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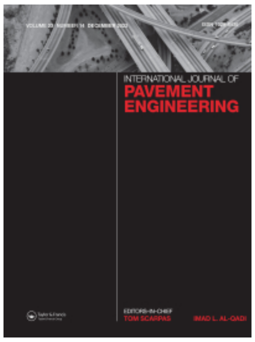

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Various methods to correlate the state of practice asphalt mixture laboratory aging conditioning methods with field aging durations

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ABSTRACT

The aging of asphalt pavements leads to less flexible asphalt mixtures that are prone to cracking and spalling. In this study, the relationship between lab and field aging was evaluated based on both theoretical asphalt aging models and practical asphalt and asphalt mixture performance tests. The results show that the corresponding field aging duration calculated using the mixture testing, especially the cracking test, is more conservative than the traditional aging models or binder rheological measurements. 5 and 12 days appear to simulate 16 and 38 years of field aging (in New Hampshire) for the top 12.5 mm pavement, respectively, based on the asphalt binder test results. In contrast, the theoretical aging model considers climatic conditions and suggests that 5 and 12 days simulate in-field aging of 6.2 and 15.0 years, respectively. The asphalt mixture test results indicate that the laboratory aging conditions simulate minimal field aging durations. This is because the damage to the asphalt pavement structure caused by climatic conditions and traffic loads is fully considered. This could be very useful for designing a more reliable and durable pavement incorporating intricate field conditions.

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KEYWORDS
Asphalt mixture; asphalt binder; aging; laboratory aging condition; field aging duration

1. Introduction

Asphalt aging could cause a decline in asphalt pavement performance (Jing *et al.* 2019, Hu *et al.* 2021, Sun *et al.* 2021). Pavement field aging is complex and subject to various environmental factors, including ambient temperatures, ultraviolet light, oxygen, and rain (Guo, Yin, *et al.* 2023, Guo, Zhang, *et al.* 2023b, Sun *et al.* 2023). Considering this, it is difficult to carry out studies targeting field aging of pavements, which is time-consuming and costly (Sirin *et al.* 2018). Therefore, the development of laboratory accelerated aging methods for asphalt mixtures is critical.

Various laboratory conditioning procedures were performed to prepare the long-term aged asphalt mixtures. For simulating 5–10 years of field aging, AASHTO R30 recommended placing compacted asphalt mixture specimens in an oven at 85°C for 120 h (Harrigan 2007). However, this aging method resulted in radially distributed aging gradients between the interior and surface of the asphalt mixture. Jacobs *et al.* found a relatively consistent trend in binder and loose mixture oven aging. For oven aging of compacted asphalt mixtures, both rheological characterisation and chemical characterisation indicated that the top layer shows the highest degree of aging, while the other layers have similar aging parameters and do not seem to be affected by the aging process (Jacobs *et al.* 2023). Omairey *et al.* performed aging simulations of asphalt pavements using a multiphysics field modelling approach. They found that the difference in oxygen content between the upper and lower layers of the pavement produces an oxygen pressure gradient that leads to differences in the degree of asphalt aging in the pavement structure (Omairey *et al.* 2023). In addition, the conditioning procedure has a single temperature and duration and does not consider field temperature and climate variations (Ling *et al.* 2017, Elwardany *et al.* 2018, Wen and Wang 2019). In contrast, conditioning of loose asphalt mixtures show more uniform and faster (better oxygen diffusion) compared to that of compacted samples (Elwardany *et al.* 2017). For aging conditioning, loose asphalt mixtures are typically placed in an oven at 135°C for 24 h which is expected to simulate field aging of 7–10 years (Asphalt Institute 2003, Ding *et al.* 2023). However, Petersen *et al.* found that high-temperature conditions (greater than 100°C) lead to thermal decomposition of the sulfoxide in the asphalt binder, affecting the cracking resistances of the mixtures (Petersen 2009, Rad *et al.* 2017). Hu *et al.* found that the oxidation of asphalt molecules from different fractions is significantly affected by temperature. Asphaltenes have the lowest oxidation temperatures, followed by polar aromatics and cycloalkyl aromatics. The aging of asphalt at higher temperatures easily overcomes the energy barrier of the cleavage reaction, leading to more pyrolysis accompanied by oxidation

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(Hu *et al.* 2020). The latest research from the National Cooperative Highway Research Program (NCHRP) 09-54 indicated that the optimum aging temperature for loose asphalt mixtures is 95°C, without causing chemical and performance changes in the asphalt binders (Branthaver *et al.* 1993, Kim *et al.* 2018, 2020).

Even though there are many different laboratory aging conditioning procedures for asphalt mixtures, it is also extremely important to establish a correlation between the laboratory conditioning procedures with the actual field aging durations to bridge the laboratory and field connections and for the purpose of evaluating the long-term performance of asphalt mixtures in laboratory. Elwardany *et al.* tested the asphalt binder carbonyl and sulfoxide absorbance data. They found that the loose asphalt mixtures aged at 95°C for 21 days had oxidation levels equivalent to those on the surface of the 8-year field core from McLean, Virginia (Elwardany *et al.* 2017). Zhang *et al.* compared the high-temperature PG values of laboratory and field-aged asphalt binders and found that loose mixtures aged at 85°C for 2, 5, and 7 days could simulate approximately 0, 1.8, and 3 years of field aging (in Iowa) for the top 38.1 mm pavement (Zhang *et al.* 2018). Besides, many studies have established a correlation between laboratory conditioning procedures and field aging durations using asphalt mixture performance tests. Islam *et al.* determined the laboratory conditioning equivalence of field aging using the indirect tensile strength test and found that the aging of asphalt mixture at 85°C for one day was close to one-year field duration (in New Mexico) for the top 50 mm pavement (Islam *et al.* 2015). Yin *et al.* identified the equivalent field aging durations of asphalt mixtures in seven field projects (surface layers) across the United States. They found that the aging durations corresponding to two weeks at 60°C and 5 days at 85°C in lab were equivalent to 7–12 months and 12–23 months in the field, respectively, using the resilient modulus and Hamburg wheel tracking tests (Yin *et al.* 2017). Based on the mixture complex modulus testing data from both lab and field-aged mixtures, Zhang *et al.* proposed that 95°C for 5 days aging condition could simulate the field aging of 4 years (in New Hampshire) for the top 12.5 mm pavement, respectively, and found that the field pavement surfaces aged the most, with the aging rate decreasing as the pavement depth increased (Zhang *et al.* 2019). As described above, various methods have been used to investigate the correlations between the laboratory conditioning procedures and field aging durations for asphalt mixtures and flexible pavement. However, the same laboratory aging conditioning procedure might be correlated to the different field aging durations based on the testing methods and materials as well as the local climatic conditions. At present, there is a lack of comprehensive study to systematically evaluate the relationship between lab and field aging using the disparate methods. To this end, this study is motivated to comprehensively compare and correlate the relationship between laboratory conditioning procedures and field aging durations through both theoretical asphalt aging models and practical asphalt and asphalt mixture performance tests.

