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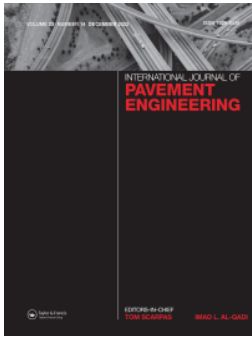
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RESEARCH ARTICLE



Effect of medium-term oven aging (MTOA) on the age-related and fatigue cracking performance of asphalt mixes containing recycled materials

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ABSTRACT

In this study, a medium-term oven aging (MTOA) protocol of 20 h at 100 °C was applied to loose plant-produced mixes to evaluate the age-related and fatigue cracking resistance of asphalt mixes containing recycled materials. To evaluate the age-related cracking resistance, the indirect tensile IDEAL cracking tolerance test was performed on 27 plant-produced mixes, and fatigue cracking resistance was evaluated using the four-point bending (4PB) test on four selected mixes. MTOA resulted in an increase in strength and a reduction of the cracking tolerance index (CT_{Index}), while the fracture energy did not change much. Overall, the indirect tensile strength increased on average by 150 kPa (somewhat uniform shift for different mix types), and the CT_{Index} decreased by approximately 38% on average, indicating that the change in the CT_{Index} value depended on the short-term aged value. Based on 4PB test results, MTOA resulted in an increase of the dynamic modulus of the four mixes between 10% and 30% at 20 °C and 1 Hz, and a reduction of approximately 50% for the 4PB fatigue life for three out of the four mixes at strain levels of 400–700 $\mu\epsilon$, which are typical of thin overlays on cracked pavements. The fourth mix showed little effect of MTOA on 4PB fatigue life.

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(RAS); recycling agent (RA)

Introduction

Asphalt mixes age in service, changing the stiffness, affecting the cracking under environmental conditions (age-related cracking), and fatigue cracking (cracking under repeated traffic loading) properties. All asphalt binders age, and some asphalt binders age faster than others. Therefore, evaluating the cracking resistance of the corresponding unaged asphalt concrete may produce misleading conclusions regarding longer-term performance (Bell et al., 1994b; Rahman et al., 2023b). The permanent deformation properties affecting surface rutting will nearly always improve with ageing. Balanced mix design (BMD) for asphalt mixes is based on measuring relevant properties for critical distress mechanisms and ensuring that a mix is ‘balanced’ in its design and when placed during construction, meaning that it meets performance-related property requirements for all the distress mechanisms. For the implementation of BMD, it is important to simulate the longer-term ageing of asphalt mixes in the laboratory to assess their effect on the stiffness and cracking properties, which is the focus of this paper.

BMD is intended for use in routine mix design and construction quality testing. BMD, including longer-term aging assessment, therefore requires tests and material conditioning processes that fit within constraints for time, cost, and complexity. This paper presents results for a medium-term ageing protocol that is likely to fit within those constraints and its effects on mix stiffness, resulting from an age-related cracking test, and a fatigue cracking test. This paper also discusses preliminary ideas for developing performance-related specifications (PRS) using the ageing protocol and those tests.

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Different researchers have proposed different laboratory ageing techniques for the simulation of asphalt pavement field ageing (Al-Qadi et al., 2019; Chen et al., 2018; Kim et al., 2018; Rahman et al., 2024a; Zahid and Rahman, 2025; Zhou et al., 2025). Some have considered the ageing of compacted asphalt concrete (AC) specimens (Al-Qadi et al., 2019; Bell and Abwahab, 1994a; Harvey & Tsai, 1997; Rahbar-Rastegar et al., 2018), while others have suggested the ageing of loose AC mixes (Chen et al., 2018; Kim et al., 2018; Rahman et al., 2024a; Zahid and Rahman, 2025; Zhou et al., 2025). The current AASHTO R121 specification proposed five different laboratory ageing procedures (A–E) to simulate the long-term field aging of asphalt mixes. Both compacted and loose specimens were considered for the long-term oven aging (LTOA) by AASHTO R121. Also, depending on the ageing methods (A–E), the ageing temperature varies between 85 °C and 135 °C, and the ageing duration varies between 6 h and 5 days.

Temperature selection for LTOA of AC mixes is still a point of debate for the research community. The disturbance of the polar molecular groups and sulfoxide decomposition for the asphalt binders were reported at temperatures greater than 100 °C, which may not occur during long-term field aging (Kim et al., 2018; Petersen, 2009). Therefore, many researchers have adopted an oven ageing temperature of 95 °C for LTOA (Al-Qadi et al., 2019; Kim et al., 2018; Rad et al., 2017). However, using a lower ageing temperature (e.g. 95 °C) may require longer ageing times in the laboratory to match ageing in the field at the surface than are feasible for quality control (QC)/quality assurance (QA) purposes for BMD implementation. To solve this issue, Rahman et al. (2024a) proposed a medium-term oven aging (MTOA) protocol, which includes a lower oven aging temperature (100 °C) with a shorter aging period (20 h, overnight in a production laboratory) and is expected to simulate the aging to mid-life (2–15 years, depending on the depth and the climate region) for a given asphalt pavement (Rahman et al., 2024a, Caltrans, 2025). It was reported by Rahman et al. (2024a) that loose mix oven ageing of 20 h at 100 °C simulated field ageing 0.5–2.2 in (12–56 mm) depth after 6–8 years of service in hot California climate regions. As the ageing parameters of asphalt change almost linearly after initial short-term ageing, MTOA may be sufficient to predict long-term performance of asphalt pavement with a shorter turnaround period for QC/QA purposes (Petersen, 2009).

MTOA is applied to the loose mix, either batched and produced in the laboratory and first subjected to short-term oven ageing or produced in the plant, where the effects intended to be simulated by laboratory short-term oven aging occur as part of the plant mixing process (Rahman et al., 2024a, Caltrans, 2025). The main reason to apply MTOA as part of performance-related testing (PRT) for BMD is that age-related cracking and fatigue cracking of thin asphalt layers, two of the main asphalt pavement distress mechanisms, are likely to occur in aged asphalt concrete. The use of the MTOA in the laboratory is expected to better predict the age-related cracking and fatigue cracking performance of AC pavement after long-term field aging than testing on short-term aged mix or mix sampled at the plant and tested directly. The ageing duration (20 h) for MTOA is selected as the time that the mix can spend in the oven close to one workday, and the compaction of the MTOA-conditioned samples for PRT can be done at the start of the next day. Recent research has shown that the temperature and access to the air history of the asphalt mix, prior to specimen fabrication, have a considerable effect on the outcome of some PRT results (Elkashef et al., 2022). MTOA is also expected to reduce PRT results variability associated with silo time (time spent in silos before AC mixes are transported to the job site) and the ageing footprint during loose mix sampling, handling, and storage for AC mixes containing recycled materials.

Various recycled materials have been used in the maintenance, rehabilitation, and construction of new asphalt pavements to enhance their environmental sustainability and reduce their life cycle costs (Al-Qadi et al., 2007; Newcomb & Epps, 1981). The evaluation of mix performance following MTOA is also expected to provide a better idea of the effects of higher percentages of recycled asphalt pavement (RAP), and the inclusion of recycled asphalt shingles (RAS), and recycling agents (RA) than short-term aging because greater blending of recycled asphalt occurs with additional aging, and there is the potential that some RAs may lose some of their beneficial effects with longer-term aging. The use of high contents (greater than 15%) of RAP and the use of RAS in asphalt pavement is currently under investigation (Al-Qadi and Ozer, 2015; Dinis-Almeida et al., 2012; Newcomb & Epps, 1981; Rahman et al., 2023a, 2025). The most common techniques to counterbalance the effects of highly aged RAP/RAS binders are to use softer virgin binders and to use a suitable RA. Owing to the application of RA for RAP/RAS mixes, it is important to evaluate the efficiency of RA after extensive ageing for AC mixes containing RA. The effect of

ageing on the mechanical properties of AC mixes containing recycled materials is a crucial question. The addition of aged binder (fewer volatile materials available for further ageing) from RAP/RAS is expected to reduce the ageing rate of AC mixes and cause minimal change in stiffness after ageing.

There have been few studies on the effects of extensive ageing (LTOA/MTOA) on the age-related and fatigue cracking performance of AC mixes containing RAP, RAP/RAS, and RA. Also, it is important to know the dependency of the longer-term performance of asphalt pavement on the virgin binder source/mix type. Based on this problem statement, the objectives of this study are to evaluate:

- The effects of MTOA on the stiffness and age-related cracking performance of AC mixes containing RAP/RAS and RA.
- The effects of virgin binder source on the age-related cracking performance of AC mixes.
- The effect of MTOA on the variability of performance-related test (PRT) results.
- The effects of MTOA on the flexural stiffness and fatigue performance of AC mixes.

Materials and methods

Experimental design

Figure 1 shows the overall flow diagram of this study. The dataset considered in this study includes 27 plant-produced mixes that were sampled in metal buckets between 2020 and 2024. A summary of the mixes is shown in Table 1. In this study, a wide variety of mixes was considered, including hot mix asphalt (HMA) with plain binders, gap-graded rubberised hot mix asphalt (RHMA-G), HMA with polymer-modified binders (HMA-PM), and HMA with 100% RAP binder (HyRAP). Four different binder sources (Source VB, Source M, Source SJ, and Source VW) were considered in this study to evaluate the effect of binder sources on the longer-term performance of AC mixes. For mixes containing high RAP content

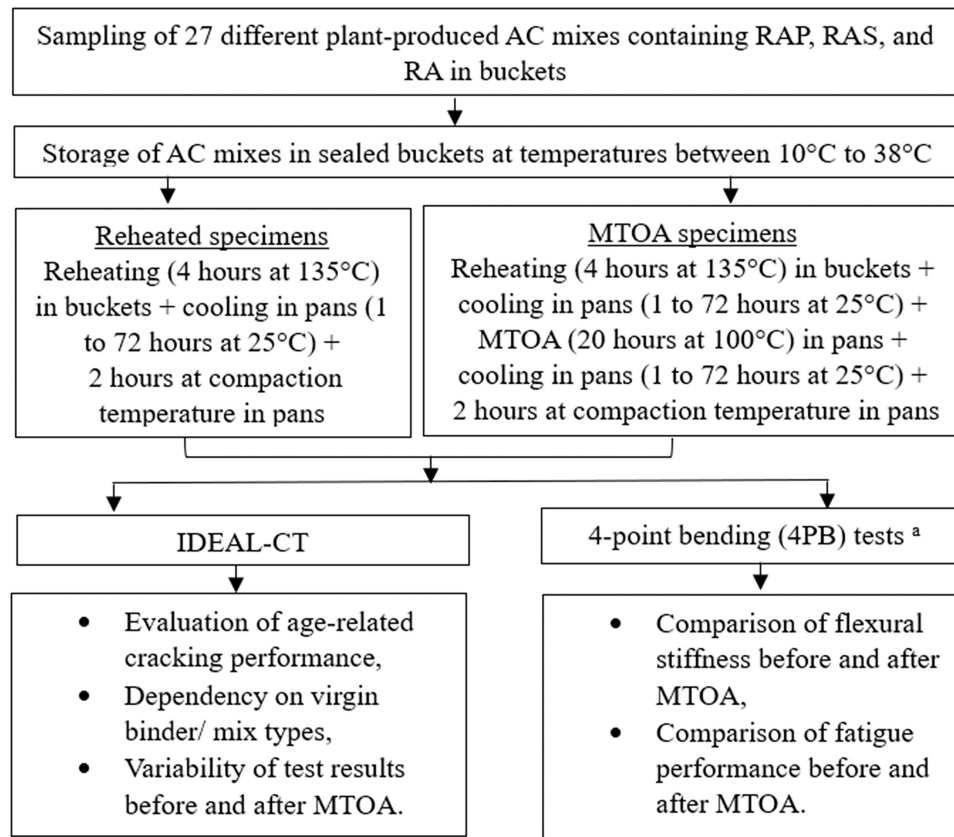


Figure 1. Workflow diagram. ^a4PB tests for four selected mixes.

Table 1. Asphalt concrete mixes were used in this study.

