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Full Length Article

Effect of aging kinetics on the fatigue behavior of asphalt mixtures incorporating various RAP contents

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ABSTRACT

Aging significantly impacts the mechanical performance of asphalt mixtures, particularly in terms of fatigue resistance. Although several studies have investigated the fatigue behavior of asphalt mixtures with and without reclaimed asphalt pavement (RAP), limited research has studied the effect of aging kinetics on the fatigue resistance of asphalt mixtures containing RAP. This study investigates the impact of aging kinetics on the fatigue performance of asphalt concrete (AC) incorporating various RAP contents (0%, 20%, and 40%). All asphalt mixtures were subjected to short-term (STA) and long-term aging (LTA). The stiffness of asphalt mixtures was measured at 15°C and 20°C using the Indirect Tensile Stiffness Modulus (ITSM) test. The effect of aging on the stiffness was evaluated through the Aging Modulus Ratio (AMR). Fatigue performance was estimated using the Indirect Tensile Fatigue Test (ITFT) at 20°C. Recovered binders from AC were characterized using penetration, softening point, and Dynamic Shear Rheometer tests. A new method, comparing mixing rule predictions with real measured binder properties, confirmed full blending between virgin and RAP binders. The mechanical results indicate that the stiffness modulus increased significantly after both short and long-term aging for all mixtures, irrespective of RAP content. Additionally, reclaimed asphalt pavement addition increased the asphalt mixture stiffness for a given aging level. The asphalt mixture with 40% RAP showed greater resistance to aging based on AMR values. Furthermore, reclaimed asphalt pavement addition improved the fatigue performance of asphalt mixtures.

1. Introduction

Fatigue cracking is one of the primary forms of structural damage observed in flexible pavements. This type of deterioration occurs in asphalt mixtures due to repeated vehicular loading, where the Asphalt Concrete (AC) materials accumulate damage over time. This accumulative damage propagates through micro and macro-cracks (stress concentration), and eventually leading to pavement failure [1–3]. Several factors influence the fatigue performance of asphalt pavements, including the thickness of the asphalt layer, interface conditions between layers, and air void content [4–7]. Additionally, the properties of the asphalt binder play a crucial role in the fatigue resistance of the asphalt mixture [8].

In addition, the aging process significantly alters the mechanical properties of asphalt binders, resulting in increased stiffness and reduced fatigue resistance [9–13]. Therefore, various laboratory methods have been developed to simulate both short- and long-term aging of asphalt mixtures. During the aging laboratory process, the loose or compacted asphalt mixtures are exposed to elevated temperatures for specified durations. Current standards, such as XP CEN/TS 12, 697–52 and NCHRP 09–54, recommend heating loose mixtures at 135°C for four hours to simulate short-term aging. For long-term aging, mixtures are conditioned at 85°C for extended periods.

Various test methods have been used to assess the fatigue performance of asphalt mixtures, including the two-point bending test (2-PB) [14–16], three-point bending test (3-PB) [17–20], four-point bending test (4-PB) [14,21,22], tension-compression test [23–27], indirect tensile cracking test (IDEAL-CT) [28,29], and indirect tensile fatigue test (ITFT) [30,30–32]. However, despite its simplicity particularly in preparing cylindrical specimens, the ITFT remains underutilized for fatigue assessment. Notably, Belhaj et al. [33] found a strong correlation between fatigue results from the 4-PB test on prismatic specimens and the ITFT on cylindrical specimens.

On the other hand, given the growing interest in sustainability and

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the reduction of natural resources, the use of Reclaimed Asphalt Pavement (RAP) has gained significant attention. RAP is a valuable resource containing both aggregates and aged asphalt binder. However, aged RAP binder is harder and more brittle than virgin binders, which can negatively impact the mechanical performance of asphalt mixtures [34–39]. In effect, the aged RAP binder increases the brittleness of the mixture, potentially leading to premature cracking and reduced fatigue life [40]. Additionally, RAP properties can vary significantly, affecting the mechanical behavior and durability of asphalt mixtures, particularly at high RAP contents [39,41]. Consequently, current practices often limit the RAP content to approximately 30% [42,43]. Xing et al. [43] further highlighted the challenge of achieving complete blending between RAP and virgin binders, especially at high RAP levels.

In general, incorporating RAP enhances the stiffness and rutting resistance of asphalt mixtures [43–48]. It is commonly believed that the asphalt mixtures containing RAP exhibit reduced fatigue performance. Several studies [40,42,49–52] reported that adding 25% and 40% RAP improved the fatigue life of asphalt mixtures compared to virgin mixtures, regardless of binder grade. Other studies have shown that mixtures with high RAP content are more prone to early cracking [46,53,54]. Interestingly, Ma *et al.* [42] observed that fatigue life improves with RAP content up to 30%, but further increases lead to a decline in fatigue performance, suggesting the existence of an optimum RAP content for fatigue cracking resistance. This optimum content may be influenced by several factors, including the degree of aging of the RAP binder, the grade and content of the virgin binder, and the use of a recycling agent.

To enhance RAP incorporation in hot and warm mix asphalt, recent research has focused on using rejuvenators to restore the properties of aged binders [34,37,39,41,55,56]. Several studies have demonstrated that commercial rejuvenators, bio-rejuvenators, and waste oils can effectively recover the physical, rheological, and fatigue performance properties of aged binders [39,57–61].

In France, reclaimed asphalt aggregates are widely reused in road construction, including new projects, maintenance, and road reinforcement. Typically, RAP content ranges from 20% to 40% without the use of a rejuvenator. Additionally, A 35/50-grade bitumen is commonly used as the virgin binder, assuming full blending with the RAP binder. This study investigates the impact of aging on the fatigue resistance of asphalt mixtures containing 20% and 40% RAP with a 35/50-grade virgin binder, without a rejuvenator, by reproducing real on-site conditions.

