration and two replicates were tested for each bitumen, and the averaged value was applied for characterisation.

2.4.2. Fourier transform infrared spectroscopy

For this investigation, a Nicolet 8700 Fourier transform infrared (FTIR) radiation spectrometer with an attenuated total reflectance (ATR) accessory was applied to characterise the chemical structure of bitumen under different conditions, which can reflect the ageing degree of both surface and base layer bitumen. A tiny piece of bitumen sample was placed on the diamond surface of the spectrometer and squeezed by a mental penetrator to achieve full contact between bitumen and diamond. Each bitumen was tested three times, and

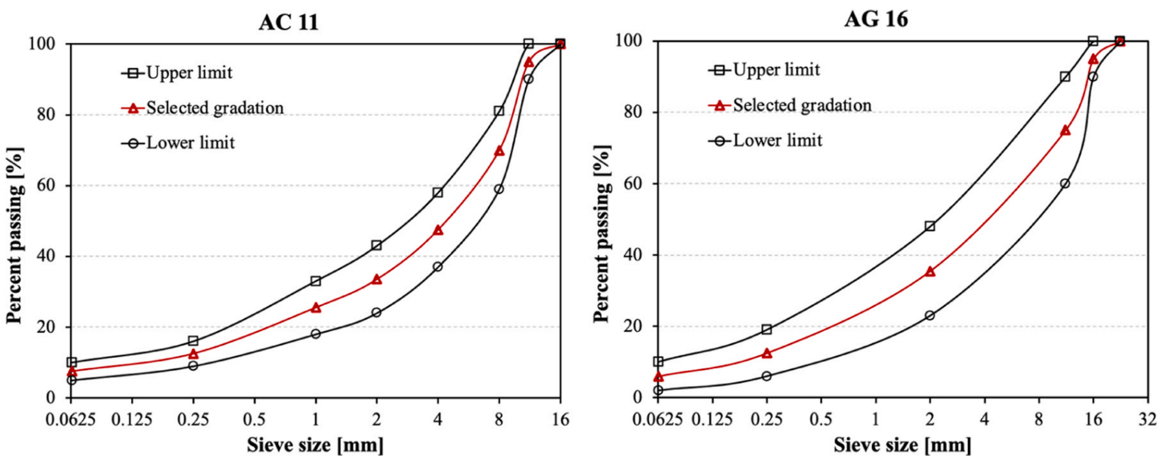

Fig. 1. Aggregate gradation for AC 11 (left) and AG 16 (right).

Table 2
Binder content and air voids of studied asphalt mixtures.

Asphalt mixture	Binder content [%]	Air void [%]
AC11–70/100	5.1	3.7
AC11-PMB	5.2	2.4
AG16–160/220	4.6	8.0

Table 3
The basic information of the four road segments.

Road segment	Service time	Surface layer			Base layer		
		Bitumen type	Thickness	Air void	Bitumen type	Thickness	Air void
Segment 1	4 years	70/100	50 mm	4.5 %	160/220	130 mm	8.7 %
Segment 2	6 years	PMB		3.2 %	160/220		8.3 %
Segment 3	7 years	70/100		6.1 %	160/220		9.1 %
Segment 4	9 years	PMB		3.9 %	160/220		8.6 %

Table 4
Service conditions of the four segments.

Road section	Annual average daily traffic	Heavy vehicle percentage [%]	Average annual temperature [°C]	Average annual precipitation [mm]
Segment 1	2700	10	5.6	632.40
Segment 2	8621	14	6.1	703.69
Segment 3	5195	22	3.66	746.99
Segment 4	14300	18	5.98	752.87

the spectrum with the largest absorbance peaks was used for further analysis.

2.4.3. Intermediate temperature sweep

A dynamic shear rheometer was used to conduct an intermediate temperature sweep at a temperature range of 5 – 30 °C (with an interval of 1 °C) and a constant frequency of 10 rad/s for characterising the stiffness and viscous-elastic response of bitumen. A plate with a diameter of 8 mm and a thickness of 2 mm was selected for the test. Two replicates of each type of bitumen were prepared for the test, and the mean value was used for analysis and discussion.

2.4.4. Rutting factor and pass temperature measurement

The performance grade (PG) test in this study was applied to evaluate the rutting resistance of both serviced bitumen and reference bitumen. Two main parameters of the PG test are the rutting factor and pass temperature, which respectively indicate the ability to resist permanent deformation and failure critical value of bitumen. The rutting factor ($G^*/sin\delta$) is determined by the complex modulus (G^*) and phase angle (δ). In this test program, the frequency is fixed at 10 rad/s, and the test temperature starts from 58 °C with an increase of 6 °C until failure (rutting factor $<$ 1 kPa). Bitumen specimens were made to 25 mm diameter and 1 mm thickness for the test. Each specimen was tested twice, and the average value was finally applied.