Mix label ^a	Type	Maximum aggregate size	RAP (%) ^b	RAS (%) ^b	Virgin/base binder PG	Virgin/base binder source	Recycling agents (RA)	4PB tests	# Lots
HMA-4.88 (R10)	HMA	3/4 in.	10	0	64-10	Source VB	None	x	1
HMA-4.87 (R15)	HMA	3/4 in.	15	0	64-16	Source VB	None	x	1
HMA-Sac-5 (R22)	HMA	3/4 in.	22	0	64-16	Source VB	None	Yes (√)	1
HMA-ELD-49 (R10)	HMA	1/2 in.	10	0	64-16	Source M	None	x	1
PM-SJ-26 (R0)	HMA-PM	3/4 in.	0	0	64-28M	Source VB	None	Yes (√)	2
PM-SJ-26 (R25)	HMA-PM	3/4 in.	25	0	58-34M	Source VB	Tall Oil	x	2
PM-SJ-26 (R30)	HMA-PM	3/4 in.	30	0	58-34M	Source VB	Tall Oil	x	2
PM-SJ-26 (R35)	HMA-PM	3/4 in.	35	0	58-34M	Source VB	Tall Oil	x	2
PM-SJ-26 (R40)	HMA-PM	3/4 in.	40	0	58-34M	Source VB	Tall Oil	Yes (√)	2
PM-SJ-26 (R25S3)	HMA-PM	3/4 in.	25	3	58-34M	Source VB	Tall Oil	x	2
PM-SJ-26 (R15)	HMA-PM	3/4 in.	15	0	64-28M	Source VB	None	x	1
PM-SBD-215 (R0)	HMA-PM	3/4 in.	0	0	64-28M	Source SJ	None	x	2
PM-SBD-215 (R25)	HMA-PM	3/4 in.	25	0	58-34M	Source SJ	Tall Oil	x	2
PM-SBD-215 (R30)	HMA-PM	3/4 in.	30	0	58-34M	Source SJ	Tall Oil	x	2
PM-SBD-215 (R35)	HMA-PM	3/4 in.	35	0	58-34M	Source SJ	Tall Oil	x	2
PM-SBD-215 (R40)	HMA-PM	3/4 in.	40	0	58-34M	Source SJ	Tall Oil	x	2
PM-SBD-215 (R23)	HMA-PM	3/4 in.	23	0	58-34M	Source SJ	None	x	1
R-SON-1 (R0)	RHMA-G	1/2 in.	0	0	64-16	Source VB	None	x	1
R-SON-1 (R10)	RHMA-G	1/2 in.	10	0	64-16	Source VB	None	x	1
R-SON-101 (R0)	RHMA-G	3/4 in.	0	0	64-16	Source VB	None	x	1
R-SON-101 (R10)	RHMA-G	3/4 in.	10	0	64-16	Source VB	None	x	1
R-VEN-1 (R0)	RHMA-G	1/2 in.	0	0	64-16	Source VW	None	Yes (√)	1
R-VEN-1 (R10)	RHMA-G	1/2 in.	10	0	64-16	Source VW	None	x	1
R-IMP-186 (R0)	RHMA-G	1/2 in.	0	0	70-10	Source VW	None	x	1
R-IMP-186 (R10)	RHMA-G	1/2 in.	10	0	70-10	Source VW	None	x	1
R-SLO-41 (R10)	RHMA-G	3/4 in.	10	0	64-16	Source SJ	None	x	1
HyRAP	HMA	3/8 in.	100	0	N.A.	--	Petroleum based	x	5

^a HMA: hot mix asphalt, PM: polymer-modified mix, R: rubberised HMA. The code (RxSy) indicates x% RAP and y% RAS.

^b RAP and RAS percentages refer to aggregate replacement.

(>25% RAP aggregate by total weight of aggregates), except for the HyRAP mix, a tall oil-based RA was used, as shown in Table 1. The tall oil RA is classified as RA 0 based on kinematic viscosity at 60 °C following ASTM D4552-20 classification. For the HyRAP mix, a petroleum-based RA was used with 100% RAP content. The naming convention for the AC mixes was selected to include the mix type, project information, and percentage of RAP/RAS used. For example, the mix name 'PM-SJ-26 (R0)' refers to a polymer-modified (PM) mix, collected from the SJ-26 field project, which contains 0% RAP by total weight of aggregates (Table 1). Some mixes were sampled once, while others were sampled several times during construction (quality control 1 [QC1], QC2, etc.) (see 'number of lots sampled column' in Table 1).

The mixes were shipped to the laboratory from the job site just after sampling, then kept in a covered shed in sealed metal buckets until specimen preparation. For the mixes tested as part of this study, the storage temperatures varied between 10 °C and 38 °C. The loose mixes in the metal buckets were used to produce two sets of specimens: one set was not subjected to any intentional ageing, just reheating to break down the loose mix and reach compaction temperature (the term 'Reheating' was used to refer to this procedure), while the other set was also subjected to MTOA conditioning. Both reheating and MTOA conditioning were conducted according to the Caltrans test method CT320 (Caltrans, 2025). The mixing time and conditions, and reheating/cooling process used to put in pans and reheating for compaction, were found to be important variables for the tested properties and are included in this method (Caltrans, 2025).

First, the asphalt mix buckets collected from plants were reheated at 135 °C for 4 h, and mixes were transferred into small pans after splitting and allowed to cool down at controlled room temperature for a

minimum of 1 h and not exceeding 72 h. Loose mixes kept in the pans for more than 3 h were covered with aluminium foil and kept out of direct sunlight (Figure 1).

For the reheating specimens, uncovered loose mixes were then heated to compaction temperature for 2.00 ± 0.25 h. In this study, loose mixes for MTOA specimens went through an additional heating of 20.0 ± 0.5 h at 100 ± 3 °C and then a cooling process for 1–72 h at controlled room temperature before heating at compaction temperature for 2.00 ± 0.25 h (Figure 1).

All mixes shown in Table 1 were tested in the IDEAL-CT test, while four mixes (PM-SJ-26 [R0], PM-SJ-26 [R40], HMA-Sac-5 [R22], and R-VEN-1 [R0]) were also tested in four-point bending (4PB) stiffness and fatigue (Figure 1). To cover the different mix types (HMA, PM-HMA, and R-HMA), these mixes were selected for the 4PB testing in this study. HyRAP with 100% RAP is not a common mix for the asphalt industry. Therefore, the HyRAP mix was not considered for the fatigue cracking evaluation. Also, PM-SJ-26 [R40] mix with 40% RAP, and RA was considered to evaluate the effect of RAP and recycling agents on the fatigue performance after MTOA.

Laboratory testing

Binder testing

To evaluate the effect of base binder source on the long-/medium-term performance of AC mixes, both base and extracted binders were tested in the laboratory. Binders from two plant-produced mixes (PM-SJ-26 [R0] and PM-SBD-215 [R0]) with two different binder sources (Source VB and Source SJ) were extracted and recovered in the laboratory. An auto-extractor was used to extract the asphalt binder from the asphalt mixes using Trichloroethylene (TCE), following the ASTM D 8159 method. The extracted binder was then recovered using the rotary evaporation process following ASTM D 5404. Also, base binders collected from three different refineries (Source VB, Source VW, and Source SJ) were tested directly to evaluate the binder's rheological properties.

A dynamic shear rheometer (DSR) was used to evaluate the rheological properties of both extracted and base binders. The complex shear modulus (G^*) and phase angle (δ) values were evaluated at four different temperatures (5 °C, 10 °C, 25 °C, and 40 °C) and 16 different testing frequencies (0.02–15.92 Hz). In this study, the Glover-Rowe (GR) parameter was used to track the ageing-related cracking susceptibility of the binders. The GR parameter was calculated using G^* and δ values at 15 °C and 0.005 rad/sec as expressed in the following equation:

$$GR = \frac{G^* \cos^2 \delta}{\sin \delta} \quad (1)$$

Mix testing

For mix testing, all specimens were compacted to 7% air voids with a 0.5% tolerance around that target. The following mix tests were conducted in the laboratory to characterise the cracking performance of the asphalt mixes.

Indirect tensile cracking tolerance (IDEAL-CT) In this study, IDEAL-CT was performed on the prepared asphalt specimens, followed by ASTM D8225. At least five specimens were tested for each mix type. All specimens were conditioned at 25 °C for 2 h prior to testing. The strength and CT_{Index} [Equations (2)–(5)] were determined as the cracking resistance parameters. It should be clarified that cracking evaluated by IDEAL-CT is defined as the low-temperature and age-related cracking phenomenon, which depends on the mix properties and the environment, and not the bottom-up fatigue cracking phenomenon, which depends on the interaction of traffic loading, the pavement structure, the environment, the mix stiffness and fatigue cracking properties.

$$CT_{Index} = \frac{t}{62} \times \frac{I_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \quad (2)$$

where t = thickness, D = diameter, G_f = failure energy $\left(\frac{J}{m^2}\right)$

$$G_f = \frac{W_f}{D \times t} \times 10^6 \quad (3)$$

where the W_f = total area under the load-displacement curve until 0.1 kN load was reached after the peak
 I_{75} = displacement at 75% of the peak load

$$|m_{75}| = \left| \frac{P_{85} - P_{65}}{I_{85} - I_{65}} \right| \quad (4)$$

where P_{85} = of the peak load

P_{65} = 65% of the peak load

I_{85} = displacement at P_{85}

I_{65} = displacement at P_{65}

$$\text{Strength, } \sigma_0 = \frac{\text{Peak load}}{2rt} \quad (5)$$

where the r = radius of the sample

Fatigue cracking resistance. AASHTO T321 was followed to evaluate the fatigue cracking resistance of four selected plant-produced asphalt mixes. These mixes were selected to cover different types of AC mixes (such as polymer-modified HMA (HMA-PM) with and without RAP/RA, RHMA-G, and traditional HMA with high RAP). The asphalt beams were prepared using a rolling wheel compactor. Beam specimens were subjected to four-point bending by applying sinusoidal loading at three different strain levels (high, intermediate, and low) at a frequency of 10 Hz and a temperature of 20 °C. In this study, the testing method currently listed in AASHTO T321 was altered to optimise the quantity and quality of the data collected. Replicate specimens were first tested at high and medium strain levels to develop an initial regression relationship between the fatigue life and strain [Equation (6)]. Strain levels were selected, based on experience, to achieve fatigue lives between 10,000 and 100,000 load cycles at high strains and between 300,000 and 500,000 load cycles at medium strains. Additional specimens were then tested based on the initial linear regression relationship to obtain a fatigue life of approximately 1 million load repetitions at lower strain levels. The final regression relationship was then modified to accommodate the measured stiffness at the lower strain level.

$$\ln(N) = A + B * \ln(\epsilon) \quad (6)$$

where N = fatigue life (number of cycles)

ϵ = strain level (μstrain)

A and B = model parameters

The strain level at one million load repetitions (ϵ_6) was considered as the fatigue performance parameter based on previous literature (Jiao and Harvey, 2023, 2022).

Results and discussion

MTOA effects based on IDEAL-CT results

Comparison between reheated and MTOA-conditioned IDEAL-CT results

As mentioned earlier, a total of 27 asphalt concrete mixes were used for comparison between reheated and MTOA-conditioned IDEAL-CT test results. Most of the mixes had replicate sets sampled twice (QC1 and QC2) on different days of production (Table 1). The IDEAL-CT results are shown in Figure 2. Each data box in Figure 2 shows the variability across the specimens within each mix.