In this study, the laboratory aging procedures (5 and 12 days at 95°C) were used as the mediate and long-term aging conditions of the four laboratory-produced asphalt mixtures. Next, the field aging durations corresponding to these two levels of laboratory aging condition were determined using the various methods that can be generally grouped into three categories including: (1) using existing aging models, e.g. climatic aging index (CAI) model and cumulative degree-days (CDD); (2) using binder rheological properties measured from binder testing, e.g. bending beam rheometer (BBR) test and frequency and temperature sweep test using dynamic shear rheometer (DSR), and (3) using asphalt mixture

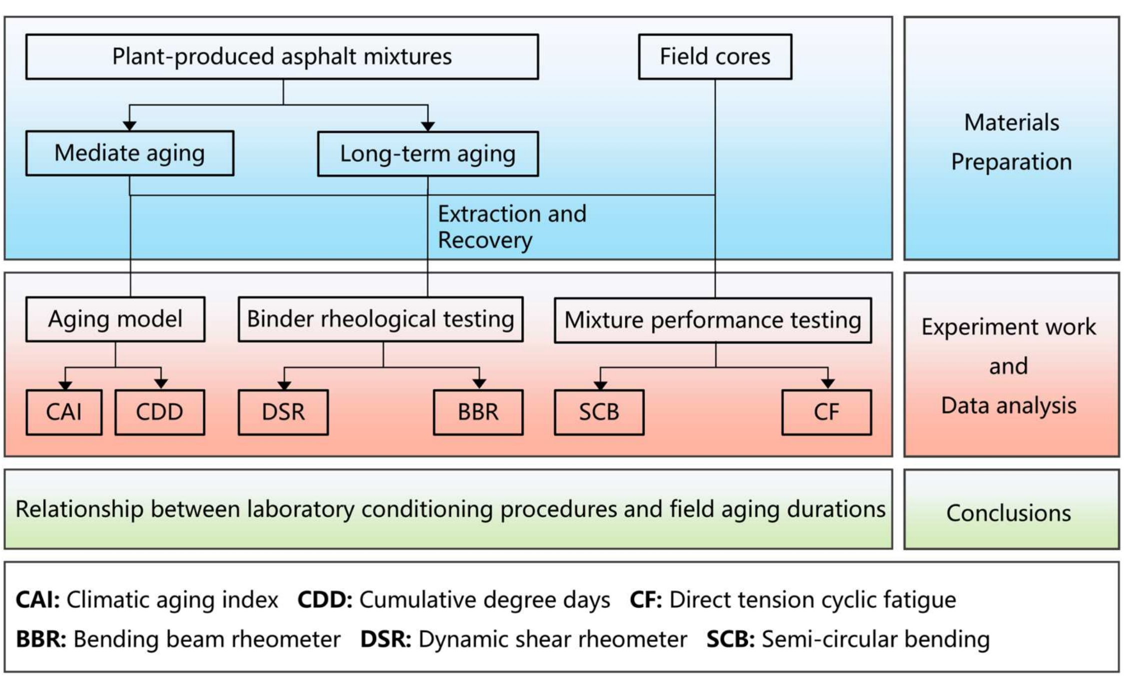

Figure 1. Research flow chart.

performance measured from the disparate performance tests, e.g. dynamic modulus (E*), semi-circular bending (SCB) and direct tension cyclic fatigue (CF) tests. The relationships between laboratory and field aging obtained from the different methods were then compared and evaluated. The research flow chart showing the overall framework of this study is illustrated in Figure 1.

2. Material

Four plant-mixed laboratory-compacted asphalt mixtures (aggregates with a nominal maximum particle size of 12.5 mm) were prepared and evaluated in this study. The asphalt binders were all unmodified binders. These mixtures were collected from the same asphalt plant. The following abbreviation system was used to identify the asphalt mixtures with different designs: 'Binder performance grade (PG) – Recycled asphalt content', as shown in Table 1. For example, PG5234-RA20, 'PG5234' indicates a high-temperature PG of 52°C and a low-temperature PG of 34°C for the virgin asphalt binder in the mix, 'RA20' represents that the ratio of the recycled asphalt binder weight to the total asphalt binder weight is around 20% in the mix. In this study, the binders with the same PG were of the same source and the only difference between the two mixtures with the same PG was the RAP content.

3. Methodology

3.1 Aging method

Four loose asphalt mixtures (PG5234-RA20, PG5234-RA30, PG5828-RA20, and PG5828-RA30) were subjected to short-term aging (STA) during field production (AASHTO 2002). For mid-term and long-term aging (LTA), the loose asphalt mixture were placed in the oven at 95°C for 5 and 12 days. After aging, the loose asphalt mixtures were heated at 135°C for two hours for sample fabrication for laboratory performance testing. The air void of the laboratory specimen was controlled at 6 ± 0.5%. In addition to lab aging, these four asphalt mixtures were placed in the corresponding field sections in 2018, and sample cores were drilled from the field sections (within the wheel path) in 2023 (around 5 years in service) with a diameter of 150 mm and a height of 37.5 mm. Table 2 lists the air voids of the field cores.

Notably, there is a difference in the air voids between the different asphalt mixtures potentially due to the construction variation and traffic compaction effect. Furthermore, the air voids of the field cores are also different with the lab compacted specimens, which should be taken into consideration when comparing the performance data measured from the cores and the laboratory specimens. This will be described in detail in the following sections.

Table 1. The asphalt mixture information.

Mixture ID	Virgin binder grade	NMAS (mm)	Total binder content (%)	Recycled binder content (%)
PG5234-RA20	PG 52-34	12.5	5.5	20
PG5234-RA30	PG 52-34	12.5	5.5	30
PG5828-RA20	PG 58-28	12.5	5.5	20
PG5828-RA30	PG 58-28	12.5	5.5	30

3.2 Extraction and recovery of asphalt binders

The obtained field cores were 37.5 mm in height and were cut into two layers horizontally with a thicknesses value of 12.5 and 25 mm, respectively, and then subjected to asphalt binder extraction and recovery processes. The specific flow chart is shown in Figure 2. The layers and laboratory-produced asphalt mixtures were broken into small particles by hammering and then soaked in a trichloroethylene solution for 30 min to dissolve the asphalt binder on the surface of the aggregates. The asphalt mixture quick separator was used to filter coarse aggregates. The centrifuge was then used to obtain the solution without fine aggregate particles and mineral powders. The extraction and recovery of the asphalt binder from the remaining solution was performed using a rotary evaporator under a nitrogen atmosphere at a temperature of 140 ± 3°C according to ASTM D7906-14 (Rajib *et al.* 2021). The extracted and recovered asphalt binder was then poured into containers. The recovered binder was confirmed to be solvent-free and used for subsequent performance testing.

3.3 Climatic aging index (CAI)

The climatic aging index (CAI) proposed by Project NCHRP 09-54 based on the kinetic model was used to determine the laboratory aging durations matched to field aging, defined as Equation (1) (Elwardany *et al.* 2018, Kim *et al.* 2020). It can be applied to different pavement depths since it is calculated using hourly pavement temperature data. The detailed calculation procedure could be found in our previous studies (Kim *et al.* 2021).

$$t_{oven} = \mathrm{CAI} = \sum_{i=1}^{N} 0.0437 d^{-0.426} e^{\frac{-1601.167}{T_i}} \quad (1)$$

where t_{oven} is the laboratory aging duration at 95°C corresponding to field aging; d represents the depth of interest; T_i is equal to the temperature at the time and depth of interest. To calibrate the CAI model, the 10 years historical temperature

Table 2. Air voids for samples from field cores.