2. Material and methods

This study investigates the impact of short and long-term thermal aging, as well as the incorporation of different RAP contents, on the fatigue performance of AC. The RAP used in this study was supplied by VINCI Construction and has a maximum aggregate size of 10 mm and 5.47% binder content. Three RAP contents are evaluated: 0%, 20%, and 40% by weight of the total AC mixture. The particle size distributions of the three mixtures are illustrated in Fig. 1, demonstrating that the gradations are nearly identical. This similarity in aggregate distribution suggests that any observed differences in fatigue performance among the mixtures can be attributed to variations in RAP content rather than granular skeleton.

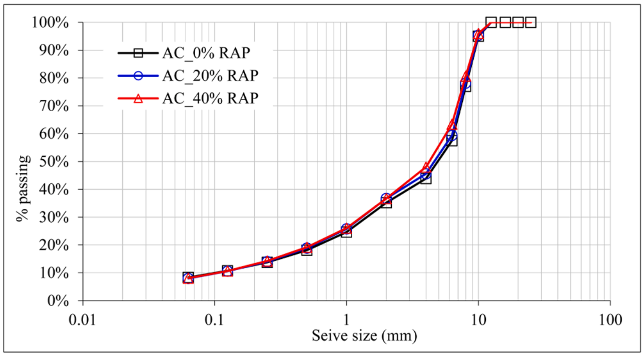

Fig. 1. AC gradation curve of 0%, 20%, and 40%RAP.

A 35/50 penetration-grade bitumen was utilized as the virgin binder in the mixtures, without the addition of any rejuvenating agents. Additionally, it is assumed that complete blending occurs between the virgin and the RAP binders, by reproducing real on-site conditions commonly adopted by industrial road companies in France.

To ensure a consistent design across the asphalt mixtures, the total binder content for each AC mix is determined using the same richness modulus value (K=3.5) in accordance with the French formulation method [62]. The richness modulus K represents the conventional thickness of the binder film coating the aggregate [63]. As the RAP content increases, the amount of virgin binder is reduced, while the total binder content is adjusted to maintain the target richness modulus. The binder contents for each mixture are summarized in Table 1.

2.1. Preparation and mixing of AC

Before mixing, all components were preheated to specific temperatures. The virgin asphalt binder was heated to 160°C for 2 hours, the mineral aggregates were kept at 170°C overnight, and the RAP material was conditioned at 110°C for 2 hours to minimize additional aging of the RAP binder. The mixing process was carried out at 160 ± 5°C according to EN 12697-35 standards. For AC mixtures without RAP, the mixing time was set to 3 minutes, while for those containing RAP, the mixing duration was extended to 5 minutes to ensure homogenous mixtures.

Cylindrical specimens, with dimensions of 50 ± 1 mm in height and 100 mm in diameter, were manufactured using the Marshall compaction method, applying 50 blows per face. A total of 54 specimens were prepared, with six specimens for each aging level and RAP contents. The air void content of all specimens was calculated using the ratio between the apparent density of the asphalt concrete (AC), measured by the geometric method according to EN 12697-6, and its bulk density. The air void values ranged between 4.9% and 6.2%.

2.2. Thermal short and long-term aging

The laboratory aging of the AC mixtures was conducted following the XP CEN/TS 12697-52 protocol to simulate both short-term and long-term thermal aging conditions. For short-term aging (STA), the loose uncompacted asphalt mixtures were conditioned in a ventilated oven at 135°C for 4 hours. For long-term aging (LTA), the short-term aged mixtures were further conditioned at 85°C for 9 days, with regular mixing at 2, 5, and 7 days. After aging, the asphalt mixtures were compacted into cylindrical specimens using the Marshall compaction procedure as described above.

2.3. Indirect tensile stiffness modulus ITSM test

The stiffness modulus is a critical parameter in evaluating the fatigue resistance of asphalt mixtures since it controls the strain level imposed by the traffic [64]. The stiffness modulus (E) of the AC specimens was determined using the ITSM test, a non-destructive test, according to EN 12697-26, Annex C. Haversine loading pulses with rest periods were

Table 1
Contents of virgin, RAP, and total binders.

Asphalt mixture	AC_0%RAP	AC_20%RAP	AC 40%_RAP
Richness modulus	3.5	3.5	3.5
RAP binder content	0%	1.09%	2.18%
Virgin binder content	5.48%	4.43%	3.43%
Total asphalt binder content	5.48%	5.52%	5.61%

applied across the vertical diameter plane of cylindrical AC specimens, and the resulting horizontal deformations were measured using linear variable differential transducers (LVDTs). Each specimen was tested twice, at 0° and 90° rotating around X-axis. The stiffness modulus was calculated using Eq. (1).

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

Where F is the peak dynamic load (N), ν is the Poisson's ratio (assumed to be 0.35 for asphalt mixes), z is the horizontal deformation (mm), and h is the thickness of the specimen (mm).

In France, the reference temperature for pavement design is 15°C, and the stiffness modulus at 15°C and 10 Hz is used in the design process. Additionally, the fatigue test in this study will be conducted at 20°C. Therefore, the stiffness modulus of all AC mixtures is measured at both 15°C and 20°C.

2.4. Indirect tensile fatigue test ITFT

Several laboratory testing and models are developed to predict the fatigue life of asphalt mixtures. Wöhler's model is one of the most used models to predict the fatigue life of asphalt mixtures.

The fatigue life of the AC mixtures was evaluated using the Indirect Tensile Fatigue Test (ITFT) at 20°C, following the EN 12697-24, Annex E standard. A controlled haversine compressive load was applied along the vertical diameter plane of the cylindrical specimens, with a loading duration of 0.1 seconds and a rest period of 0.4 seconds. The repeated compressive loads generated a uniform indirect tensile stress along the horizontal plane diameter, leading to a vertical crack formation along the diameter of the specimen.

The fatigue life (N_f) was defined as the number of loading cycles required to cause specimen failure or until the vertical deformation reached 10 mm, as illustrated in Fig. 2.

Normally, EN 12697-24, Annex E requires at least three strain/stress levels and six specimens for each strain/stress level. In this study, three different stress levels were applied to each AC mixture, but due to a lack of specimens, only two specimens were tested per stress level, resulting in a total of six specimens for each mixture.