2.4.5. Multiple shear creep recovery test

Multiple shear creep recovery (MSCR) test was conducted to characterise the anti-rutting ability and recovery property of bitumen. According to the standard EN 16659:2015 [39], the bitumen specimens with dimensions of 25 mm diameter × 1 mm thickness were tested at 60 °C. Two constant creep stress modes, 0.1 kPa and 3.2 kPa, were loaded on bitumen specimens. Each stress mode runs for ten cycles, and each cycle is a combination of a 1 s duration of loading and a 9 s duration of recovery. As a result, non-recoverable creep compliance (J_{nr}) and percent recovery ($\%R$) of bitumen were obtained at two stress modes based on the calculation expressed in Eqs. (1) and (2). For this test, two replicates were tested for each bitumen type, and the mean value was applied in this study.

$$\%R = \frac{\varepsilon_p - \varepsilon_u}{\varepsilon_p} \times 100\% \quad (1)$$

$$J_{nr} = \frac{\varepsilon_u}{\sigma} \quad (2)$$

where ε_p is the peak strain, ε_u is the uncovered strain and σ is the applied stress level (0.1 kPa or 3.2 kPa).

2.4.6. Cyclic indirect tensile test

The cyclic indirect tensile test was performed to analyse the dynamic modulus of asphalt mixtures by the servo-pneumatic universal testing machine. According to standard EN 12697–26:2018 specification and previous references [40–42], four parallel specimens for each asphalt mixture type were tested at five testing temperatures (-15 °C, −10 °C, 0 °C, 15 °C and 30 °C) and six frequencies (10 Hz, 5 Hz, 3 Hz, 1 Hz, 0.3 Hz, and 0.1 Hz). The master curve of dynamic modulus over frequency was constructed using the sigmoidal function shown as follows:

$$\log(|E^*|) = \delta + \frac{\alpha}{1 + e^{\beta - \gamma \log(f_r)}} \tag{3}$$

where f_r is the frequency at reference temperature, δ, α, β and γ are model factors.

2.4.7. Statistical analysis method

The difference between the performance of core samples and laboratory samples reflects the ageing or deterioration degree of the serviced asphalt pavements. The variations of the physical properties, chemical composition, rheological properties, rutting resistance and recovery properties of base layer bitumen and the mechanical properties of asphalt mixtures were characterised by the mean absolute percentage error (*MAPE*). The *MAPE* was calculated by the following formula.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_{svcsi} - y_{0i}}{y_{0i}}\right| \times 100 \tag{4}$$

where n is the size of the data sets, y_{svcsi} is the performance parameter of the serviced asphalt pavements and y_{0i} is the performance parameter of the laboratory samples.

The significance of surface layer bitumen type and service time in base layer performance was assessed by SPSS software. The correlation between service time and base layer performance was evaluated by the Pearson correlation coefficient. However, the correlation between bitumen type of surface layer and base layer performance was evaluated by eta squared, as bitumen type is a categorical variable.

3. Results and discussion

3.1. The physical properties of surface layer and base layer bitumen

The penetration and softening point of the bitumen from the four road segments are measured and presented in Fig. 2. The higher softening point and lower penetration compared to reference bitumen regardless of the surface or base layer were observed, which indicates the ageing of bitumen after a servicing period. Regarding the physical properties of surface layer bitumen (PMB and 70/100), both PMB and 70/100 led to decreased penetration and increased softening point over service time. It is worth noting that the softening point of PMB decreased at 6 years and then increased at 9 years compared to the reference bitumen, which is connected with the complicated reaction between polymers and bitumen and the dynamic equilibrium between bitumen oxidative ageing and chain fracture of polymers. Moreover, PMB showed better stability under external servicing conditions than 70/100 as the magnitude grade of 70/100 after servicing was more severe. In contrast, the base layer bitumen (160/220) responded dramatically after 4 – 9 years of servicing. The soft and volatile bitumen type induces large variations in physical properties. It is worth noting that the base layer bitumen of asphalt pavement paved with 70/100 surface layer bitumen has lower penetration and similar softening point as the ones with PMB surface layer bitumen, demonstrating the potential of the effect of surface layer type on bitumen performance of base layer bitumen. For example, the penetration of 160/220–9 years (PMB surface layer bitumen) is 10 % higher than that of 160/220–7 years (70/100 bitumen), which indicates that PMB as the surface layer bitumen can prevent not only surface layer bitumen but also base layer bitumen from ageing. By comparing the two figures, the changes in physical properties of base layer bitumen were much higher than that of surface layer bitumen after the same service time, whereas the base layer bitumen (160/220) suffered less severe environmental impact compared to the surface layer (PMB and 70/100), indicating worse performance and ageing resistance of the base layer bitumen (160/220).

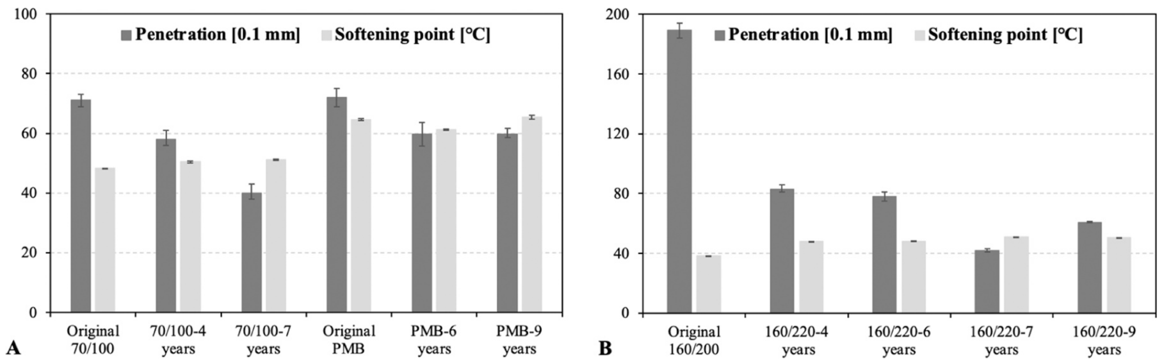

Fig. 2. Physical parameters of surface layer bitumen (A) and base layer bitumen (B).