Figures 3–6 show the percent change in the CT_{Index} and strength after MTOA conditioning for HMA with a conventional binder, RHMA-G with a rubberised binder, HMA-PM with a polymer-modified binder, and HMA-100%RAP mix types, respectively. Figure 3 shows that the HMA with 22% RAP (HMA-

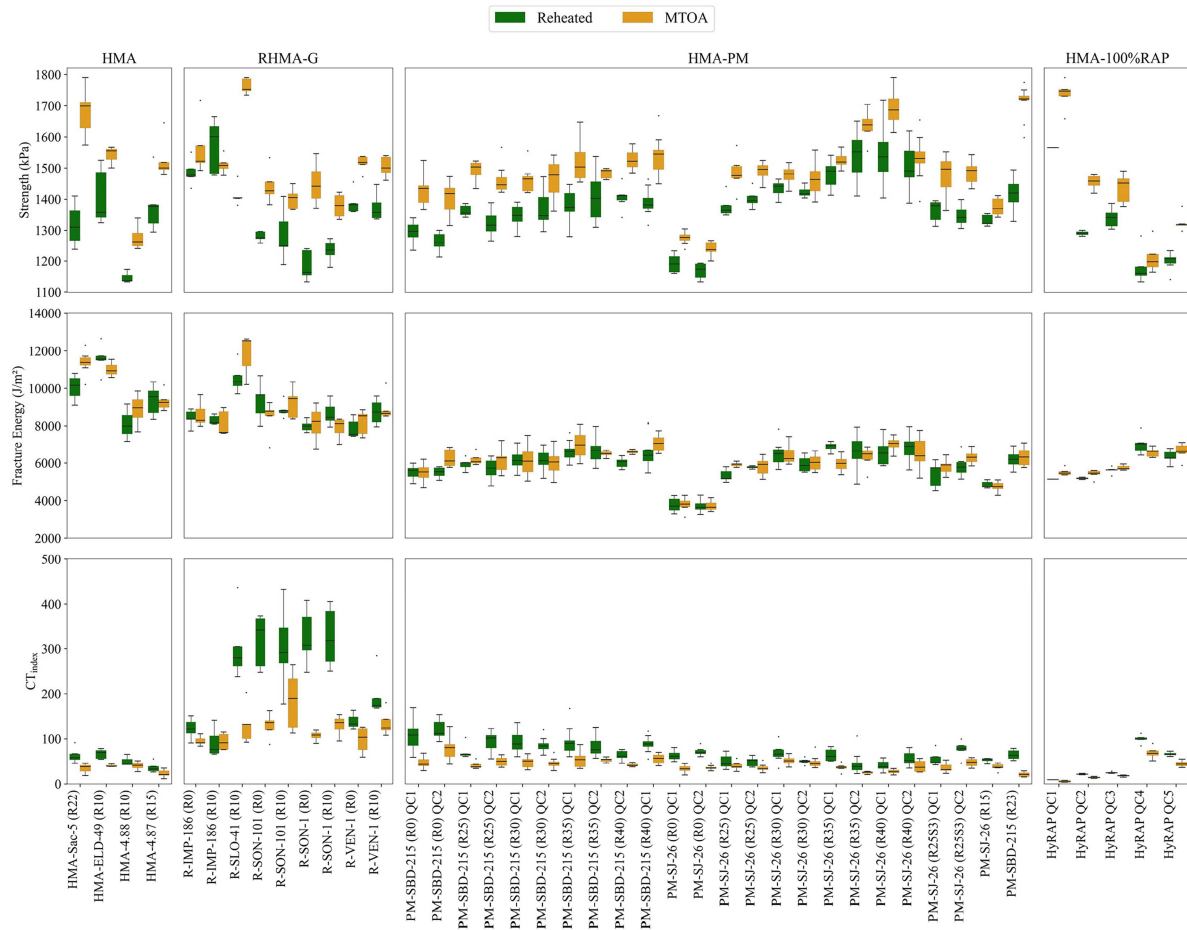


Figure 2. IDEAL-CT results for all asphalt concrete mixes after reheating and MTOA. Note: QC1 and QC2 (quality control 1 and quality control 2) suffixes refer to two samplings of the same mix. Green indicates reheated sample, orange indicates reheat + MTOA sample.

Sac-5 [R22]) has a greater change in both CT_{Index} and strength compared to other HMA mixes. The HMA-Sac-5 (R22) had the highest percentage of RAP (22%) compared to other mixes shown in Figure 3. However, the aged binder from RAP is expected to reduce the ageing rate of mixes and cause minimal change in the CT_{Index} and strength values after MTOA conditioning. This outcome may be attributed to several factors, such as the aging characteristics of the virgin binders, the aged RAP binder, and the degree of blending between RAP and virgin binders.

Another factor to consider beyond the properties of the binders and their blending comes from Bell et al. (1994b), who reported that the chemical bonding between the aggregates and asphalt binder is expected to influence the ageing rate of AC mixes. Therefore, the ageing of AC mixes containing recycled materials is much more complicated than that of mixtures of fully blended asphalt binder with RAP. Several factors can control the overall ageing trend of AC mixes containing RAP/RAS.

A greater change in IDEAL-CT parameters for high RAP content mixes without RA has also been observed for HMA-PM mixes, as shown in Figure 5. The PM-SBD-215 (R23) mix has the highest percentage of RAP (23%) without the use of a recycling agent. The change in the CT_{Index} and strength values after MTOA ageing for the PM-SBD-215 (R23) mix were 67% and 47%, respectively, which are high values compared to the other HMA-PM mixes containing RA, which indicates that the addition of RAP does not reduce the ageing rate of AC mixes. Figure 5 also shows that the use of a recycling agent can reduce the MTOA effect on mixes containing a high percentage of RAP. For example, the PM-SBD-215 (R40) QC1 and QC2 mixes present a lower change in the CT_{Index} and strength compared to the PM-SBD-215 (R23) mix (Figure 5), despite having a higher RAP content. This is attributed to the recycling agent

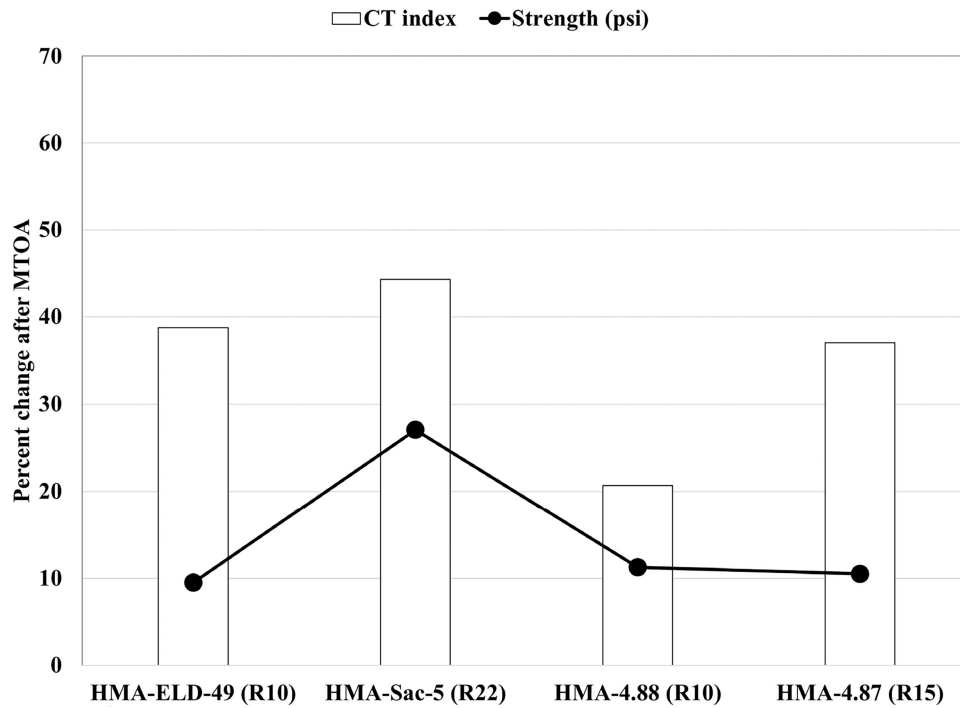


Figure 3. Percent change in CT_{Index} and strength values after MTOA for HMA mixes.

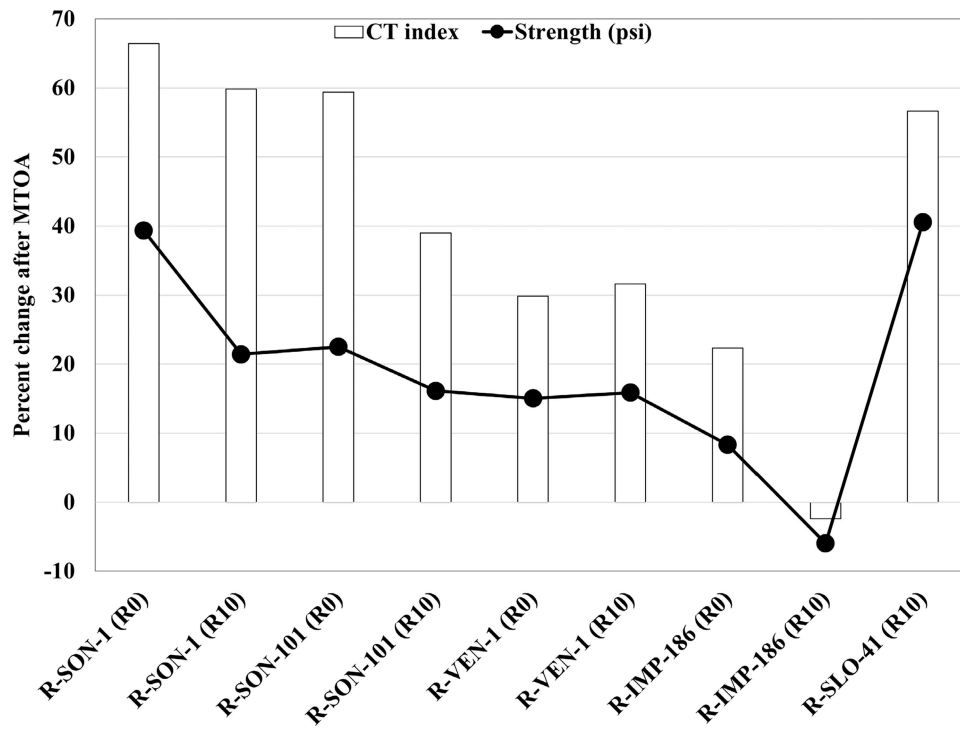


Figure 4. Percent change in CT_{Index} and strength values after MTOA for RHMA-G mixes.

added to the PM-SBD-215 (R40) QC1 and QC2 mixes, whereas no recycling agent was added to PM-SBD-215 (R23) (Table 1). Therefore, the use of a recycling agent can counteract the effect of adding a high percentage of RAP/RAS. Similar findings were also reported by other researchers (Bajaj et al., 2020; Rahman et al., 2023a).

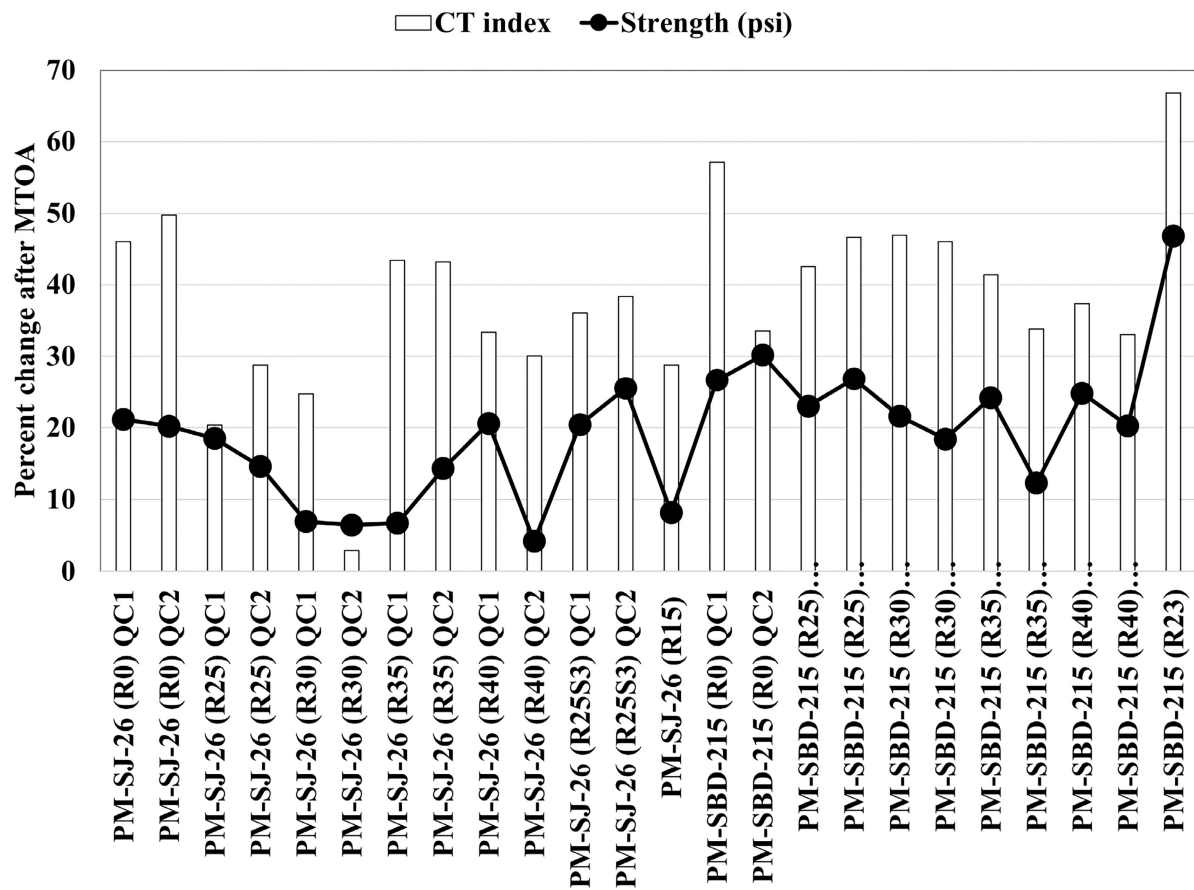


Figure 5. Percent change in CT_{Index} and strength values after MTOA for HMA-PM mixes.

