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ARTICLE

Durability and Cracking Resistance Evaluation of Recycled Asphalt Concrete Pavement with High RAP Content

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ABSTRACT: To address the critical issues of low-temperature cracking and insufficient fatigue durability in high-content Recycled Asphalt Pavement (RAP) mixtures caused by aging-induced embrittlement, this study aims to establish a cross-scale cracking resistance evaluation system ranging from binder rheological properties to mixture failure behavior. This research selected various RAP contents (15%–60%) and rejuvenator dosages (0%–12%) to quantify the fatigue damage evolution of rejuvenated binders using Linear Amplitude Sweep (LAS) tests combined with the Viscoelastic Continuum Damage (VECD) model. Furthermore, Semi-Circular Bend (SCB) tests were employed under two loading modes—low-temperature (−12°C) monotonic loading and intermediate-temperature (20°C) cyclic loading—to evaluate the low-temperature fracture toughness and fatigue life of the mixtures, respectively. Experimental results indicate that the hardening of aged asphalt in RAP significantly impairs the stress relaxation capacity of the material, leading to a decay in cracking resistance. LAS tests confirmed that the rejuvenator effectively softens the binder and retards micro-crack propagation; specifically, a 12% dosage increased the fatigue life of the aged binder by approximately 56%. At the mixture level, low-temperature SCB tests revealed a "dosage threshold" effect for high RAP content: for mixtures with 60% RAP, low dosages of rejuvenator showed limited improvement, whereas a 12% dosage was required to significantly elevate the fracture energy (Gf) from 5.57 to 6.49 J/m^2, realizing a transition from brittle to ductile behavior. Cyclic SCB tests further demonstrated that 60% RAP caused a precipitous drop in fatigue life by 74% compared to the virgin mixture (down to 1896 cycles), while the addition of 12% rejuvenator restored the life to 5967 cycles, significantly reversing the risk of fatigue cracking. This study quantifies the non-linear gain laws of rejuvenator dosage on cracking resistance and confirms that adopting a high-dosage rejuvenator strategy (>9%) is a key technical pathway to ensure the long-term cracking durability of high-RAP pavement.

KEYWORDS: Recycled asphalt mixture (RAM); cyclic loading; semi-circular bend (SCB) test; cracking resistance; fatigue life

1 Introduction

Under the grand backdrop of global climate change mitigation and the pursuit of "Carbon Neutrality" strategies, transportation infrastructure construction is undergoing a profound transformation from scale expansion to green and low-carbon development. As the mainstream form of highway construction, the maintenance and reconstruction of asphalt pavements generate hundreds of millions of tons of Reclaimed Asphalt Pavement (RAP) materials annually. According to 2024 statistics from the World Road Association

(PIARC), global asphalt pavement maintenance and reconstruction projects produce over 200 million tons of RAP each year [1]. Treating this RAP as construction waste for landfill not only occupies valuable land resources and poses potential environmental pollution risks to soil and groundwater, but also constitutes a tremendous waste of resources [1,2]. To mitigate these environmental impacts, various sustainable pavement technologies have been extensively explored, such as cold in-place recycling mixtures [3] and the utilization of tire-derived aggregates in rubber-modified asphalt mixtures [4]. Meanwhile, as a non-renewable petroleum-based material, the production of virgin asphalt is accompanied by significant greenhouse gas (GHG) emissions, and its price is significantly affected by fluctuations in the international crude oil market [5]. Research in Life Cycle Assessment (LCA) indicates that, compared to full-depth new pavements, hot recycling technology utilizing high-content RAP (>40%) can significantly reduce energy consumption and carbon footprint, offering substantial ecological benefits and economic value [6,7]. Therefore, maximizing RAP content while ensuring the long-term service performance of pavements has become a critical technical bottleneck urgently needing to be overcome in the field of road engineering [8].