Mixture ID	Replicates	PG5234-RA20	PG5234-RA30	PG5828-RA20	PG5828-RA30
Dynamic modulus test	Replicate 1	4.83%	4.43%	5.26%	6.65%
	Replicate 2	4.37%	5.01%	2.56%	7.57%
	Replicate 3	6.85%	7.48%	4.59%	2.14%
	Replicate 4	5.69%	6.03%	3.49%	3.74%
	Average	5.41%	5.74%	3.91%	5.03%
	Standard deviation	1.09%	1.34%	1.19%	2.52%
SCB test	Replicate 1	7.23%	9.03%	12.00%	8.06%
	Replicate 2	7.47%	9.31%	12.12%	8.24%
	Replicate 3	12.12%	11.38%	3.89%	7.39%
	Replicate 4	14.18%	11.40%	2.82%	7.49%
	Average	10.25%	10.28%	7.71%	7.79%
	Standard deviation	3.45%	1.29%	5.05%	0.42%

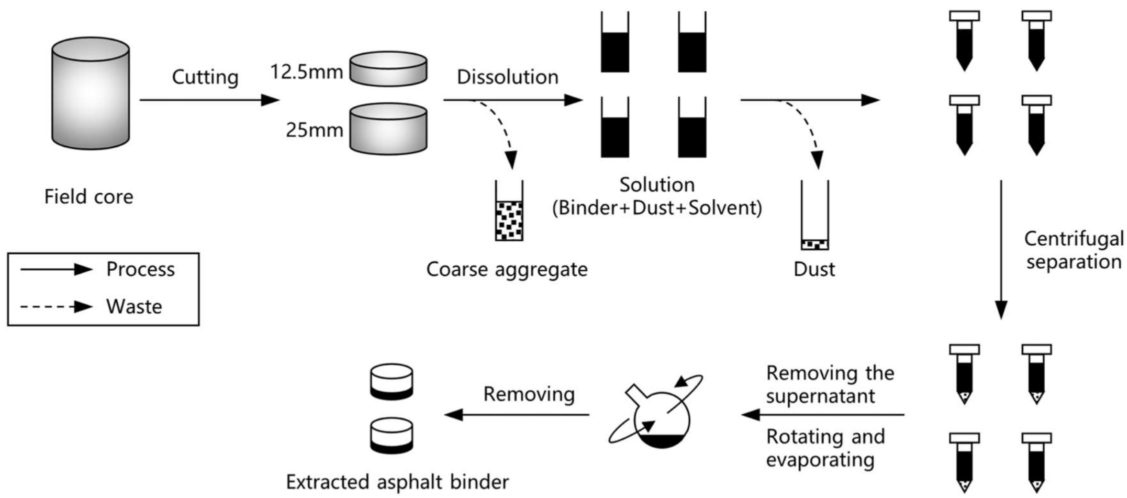

Figure 2. Flow diagram of binder extraction and recovery from the specimens.

data was extracted from the weather station that is closest to the project location to compute the T_i using the enhanced integrated climactic model (EICM).

3.4 Cumulative degree days (CDD)

Considering the effects of climate and construction period, the cumulative degree days (CDD) parameter was used to measure the aging degree of the asphalt in the field. According to Chen *et al.* the asphalt pavement temperature for each day above the base temperature is counted as a certain number of degree-days (2018). CDD is defined as the sum of all these degree-days from the start of construction to the core drilling, as shown in Equation (2).

$$\mathrm{CDD} = \sum_{i=1}^{n} \max(T_{\max,i} - 32, 0) \tag{2}$$

where n is the number of days in the time period from construction to coring, and $T_{\max,\ i}$ is equal to the maximum daily temperature in Fahrenheit for day i.

3.5 Testing and analysis methods

3.5.1 Bending beam rheometer (BBR) test

ΔT_c was calculated based on the bending beam rheometer (BBR) test results to characterise the resistance of asphalt binder to unloaded cracking, as shown in Equation (3). A more negative value of ΔT_c indicates that the asphalt binder is more prone to cracking. The ΔT_c values of -2.5°C and -5.0°C are usually used as the crack warning and limit values, respectively (Rowe 2011, Zhang, Moshfeghi, *et al.* 2023).

$$\Delta T_c = T_{cr}(\text{stiffness}) - T_{cr}(\text{m-slope}) \tag{3}$$

where T_{cr} (stiffness) and T_{cr} (m-slope) are the low-temperature grading temperature determined from stiffness and m-slope.

3.5.2 Glover-Rowe (G-R) parameter

The Glover-Rowe (G-R) parameter was used to evaluate the cracking susceptibility of asphalt binders. The frequency sweep tests were performed using a dynamic shear rheometer (DSR) with a 4 mm plate at 5°C, 15°C, and 25°C in the frequency range of 100–0.1 rad/s (Sui *et al.* 2011). The master curves of complex shear modulus and phase angle were then established and the G-R parameter was calculated at a temperature-frequency combination of 15°C - 0.005 rad/s, as indicated in Equation (4). A lower G-R parameter represents a better cracking resistance of the asphalt binder. Asphalt binder cracking begins to occur when the G-R parameter is greater than 180 kPa, and significant cracking occurs when the G-R parameter is greater than 600 kPa (Anderson *et al.* 2011).

$$G - R = \frac{|G*|(\cos\delta)^2}{\sin\delta} \tag{4}$$

where G^* and δ are the complex shear modulus and the phase angle of the asphalt binder.

3.5.3 Asphalt binder oxidation aging model

To quantitatively simulate field aging, the oxidative aging model proposed by Project NCHRP 09-54 was used in this study to establish the relationship between laboratory aging methods and field aging durations (Jin *et al.* 2011, Kim *et al.* 2020). The G-R value of 15°C, 0.005 rad/s was used as an aging indicator, as shown in Equation (5). Among them, k_c and k_f were obtained by optimising the G-R parameters of extracted asphalt binder after STA and 95°C aging conditions. After that, each asphalt binder was treated with least squares error optimisation to determine M.

$$\log G - R = \log G - R_0 + k_c t + M(1 - e^{-k_f t}) \tag{5}$$

where $G\text{-}R_0$ represents the $G\text{-}R$ parameter of asphalt binder extracted from the mixtures after STA; t is the aging duration at 95°C; k_c, $k_{f,}$ and M are all the model coefficients.