3.2. The chemical functional group of surface layer and base layer bitumen

The FTIR spectra of bitumen after and before servicing in asphalt pavement are depicted in Fig. 3. Ageing is the dominant reaction of bitumen during servicing, paving and transportation in the field. A variation in chemical functional groups definitely accompanies the chemical reaction of different compositions. In the FTIR spectrum, the increased areas of C═O and S═O groups (1700 cm^{-1} and 1030 cm^{-1}) are the results of bitumen ageing [43]. Moreover, C-H at 698 cm^{-1} of PMB is also heavily influenced by bitumen ageing as a result of decreased peak [44]. As presented in Fig. 3A (surface layer bitumen), both 70/100 and PMB resulted in sharper peaks at 1700 cm^{-1} and 1030 cm^{-1} compared to reference bitumen, and the magnitude grade increased over service time, indicating a more severe ageing degree of surface layer bitumen. In addition, the specific chemical bond C-H at 698 cm^{-1} of PMB was also decreased over service time, which further verifies the increased ageing degree of surface layer bitumen. In comparison with 70/100, PMB was less affected in terms of chemical structure, indicating ageing resistance of PMB.

Furthermore, the same changing trend was found for base layer bitumen (160/220) as shown in Fig. 3B, which is the two chemical groups indicating bitumen ageing increased after servicing in the field. Moreover, the increasing magnitude is determined by both service time and the surface bitumen type. For example, ranking the C═O peak at 1700 cm^{-1} in ascending order: Original 70/100, 160/220–6 years, 160/220–9 years, 160/220–4 years and 160/220–7 years. Amongst these, 160/220–6 years and 160/220–9 years were paved for the asphalt pavements with PMB surface layers, which have better anti-ageing performance than the asphalt pavements with 70/100 surface layers. This result implies that the bitumen type of surface layer has an unignored effect on the anti-ageing performance of the base layer bitumen. The changes in base layer performance in turn provide different degrees of support for the surface layer.

3.3. The intermediate-temperature rheological properties of surface layer and base layer bitumen

The rheological properties characterised by complex modulus and phase angle of bitumen are shown in Fig. 4. It is obviously found

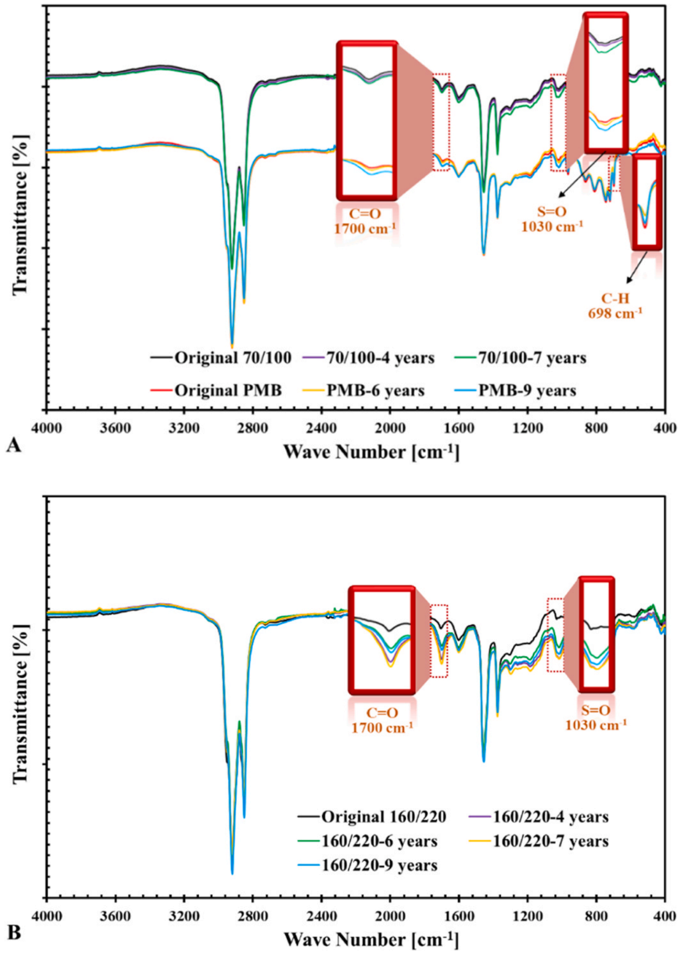

Fig. 3. The FTIR spectra of bitumen (A: PMB and 70/100 of surface layer; B: 160/220 of base layer).