Despite the broad application prospects of Recycled Asphalt Mixtures (RAM) with high RAP content, in practical engineering, the durability of recycled pavements often faces severe challenges when RAP content exceeds 30% or even 40% [9]. The core issue lies in the severe aging of the asphalt binder within the RAP. During long-term service, asphalt undergoes a series of physicochemical hardening processes under the combined effects of heat, oxygen, light, and moisture [10]. Macroscopic rheological characteristics show that the complex shear modulus (G^*) of aged asphalt increases significantly while the phase angle decreases, exhibiting distinct "hard and brittle" features [11,12]. This deterioration in rheological properties leads to a drastic decline in the stress relaxation capacity of the asphalt binder. When a high proportion of aged asphalt is present in the mixture, although it contributes to improved rutting resistance to a certain extent, the hardened asphalt film cannot effectively dissipate accumulated internal stresses under low-temperature environments or repeated traffic loading. This susceptibility makes it prone to inducing the initiation and propagation of micro-cracks at the aggregate-asphalt interface, ultimately leading to early distresses such as thermal cracking or fatigue cracking [13,14].

To restore the rheological properties of aged asphalt, rejuvenator technology has been widely applied in the design of recycled pavements [15]. Based on compatibility and rheological theories, rejuvenators typically contain light oil components aimed at adjusting the component ratio of aged asphalt through penetration and softening effects, thereby reducing its viscosity and restoring viscoelasticity [16]. In recent years, with increasing environmental requirements, bio-based rejuvenators (such as waste vegetable oils, tall oils, etc.) have gradually become a research hotspot due to their excellent penetration ability and renewable characteristics [17,18]. Recent studies have further demonstrated the potential of bio-additives in enhancing binder performance; for instance, bio-asphalt binders have shown promising rutting resistance characteristics in Multiple Stress Creep Recovery (MSCR) tests [19], and sustainable additives like olive pomace oil combined with polymers have been proven to effectively improve the physical and rheological properties of asphalt binders [20]. However, existing regeneration technologies still have limitations. On one hand, the degree of diffusion and blending of the rejuvenator within the RAP directly affects the regeneration effect; insufficient diffusion may lead to the "black rock" phenomenon within the mixture, resulting in weak interfacial bonding [21]. On the other hand, traditional evaluation indicators for rejuvenators often focus on the restoration of empirical parameters like penetration and softening point, lacking in-depth consideration of the fatigue resistance of rejuvenated binders under complex stress states. Some studies point out that although certain rejuvenators can temporarily soften asphalt, secondary aging may occur after long-term service, leading to a renewed rapid decay in the pavement's cracking resistance [22,23].

Accurately evaluating the cracking resistance of recycled mixtures is core to guiding mix design and life prediction. Traditional evaluation methods such as the Indirect Tensile Test (IDT) or Four-Point Bending Test (4PB), while mature in application, often suffer from complex specimen preparation, long duration, and high data variability [24]. In recent years, evaluation methods based on damage mechanics and fracture mechanics have gained favor due to their clear mechanisms and high efficiency. At the binder level, traditional Superpave PG grading parameters have limitations in evaluating the fatigue performance of modified and recycled asphalts. The Linear Amplitude Sweep (LAS) test, based on Viscoelastic Continuum Damage (VECD) theory, can more accurately predict fatigue life at different strain levels and shows good correlation with field cracking performance [25–27]. At the mixture level, the Semi-Circular Bend (SCB) test has become an important means for evaluating cracking resistance due to the ease of obtaining specimens and controllable fracture modes [28]. Current SCB research mostly employs monotonic loading modes to determine fracture energy, primarily reflecting the material's ultimate cracking strength [29]. However, actual pavement structures are subjected to cyclic traffic loading, and the material undergoes a dynamic fatigue process of damage accumulation. The latest research trends indicate that combining monotonic SCB with Cyclic SCB tests can more comprehensively reveal the durability characteristics of high-modulus materials (such as high-RAP mixtures) during the damage accumulation stage [30–32].