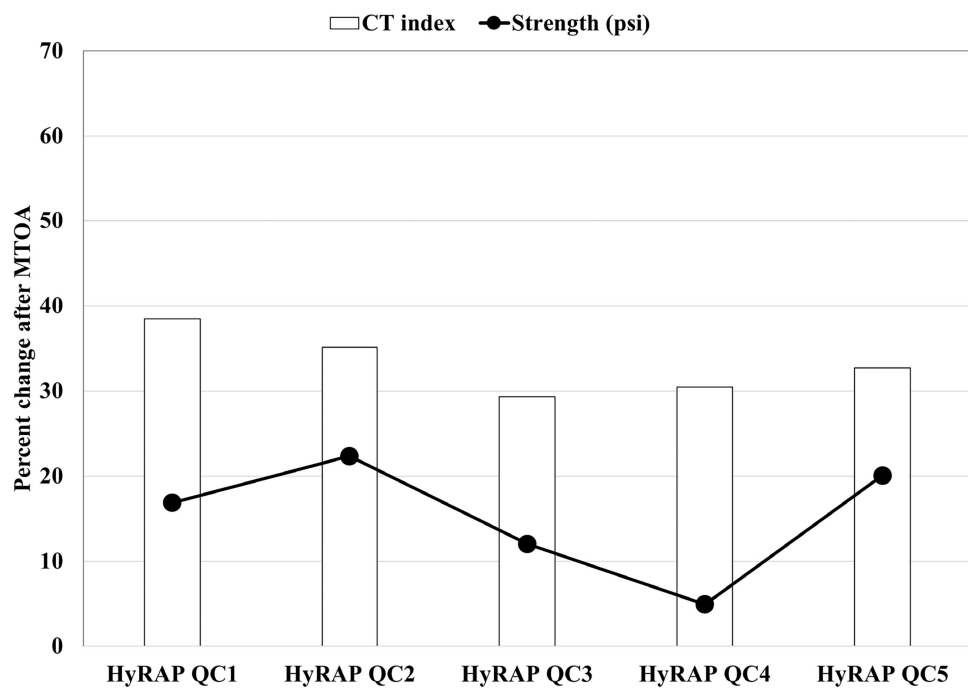


Figure 6. Percent change in CT_{Index} and strength values after MTOA for HMA-100%RAP mixes.

Figure 4 shows the percent change in the CT_{Index} and strength after MTOA conditioning for RHMA-G mixes. An increase in the CT_{Index} value was observed for the R-IMP-186 (R10) mix after MTOA conditioning (Figure 4). This may be attributed to variability in the sampling, sample production, and test results. Figure 6 presents the percent change in the CT_{Index} and strength after MTOA conditioning for the HMA-100%RAP mix type. The change in CT_{Index} values varied between 30% and 40% for different QC samples collected for the HMA-100%RAP mix (Figure 6).

Figures 7–9 illustrate the effect of the MTOA on the CT_{Index} , strength, and fracture energy from the IDEAL cracking test, respectively. The figure shows the results identified by mix type and by the different binder sources within each mix type. It is well-known that different binder sources have different ageing susceptibilities (Bell et al., 1994b). Nonetheless, the data in the figures do not seem to present any trend versus binder source. Overall, MTOA reduced the CT_{Index} compared to the reheated condition by a ratio averaging 0.38. This can be seen from the regression line in Figure 7, which shows that the amount of reduction from the MTOA compared to reheating generally had a linear trend. The red lines in Figure 7 show the regression band at a 95% confidence interval. This band can be considered as the primary threshold for the CT_{Index} value after MTOA for screening of BMD mixes. Any AC mixes performing below this band are expected to show a greater loss in the CT_{Index} value after MTOA conditioning.

MTOA increased the IDEAL-CT strength by a fixed value regardless of the reheated strength, with the increase averaging 21.8 psi (150 kPa), as shown by the regression line in Figure 8. MTOA did not appear to have much effect on the fracture energy, with a few exceptions, as shown in Figure 9.

The CT_{Index} values of the RHMA-G mixes were found to be much higher compared to other mix types. For example, the CT_{Index} values observed for R-SON-1 (R0) (RHMA-G mix type) after reheating and the MTOA were 326 and 109, respectively. Whereas the CT_{Index} values observed for a typical polymer-modified AC mix (PM-SBD-215 [R0] QC1) after reheating and MTOA were 109 and 47, respectively. Approximately two to three times greater CT_{Index} values were observed for the R-SON-1 (R0) (RHMA-G mix type) mix compared to PM-SBD-215 (R0) QC1 (HMA-PM) mix. For mixes other than RHMA-G, MTOA reduced the CT_{Index} in a fixed ratio of approximately 0.37 while increasing the strength in a fixed amount of approximately 21.2 psi (146 kPa). MTOA was found to show a similar effect on the CT_{Index} and strength values for all four mix types tested: HMA, HMA-PM, RHMA-G and 100% RAP.

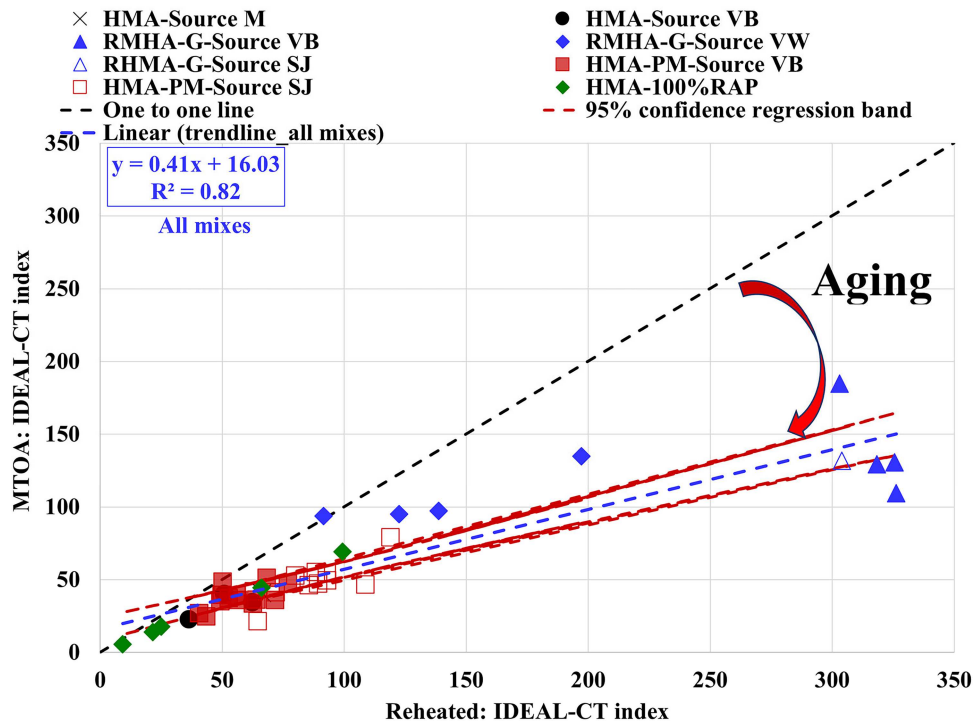


Figure 7. Effect of MTOA on the CT_{Index} (by mix and binder source types).

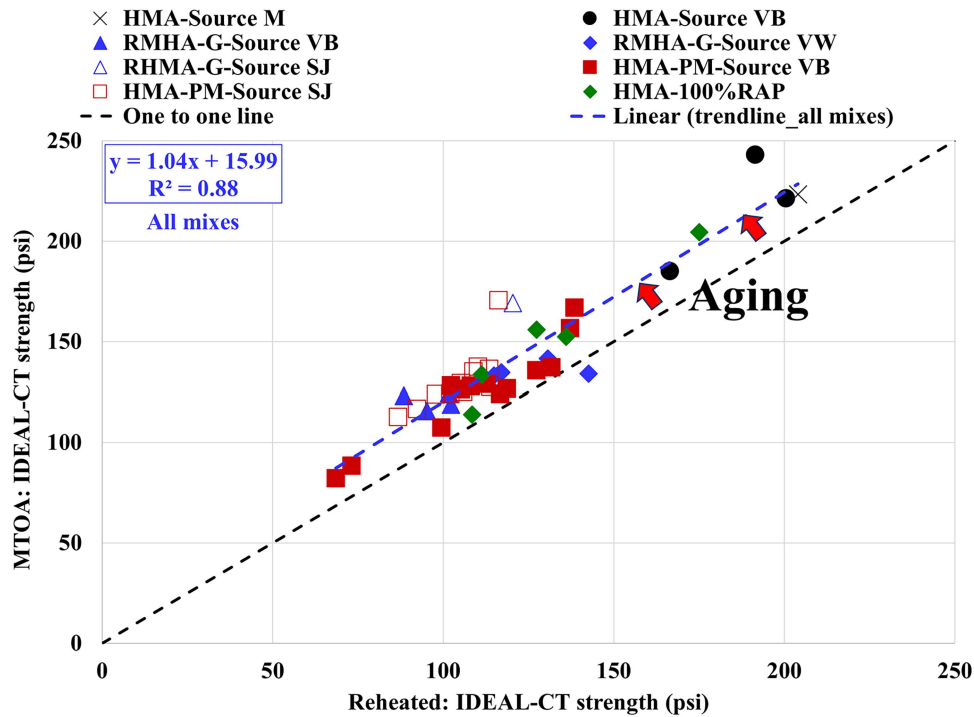


Figure 8. Effect of MTOA on the strength values (by mix and binder source types).

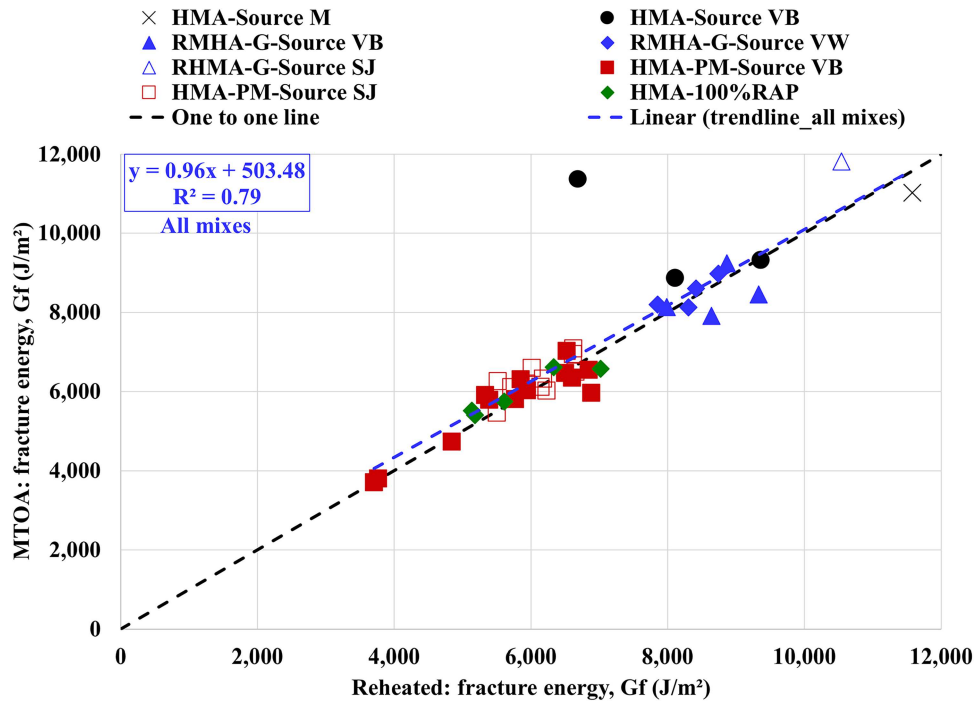


Figure 9. Effect of MTOA on the fracture energy (by mix and binder types).

Effect of binder ageing susceptibility on IDEAL-CT results

As discussed earlier, previous literature suggests that different binder sources present different ageing susceptibility (Bell et al., 1994b, Petersen, 2009; Rahman et al., 2023b). The binder sources used for producing the RHMA-G and HMA-PM mixes in the set of mixes used for this study included Source VB,

Source VW, and Source SJ refineries. The change in the binder indices with ageing for both RHMA-G and HMA-PM mixes is discussed below.