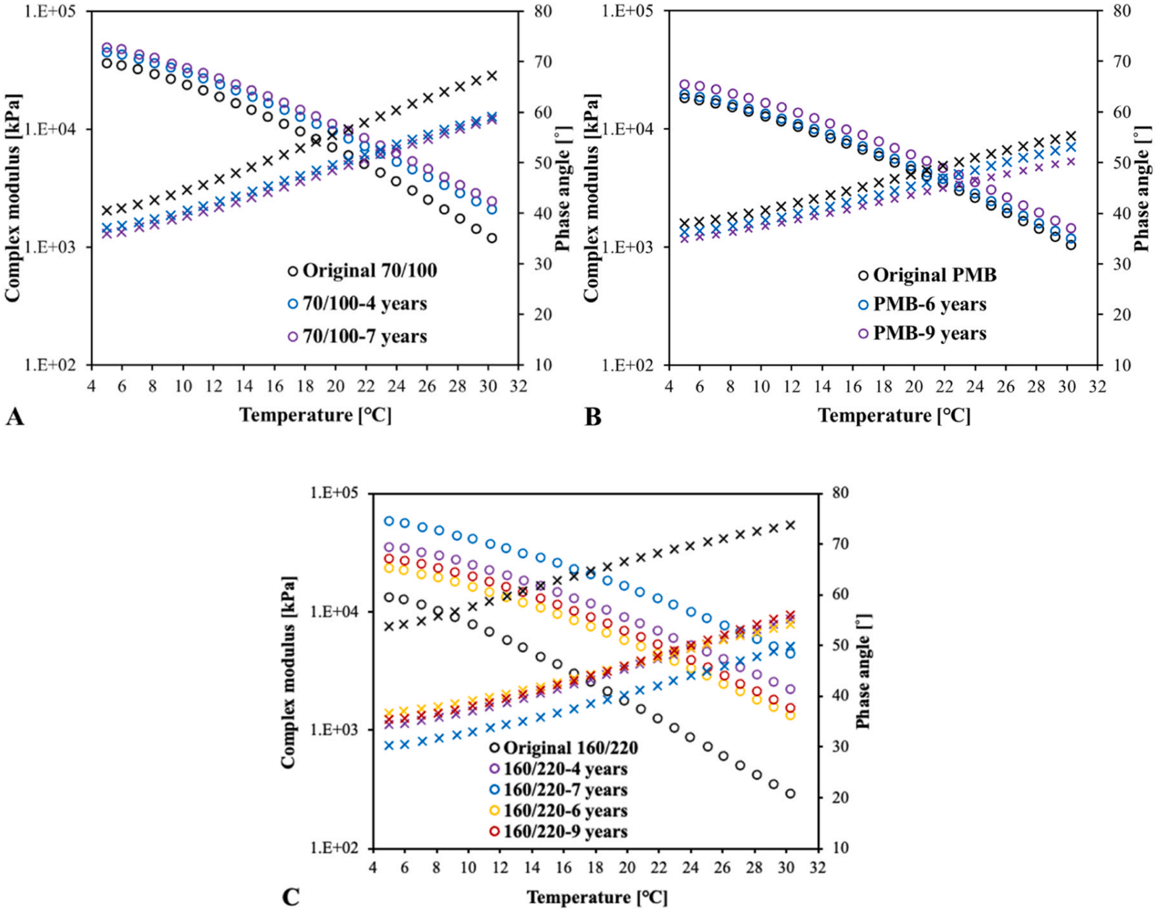

Fig. 4. The complex modulus and phase angle of bitumen (A: 70/100 of surface layer; B: PMB of surface layer; C: 160/220 of base layer).