In summary, addressing the issues of fatigue cracking and low-temperature brittleness common in high-RAP recycled asphalt mixtures, this study aims to establish a cross-scale cracking resistance evaluation system ranging from binder rheological properties to macroscopic mixture failure behavior. This research utilizes LAS tests to quantify the corrective effects of different rejuvenator dosages on the fatigue damage characteristics of aged asphalt. Concurrently, it innovatively combines low-temperature (−12°C) monotonic loading with intermediate-temperature (20°C) cyclic loading SCB tests to systematically explore the influence laws of RAP content and rejuvenators on the low-temperature fracture toughness and fatigue life of asphalt concrete. The study places particular emphasis on analyzing the performance attenuation characteristics of high-content (60%) RAP mixtures, with the goal of establishing the optimal rejuvenator dosage threshold that meets long-life pavement requirements, thereby providing a scientific basis for the durable application of high-proportion RAP.

2 Materials and Methods

2.1 Raw Materials

2.1.1 Asphalt

The RAP material used in this study was obtained from an expressway asphalt pavement with a service life of 10 years. Testing revealed an asphalt content of 5.1% in the RAP. To accurately evaluate the performance of the aged asphalt, the experiment employed centrifugal extraction and rotary evaporation methods (as shown in Fig. 1) to recover asphalt from the RAP.

Comparing the virgin asphalt with the recovered RAP asphalt (Table 1), the performance of the aged asphalt has significantly deteriorated. The penetration (25°C) is far lower than the 65.1 (0.1 mm) of the virgin asphalt, indicating severe hardening due to aging. The ductility of the RAP asphalt dropped drastically to 1.6 cm, compared to 38.2 cm for the virgin asphalt, suggesting extremely poor deformability at low temperatures and a high susceptibility to brittle fracture. The softening point of the RAP asphalt was 66.4°C, slightly lower than the 69.6°C of the virgin asphalt, which may be related to specific aging behaviors of certain components, though it still maintains high-temperature stability. The most significant change lies in viscosity; the RAP asphalt reached 3550 Pa·s, more than double that of the virgin asphalt (1585 Pa·s), which will significantly affect the mixing and compaction performance of the mixture.

Figure 1: Extraction and distillation apparatus for aged asphalt binder.

Table 1: Basic technical indicators of asphalt binders.

Index	Penetration (25°C, 100 g, 5 s) (0.1 mm)	Ductility (5 cm/min, 5°C) (cm)	Softening Point (°C)	Brookfield Viscosity (135°C) (Pa·s)
Virgin Asphalt	65.1	38.2	69.6	1585
RAP Asphalt	25.0	1.6	66.4	3550

2.1.2 Rejuvenator

To restore the performance of the aged asphalt, a rejuvenator designated as 'YJ' was selected for this study. The physicochemical indicators of YJ are shown in Table 2. This rejuvenator is brownish-black, with a density of 0.966 g/cm^3 and a viscosity of 284 mPa·s at 60°C. Its relatively high weight-average molecular weight (2320 Daltons) helps ensure stability during long-term service and resistance to volatilization.

Table 2: Physicochemical indicators of YJ rejuvenator.

Type	Density (g/cm^3)	Color	Viscosity at 60°C (mPa·s)	Weight-Average Molecular Weight (Daltons)
YJ	0.966	Brown-Black	284	2320

The YJ rejuvenator utilized in this study is a self-developed product. Its chemical composition consists of approximately 50% high-viscosity vegetable oil, 15% polymeric additives, and the remainder being mineral diluent oil. In the preparation process, the virgin asphalt was first blended with the extracted RAP binder. Subsequently, the rejuvenator was added at dosages of 3%, 6%, 9%, and 12% by weight of the total binder mass. The selection of the upper dosage limit was based on preliminary penetration tests performed on a binder blend containing 60% extracted RAP binder and 40% virgin asphalt. The results indicated that a 15% rejuvenator dosage yielded a penetration of 98.1 (0.1 mm), which was considered excessive and potentially detrimental to high-temperature stability. In contrast, the 12% dosage resulted in a penetration of 79.6 (0.1 mm), falling within the optimal engineering range. Consequently, the rejuvenator dosages were finalized at 3%, 6%, 9%, and 12% for this study.