The applied stresses (σ) were selected to produce an initial strain (ε_0) between 70 and 400 microstrains (μm/m) at 10 cycles, corresponding to stress levels ranging from 600 to 1200 kPa.

The fatigue equations were established using Wöhler's model, based on the relationship between the number of cycles to failure (N_f) and the applied stress (σ), as given in Eq. (2):

$$N_f = A(\sigma)^{-B} \tag{2}$$

where A, and B are the intercept and slope of the fatigue curve, respectively. They depend on the properties of AC. The higher the B slope value, the more sensitive the material is to fatigue.

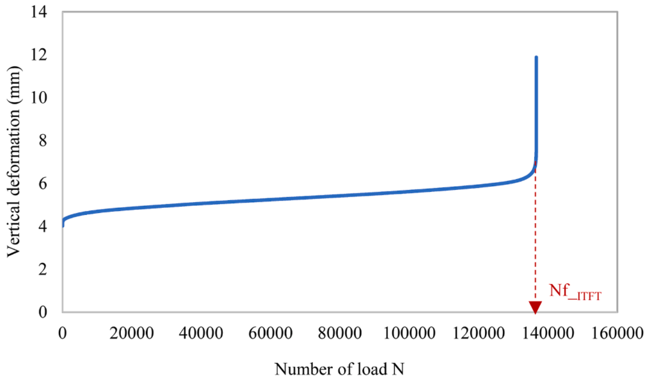

Fig. 2. Typical presentation for the used failure criterion of AC_40%RAP_STA.

Previous studies have noted that under ITFT conditions, asphalt mixtures may accumulate permanent deformation, particularly at elevated temperatures, due to their viscoelastic behavior [65]. However, since the binder used in this study is a 35/50 penetration-grade bitumen and the ITFT test was conducted at 20°C, the influence of viscoelastic behavior is considered minimal, and its impact on fatigue life is assumed to be negligible.

As previously stated, the air voids content of the specimens ranged from 4.9% to 6.2% [65]. This slight variation is not expected to significantly impact the stiffness modulus or fatigue life of the asphalt mixtures. Therefore, the effect of air void content is excluded from further analysis in this study.

2.5. Recovery and characterization of asphalt binders

After the fatigue test, the broken samples, AC_0%RAP, AC_20%RAP, and AC_40%RAP, are used to recover the corresponding binders (B_0%RAP, B_20%RAP, and B_40%RAP). Binder extraction is performed using the Asphaltanalysateur equipment (Fig. 3a) with tetrachloroethylene as the solvent. The asphalt mixtures undergo multiple washing cycles, ensuring complete binder removal. For all mixtures, both virgin and RAP binders are fully extracted, confirming full blending during the extraction phase. The recovered binders are then separated from the solvent using a rotary evaporator (Fig. 3b) through vacuum distillation.

All virgin, RAP, and recovered binders are characterized using the penetration test (EN 1426), the softening point test (EN 1427), and the dynamic shear rheometer (DSR) test (EN 14770). Two replicates are tested for each sample. For rheological characterization, a frequency sweep is conducted from 0.1 to 10 Hz, while the temperature sweep ranges from -20°C to 70°C. The master curves are constructed based on the Time-Temperature Superposition Principle (TTSP) using the Williams-Landel-Ferry (WLF) equation [66,67]. The penetration (Pen), softening point (SP), complex modulus (G*), and phase angle (δ) at 15°C and 10 Hz for both virgin and RAP binders are summarized in Table 2.

Fig. 4 illustrates the methodology and tests used to analyze the effect of RAP addition and aging on the stiffness modulus and fatigue performance of asphalt concrete.

3. Results and discussions

3.1. Assessment of RAP binder mobilization

As previously mentioned, it is assumed that complete blending occurs between the virgin and RAP binders, by reproducing real on-site conditions in France. To verify this assumption and assess the degree of homogeneity between the RAP and virgin binders, the physical properties (penetration and softening point) and rheological properties (complex modulus and phase angle) of the recovered binders from asphalt mixtures (B_AC) are measured. Additionally, mixing rules are applied to calculate the penetration (pen), softening point (SP), complex modulus (G*), and phase angle (δ) of the blended binders, assuming full blending between the virgin and RAP binders.

As the predicted properties were compared with the measured properties of the recovered binder in AC, the properties of the recovered binder from AC without RAP (B_0%RAP) were considered instead of those of the virgin binder, as indicated in Eqs. 3 to 6.

$$a\log pen_{B\_0\%RAP} + b\log pen_{RAP\ binder} \ = (a+b)\log pen_{Blended\ binder} \tag{3}$$

$$aSP_{B\_0\%RAP} + b\ SP_{RAP\ binder} \ = (a+b)\log pen_{Blended\ binder} \tag{4}$$

$$a\log G^{*}{}_{B\_0\%RAP} + b\log G^{*}{}_{RAP\ binder} \ = (a+b)\log G^{*}{}_{Blended\ binder} \tag{5}$$

$$a\log \delta_{B\_0\%RAP} + b\log \delta_{RAP\ binder} \ = (a+b)\log \delta_{Blended\ binder} \tag{6}$$

The measured and predicated penetration and softening point values of the recovered binders from the three unaged asphalt mixtures are

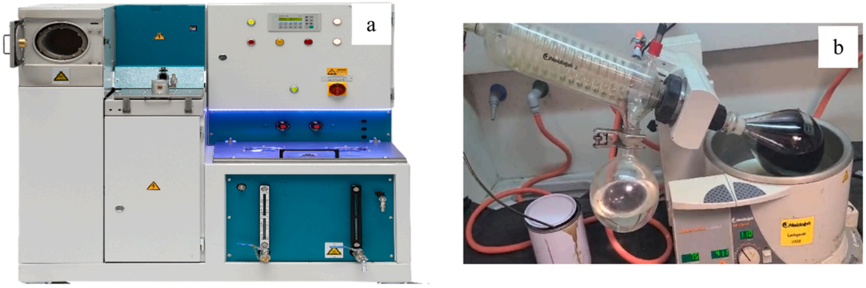

Fig. 3. a. Asphaltanalysateur to extract binder from AC, b. Rotary evaporator to separate binder from solvent.