Ageing susceptibility of base binders of RHMA-G mixes. The base binder sources used for R-SON-101 (R0 & R10), R-VEN-1 (R0 & R10) and R-SLO-41 (R10) RHMA-G mixes were Source VB, Source VW, and Source SJ, respectively. For all three mixes, a PG64-16 base binder was used. The base binders were collected from the asphalt plant and were tested using a DSR at different ageing levels (unaged, RTFO-aged and PAV20-aged [20 h]). Figure 10 shows the Glover-Rowe (GR) parameters in the black space diagram for all three base binders. Figure 10 illustrates that the Source SJ base binder showed much lower GR values compared to other binder sources at all three ageing conditions. Several researchers have suggested that lower binder GR values indicate less chance of age and low-temperature cracking for the AC mixes (Mensching et al., 2016; Singhvi et al., 2022).

The reheating and MTOA conditions of AC mixes can be considered somewhat similar to the RTFO and PAV20 ageing conditions of the asphalt binder, since RTFO is intended to simulate ageing from mixing, transport to the site, compaction, and up to 1 or 2 years of service, while PAV20 ageing has been shown to approximately correspond to 2–10 years of aging in the field depending on the depth below the surface layer in the upper 60 mm (0.2 ft) of the pavement (Hveem et al., 1963; Smith et al., 2018). Figure 11 shows the complex modulus after PAV20 ageing normalised to the complex modulus after RTFO ageing for all three base binders. The normalized complex moduli indicate that the strongest effects of additional aging from PAV conditioning occurred at the lowest frequencies (shown on the left side of the x-axis), which also correspond to the highest temperatures, while there was not much effect of the PAV aging on the moduli at the fastest frequency loading, which also corresponds to the coldest temperatures (shown on the right side of the x-axis). At the intermediate frequencies in the middle of the x-axis, which also correspond to intermediate temperatures, there is an effect of ageing on the moduli, and the effects of ageing vary depending on the base binder.

The IDEAL-CT tests were conducted at an intermediate temperature of 25 °C in the laboratory. Therefore, binder complex modulus values at a 10 Hz reduced frequency can be a good parameter for comparing the mix IDEAL-CT results. Based on the normalised stiffness at 10 Hz reduced frequency, the rank order from least ageing susceptible to most ageing susceptible base binder sources: (1) Source SJ, (2)

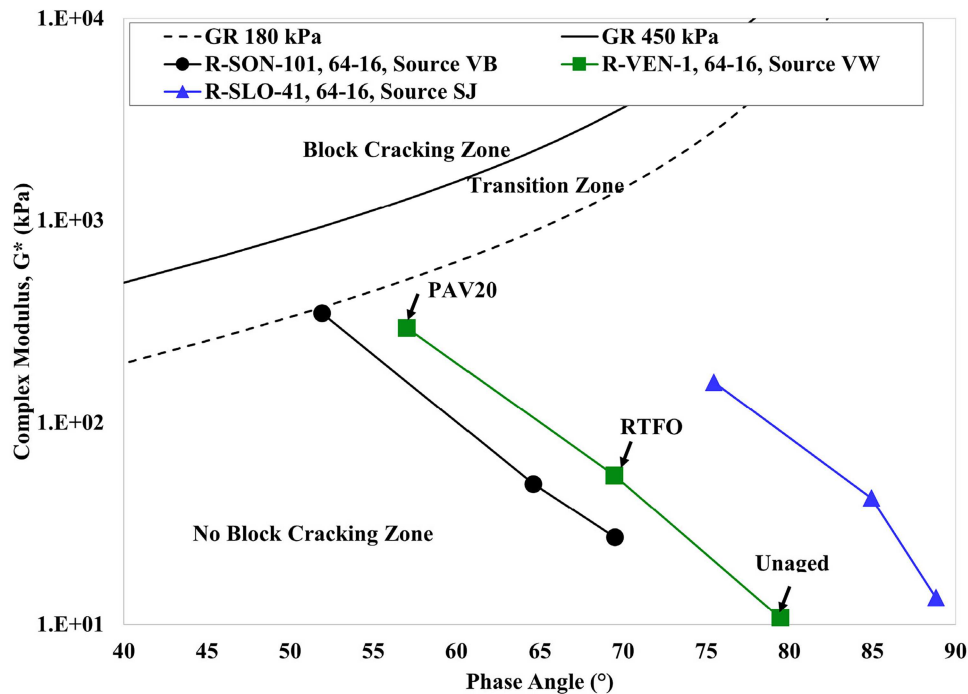


Figure 10. Black space diagram with Glover-Rowe (GR) parameters for the base binders of RHMA-G mixes.

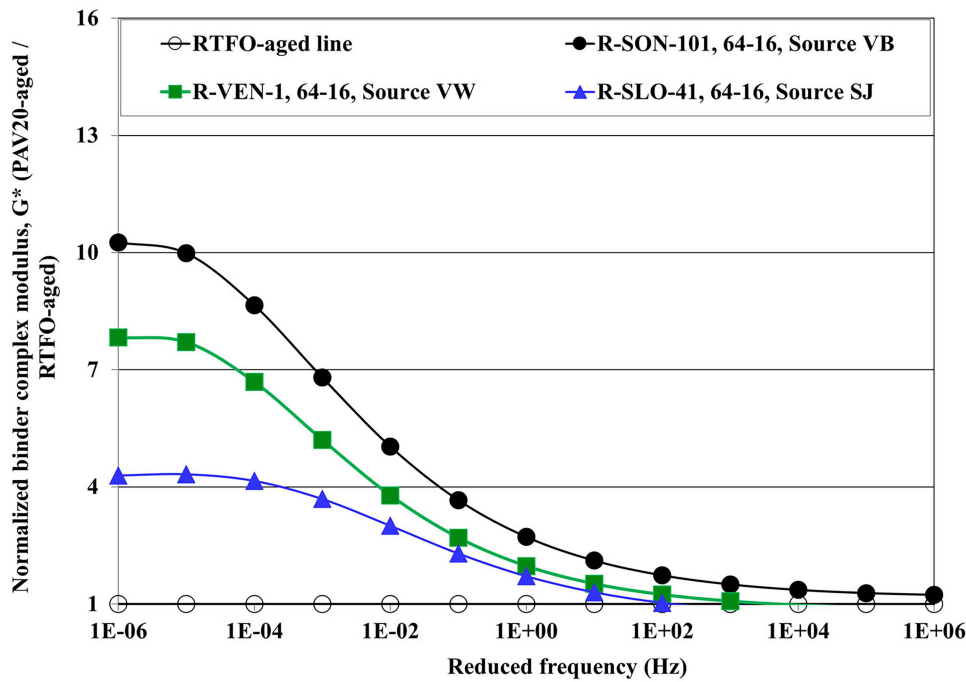


Figure 11. Normalised binder complex modulus G^* (PAV20-aged/RTFO-aged) for the base binders of RHMA-G mixes.

Source VW, and (3) Source VB. Therefore, RHMA-G mixes with the Source SJ binder source (R-SLO-41 [R10]) are expected to show less drop in CT_{Index} values (close to the one-to-one line in Figure 7) after MTOA compared to other RHMA-G mixes. However, the R-SLO-41 (R10) mix showed a similar drop in CT_{Index} value compared to other RHMA-G mixes. The CT_{Index} values observed for R-SLO-41 (R10) with Source SJ base binder after reheating, and MTOA were 304 and 132, respectively, while the CT_{Index} values observed for a typical RHMA-G mix with Source VB binder source (R-SON-101 [R0]) after reheating and MTOA were 318 and 129, respectively. The percent changes in CT_{Index} values after MTOA observed for R-SLO-41 (R10) with Source SJ and R-SON-101 (R0) with Source VB binder source were 57% and 59%, respectively, which can be considered equal.

These results indicate that the binder ageing susceptibility is being modified by other factors in the mix. These results, showing little correspondence to the amount of aging susceptibility between the binder and mix aging, match those identified in the 1994 SHRP report comparing binder and mix aging results for combinations of 8 binders and 4 aggregates which states: 'As with the short-term aging comparisons, there is little similarity between the rankings for long-term aging of mixes and those for asphalt alone' (Bell et al., 1994b).

It should be noted that only one RHMA-G mix with Source SJ binder source has been considered in this study. More RHMA-G mixes with Source SJ binder source are required to reach a stronger conclusion. Also, it should be noted from Figure 11 that the differences in the normalised complex modulus among different binder sources are much greater at lower reduced frequencies or for high temperatures. At intermediate reduced frequencies, the differences among different binder sources are lower compared to low reduced frequencies.

The RHMA-G mixes with the Source VW binder source showed less drop in CT_{Index} values compared to RHMA-G mixes with Source VB binder (Figure 7), supporting the binder results shown in Figures 10 and 11. The strength results shown in Figure 8 follow a similar trend to that of CT_{Index} values. A lesser increase in strength values was observed for RHMA-G mixes with the Source VW binder source compared to RHMA-G mixes with Source VB.

Ageing susceptibility of extracted binders from HMA-PM mixes. For the HMA-PM mixes, the binder tests were conducted on the extracted binders obtained from the plant-produced mixes. It is well

established that full blending occurs between RAP and virgin binders due to the forced extraction procedure, while full blending may not occur during plant production of mixes containing RAP (Rahman et al., 2023b, 2023a). Therefore, only the HMA-PM mixes without RAP were considered to evaluate the effect of binder sources on the IDEAL-CT results.

As shown in Table 1, the binder sources used for PM-SJ-26 (R0) and PM-SBD-215 (R0) HMA-PM mixes, with 0% RAP content, were Source VB and Source SJ, respectively. For both cases, PG64-28M binders were utilised in producing the mixes. Both mix types were collected from the asphalt plant at two different production times (QC1 and QC2), as shown in Table 1. However, the binders were extracted from only the QC1 samples of both mixes. The extracted binders were tested using a DSR at different ageing levels (plant extracted, PAV20, and PAV40-aged) in the laboratory. Figure 12 shows the complex modulus in the black space diagram for both extracted binders together with the Glover-Rowe (GR) cracking zone curves. Figure 12 shows that the Source SJ binder is further away from the GR cracking zone compared to the Source VB binder. A similar finding was also shown in Figure 10 (unmodified binders) for the same binder sources. Figure 13 shows PAV20-aged binder complex moduli for the two binders, normalised by their moduli in the RTFO-aged condition. The results show similar trends as were seen for the unmodified binders in Figure 11 (Source SJ modified binder has a trend of fewer effects of PAV ageing at the slowest frequencies, which correspond to the highest temperatures).

Figure 14 shows the CT_{Index} values after reheating and MTOA for both HMA-PM mix types at two different production times (QC1 and QC2). The PM-SBD-215 (R0) mix with Source SJ binder source was found to show higher CT_{Index} values compared to the PM-SJ-26 (R0) mix with Source VB (Figure 14). This outcome is likely related to the lower stiffness (dynamic modulus) and higher phase angle of the Source SJ binder compared to the Source VB binder (Figure 12).

As can be seen in Figures 14 and 15, the CT_{Index} and strength values of HMA-PM virgin mixes were found to follow the overall trend lines irrespective of their binder sources. Figure 16 compares the percent change in binder stiffness (G^* at 10 Hz reduced frequency) and percent change in IDEAL-CT mix properties (CT_{Index} and strength values) for the two HMA-PM binder sources. An opposing trend between the binder and mix percent changes can be seen in Figure 16. A relatively lower

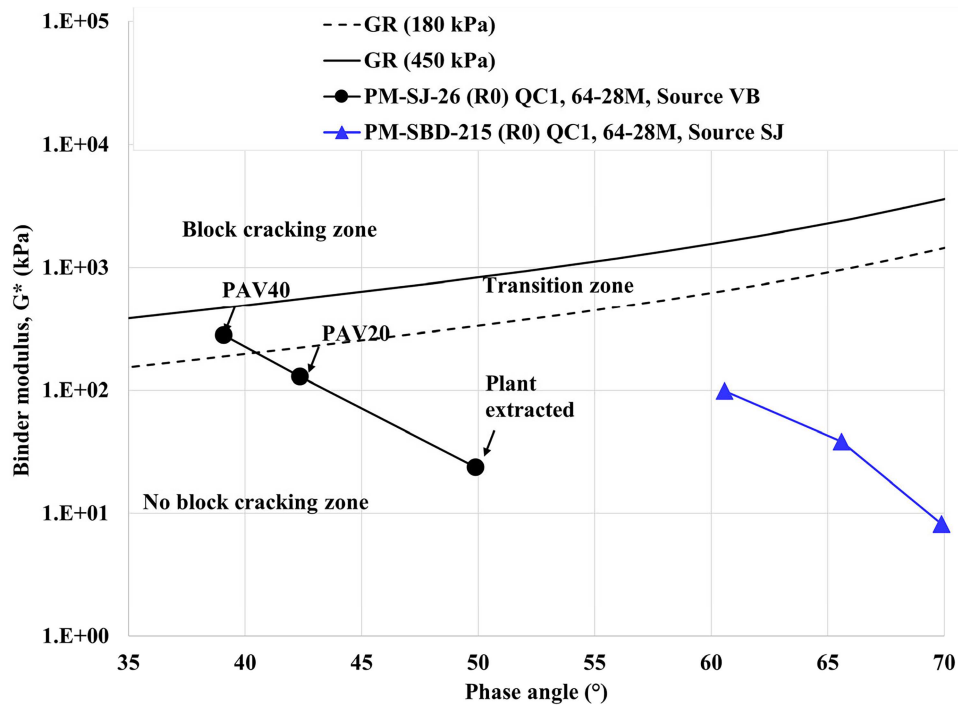


Figure 12. Black space diagram with Glover-Rowe (GR) parameters for the extracted binders of HMA-PM virgin mixes.