2.2 *Mix Design and Specimen Preparation*

Fig. 2 shows the aggregate gradation curve for the AC-13 fine-graded asphalt mixture adopted in this study. The mix design strictly follows the requirements of the Chinese "Technical Specifications for Construction of Highway Asphalt Pavements" (JTG F40). The black and red curves in the figure indicate the upper and lower limits specified by the standard, respectively. The experimental design gradation lies entirely within this range and closely aligns with the median gradation line. This continuous dense-graded structure is reasonably designed to ensure that the recycled mixture possesses good skeletal density and meets pavement performance requirements.

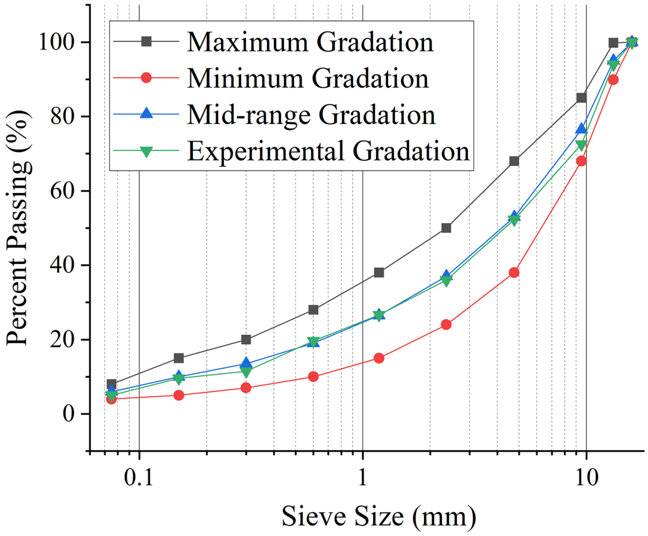

Figure 2: Gradation curve of AC-13 recycled asphalt mixture.

RAP content was set at four gradients: 15%, 30%, 45%, and 60%, with rejuvenator dosages of 3%, 6%, 9%, and 12%, respectively. The designed asphalt-aggregate ratio was 5.3%. Fig. 3 illustrates the molding and preparation process for the recycled asphalt mixture. First, the RAP was placed in an oven at 150°C for 1 h to activate the aged asphalt. Subsequently, the preheated RAP was mixed with heated virgin aggregates, base asphalt, and the rejuvenator in a mixer at 175°C until fully blended. Finally, the uniformly mixed asphalt mixture was subjected to standard compaction to form Marshall specimens for testing.

2.3 *Asphalt Binder Fatigue Test*

This study evaluated the fatigue performance of recycled asphalt binders using the Linear Amplitude Sweep (LAS) test based on a Dynamic Shear Rheometer (DSR), in accordance with the "Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering" (JTG 3410-2025) and AASHTO TP101 standards. This method, combined with Viscoelastic Continuum Damage (VECD) theory, tested samples (8 mm diameter, 2 mm gap) of rejuvenated asphalt at 25°C. The test consists of two phases: first, a frequency sweep from 0.2 to 30 Hz to determine the undamaged material constant; followed by an amplitude sweep at 10 Hz with shear strain increasing linearly from 0.1% to 30% (as shown in Fig. 4). By analyzing the cumulative damage evolution process, this method allows for the rapid and accurate prediction of the fatigue life of aged asphalt at different strain levels.