Table 2
Physical properties of virgin and RAP binders.

Binder	pen (0.1 mm)	SP (°C)	G* at 15°C, 10 Hz (Pa)	δ at 15°C, 10 Hz (°)
35/50 virgin binder	39 ± 0.5	53.6 ± 0.4	3.92 ± 0.7 10^7	38.2 ± 1.4
RAP binder*	15 ± 1	70 ± 0.2	7.66 ± 0.8 10^7	27.5 ± 1

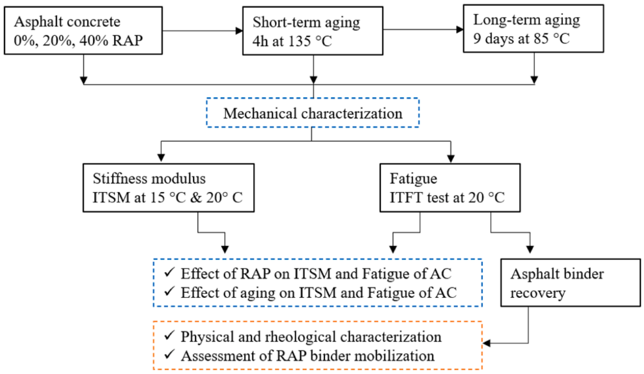

Fig. 4. A flowchart illustrating the methodology and tests used for this study.

summarized in Table 3. The results show that these values are nearly identical, particularly for the 20% RAP mixture, suggesting that almost all RAP binder was effectively mobilized to coat the aggregates durinSg mixing at 165°C for 5 minutes.

Similarly, the measured and predicted complex modulus and phase angle of the recovered binders are plotted in the Black diagram as shown in Fig. 5. The results show that the Black diagrams, derived from both measured and calculated rheological properties, are nearly superimposed for both 20% and 40% RAP mixtures. This confirms that the virgin and RAP binders fully blended during AC preparation. Moreover, the proposed method, based on comparing mixing rule predictions with the measured properties of the recovered binder, effectively assesses the homogeneity between virgin and RAP binders. To the authors' knowledge, this approach has not been previously reported in the literature.

Table 3
Measured and predicted penetration and softening point of recovered binders.

% RAP	Pen (0.1 mm) measured	Pen (0.1 mm) calculated	Standard deviation
B_0%RAP	24 ± 1	-	-
B_20% RAP	20 ± 2	22	1.4
B_40% RAP	16 ± 1	20	2.7
% RAP	SP (°C) measured	SP (°C) calculated	Standard deviation
B_0%RAP	59.8 ± 0.4	-	-
B_20% RAP	64 ± 1	61.8	1.5
B_40% RAP	68.8 ± 0.1	64	2.9

3.2. *Effect of aging and RAP content on the stiffness modulus*

The stiffness modulus of all asphalt concrete (AC) mixtures was measured at 15°C and 20°C using the Indirect Tensile Stiffness Modulus (ITSM) test, as shown in Fig. 6. The results indicate that the stiffness modulus increased for all AC mixtures after both short-term (STA) and long-term aging (LTA), regardless of the RAP content. This increase in stiffness can be primarily attributed to the hardening of asphalt binders during the aging process. Jia *et al.* [68] reported that the increased brittleness and stiffness of aged asphalt mixtures result mainly from the volatilization of lighter components within the asphalt binder, leading to a stiffer and more brittle material.

Additionally, at the same aging level, the stiffness modulus consistently increased with higher RAP content. This can be attributed to the inherent high stiffness of the RAP binder, which increases the stiffness of the recomposed binder in the AC mixtures. This finding aligns with previous studies that have reported a significant increase in stiffness modulus and rutting resistance of asphalt mixtures with RAP incorporation [47,48]. However, as aging progresses to a long-term phase, both 20% and 40% RAP content mixtures demonstrate similar stiffness modulus values at 15°C and 20°C, suggesting the AC reaches a stiffness "plateau". It suggests that the RAP binder, already aged before incorporation, has reached an aging limit, and the added binder has similarly reached a maximum stiffness with prolonged aging.

Additionally, Fig. 6 indicates that the relative difference between the stiffness moduli measured at 15°C and 20°C diminished as aging progressed and RAP content increased. This trend suggests that asphalt mixtures containing RAP exhibit reduced thermal susceptibility compared to virgin asphalt mixtures, thus enhancing their stability against temperature variations.

The effect of aging on the stiffness moduli of AC is evaluated based on the Aging Modulus Ratio (AMR), as defined in Eq. 7. An AMR value closer to 1 indicates a lesser evolution of stiffness modulus of asphalt mixtures during aging. Fig. 6 illustrates the variation of AMR values after both STA and LTA for all tested AC mixtures.

$$AMR = \frac{E_{before\ aging}}{E_{after\ aging}} \tag{7}$$

Generally, the results show that the AMR values decreased for all mixtures as aging progressed, indicating a reduction in resistance to aging. During STA, the stiffness modulus of AC containing 40% RAP was more significantly affected compared to those with 0% and 20% RAP, as evidenced by the lower AMR values. This suggests that the higher RAP content initially experiences greater stiffness changes during STA. However, after LTA, the AC with 40% RAP demonstrated less evolution after aging at both testing temperatures (15°C and 20°C), as shown by its relatively higher AMR values. This finding indicates that the addition of

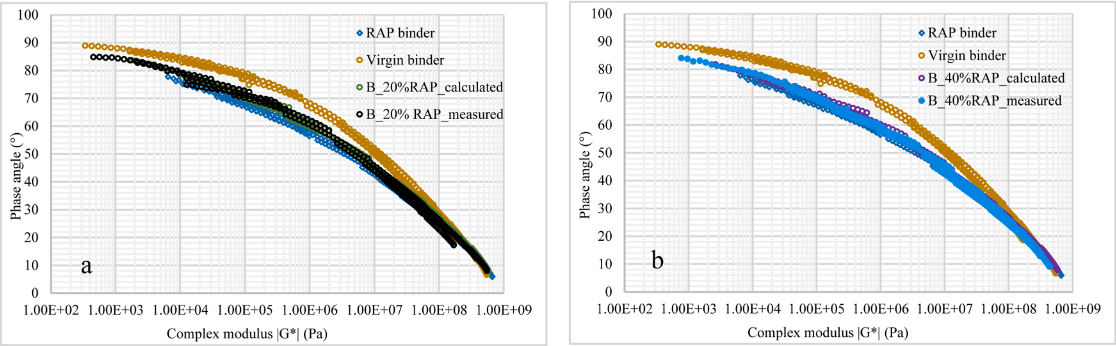

Fig. 5. Black diagram derived from both measured and calculated rheological properties, a. 20%RAP, b. 40%RAP.