3.5.4 Dynamic modulus (E*) test

The composite modulus test was used to characterise the linear viscoelastic properties of asphalt mixtures. The test was conducted using an Asphalt Mixture Performance Tester (AMPT) on 150×100 mm cylindrical specimens (110×38

mm for field cores) in accordance with AASHTO TP132 (Wu *et al.* 2017, Saleh *et al.* 2020). The dynamic modulus (E^*) and phase angle (δ) of the asphalt mixtures were obtained by testing three replicate samples at three temperatures (4.4, 21.1, and 37.8°C; 2.9, 18.0, and 30.0°C for field cores) with each at six loading frequencies (25, 10, 5, 1, 0.5, and 0.1 Hz). Subsequently, the master curves of dynamic modulus (E^*) and phase angle (δ) were constructed with a reference temperature of 20°C (Su *et al.* 2018). Considering the lower air void of field core can result in a higher modulus but lower phase angle, the research team used a correction factor of 7% per 1% air void change (Li and Youtcheff 2018) to adjust the modulus and phase angle values of field cores to compare the values with laboratory specimens.

3.5.5 Semi-circular bending (SCB) test

The semi-circular bending (SCB) test was used to examine the medium-temperature fracture properties of asphalt mixtures. The test procedure was carried out with a single load loading at 25°C and a 0.5 mm/min loading rate. The fracture energy (G_f) was calculated based on the obtained load-displacement curve to evaluate the cracking resistance of the asphalt mixture, as indicated in Equation (6) (Zhang, Gu, *et al.* 2023). Considering the combined effect of the fracture energy and the slope at the inflection point, the Illinois flexibility index (FI) was then calculated using Equation (7) (Al-Qadi *et al.* 2019, Zhou *et al.* 2020).

$$G_f = \frac{W_f}{A_{lig}} \quad (6)$$

$$FI = \frac{G_f}{|m|} \quad (7)$$

where W_f is the work of fracture, equal to the area under the load-displacement curve; A_{lig} is the fracture area; and m is the slope at the inflection point of the load-displacement curve after the maximum load.

The FI value was also adjusted based on the air voids of field cores to compare to the laboratory specimens, as shown in Equation (8) (Barry 2016, Batioja-Alvarez *et al.* 2019):

$$FIAVcorrected = FI * \frac{0.0651}{AV - AV^2} \quad (8)$$

where FI is the measured Illinois flexibility index; and AV is the air void of the field cores.

3.5.6 Direct tension cyclic fatigue (CF) test

Direct tension cyclic fatigue (CF) test was used to examine the fatigue resistance of the asphalt mixture. The test was conducted on 130 × 100 mm specimens (110 × 38 mm for field cores). After the samples were pretreated by holding at a temperature equal to $(\frac{PGHT - PGLT}{2} - 3)$°C, they were subjected to the direct tensile cyclic fatigue test by AASHTO TP 107. The fatigue damage evolution of asphalt mixtures was then predicted based on the simplified viscoelastic continuous damage (S-VECD) model using FlexPave™ software. The D^R failure criterion was calculated in Equation (9). D^R is the average reduction in pseudo-stiffness per loading cycle, describing the average decrease in material integrity until failure (Wang and Richard Kim 2019).

$$D^R = \frac{\int_0^{N_f} (1 - C)}{N_f} \quad (9)$$

where N_f represents the number of cycles to failure; C is the pseudo-stiffness.

4. Results and discussion

4.1 Correlating using existing theoretical methods/models

4.1.1 Climatic aging index calculation

Figure 3 shows the CAI calculation results. The dashed line is the fitted curve based on the calculated values at the different pavement depth. It is observed that a more severe laboratory aging condition (duration@95°C) correspondingly simulates a longer time of field aging at a given pavement depth. The field aging duration gradually increases with the increase of pavement depth for the same laboratory aging condition. For instance, 5 days at 95°C laboratory aging condition simulates 5.3 years of field aging near pavement surface, while 12 days at 95°C laboratory aging condition can simulate 12.7 years. This indicates that there is an aging gradient within the pavement structure. The surface of the asphalt pavement ages faster than the material in the layer with a deeper depth, which can be attributed to the warmer temperature and better oxygen access/diffusion as well as the solar illumination effect near the pavement surface. The CAI modelling result suggests that 5 days at 95°C laboratory aging condition is equivalent to 6.2 years of field aging at a depth of 12.5 mm, and 12 days at 95°C laboratory aging condition corresponds to 15.0 years of field aging based on the local climate data.

4.1.2 Cumulative degree-days (CDD) result

Chen *et al.* comprehensively evaluated the relationships between the different laboratory aging conditioning methods and the field aging durations as quantified by the CDD based on the measured rheological properties of both lab-aged binders and binders from the field cores (top 1 inch). The result indicated that 5 days at 95°C laboratory aging condition can be used to simulate around 50,000–80,000 CDD of field aging duration (Chen *et al.* 2018). Considering 8900 CDD per year that is calculated using the local climate data, this laboratory aging conditioning level is expected to simulate 5.6–8.9 years of field aging, which is in line with the observations from the CAI model. The 12 days at 95°C aging level is extrapolated to simulate about 13–20 years of field aging duration.

4.2 Correlating using binder data

4.2.1 Δt_c value

Figure 4 shows the ΔT_c value for the binder samples extracted and recovered from the four mixtures and the corresponding field cores. Field core L1 represents the asphalt binder extracted from the surface layer of the field core (12.5 mm thickness) and Field core L2 represents the asphalt binder

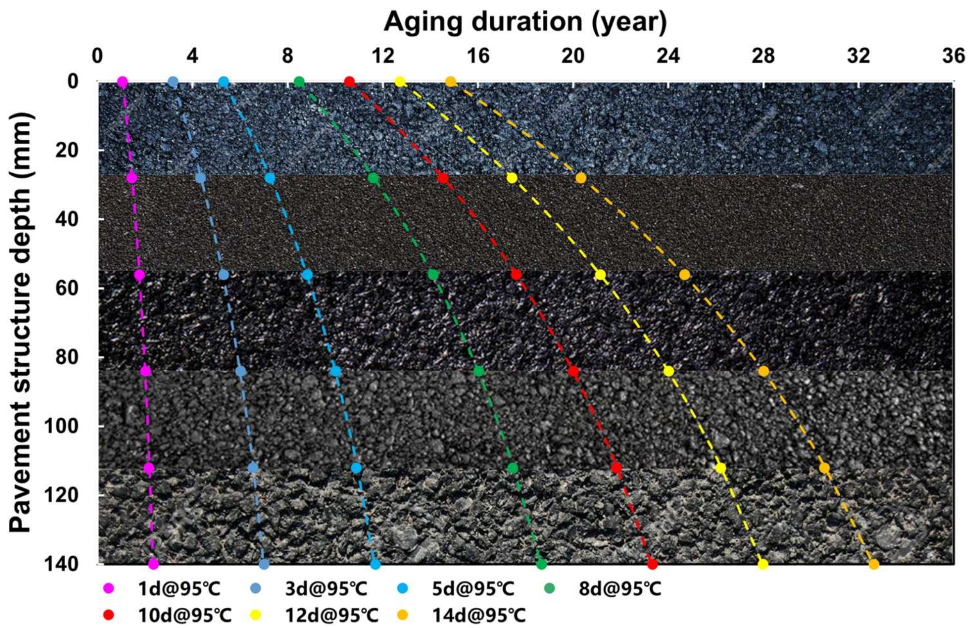

Figure 3. Relationship between field aging duration and pavement depth based on CAI calculation results.

extracted from the bottom of the field core (25 mm thickness). The red dashed line and the red solid line represent the cracking warning value (−2.5°C) and the cracking limit value (−5.0°C), respectively.