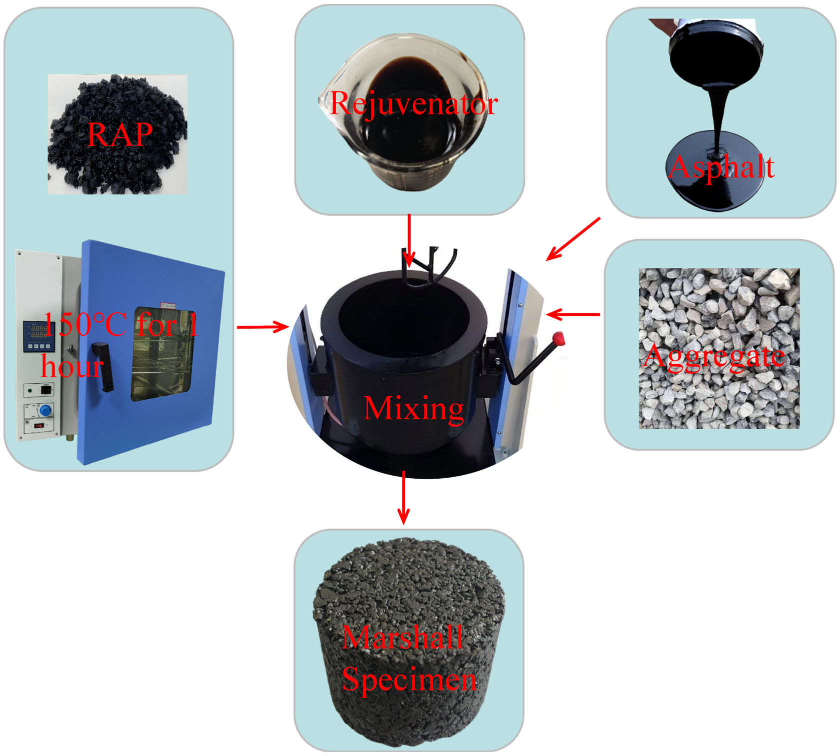

Figure 3: Preparation process of recycled asphalt mixture.

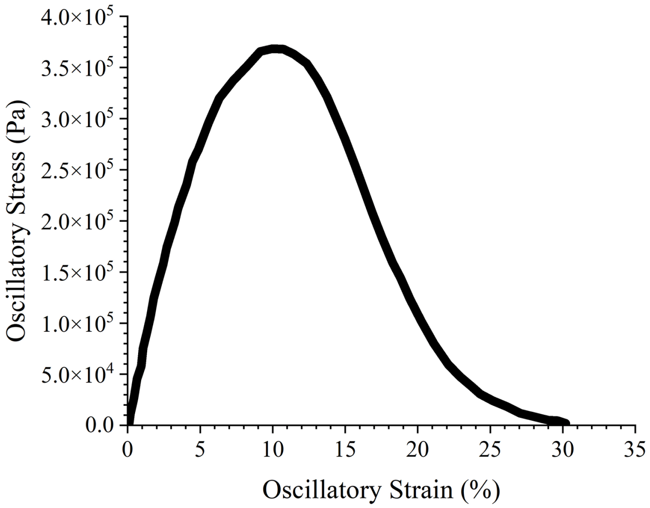

Figure 4: Curve of linear strain sweep from 0.1% to 30%.