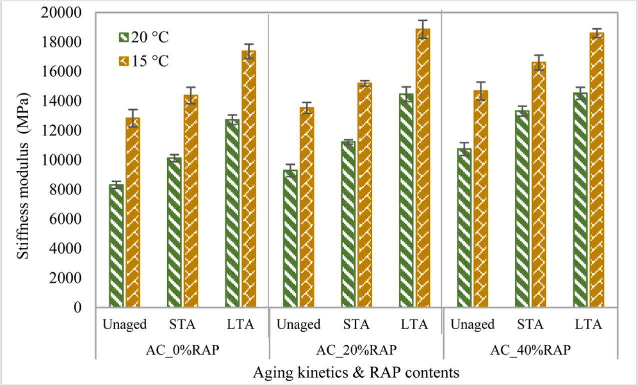

Fig. 6. Stiffness modulus of all tested AC.

RAP content, up to 40%, may enhance long-term aging resistance, based on stiffness modulus variation at 15 and 20°C. The results presented in Fig. 7 further indicate that the effect of aging on the stiffness modulus is more pronounced at 20°C compared to 15°C, as evidenced by lower AMR values at 20°C across all AC mixtures. This indicates that aging affects the stiffness modulus more significantly at higher temperatures. Similar observations were reported by [69,70], who demonstrated that the stiffness of asphalt mixtures is primarily impacted by aging at higher temperatures or lower reduced frequencies.

3.3. *Effect of aging on the fatigue life of the asphalt mixtures*

Fig. 8 illustrates the variation of the normalized stiffness modulus as a function of the number of loading cycles during the fatigue test conducted at 20°C under a constant applied stress. For all tested AC mixtures, the stiffness modulus exhibits three distinct phases throughout the fatigue life test. The pre-localization phase (phase I) is characterized by a rapid decrease in stiffness modulus, primarily attributed to the heating of samples and the effects of thixotropy. The localization phase (phase II) shows a linear decrease in stiffness modulus, reflecting the accumulation of fatigue damage within the AC mixtures. During this phase, micro-cracks interact and gradually coalesce, creating stress concentration zones. Given the hardness of the virgin and recomposed binders at 20°C, where the viscoelastic effect is minimal, this linear reduction in stiffness can be attributed only to fatigue damage, excluding any contributions from permanent deformation. The post-localization phase (phase III) is characterized by the rapid propagation of macro-cracks, ultimately leading to material failure. Since Phase II exhibits a linear relationship between stiffness modulus and loading cycles, Phases I and III are identified when deviations from this linear trend occur.

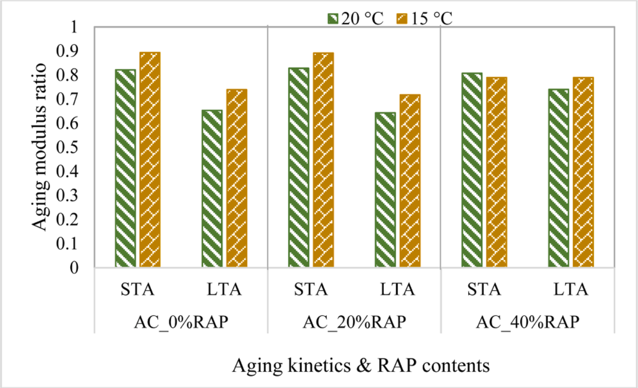

Fig. 7. Aging modulus ratio at short and long-term of different AC.

Fig. 8a–c illustrate the effect of aging on the stiffness modulus variation for AC mixtures with and without RAP during fatigue testing. To facilitate meaningful comparisons, the stiffness modulus of all AC mixtures is normalized by their corresponding initial stiffness modulus (E/E_0), where E_0 represents the average stiffness modulus measured during the first 100 loading cycles.

For all mixtures, the slope of the stiffness modulus variation in Phase II diminishes with aging, suggesting that aged AC mixtures become less sensitive to repeated loading. Moreover, both the unaged and short-term aged AC mixtures, regardless of RAP content, exhibit abrupt macro-crack propagation (phase III), indicating a brittle failure mechanism. In contrast, the long-term aged AC mixtures, with and without RAP, exhibit less abrupt failure, indicating slower macro-crack propagation.

Under the same stress conditions (700 kPa), long-term aged AC mixtures required a greater number of loading cycles to fail compared to unaged and short-term aged mixtures. However, this trend may change under higher applied stress levels. As highlighted by Hu et al. [71,72], the fatigue life of bituminous materials is strain- or stress-dependent. At lower strain or stress levels, aging can improve fatigue life, whereas at higher levels, it may have a harmful effect. They demonstrated that aging does not necessarily weaken fatigue performance and that minor aging can sometimes be beneficial.

Similarly, Babadopulos *et al.* [69] found that at certain temperatures and strain levels, aged mixtures can exhibit similar or even superior fatigue resistance compared to unaged mixtures. They stated that the aged asphalt mixtures could have better fatigue resistance than the unaged ones, depending on how the stiffness of the asphalt mixture increases due to aging. Saleh *et al.* [10] further demonstrated that the relative change in stiffness due to aging varies from mixture to mixture. Additionally, Jia *et al.* [68], attributed the reduction in fatigue life after aging to the deterioration of asphalt binder properties caused by oxidation.