As shown in Figure 4, the ΔT_c values of these mixtures were all lower than -5.0°C after 12 days aging, implying that the binders have a high susceptibility to thermal cracking. For the mixtures with the same recycled asphalt content, the ΔT_c value using PG5234 asphalt binder is greater than that using PG5828 asphalt binder. This difference may be due to the type of asphalt binder. The ΔT_c values increase as the pavement depth increases, indicating that there is an aging gradient within the pavement structure in the field and the surface layer exhibits the highest deterioration level. For these mixtures, the ΔT_c values for the first layer reach the thermal cracking warning value, indicating that a thermal cracking may occur. ΔT_c values for all field cores were in between the STA and 5 days aging conditions, implying that 5 days laboratory aging condition is expected to simulate greater than 5 years of field aging.

4.2.2 G-R parameter

Figure 5 illustrates the G-R parameter for binders extracted and recovered from samples. The red dashed line and the red solid line represent the cracking warning value (180 kPa) and the cracking limit value (600 kPa), respectively.

Similar to the results of the ΔT_c values, the G-R parameters of these mixtures are all higher than the cracking warning value after 12 days aging, as shown in Figure 5. This means that they are prone to durability cracking problems. After 5 days aging condition, the G-R parameters of PG5234-RA30 and PG5828-RA30 are respectively higher than that of PG5234-RA20 and PG5828-RA20. The explanation for this phenomenon is that the elastic component of the blended asphalt increases and the viscous component decreases as the recycled asphalt content increases, resulting in a more brittle (lower δ) and harder (higher G^*) asphalt that is prone to durability cracking problems (Zhang *et al.* 2020). Zhou *et al.* also found that the increase in recycled asphalt content is detrimental to the cracking resistance of asphalt

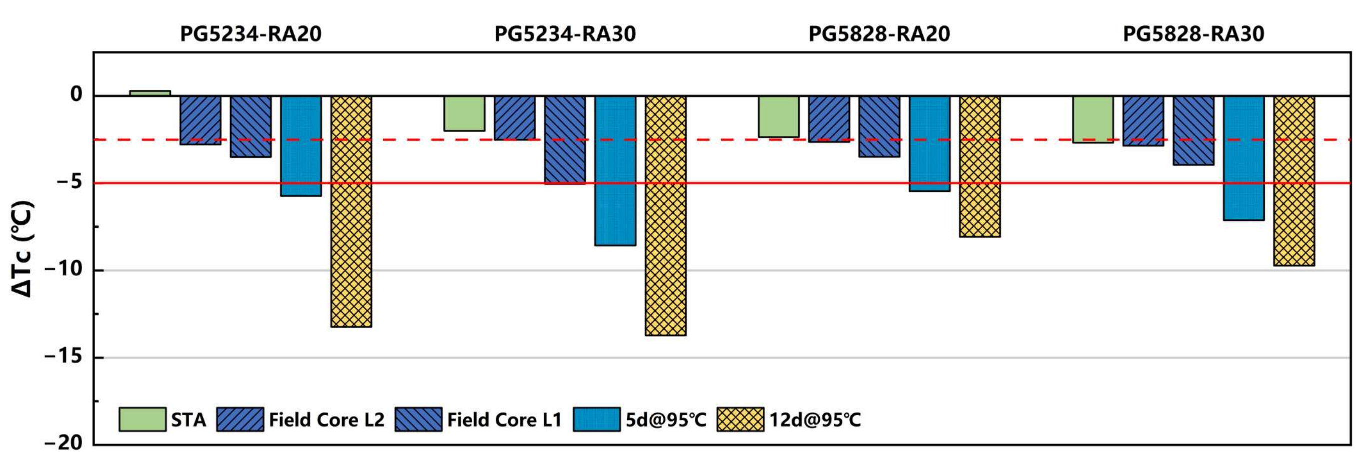

Figure 4. ΔT_c value for the binder samples extracted and recovered from the four mixtures at different laboratory aging levels and field cores.

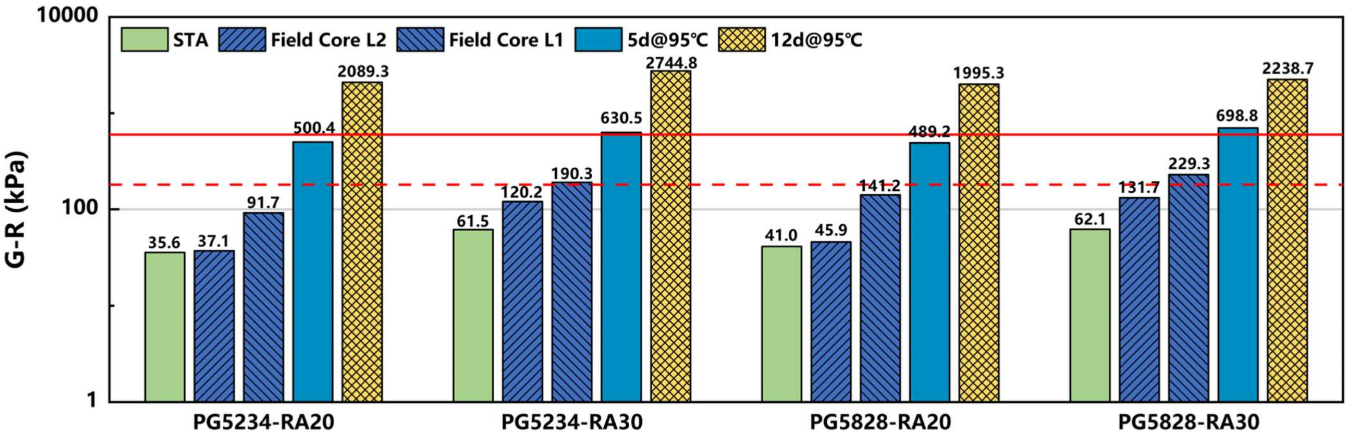

Figure 5. G-R parameter for the binder samples extracted and recovered from the four mixtures at different laboratory aging levels and field cores.

binder (Zhou *et al.* 2022). The G-R parameters for the surface layer of PG5234-RA30 and PG5828-RA30 are greater than 180 kPa. This implies that the surface layer is at risk for durability cracking. For the four asphalt mixtures, the G-R parameters for 5 days aging condition are greater than and closest to that for the surface layer of the field cores. Therefore, the 5 days at 95°C laboratory aging condition is expected to simulate more than 5 years of field aging. Considering the significant differences between the properties of field cores and those of laboratory specimens, further determination of laboratory conditioning procedures corresponding to field aging durations is required.

4.2.3 Quantitative simulation of the aging gradient using laboratory conditioning methods

Figure 6 shows the calibrated models. Where *M* is related to the material itself, with higher values of *M* representing higher oxidative sensitivity of the material. For the same type of asphalt binder, the *M* value shows a decreasing trend as the recycled asphalt content increases, indicating a slower aging rate (Luo *et al.* 2018, Ingrassia *et al.* 2020). When the asphalt mixtures contain the same recycled asphalt content, the PG5234 asphalt binder shows a higher aging rate than the PG5828 asphalt binder, which may be related to the PG of the asphalt binder.