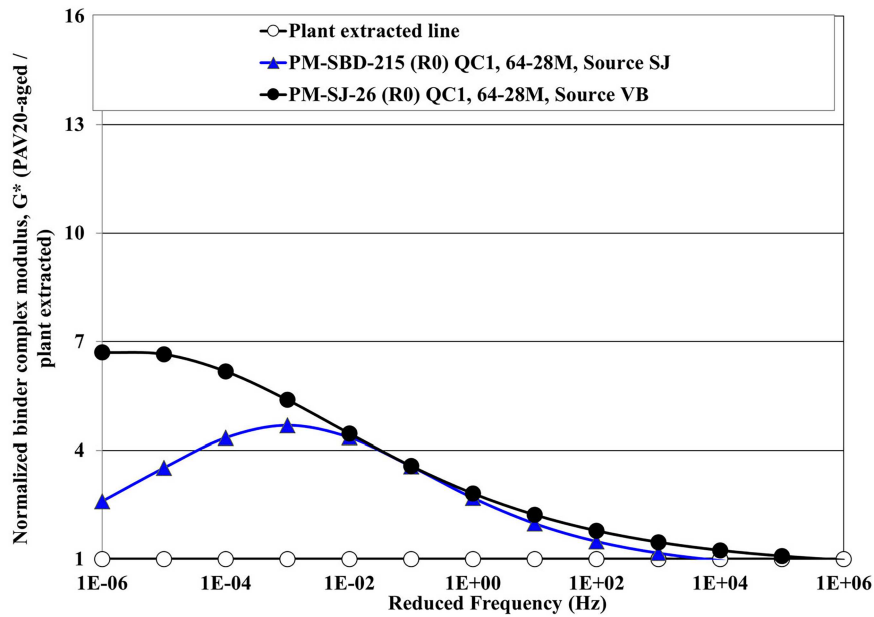


Figure 13. Normalised binder complex modulus G^* (PAV20-aged/plant extracted) for the extracted binders of HMA-PM virgin mixes.

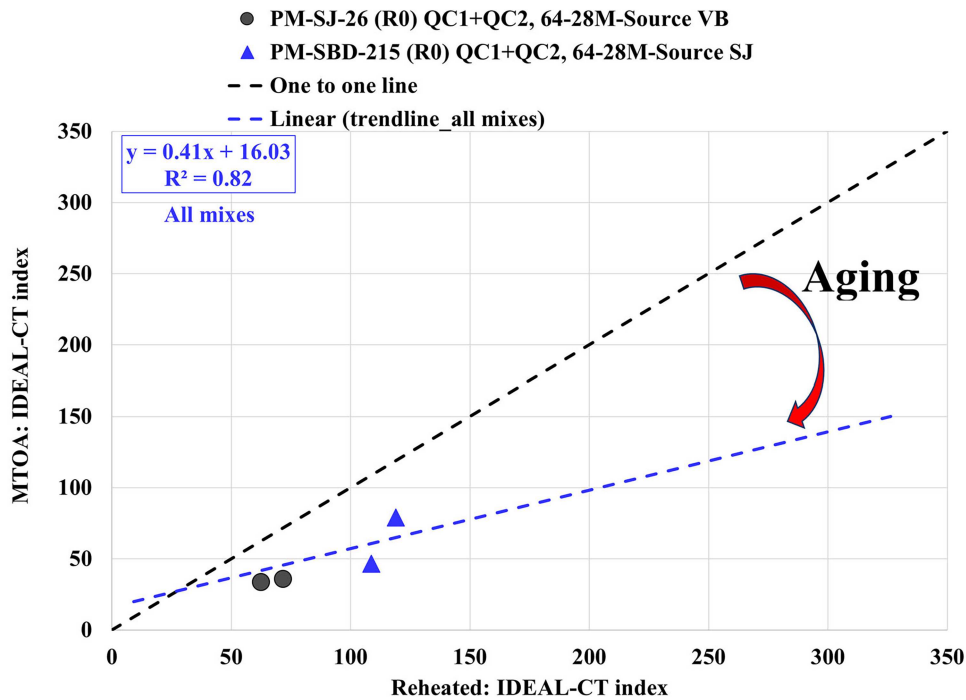


Figure 14. Effect of MTOA on the IDEAL-CT index parameters for the HMA-PM virgin mixes.

percent change (98%) in binder G^* values was observed at a 10 Hz reduced frequency from the plant extracted to PAV20 for the PM-SBD-215 (R0) mix with Source SJ binder source compared to the PM-SJ-26 (R0) mix with Source VB (122%). However, the PM-SJ-26 (R0) mix with Source VB showed lower percent changes in both mix CT_{Index} and strength values after MTOA compared to PM-SBD-215 (R0) mix with Source SJ. Therefore, binder sources may not significantly influence the performance of IDEAL-CT.

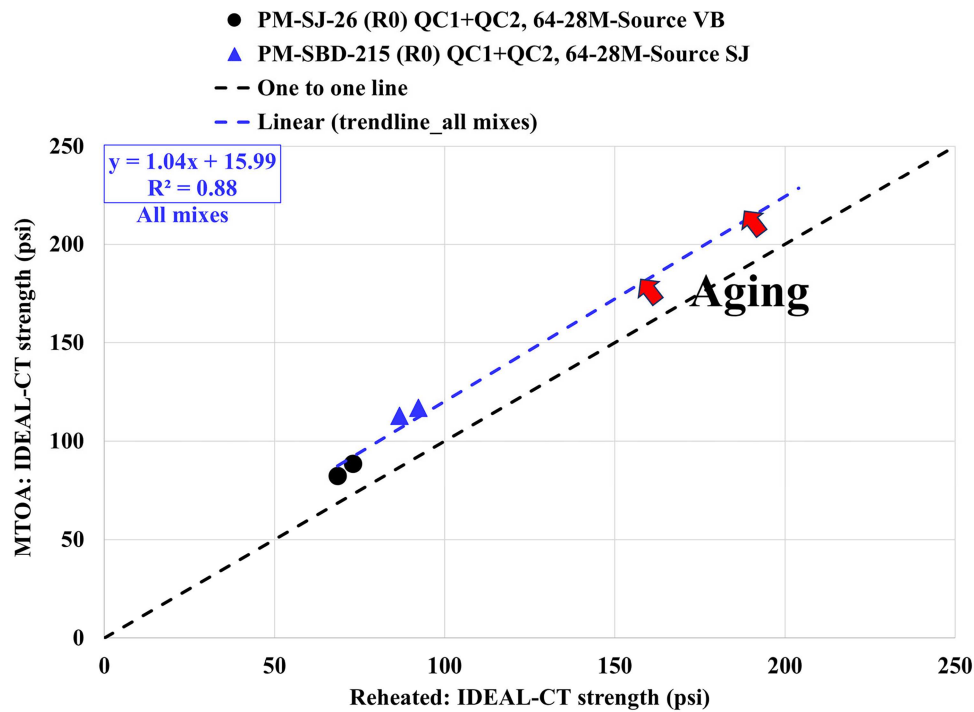


Figure 15. Effect of MTOA on the IDEAL-CT strength for the HMA-PM virgin mixes.

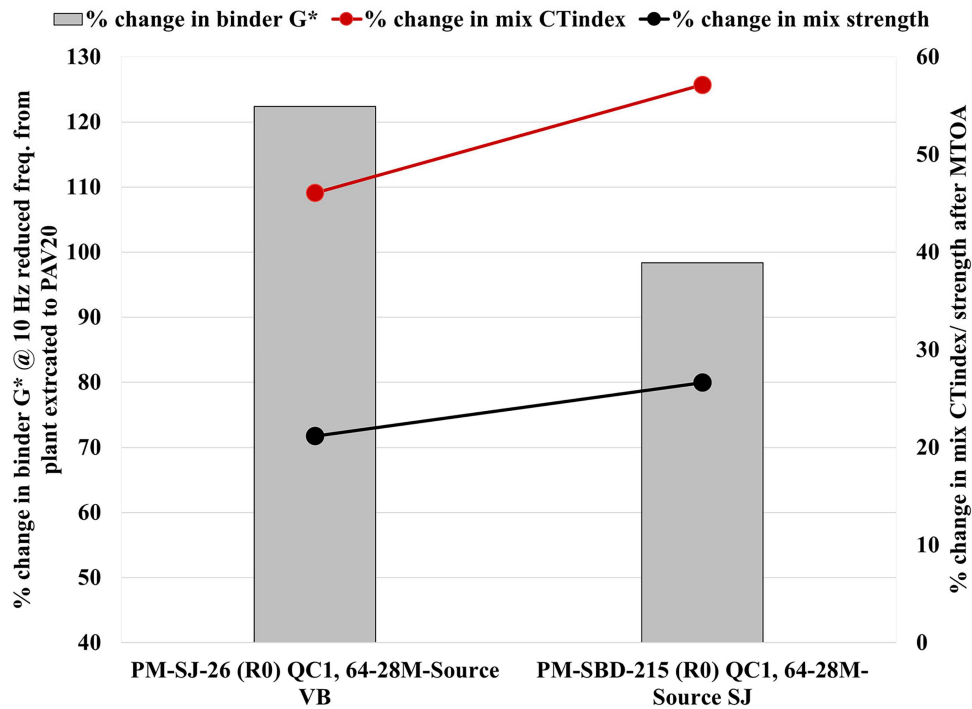


Figure 16. Percent change comparison between binder and mix properties for different binder sources.

Effect of MTOA on variability

One of the questions that this study intends to answer is whether MTOA conditioning would have any effect on the variability of IDEAL-CT results. MTOA conditioning effect on the variability can be evaluated by comparing the pooled standard error of the IDEAL-CT results for all the reheated mixes versus the same mixes after MTOA

conditioning. The standard error in this case represents the differences between 3 and 15 specimens in each set. The statistical models are shown in Equations (7) and (8) for reheated and MTOA, respectively.

$$Y_i = \mu_{RH,i} + \varepsilon_{RH} \quad (7)$$

where $\mu_{RH,i}$ is the true mean value of mix i sampled after reheating and where $\varepsilon_{RH} \sim N(0, \sigma_{RH})$

$$Y_i = \mu_{MTOA,i} + \varepsilon_{MTOA} \quad (8)$$

where $\mu_{MTOA,i}$ is the true mean value of mix i sampled after the MTOA and where $\varepsilon_{MTOA} \sim N(0, \sigma_{MTOA})$

Equations (7) and (8) were fitted to the experimental data. The outcome of the fitting is shown in Table 2 for each type of mix (HMA, RHMA-G, HMA-PM, and HMA-100%RAP). Several conclusions can be drawn from the table:

- For all mix types, the effect of MTOA conditioning on the average results of the IDEAL-CT is the same: the strength increases, the CT_{Index} decreases, and the fracture energy does not change much.
- Reheated and MTOA conditioning resulted in similar within-lot variability ($\sigma_{RH} \approx \sigma_{MTOA}$). The only exception is the CT_{Index} of HMA-100%RAP mixes, where MTOA conditioning increases the within-lot variability. The within-lot variability after reheating and reheating plus MTOA for the HMA-100%RAP mix was 6.0 and 7.3, respectively.
- Regarding the coefficient of variation (σ/μ), MTOA slightly decreases the variability of strength values and increases the variability of CT_{Index} for all mix types. For example, the coefficient of variation for strength decreases from 5.9% to 4.3% after MTOA for HMA mixes. However, the coefficient of variation for CT_{Index} slightly increases from 23.9% to 26.4% after MTOA for the same mix type. These results indicate essentially no effect of MTOA on variability.
- Strength and fracture energy have much less variability than the CT_{Index} . Without considering the HMA-100%RAP mix type, the average coefficient of variation (σ/μ) for strength and fracture energy was 7.1%, while it was 26.0% for the CT_{Index} .