Based on these findings, a hypothesis can be proposed: an increase in stiffness enhances fatigue resistance up to a certain threshold, which

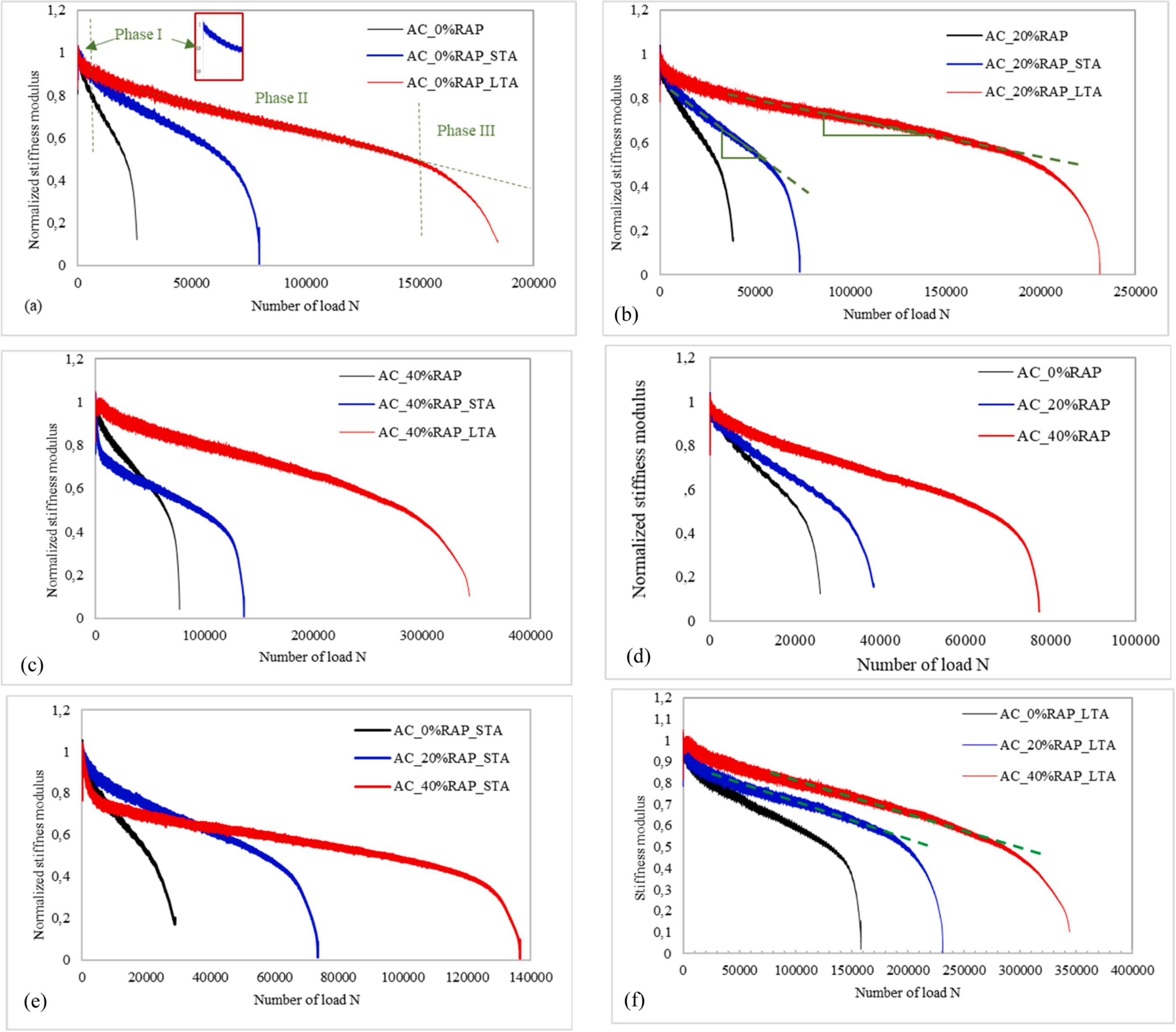

Fig. 8. variation of normalized stiffness modulus with the number of loadings. a, b, c: effect of aging, d, e, f: effect of RAP content.

varies depending on the asphalt mixture type. Beyond this stiffness limit, further increases may induce material brittleness, negatively impacting fatigue resistance.

To validate this hypothesis, further research should investigate the effects of prolonged aging (beyond nine days) to determine the stiffness threshold at which fatigue performance declines. Additionally, evaluating the fatigue properties of the extracted binders using the Linear Amplitude Sweep (LAS) test would provide a more comprehensive understanding of the impact of kinetic aging on the fatigue behavior of asphalt mixtures.

Similarly, Fig. 8d–f illustrate the effect of RAP content on the variation of stiffness modulus under repeated loading. For the unaged and short-term aged samples, the slope of stiffness modulus variation (Phase II) decreases with increasing RAP content, indicating that AC containing 40% RAP content is less susceptible to repeated loading. However, for long-term aged mixtures, the slope of stiffness modulus variation in Phase II remains nearly identical for all RAP contents.

For the same aging level and applied stress, asphalt mixtures containing 40% RAP required the highest number of load cycles to fail, followed by those with 20% RAP and, finally, mixtures without RAP. This trend indicates that incorporating RAP enhances the fatigue performance of AC mixtures, based on the indirect tensile fatigue test results at 20°C.

Fig. 9 clearly demonstrates that the fatigue life of AC mixtures decreases as the applied stress level increases, confirming that fatigue

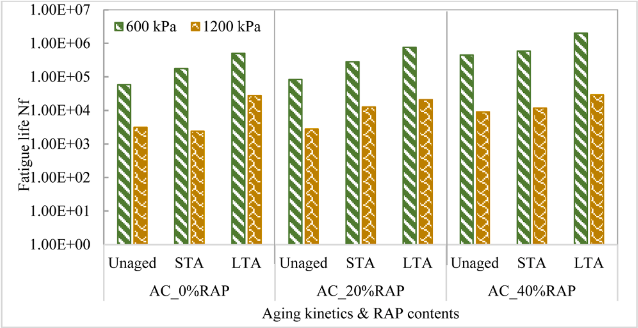

Fig. 9. Fatigue life of all AC under 600 and 1200 kPa.

performance is strain- or stress-dependent. Additionally, at a lower stress level (600 kPa), fatigue life improves with aging. However, as the stress level increases (1200 kPa), the relative improvement in fatigue life diminishes, indicating that at higher stress levels, aging becomes harmful to the fatigue resistance of asphalt mixtures.