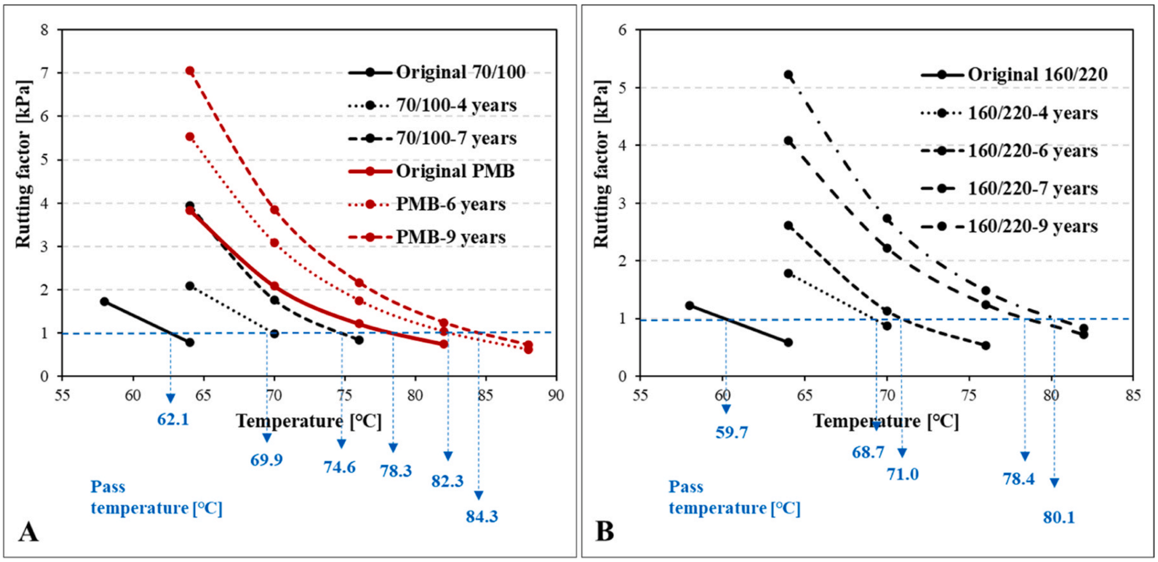

Fig. 5. The performance grade evaluation of bitumen (A: surface layer bitumen (70/100 and PMB); B: base layer bitumen).

that the complex modulus increased and the phase angle decreased over service time for the surface layer. This means the hardening and elastification occur during the service period, which is caused by bitumen ageing. Regarding the two bitumen types of the surface layer, the changes in two rheological parameters of 70/100 were slightly higher than that of PMB, revealing the better durability of PMB than 70/100. This result is in line with Raqiqa's results [45]. A worthy phenomenon of base layer bitumen (160/220) was found that the changes in complex modulus and phase angle were not related to service time. This fact is in line with the results of physical properties and chemical structure analyses, which originates from the surface layer biner type. Specifically, 160/200 with the surface layer bitumen of PMB was less influenced over service time than 160/200 with the surface layer of 70/100, which could be explained by the better ageing resistance and penetration resistance of PMB. In addition, the differences in complex modulus and phase angle between serviced base layer bitumen and original 160/200 are huge and higher than that of surface layer bitumen (both 70/100 and PMB). This phenomenon is similar to physical properties, which originates from the bad anti-ageing performance of 160/220.

3.4. Permanent deformation resistance

Fig. 5 reports the rutting factor curves for all bitumen conducted by performance grade test until failure that rutting factor is lower than 1 kPa, as well as corresponding pass temperature. As shown in Fig. 5A, the bitumen 70/100–4 years and 70/100–7 years has 12.6 % and 20.1 % higher pass temperatures than the reference bitumen, respectively. The pass temperatures of bitumen PMB-6 years and PMB-9 years are 5.1 % and 7.7 % higher than the one of the reference bitumen. The two types of bitumen of the surface layer had increased rutting factor after serving in the field, and the magnitude grade increased over service time. The pass temperature has the same changing trend as the rutting factor for surface layer bitumen. The rutting factor and pass temperature of base layer bitumen (160/220) are shown in Fig. 5B, ranking the two parameters in ascending order: original 160/220, 160/220–4 years, 160/220–6 years, 160/220–7 years and 160/220–9 years. This result implies that the two parameters are correlated to service time and the surface layer type, which proves that the base layer performance is determined by both surface layer bitumen and service time.

3.5. Anti-rutting ability and recovery property of bitumen

The MSCR test was employed to characterise the deformation resistance and recovery properties of served and original bitumen, the results of which are presented in Fig. 6. Higher *%R* and J_{nr} indicate better recovery ability and worse rutting resistance. As shown in Fig. 6 A, the long-term service period reduced around 80 % and 70 % J_{nr} values of PMB and 70/100 over service time, respectively, resulting in better rutting resistance. In terms of *%R* of surface layer bitumen, 70/100 showed an approximately 20 % increasing tendency over the service life, whereas it was a different circumstance for the PMB that the *%R* increased slightly and decreased after 9 years of servicing, suggesting the different recovery behaviours of the two surface layer bitumen due to the more complicated structure of PMB. Fig. 6B shows the *%R* and J_{nr} parameters of base layer bitumen (160/220). Serviced bitumen had generally increased *%R* and decreased J_{nr}. However, the changes in the two parameters did not vary over service time but the surface layer type presented a similar development trend as the changes in the physical, chemical and rheological properties of bitumen. The *%R* values of the bitumen 160/220–6 years and 160/220–9 years increase with the service life by about 5 times as much as the ones of bitumen 160/220–4 years and 160/220–7 years. It can be concluded that the properties of base layer bitumen are highly dependent on the surface layer bitumen type or performance.

3.6. Temperature and frequency-dependent characteristics of asphalt mixtures

The temperature and frequency-dependent characteristics of asphalt mixtures were analysed using the master curve of dynamic modulus as shown in Fig. 7. As the figure demonstrated, the dynamic moduli of surface layer mixtures with 70/100 changed dramatically after 4 and 7 years servicing, especially at higher frequencies (1.E+05–1.E+08) and lower frequencies (1.E-03–1.E-10). The findings indicate that the asphalt mixtures become stiffer and less sensitive to loading frequencies and temperatures, which is orginated from bitumen ageing and premature damages. The changes in dynamic moduli of surface layer asphalt mixtures are not