2.4 Asphalt Mixture Fatigue Test

2.4.1 Low-Temperature Cracking Resistance

To accurately evaluate the cracking toughness of recycled asphalt mixtures in extreme cold climates, the Semi-Circular Bend (SCB) test was selected. Specimens were cut from gyratory compacted cylinders. To simulate initial defects within the pavement structure, a standard notch was pre-fabricated at the center of the bottom of the semi-circular specimen, with the notch length strictly controlled at 15 ± 1 mm and width at 2 ± 0.5 mm. To minimize the impact of specimen preparation variability on results, volumetric indicators were checked for all specimens after cutting; only specimens with air voids within the range of 4 ± 0.5% were retained. For each experimental condition, three parallel specimens were tested to ensure data reliability. The test relied on a UTM-100 universal material testing machine equipped with an environmental chamber. The test temperature was constant at −12°C, and the span between bottom support points was set to 120 mm. The test procedure was as follows: first, a preload of 0.1 kN was applied to eliminate contact gaps and ensure system stability; subsequently, monotonic loading was applied in displacement control mode at a strict rate of 50 mm/min until the specimen fractured completely. The system recorded load and vertical displacement data in real-time. Based on fracture mechanics theory, Fracture Energy (Gf) was obtained by calculating the area under the load-displacement curve, and the final result was reported as the average of the three replicates to quantify the material's potential to resist low-temperature crack propagation [20,26].

2.4.2 Fatigue Cracking

To comprehensively evaluate the long-term durability of asphalt mixtures under actual pavement service environments, this study utilized the UTM-100 multifunctional material testing machine (as shown in Fig. 5) for fatigue cracking tests. The equipment, featuring a high-precision environmental chamber and servo-hydraulic loading system, performed tests at an intermediate temperature of 20°C using the Semi-Circular Bend (SCB) mode under repeated loading. Unlike monotonic loading, the repeated loading test adopted a stress-controlled mode to simulate the repetitive action of traffic loads on the pavement structure. The stress level was set based on the ultimate strength measured from the monotonic SCB test at the same temperature (20°C); a stress ratio of 0.25 was uniformly selected for this study. To ensure data reliability, three parallel specimens were tested for each experimental condition, and the Standard Deviation (SD) was calculated to assess data variability. The fatigue failure criterion was adopted from ASTM D8044, defined as the "second inflection point" of the displacement-cycle curve, corresponding to the critical transition from stable crack propagation to unstable failure. By recording the number of load cycles at failure based on this criterion and calculating the average value, the influence of different rejuvenator and RAP contents on the fatigue cracking resistance of the material was quantified.

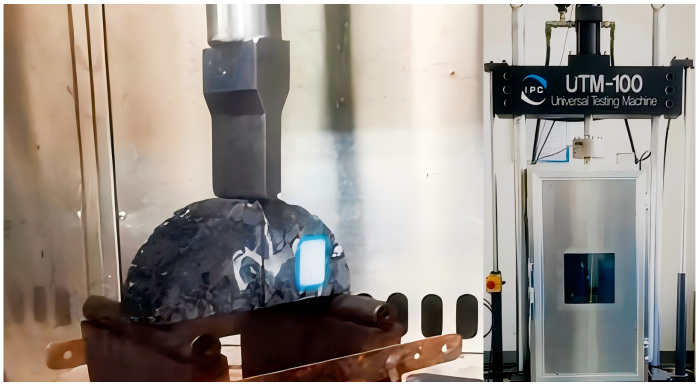

Figure 5: Photos of low-temperature and fatigue cracking tests.

3 Results and Analysis

3.1 Binder Fatigue Performance

Fig. 6 displays the damage characteristic curves (C-D curves) of asphalt binders with different rejuvenator dosages calculated based on VECD theory, where the ordinate C represents pseudo-stiffness (reflecting material integrity) and the abscissa D represents the cumulative damage variable. Observing the curve evolution characteristics, the curve for the aged asphalt without rejuvenator (0% group) is positioned highest and descends relatively gently, extending to a higher damage level. This reflects the high modulus and severe aging-induced brittle characteristics of the aged asphalt, indicating a rigid internal structure lacking flexible deformation capacity. As the rejuvenator dosage increases from 3% to 12%, the C-D curve shifts generally to the bottom left. Specifically, the 12% dosage group exhibits the steepest decline in pseudo-stiffness with increasing damage D. This morphological transition profoundly reveals the modification mechanism whereby the rejuvenator significantly softens the asphalt binder, transforming it from a "hard-brittle" state to a "flexible-ductile" state. Notably, although the pseudo-stiffness of the high-dosage group drops rapidly in C-D space, this does not imply a deterioration in fatigue resistance. Conversely, due to its significantly reduced modulus, the shear stress generated under the same strain control mode is smaller, effectively slowing down stress concentration and crack propagation rates during actual loading. Combined with subsequent fatigue life prediction results, this shift of the C-D curve to the bottom left is the micromechanical manifestation of the rejuvenator improving fatigue durability by restoring asphalt flexibility and reducing stiffness.