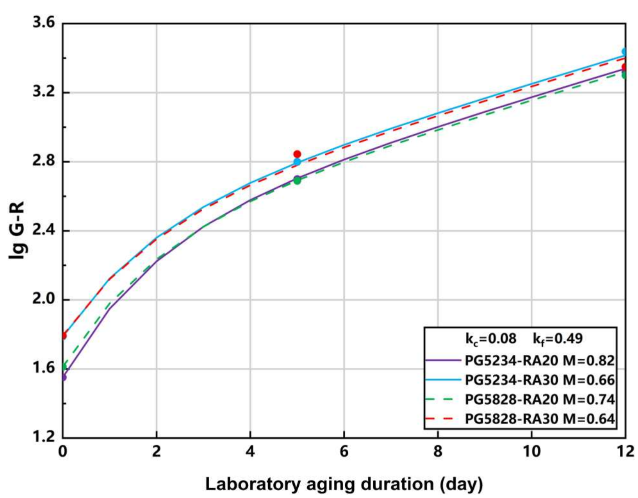

Figure 6. The calibrated model.

With the calibrated model in Figure 6, the laboratory aging durations corresponding to the aging duration of two layers for the field cores are determined, as shown in Table 3. The corresponding laboratory aging durations for the two layers are 1.6 and 0.5 days, respectively. This suggests that asphalt material in the first layer ages about 3.2 times faster than the second layer. Based on the above data, it can be noted that 5 days aging condition can simulate approximately 16 years of aging for the 12.5 mm surface layer in the field, while 12 days can simulate about 38 years of field aging.

4.3 Correlating using mixture data

4.3.1 Linear viscoelastic (LVE) properties

The master curves of dynamic modulus and phase angle can be constructed by means of the time-temperature superposition principle (TTSP). Considering the effect of the air void on the dynamic modulus, the results of the field core specimens were corrected, as shown in Figure 7 (represented by PG5234-RA20). The corrected dynamic modulus decreases and the phase angle increases. This suggests that the dynamic modulus correction by changes in the air void is necessary to accurately establish the relationship between the laboratory specimens and field cores.

Figure 8 shows the corrected dynamic modulus and phase angle master curves for the PG5234-RA20 and PG5234-RA30 with different laboratory conditions and the corresponding field cores. The dynamic modulus increase, and the phase angle decrease as the mixture ages, resulting in asphalt mixtures with a high susceptibility to cracking. The field cores and asphalt mixtures aged for 5 days show similar dynamic modulus and phase

Table 3. Laboratory aging durations corresponding to the 5 years for two layers of field cores.

	Laboratory aging duration (day)/(Log G-$R_{field\ core}$)				
Layers	PG5234-RA20	PG5234-RA30	PG5828-RA20	PG5828-RA30	Average
Layer1	1.1 (2.0)	1.6 (2.3)	1.6 (2.1)	2.1 (2.4)	1.6
Layer2	0.1 (1.6)	0.8 (2.1)	0.1 (1.7)	1.0 (2.1)	0.5

*Log G-$R_{field\ core}$ is the log G-R value of the field core sample used to determine the equivalent laboratory aging duration.

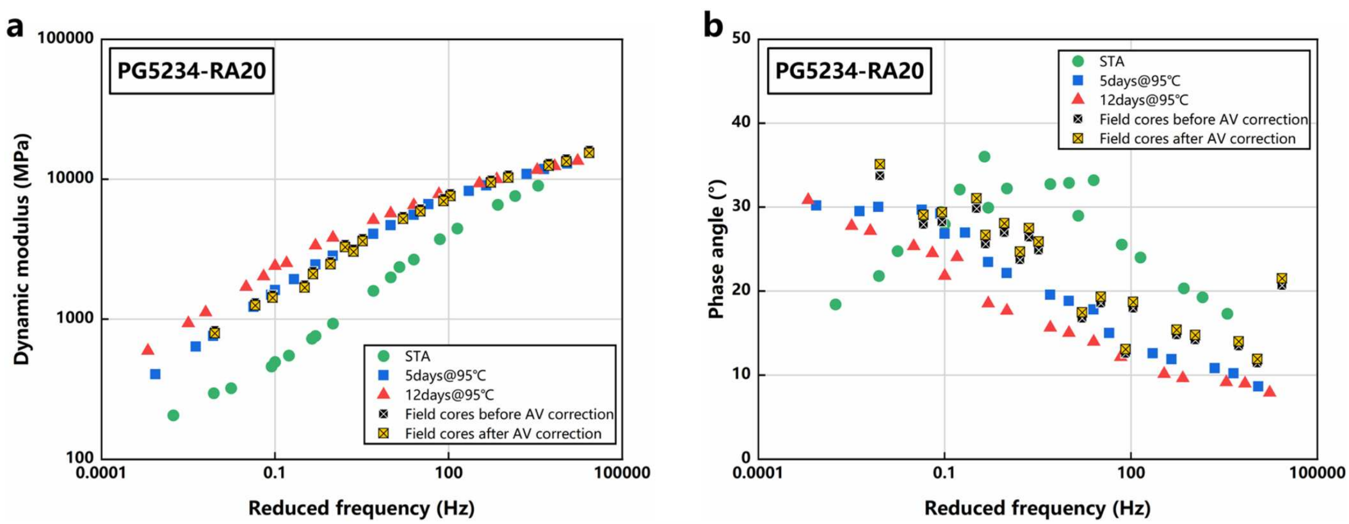

Figure 7. Comparison of dynamic modulus and phase angle for PG5234-RA20 at different laboratory aging levels with field cores before and after AV correction.: (a) dynamic modulus and (b) phase angle.