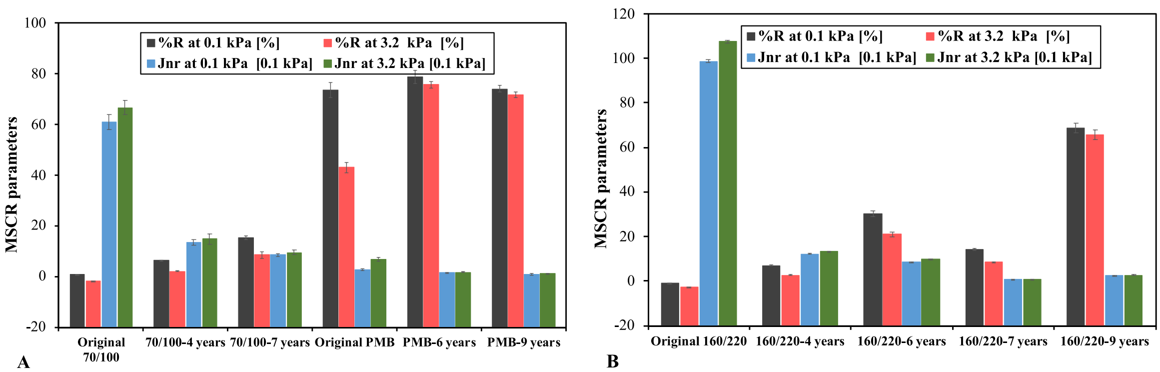

Fig. 6. *%R* and J_{nr} of surface (A) and base (B) layer bitumen.

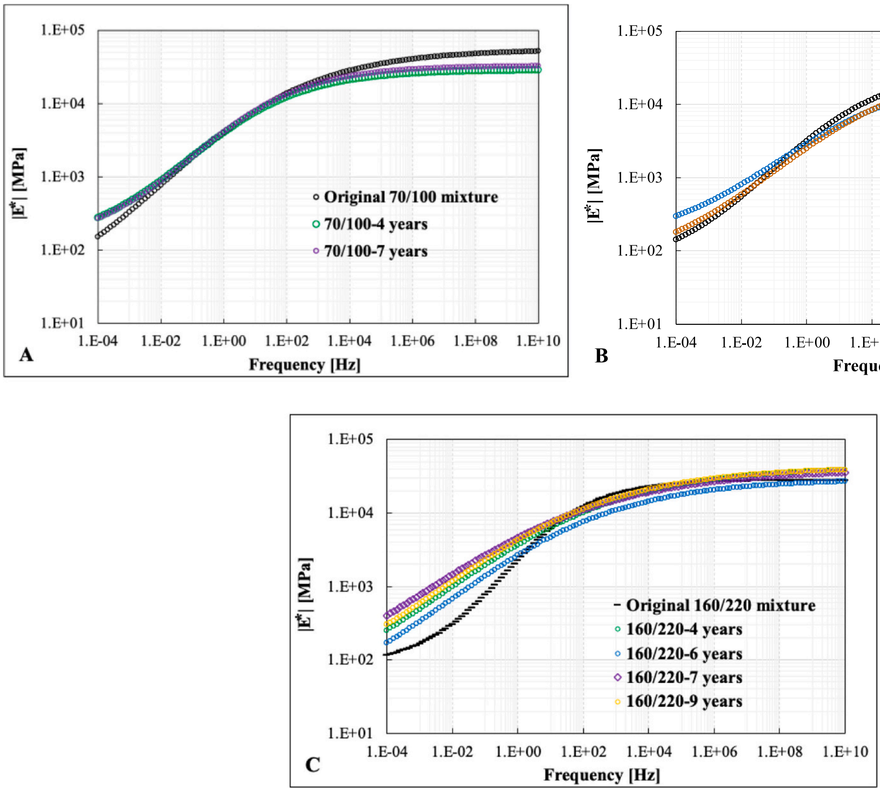

Fig. 7. The master curve of surface (A and B) and base layer mixtures (C).

strictly related to service time, which can be explained by the complex traffic loading and environmental effects on asphalt mixtures [46]. Compared with 70/100 surface layer (Fig. 7A), the surface layer of PMB mixtures (Fig. 7B) carried the minor detrimental effects as its dynamic modulus suffered the smaller variations, which is attributed to the stable structure and the addition of polymers within bitumen.

Regarding 160/220 asphalt mixtures of base layer shown in Fig. 7C, serviced asphalt mixtures had generally increased dynamic moduli at extreme temperatures (1.E+07–1.E+10 and 1.E-04–1.E+01), indicating higher stiffness after long-term service time. However, the changes in dynamic moduli were not varied over service time but the surface layer type, ranking the dynamic modulus in descending order: 160/220–7 years, 160/220–9 years, 160/220–4 years, 160/220–6 years, which represents surface layer with PMB leads to smaller changes in dynamic modulus of asphalt mixture than that with 70/100. The results imply that the surface layer bitumen plays a significant role in base layer mixture stiffness. The phenomenon of asphalt mixture stiffness is in line with the development trends of the physical, chemical and rheological properties of bitumen.

3.7. Statistical analysis of the base layer performance

As stated above, the base layer performance including bitumen and mixture properties is decided by both service time and surface layer bitumen and surface layer asphalt mixture properties. The asphalt mixture properties are greatly related to the bitumen type [34]. Thus, this section aims to quantitatively evaluate the significance of service time and surface layer bitumen type to base layer performance. The performance parameters of base layer bitumen (softening point, penetration, complex modulus, phase angle, PG (pass temperature), *%R* and J_{nr}) and asphalt mixture (dynamic modulus) were used for *MAPE* and correlation coefficient calculation.