MTOA effects on four point bending (4PB) test results

Flexural dynamic modulus

To evaluate the effect of MTOA on the flexural dynamic modulus and 4PB test results, four mixes were tested using 4PB flexural frequency sweep and fatigue procedures (PM-SJ-26 [R0], PM-SJ-26 [R40], HMA-

Table 2. Reheat versus Reheat + MTOA comparison summary.

Variable	Reheated			MTOA		
	μ_{RH}	σ_{RH}	$COV_{RH} (\sigma_{RH}/\mu_{RH})$	μ_{MTOA}	σ_{MTOA}	$COV_{MTOA} (\sigma_{MTOA}/\mu_{MTOA})$
HMA						
pooled results from 4 mix samplings (4 mixes, sampled once)						
Strength (psi)	190.4	11.3	5.9%	218.3	9.4	4.3%
Fracture Energy (J/m ²)	9773.0	779.0	8.0%	10146	663.7	6.5%
CT_{Index}	53.9	12.9	23.9%	34.6	9.1	26.4%
RHMA-G						
pooled results from 9 mix samplings (9 mixes, each mix sampled once)						
Strength (psi)	112.6	7.4	6.6%	133.0	6.9	5.2%
Fracture Energy (J/m ²)	8742.3	616.5	7.1%	8824.8	798.5	9.0%
CT_{Index}	236.3	59.5	25.2%	122.7	32.8	26.7%
HMA-PM						
pooled results from 24 mix samplings (13 mixes, each sampled once or twice)						
Strength (psi)	108.0	9.4	8.7%	128.3	9.0	7.0%
Fracture Energy (J/m ²)	5876.8	541.8	9.2%	6004.9	490.2	8.2%
CT_{Index}	70.7	18.9	26.7%	42.8	11.5	26.8%
HMA-100%RAP						
pooled results from 5 mix samplings (1 mix, sampled five times)						
Strength (psi)	131.7	7.1	5.4%	152.1	7.4	4.8%
Fracture Energy (J/m ²)	5857.1	381.8	6.5%	5972.1	287.0	4.8%
CT_{Index}	44.2	6.0	13.6%	30.2	7.3	24.2%

Note: COV = Coefficient of variance.

Sac-5 [R22], and R-VEN-1 [R0]). As shown in Table 1, the base binder for the PM-SJ-26 (R0), PM-SJ-26 (R40), and HMA-Sac-5 (R22) mixes was Source VB, whereas the binder source for the R-VEN-1 (R0) mix was Source VW. The RAP contents for the PM-SJ-26 (R40) and HMA-Sac-5 (R22) mixes were 40 and 22 by total weight of aggregate. No RAP was used in the PM-SJ-26 (R0) and R-VEN-1 (R0) mixes. A tall-oil-based recycling agent was used for the PM-SJ-26 (R40) mix only.

Figure 17 shows the dynamic modulus master curves after reheating and MTOA. The reduced frequency range in the figure (10^{-4} – 10^4 Hz) corresponds to the range of temperature and frequency applied in the four-point bending (4PB) dynamic modulus testing (10 – 30 °C and 0.01 – 15 Hz). As expected, MTOA increases the dynamic modulus values for all four mixes at almost all reduced frequencies. The mixes with RAP (PM-SJ-26 [R40] and HMA-Sac-5 [R22]) were found to show greater dynamic modulus values compared to other mixes as shown in Figure 17. This is attributed to the addition of a stiffer aged binder from the RAP to the mixes, although the PM-SJ-26 (R40) mix included a recycling agent. Similar findings have also been reported in previous literature (Guo et al., 2014; Rahman et al., 2023a; Rahman et al., 2021; Shu et al., 2008). Based on the stiffness at 1 Hz and 20 °C temperature, the PM-SJ-26 (R0) is the softest mix, then R-VEN-1 (R0), and after that PM-SJ-26 (R40) or HMA-Sac-5 (R22). Therefore, PM-SJ-26 (R0) is generally expected to show greater fatigue resistance compared to other mixes for thin structures, without considering any effects other than stiffness.

The normalised dynamic modulus master curves after MTOA ageing are shown in Figure 18. The dynamic modulus values after MTOA ageing were divided by the reheated values of the corresponding mixes and corresponding reduced frequencies to obtain the data in Figure 18. At 20 °C temperature and 1 Hz frequency, about 1.1–1.3 times increase in the dynamic modulus values was observed for the four mixes after MTOA ageing (Figure 18). The HMA-Sac-5 (R22) mix was found to show the highest increase in the dynamic modulus values (approximately 1.26 times at 20 °C temperature and 1 Hz frequency) compared to other mixes. This trend was also observed in the IDEAL-CT results for the HMA-Sac-5 (R22) mix discussed earlier. Overall, MTOA was found to activate more aged RAP binder for mixes with high RAP and no RA.

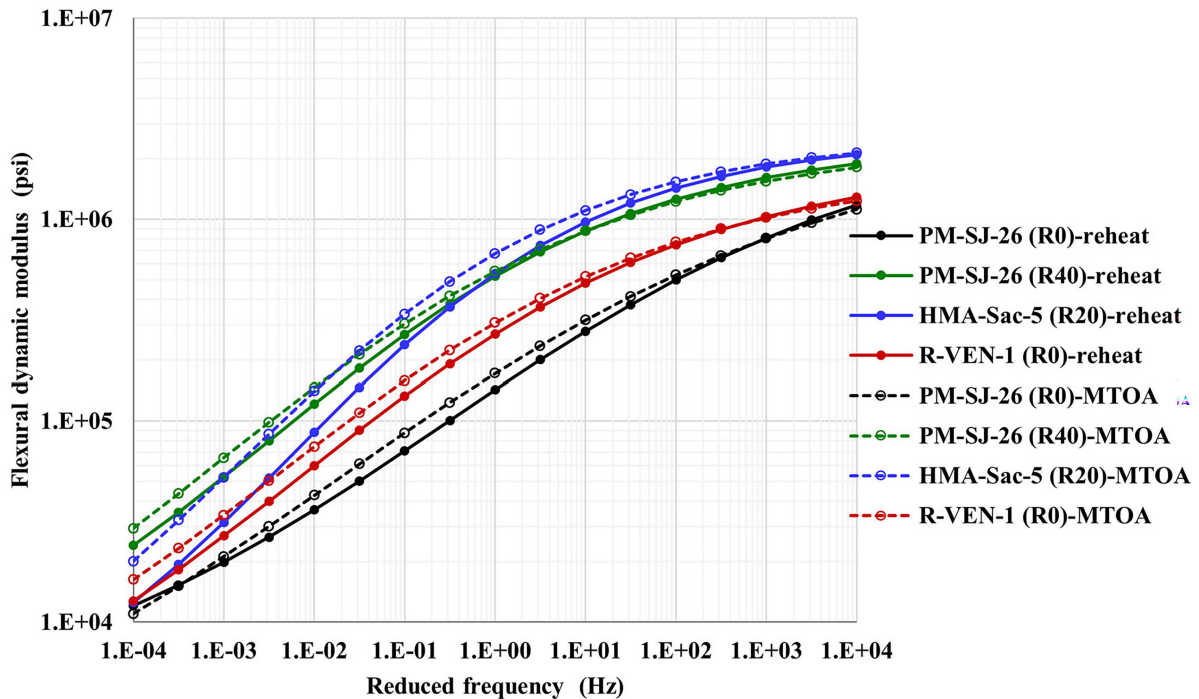


Figure 17. Flexural dynamic modulus master curves for reheated and MTOA-aged samples.

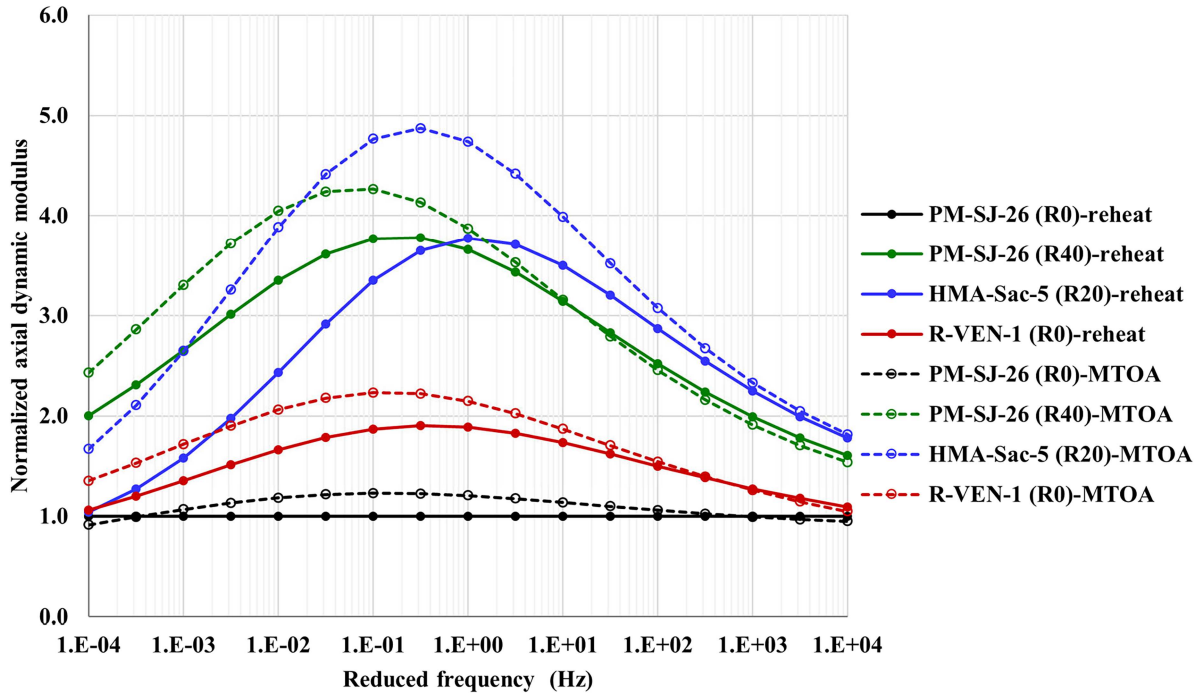


Figure 18. Normalised flexural dynamic modulus master curves after MTOA-ageing (normalised to corresponding reheated dynamic modulus values).

Flexural fatigue test

Four-point flexural beam fatigue test results for reheated and MTOA-aged samples for the four mixes (PM-SJ-26 [R0], PM-SJ-26 [R40], HMA-Sac-5 [R22], and R-VEN-1 [R0]) are shown as a Wöhler curve of log fatigue life versus log tensile strain in Figure 19; strain level @ million cycles (ϵ_6) in Figure 20; and MTOA fatigue life normalized to the results of the corresponding reheated mix at different strain levels in Figure 21.

Figures 19 and 20 show that the PM-SJ-26 (R0) mix had much longer fatigue lives for both reheating and MTOA conditions compared to other mixes. This is expected as indicated by the low stiffness of the polymer-modified PM-SJ-26 (R0) mix, which is better for thin asphalt structures (Figure 17). The strain levels at million cycles (ϵ_6) observed for the PM-SJ-26 (R0) mix after reheating and MTOA conditions were 1096 and 1062 microstrain, respectively. The ϵ_6 values observed for the PM-SJ-26 (R40) mix after reheating and MTOA conditions were 386 and 367 microstrain, respectively (Figure 20). Therefore, the addition of 40% RAP to the PM-SJ-26 (R40) mix decreased the ability to resist fatigue cracking, despite the use of a recycling agent in the PM-SJ-26 (R40) mix. Overall, MTOA reduced the ϵ_6 for three out of four mixes as shown in Figures 19 and 20. The drop in ϵ_6 values observed after MTOA for PM-SJ-26 (R0), PM-SJ-26 (R40) and R-VEN-1 (R0) mixes were 35, 19 and 104 microstrain, respectively. An increase of 18 microstrain in ϵ_6 value was observed for the HMA-Sac-5 (R22) mix after MTOA, indicating an improvement in the fatigue performance after the additional ageing. Overall, the HMA-Sac-5 [R22] mix showed the lowest fatigue life after reheating compared to all three other mixes considered in this study (PM-SJ-26 [R0], PM-SJ-26 [R40], and R-VEN-1 [R0]) (Figure 19). Therefore, the addition of MTOA did reduce fatigue life significantly for this mix.