The results presented in Fig. 10 demonstrate that the initial peak-to-peak strain, measured at 100 loading cycles, decreases with increasing RAP content and also diminishes with aging. These reductions in initial strain are primarily attributed to the increased stiffness modulus in both aged AC and AC containing RAP, indicating that the AC manufactured with RAP effectively attenuates compressive loading.

Fig. 11 illustrates the relationship between fatigue life (N_f) and the applied stress for all tested AC mixtures. The fitted Wöhler model equations as well as their R^2 are included in each plot. The variability between two replicates of fatigue results is minor for all tested AC.

Fig. 11a–c, show that within the tested stress range (600 to 1200 kPa), fatigue life increases for the aged samples. However, the fatigue curve slope “*B* parameter” increases with aging, indicating that at very high-stress levels, aging negatively impacts the fatigue resistance of asphalt mixtures. This trend is consistent with the findings of Hu et al. [72] who studied the effect of aging kinetics on the fatigue life of different penetration-grade asphalt binders using the LAS test.

Additionally, Fig. 11d–f, reveal that at the same aging levels, fatigue life increases with the addition of RAP under controlled stress conditions (600 to 1200 kPa). However, the slope of the fatigue curves also increases with higher RAP content, suggesting that at very high-stress levels or excessive RAP content, the addition of RAP can negatively impact fatigue resistance. These results indicate that incorporating RAP at appropriate contents can significantly enhance the fatigue behavior of asphalt mixtures. Similar conclusions were reported by [40,42,49–51,73], who observed improved fatigue life with increasing RAP, up to an optimum content.

Fig. 12 illustrates the fatigue life of all the AC mixtures corresponding to the horizontal strain values of 50, 100, and 150 microstrains. As expected, fatigue life decreases with increasing strain values across all tested AC mixtures. At low strain levels (50, and 100 microstrains), no definitive conclusions can be drawn regarding the effects of aging or RAP addition on fatigue life. However, at the high strain level of 150 microstrains, all AC mixtures exhibit nearly identical fatigue life. This indicates that the influence of RAP on fatigue performance is more pronounced under lower strain conditions. As previously discussed, the initial strain under the same compressive loading decreases with increasing RAP content. This indicates that, for identical traffic loading conditions, the AC mixtures with RAP would require a thinner asphalt layer compared to AC without RAP to achieve the same strain levels. Otherwise, for a given asphalt layer thickness, AC with RAP would need to higher compressive loading to reach the same strain as the virgin AC mixtures.

4. Conclusion

This study investigated the effects of aging and varying Reclaimed Asphalt Pavement (RAP) content on the fatigue performance of Asphalt Concrete (AC) mixtures without rejuvenator. The key findings can be summarized as follows:

- The proposed method, comparing mixing rule predictions with measured recovered binder properties, effectively assesses the homogeneity between virgin and RAP binders.
- The stiffness modulus variation during damage progression exhibited three distinct phases, confirming the effectiveness of the ITFT test in evaluating asphalt mixture fatigue behavior.
- Under tested stress conditions (600–1200 kPa), aged asphalt mixtures exhibited greater fatigue resistance than unaged ones. However, Wöhler’s curves suggest that at very high stress levels, aging negatively impacts fatigue resistance.
- Fatigue life increased with RAP addition under controlled stress conditions, but Wöhler’s curves indicate that excessive RAP content may negatively affect fatigue resistance at high stress levels.
- Fatigue life decreased with increasing strain levels for all AC mixtures. At high strain levels (150 microstrains), all mixtures exhibited nearly identical fatigue lives.
- Using RAP at appropriate content can significantly enhance the fatigue performance of asphalt mixtures, potentially extending pavement service life.

To further refine these findings, future studies should consider:

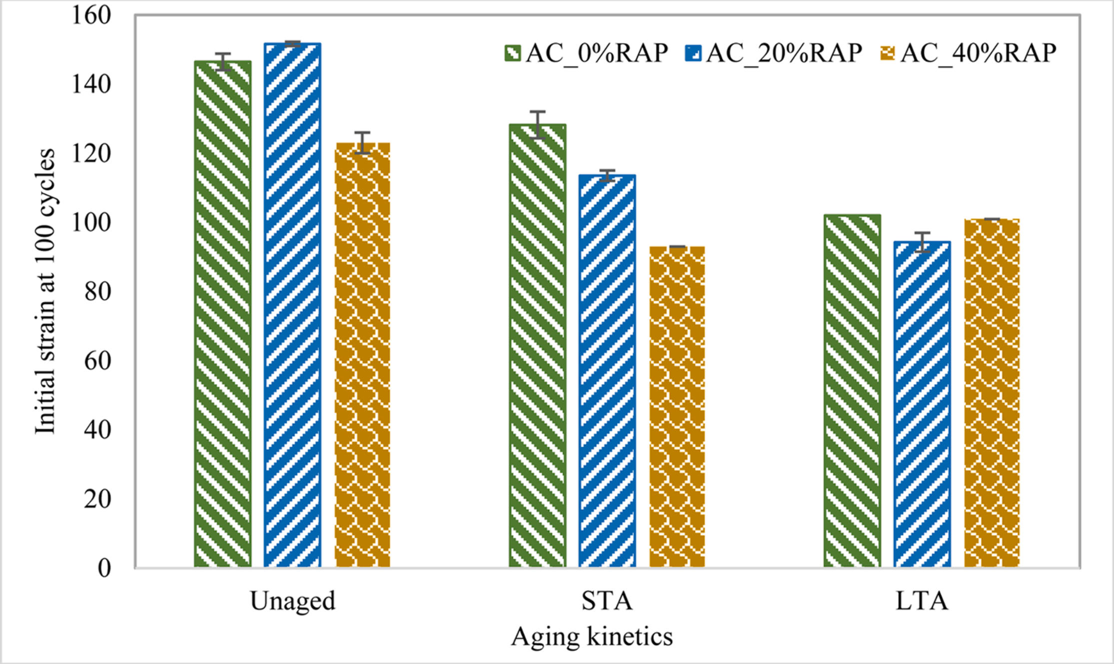

Fig. 10. Initial peak-to-peak strain under 800 kPa for all AC.