Fig. 8 shows the *MAPE* results of the base layer. *MAPEs* reflect the variation of performance parameters of base layer bitumen and asphalt mixture with different service time under distinct surface layer bitumen layers. The higher *MAPEs* represent more significant variations in the performance parameters, indicating a more serious ageing degree. Moreover, the slope of *MAPEs* indicates the ageing speed of bitumen or asphalt mixture over service time, and a steeper slope implies higher sensitivity to ageing. Fig. 8A reflects the ageing degree of base layer bitumen calculated from physical properties increased with increasing service time. Moreover, both *MAPEs* and the slope of *MAPEs* curve of the base layer bitumen under the PMB surface layer was smaller than the one under the 70/100 surface layer. This result indicates that the ageing degree of the base layer is determined by not only the service time but also the surface layer bitumen type, and the ageing speed of the base layer is highly related to the bitumen type of the surface layer. The rheological properties, PG, anti-rutting ability of base layer bitumen and the mechanical properties of base layer asphalt mixtures showed the same trends in Fig. 8B, C, D and E. These results demonstrate that surface layer bitumen type is also a significant factor in base layer

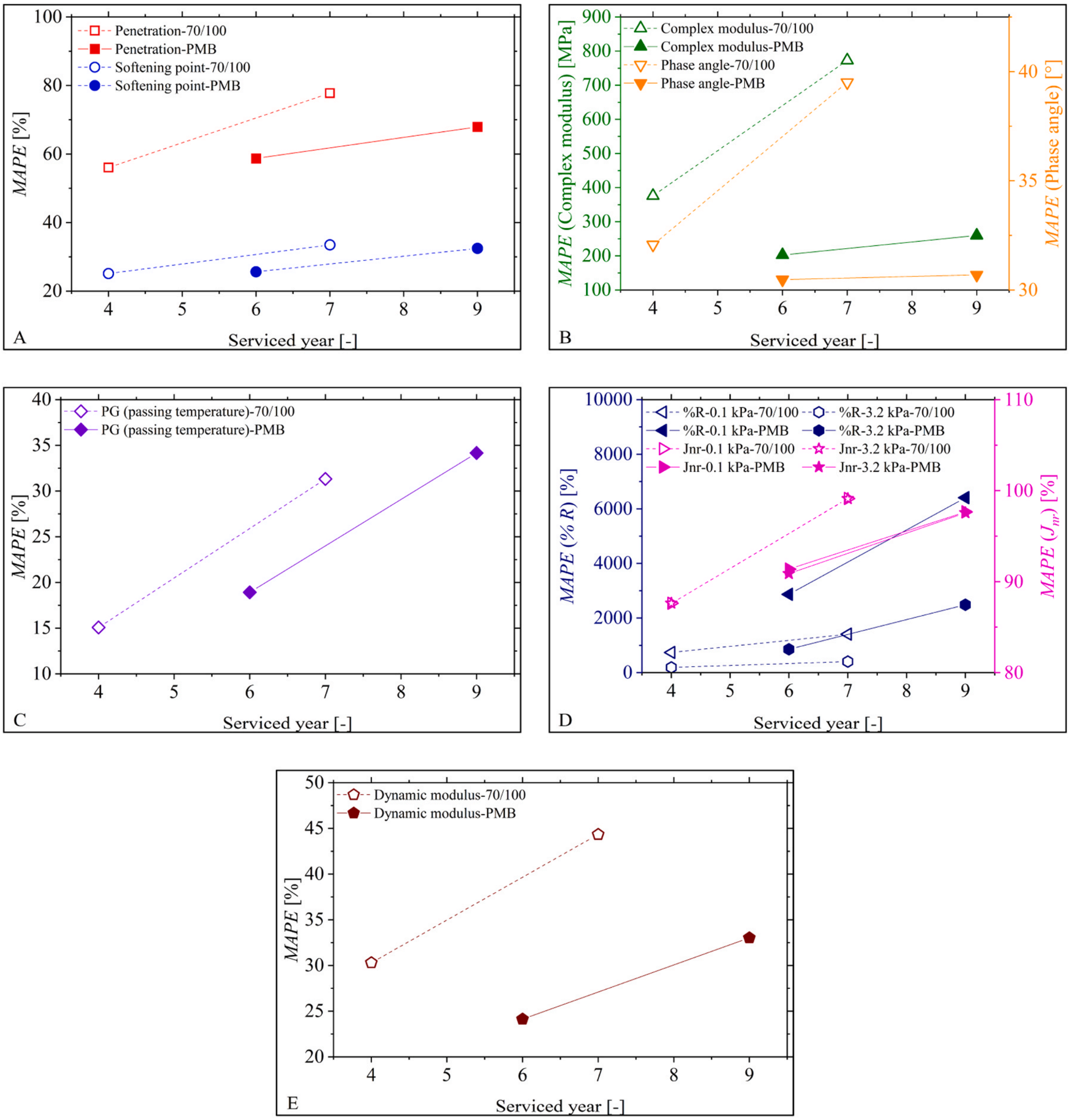

Fig. 8. *MAPEs* of difference performance after ageing for base layer bitumen 160/220: (A) physical properties, (B) rheological properties, (C) PG, (D) creep recovery properties and E dynamic modulus.

performance except for service time. An interesting phenomenon was found in %R in Fig. 8D, which showed that the base layer bitumen under the PMB surface layer had higher *MAPEs* and a steeper slope of *MAPE*s curve than that under 70/100 surface layer. These results originate from stiffer 70/100 and softer PMB of surface layer after servicing based on softening point and complex modulus results.