Overall, the slope of the Wöhler curves slightly increased due to the application of MTOA, as shown in Figure 19. Ageing is expected to produce stiffer mixes, thus increasing the fatigue life at low strain levels or for thick structures and decreasing the fatigue life at high strain levels or for thin structures. Previous literature also supported similar findings (Jiao et al., 2022; Rahman et al., 2023a).

Figure 21 shows the ratio of the fatigue life (MTOA/reheated) at different strain levels for the four mixes. As expected, the ratio of fatigue life (MTOA/reheated) decreases with the increase in strain levels for most of the mix types (PM-SJ-26 [R40], HMA-Sac-5 [R22] and R-VEN-1 [R0]). However, the PM-SJ-

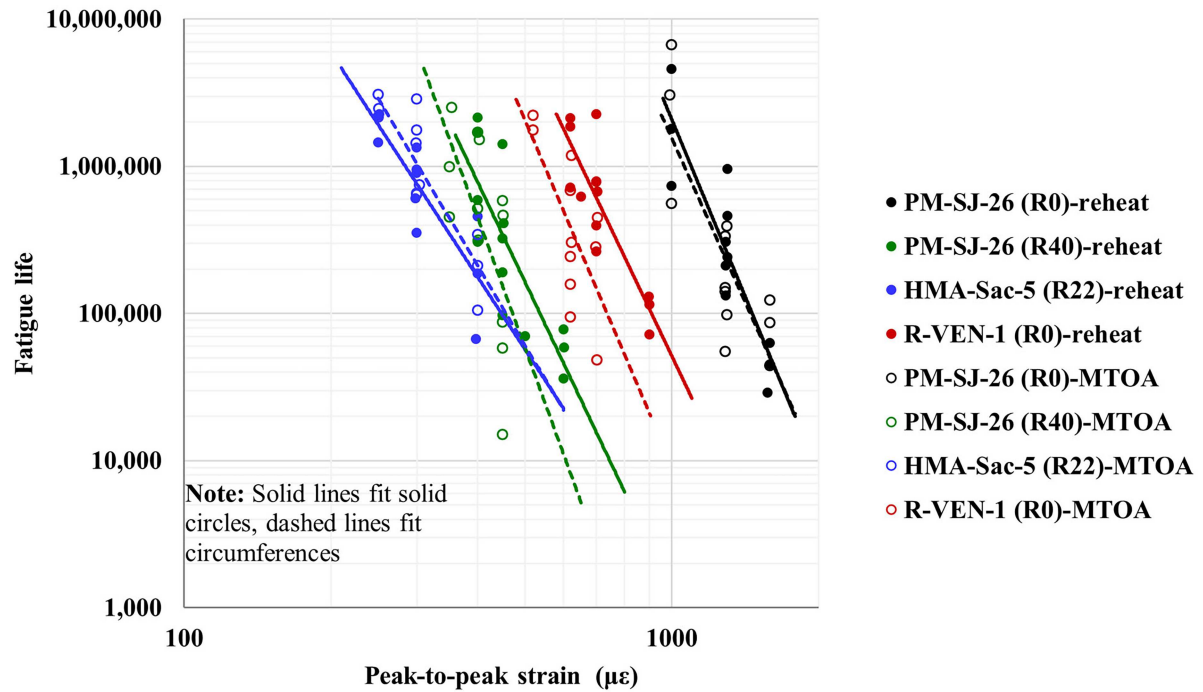


Figure 19. Flexural fatigue results for reheated and MTOA-aged samples for four mixes (Wöhler curve).

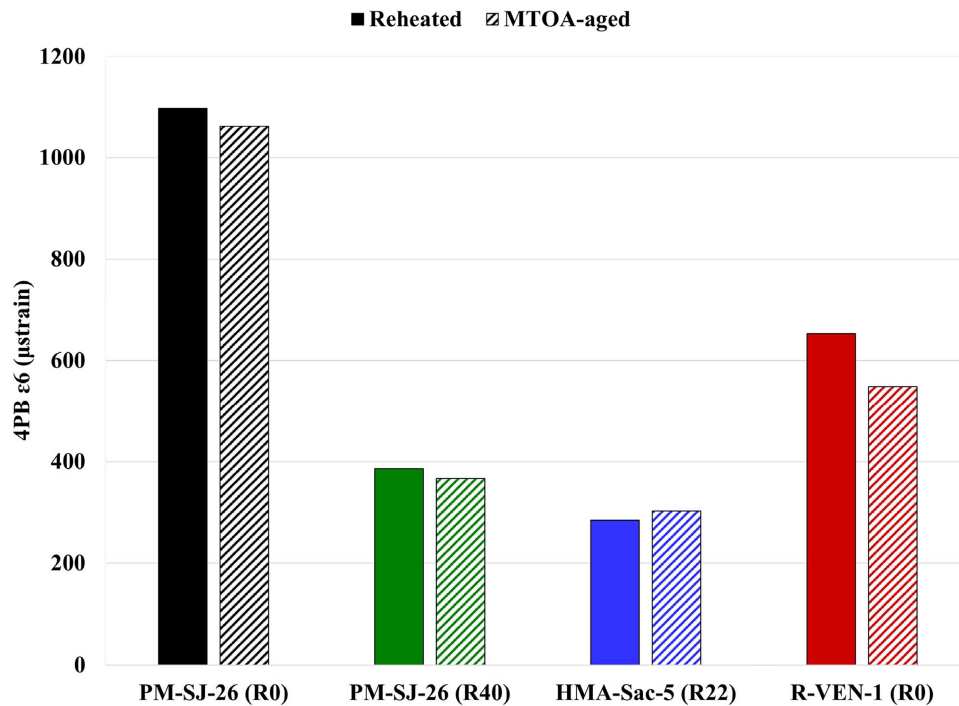


Figure 20. Strain level @ million cycles (ϵ_6) for different mixes after reheating and MTOA ageing.

26 (R0) mix was found to show a slightly opposite trend in the ratio of fatigue life (MTOA/reheated) (Figure 21). This may be attributed to the testing variability and extrapolation of the Wöhler curve at low strain levels for the polymer-modified PM-SJ-26 (R0) mix. Harvey et al. (2023) suggested that the regressions from Wöhler curves are typically found to provide reasonable estimations when extrapolated in the approximate range of 200–700 microstrain, except for polymer-modified mixes. At low strain levels,

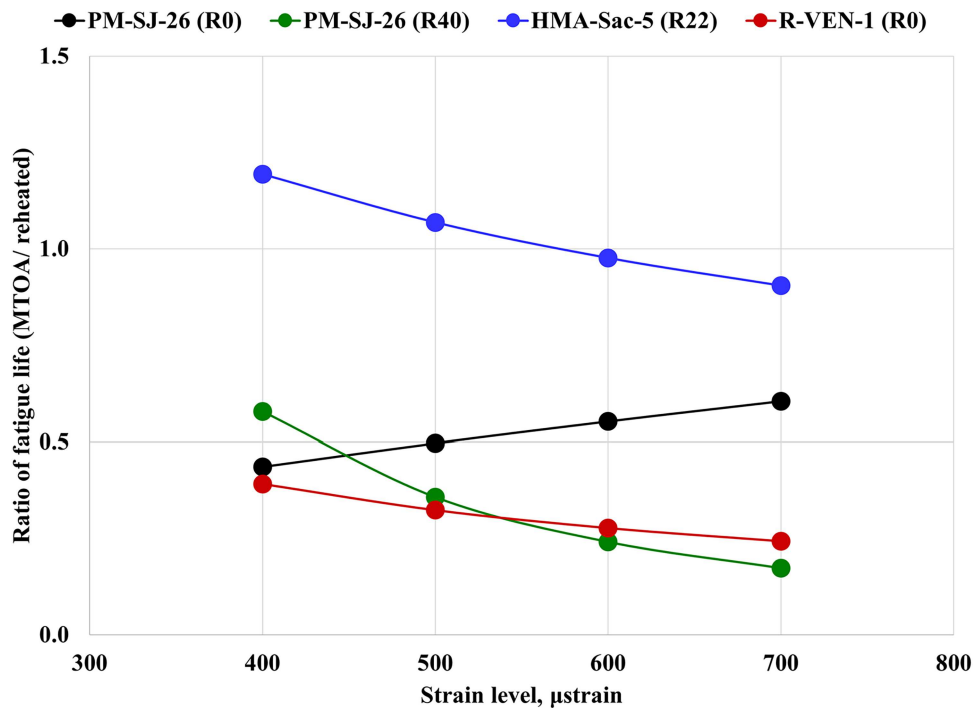


Figure 21. Ratio of fatigue life (MTOA/reheated) at different strain levels.

the polymer-modified mixes tend to have much longer actual fatigue lives than the actual extrapolated fatigue lives would indicate (Harvey et al., 2023).

Conclusions

In this study, a laboratory loose mix ageing protocol (MTOA, 20 h at 100 °C) was applied to plant-produced AC mixes containing recycled materials to evaluate the change in age-related and fatigue cracking performance with ageing. Based on this study, the following conclusions can be drawn:

- MTOA increased the strength and reduced the CT_{Index} , while the fracture energy did not change much. Overall, based on the 27 mixes that were evaluated in this study, the following changes are expected:
 - Strength increases by approximately 22 psi (150 kPa) (somewhat uniform shift regardless of original mix stiffness).
 - CT_{Index} decreases by 38% (the change in CT_{Index} is a percentage change of the unaged CT_{Index} for different mix types).
- The effects of MTOA did not seem to depend on the virgin binder source. Based on testing results from a limited number of mixes, MTOA effects are higher for mixes with medium to high RAP content (20%– 40%) and no recycling agent compared to mixes with either no RAP or with the same RAP content and recycling agent, which opposes the expectation prior to completing the study (addition of RAP reduces the aging rate of AC mixes) stated in this study. The ageing process of AC mixes containing high RAP/RAS is much more complicated than the fully blended asphalt binder with RAP.
- MTOA had little effect on the variability of the IDEAL-CT results for any of the three parameters (CT_{Index} , strength, fracture energy).
- MTOA resulted in an increase in mix flexural stiffness, particularly for low reduced frequency (high temperature). For a temperature of 20 °C and a frequency of 1 Hz, the dynamic modulus of the four mixes increased from 10% to 30% because of the MTOA. MTOA resulted in a reduction in the fatigue life of approximately 50% for three of the four tested mixes, with strain levels from 400 to 700 $\mu\epsilon$, which are typical of thin overlays of cracked pavements. For one of the mixes, MTOA did not change the fatigue life for the same strain levels.

In this study, a threshold regression band was proposed for evaluating the longer-term age-related cracking performance based on the CT_{Index} values for 27 plant-produced mixes, including high recycled content, rubberised, and polymer-modified mixes. Any AC mixes performing below this band can be considered susceptible to longer-term age-related cracking. Again, for age-related cracking, the amount of ageing that should be set as a performance-related parameter will also depend on the climate region and whether the mix is being used on the surface or below the surface in a lift that is not too deep and experiences extensive ageing. MTOA provides a means to evaluate the extent to which the AC mix ages and the trajectory of its ageing (overall, a better sense of ageing effects on the mix performance can be obtained if the performance parameters after both reheating and MTOA are known). In the long-term setting, a performance-related specification (PRS) limit requires correlating the MTOA IDEAL-CT values to observed cracking. In the short term, these results can be integrated into existing modelling and calibration to field performance. This is the next step in this research and development process. On the other hand, fatigue cracking is the interaction of mix stiffness and its effect on strain, and the fatigue life at a given strain. For thicker overlays, the increase in stiffness identified by MTOA may have a greater beneficial role on the pavement fatigue life because of reduced strain than the detrimental effect on the fatigue life at a fixed strain. The implementation of MTOA results in the PRS should be most beneficial for thinner overlays, and both the increase in stiffness and the decrease in fatigue life at a fixed strain should be included in mechanistic-empirical (ME) design calculations. For single lift overlays, a fatigue life limit can be set with MTOA, again after field calibration or initial calibration using ME modelling. For thicker overlays, there will likely be little ageing deeper than approximately 6 in., and MTOA should probably not be used for specifications at those depths (Rahman and Harvey, 2024b).

Author contributions

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