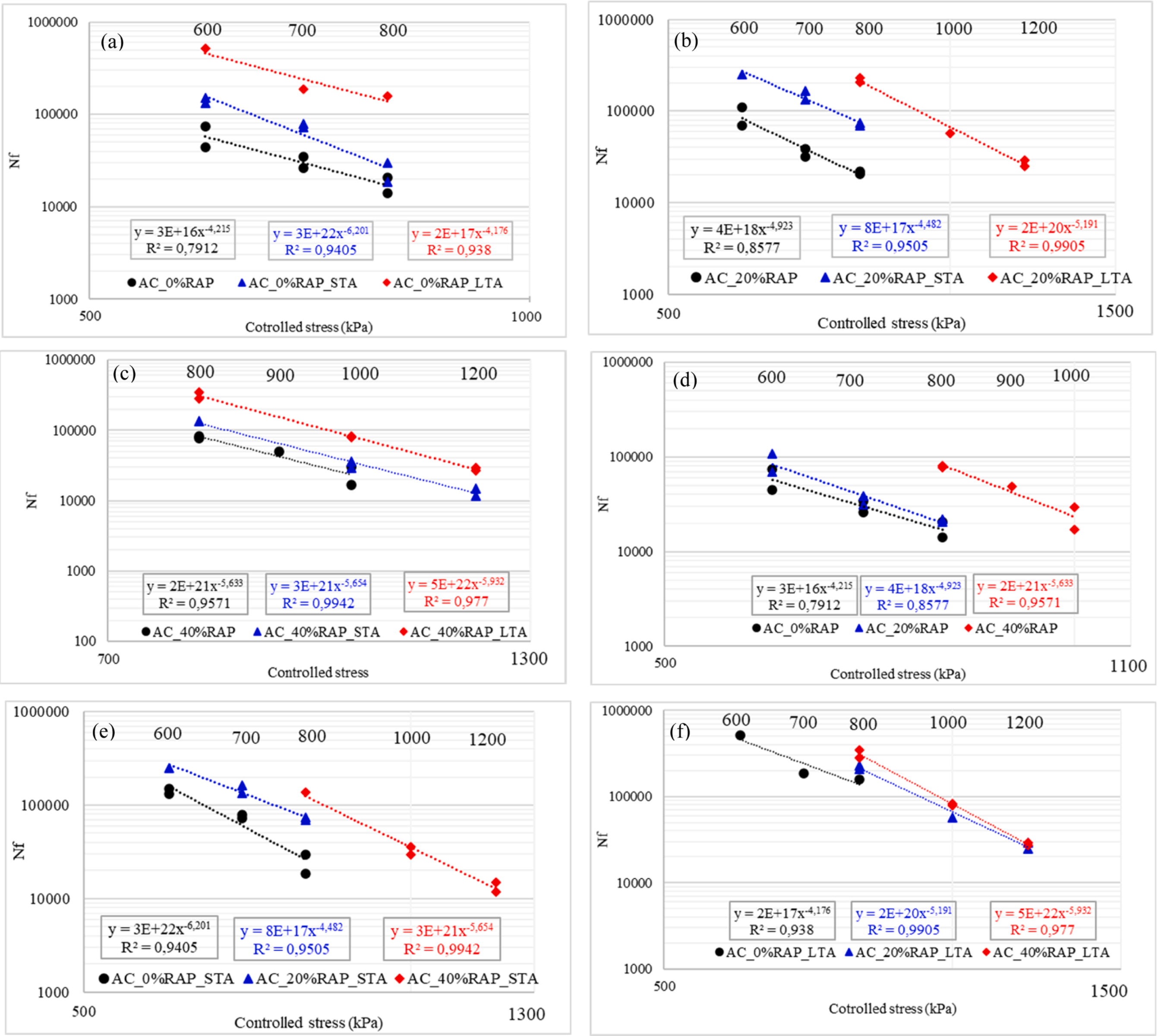

Fig. 11. Relationship between fatigue life and applied stress. a, b, c: effect of aging, d, e, f: effect of RAP content.

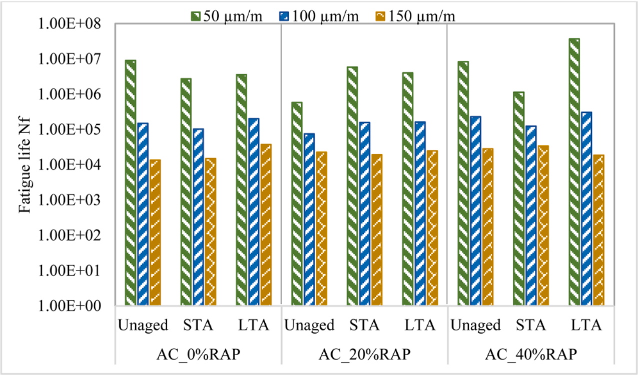

Fig. 12. Fatigue life of all AC for the same strain values.

- A deeper investigation into blending and homogeneity between virgin and RAP binders.
- Extending aging duration beyond 9 days to better understand its long-term impact on fatigue performance.
- Testing higher stress levels beyond 1200 kPa to clearly highlight the effects of aging and RAP on fatigue life under extreme conditions.
- Investigating the effect of rejuvenators on the aging and fatigue resistance of asphalt mixtures containing high RAP content.

CRediT authorship contribution statement

Mohammed Nouali: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Anne Dony:** Visualization, Validation, Supervision, Methodology. **Stéphanie Vignaud:** Visualization, Methodology, Investigation, Conceptualization. **Alan Carter:** Visualization, Validation, Supervision, Methodology.

Declaration of competing interest

There is no conflicts of interest for this paper.

Data availability

No data was used for the research described in the article.

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