The correlation between service time, surface layer bitumen type and base layer performance was evaluated using Pearson correlation coefficient and eta squared and shown in Fig. 9, respectively. The higher Pearson correlation coefficient or eta squared indicates a greater correlation between two parameters. As the figure presented, most base layer performance was highly related to service time with a correlation coefficient over 0.8, demonstrating the great significance of service time on base layer performance. Similarly, the bitumen type of surface layer also plays an important role in base layer performance, especially in penetration, phase angle and J_{nr} with eta squared of 0.925, 0.976 and 0.988.

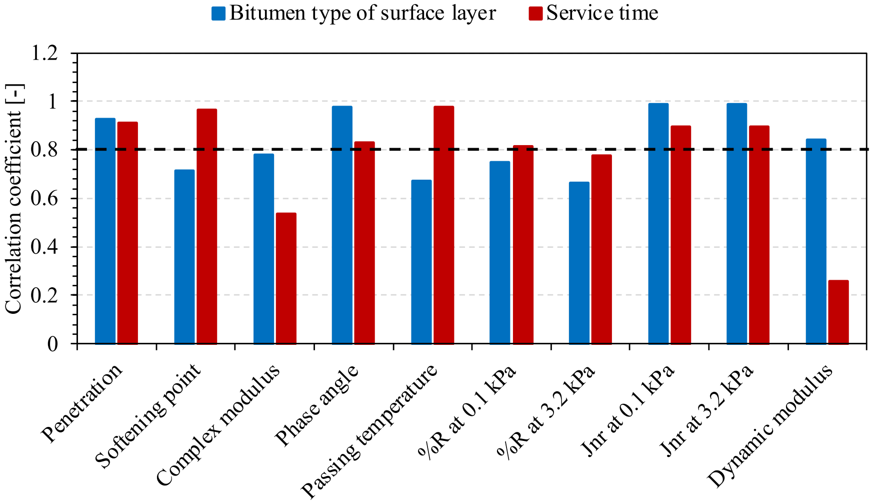

Fig. 9. Ccorrelation coefficient of base layer performance and service time (Pearson correlation coefficient) and bitumen type of surface layer (eta squared).

4. Conclusions

This study evaluated the bitumen and asphalt mixture performance of the surface layer and base layer extracted from in-service asphalt pavement over service time, as well as the influence of surface layer bitumen type on the bitumen and mixture performance of the base layer. Major conclusions were drawn as follows:

- Both surface layer and base layer bitumen were heavily aged after a long-term servicing regardless of bitumen type, resulting in increased softening point, complex modulus, rutting factor, pass temperature and percent recovery, more oxygen-contained chemical functional groups, decreased penetration, C-H groups, phase angle and non-recoverable creep compliance. Polymer modified bitumen (PMB) of the surface layer responded differently in recovery properties due to its complicated chemical structure.
- PMB showed better durability and anti-ageing properties compared to neat bitumen 70/100. The asphalt mixtures with PMB were less affected by external conditions than those with 70/100. Moreover, 160/220 of the base layer had a worse anti-ageing ability than the surface layer bitumen, presenting a greater performance change.
- The bitumen of the surface layer is greatly related to service time. In contrast, base layer bitumen performance was determined by not only the service time but also the surface layer bitumen type or performance. The asphalt mixtures showed a similar changing trend as bitumen. Therefore, PMB paved in the surface layer can not only prolong the lifespan of the surface layer but also alleviate the deterioration of the base layer, resulting in a much longer service life of asphalt pavement.
- Mean absolute percentage error (*MAPE*), Pearson correlation coefficient and eta squared results quantificationally indicated that the performance of the base layer was affected by the bitumen type of the surface layer and service time. The ageing speed of the base layer was highly determined by the bitumen type of surface layer, showing high correlation coefficients up to 0.988.

According to the conclusions stated above, this study is helpful in achieving a better understanding of the significance of surface layer bitumen on base layer performance and proposing more insights for constructing a durable and long service time asphalt pavement. Further studies involving laboratory ageing are recommended to compare with the field test, and the finite element analysis can be considered to investigate the influence of surface layer loading conditions on the mechanical behaviour of the base layer in the future, which aims to reveal the comprehensive understanding of the base layer performance development.

CRediT authorship contribution statement

Lei Zhang: Writing – review & editing, Methodology. **Rong Luo:** Writing – review & editing, Investigation. **Hao Chen:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Xuemei Zhang:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yu Liang:** Writing – review & editing. **Jianan Liu:** Writing – review & editing. **Fusong Wang:** Writing – review & editing.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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