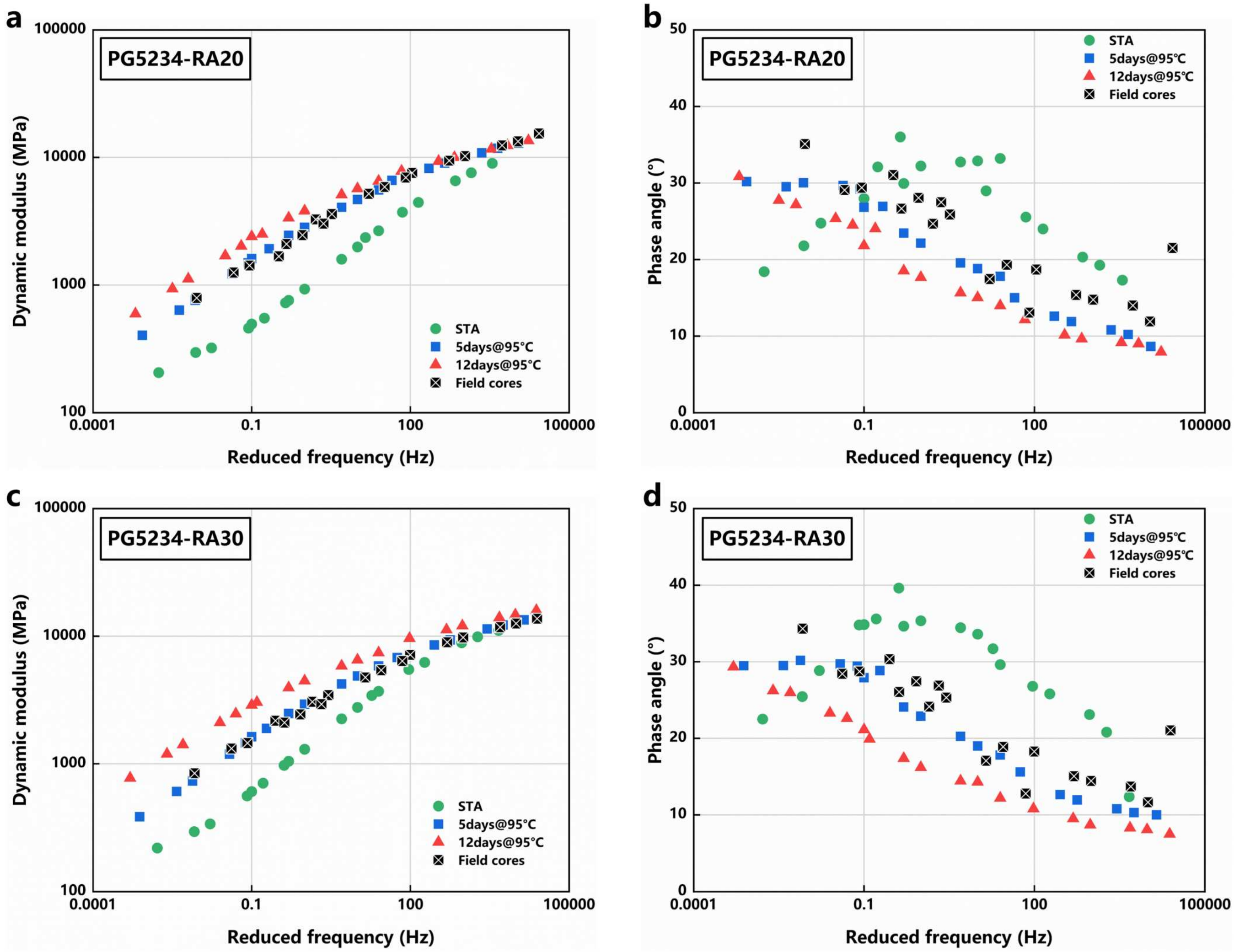

Figure 8. Comparison of dynamic modulus and phase angle for (a) PG5234-RA20 and (c) PG5234-RA30; and phase angle master curves for (b) PG5234-RA20 and (d) PG5234-RA30 at different laboratory aging levels with 5 years of field cores.

angles, while there are large differences in dynamic modulus and phase angles with asphalt mixtures after STA. Therefore, the linear viscoelastic properties results suggest that 5 days at 95°C laboratory aging condition is expected to simulate approximately 5 years of field aging. The results for the PG5828 mixtures are similar to the observations for the PG5234 mixtures.

4.3.2 Fracture properties

Figure 9 shows corrected Illinois flexibility index (FI) values for asphalt mixtures at different laboratory aging levels and the field cores. It should be noted that the test was repeated three times for each mixture and the displayed results were the average of the three test results. For the field cores, the FI values corrected by air void are smaller than the uncorrected FI values due to the fact that the air voids of the SCB test samples for the field cores are typically higher than those of the laboratory specimens. The large difference between the FI values before and after correction illustrates the necessity of air void correction for direct comparations. It can be observed that the FI values show a decreasing trend as the aging level of the asphalt mixture increases. Compared with the STA aging condition, the FI value decreases by 61.5%−71.6% after 5 days aging condition and 71.8%−78.8% after 12 days aging condition. This indicates that aging leads to a severe decrease in the cracking resistance of asphalt mixtures, especially in the first 5 days aging when the cracking resistance decreases rapidly. The FI values of both the laboratory specimens and the field cores decrease with the increase of recycled asphalt content for the same asphalt binder. This suggests that higher recycled asphalt content adversely affects the crack resistance of asphalt mixtures. This is consistent with the findings of Wang *et al.* (2020). They found that increased recycled asphalt content increases the cracking sensitivity of asphalt mixtures and tends to cause cracking problems. Notably, the corrected FI values of the field cores are close to those of the asphalt mixtures after 5 days aging condition. This means that the 5 days aging condition appears to simulate about 5-year aging in the field.

4.3.3 Fatigue properties

Figure 10 shows the D^R values obtained from the CF tests, averaged over the results of three replicates. A higher D^R value represents a better fatigue resistance of the asphalt mixture. As expected, the mixtures after the STA show the highest D^R value, indicating the best fatigue resistance. The D^R values decrease with the increase of the aging duration and show a similar trend to the FI values. However, the differences among the D^R values of the two long-term aging conditions are small. Compared with STA, the D^R values of the mixtures after 5 days aging condition decrease significantly by about 15%−21%, while the D^R values of the mixtures after 12 days aging condition decrease by approximately 20%−31%. This indicates that the fatigue resistance of asphalt mixtures decreases the fastest in the first 5 days, and then the decrease slows down, which is similar to the results of the SCB test. When the aging conditions are the same, the D^R values of PG5828-RA20 and PG5234-RA20 are generally higher than those of PG5828-RA30 and PG5234-RA30. This suggests that the increased recycled asphalt content further reduces the fatigue resistance of the asphalt mixtures (Zhang *et al.* 2022). It is worth noting that the D^R values of the field cores are all smaller than those of the asphalt mixtures under laboratory aging conditions. On the one hand, this could be attributed to the relatively smaller air voids of the field cores. On the other hand, the field cores had experienced 5 years of repetitive traffic loading, jeopardising the sample integrity of the field cores and leading to worse fatigue resistance. The results based on D^R values suggest that both 5 days and 12 days laboratory aging conditions are insufficient to simulate 5 years of field aging, which is inconsistent with the conclusions from the dynamic models and fracture properties sections.

4.4 Discussion of the difference in disparate methods

The correspondence between the laboratory conditioning and field aging durations was obtained using different methods, as summarised in Table 4. It can be observed that there is a

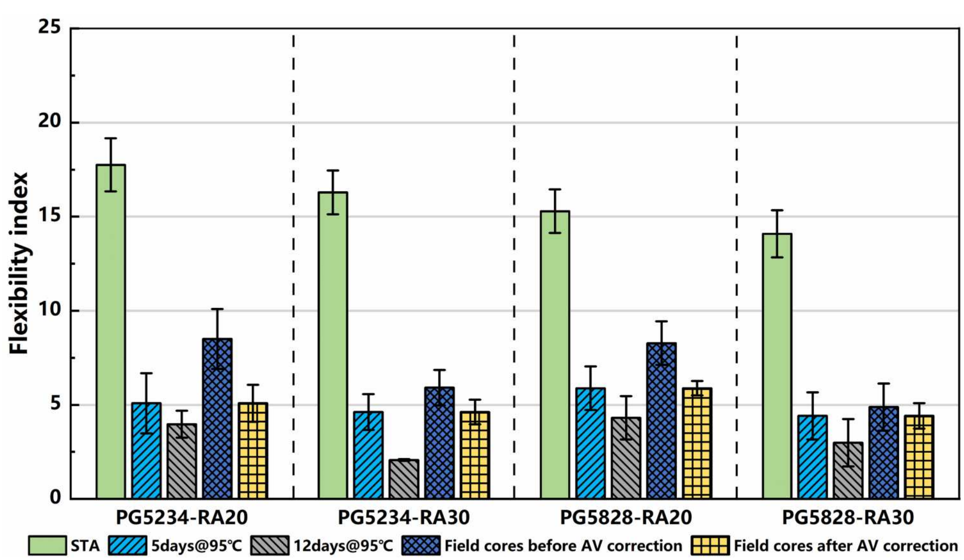

Figure 9. FI values of asphalt mixtures at different laboratory aging levels and field cores.

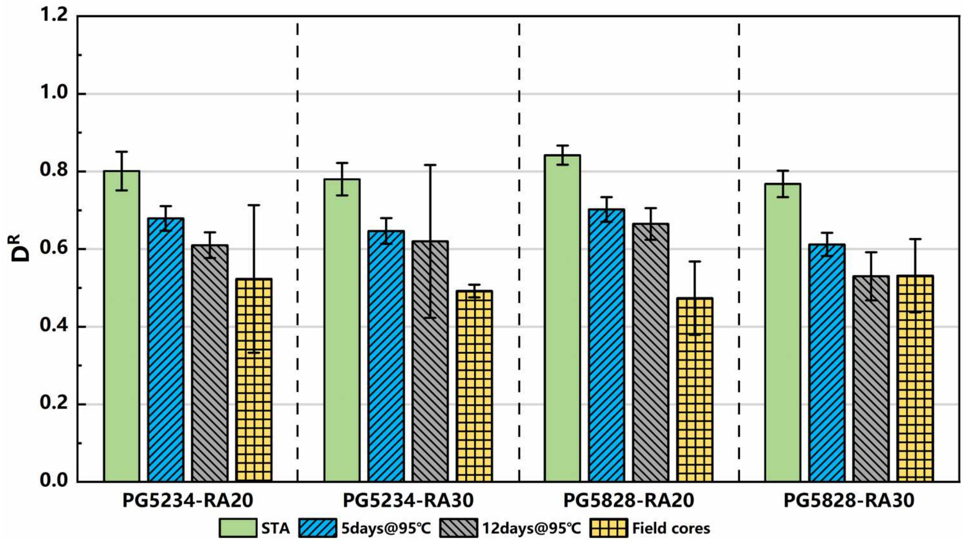

Figure 10. D^R values of asphalt mixtures at different laboratory aging levels and field cores.

Table 4. Comparison between the results from theoretical methods, binder tests and mixture tests.

	Field aging duration (year)					
	Theoretical methods		Binder data	Mixture data		
Lab aging duration	CAI	CDD	G-R	E*	FI	D^R
5d@95°C	6.2 (12.5 mm)	5.6–8.9	16	5	5	<5
12d@95°C	15.0 (12.5 mm)	13–20	38	>5	>5	<5

significant difference between the correspondences obtained by the three methods. The field aging durations obtained based on the asphalt binder test results are higher than those of the theoretical method and the least based on the asphalt mixture test results. The results of the theoretical asphalt aging method and the asphalt binder performance test show that 5 days aging condition is expected to simulate approximately 7 and 5.6–8.39 years of field aging, respectively. However, the asphalt mixture performance test results indicate that 5 days aging condition only simulated less than or equal to 5 years of field aging. Similarly, 12 days aging condition show a similar trend. There are some reasons to explain these differences: (1) There may be residual solvents (e.g. trichloroethylene) in the asphalt during the extraction process, which can alter the properties of the asphalt binder; (2) asphalt binder and RAP are fully blended after extraction and recovery, whereas the blending is not uniform in the mixture state; (3) the theoretical aging models and the binder tests employed in this study for correlating the laboratory and field aging in this study only evaluate the rheological properties of the asphalt rather than the cracking and fracture properties as revealed by the mixture performance testing; (4) the mixture testing also considers the effect of volumetric properties and the potential damage to the field cores caused by traffic loading for the correlation analysis. Overall, it can be observed that the corresponding field aging duration calculated using the mixture testing especially the cracking test is more conservative than the traditional aging models or binder rheological measurements, which evaluates the correlation beyond the traditional linear viscoelastic range of asphalt and considers many other factors for the correlation, e.g. RAP and virgin material blending, volumetric change and traffic-induced micro-damage. This could be very useful for design of a more reliable and durable asphalt mix/pavement incorporating the intricate field conditions.

5. Summary and conclusion

The purpose of this study was to compare and correct the relationship between laboratory aging conditions and field aging durations. This study consisted of four asphalt mixtures and corresponding field cores evaluated for viscoelasticity, fracture resistance, and fatigue resistance using dynamic modulus, SCB, and CF tests. The rheological properties of their extracted binder samples were tested using BBR and DSR tests. The CAI and CDD modelling were used to calculate the field aging durations corresponding to different laboratory aging conditions based on climatic conditions. The following important conclusions can be drawn:

(1) The CAI and CDD modelling results suggest that 5 days at 95°C laboratory aging condition is expected to simulate approximately 6.2 years of field aging, while 12 days at 95°C laboratory aging condition is expected to simulate approximately 15.0 years of field aging.
(2) The oxidative aging models based on G-R parameters indicate that asphalt material in the first layer ages about 3.2 times faster than the second layer. The 5 days laboratory aging condition can simulate approximately 16 years of aging for the 12.5 mm surface layer in the field, while 12 days laboratory aging condition can simulate about 38 years of field aging.
(3) The viscoelasticity and fracture properties results suggest that 5 days laboratory aging condition can simulate about 5 years of field aging, while the fatigue performance results show that 5 days laboratory aging condition is not sufficient to simulate 5 years of field aging.
(4) The field aging durations obtained based on the asphalt binder performance results are higher than those of the theoretical aging model. This may be due to residual

solvents in the extracted binder and recycled asphalt in the mixtures affecting the performance of the asphalt binder.

(5) The corresponding field aging durations in the asphalt mixture test are shorter due to the fact that these experiments take full account of the climatic environment and the structural damage caused by 5-year traffic loading.

6. Future work

This study investigates the relationship between field aging and laboratory aging of asphalt pavements under New Hampshire climatic conditions and using the local material base. Given the differences in climatic data and materials between sites, the conclusions of this study may not be directly applicable to different sites with different climatic conditions or asphalt pavements. But the overall methodology introduced in this study could be employed by other pavement researchers and engineers to correlate and compare the relationship between lab aging and field aging using local materials and climatic conditions. In future studies, we plan to further investigate the relationship between field aging and laboratory aging of asphalt pavements extensively by combining climatic data and field pavement performance data from multiple regions. At the same time, we also plan to establish the relationship between field aging and laboratory aging through the chemical characterisation of asphalt.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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