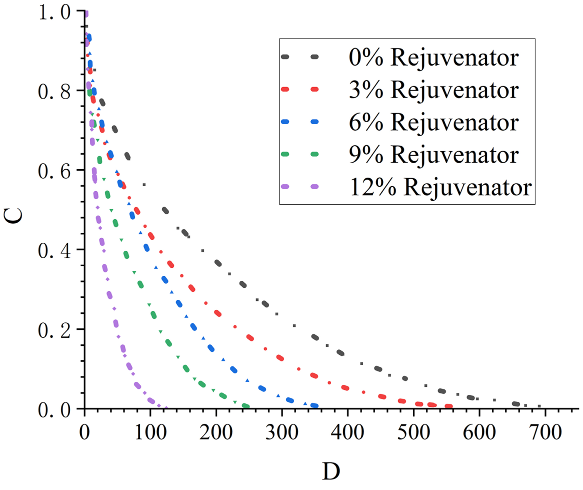

Figure 6: Damage characteristic curves of LAS test.

Fig. 7 visually presents the fatigue life (Nf) comparison of recycled asphalt binders with different rejuvenator dosages, predicted based on LAS tests and the VECD model. The bar chart data shows a significant linear positive correlation between rejuvenator dosage and asphalt fatigue life. In the control group (0% dosage), the aged asphalt, having undergone long-term aging via RTFO and PAV, exhibits high stiffness and brittleness, resulting in the lowest fatigue life of approximately 3.9 * 104 cycles. However, as the rejuvenator dosage increases from 3% to 12%, the fatigue life of the binder steadily climbs. Particularly at a 12% dosage, the fatigue life peaks at approximately 6.1 ∗ 104 cycles. Compared to the unrejuvenated state, the improvement in fatigue resistance reaches up to 56%. From the perspective of viscoelastic damage mechanics, this significant gain is attributed to the macroscopic regulation of the aged asphalt's rheological properties by the rejuvenator: the addition of the rejuvenator effectively reduces the complex shear modulus (G*) and improves the phase angle (δ) response. Under strain-controlled loading, a lower modulus means less accumulated shear stress for the same deformation, thereby reducing the dissipated damage energy in each loading cycle. VECD analysis further confirms that high-dosage rejuvenator significantly slows the growth rate of the cumulative damage variable (D), allowing the recycled binder to withstand more loading cycles before failure, providing important material assurance for the long-term durability of high-RAP pavement.

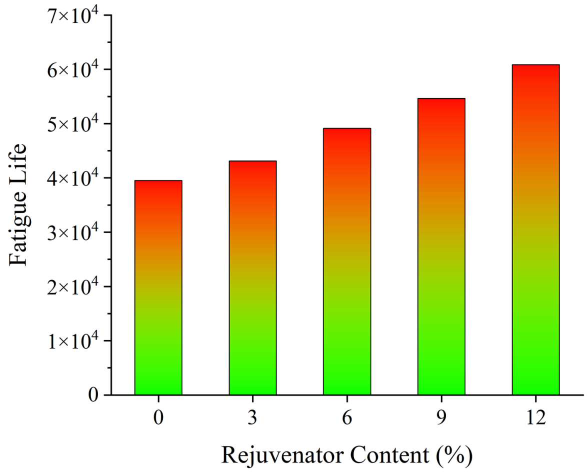

Figure 7: Fatigue life of asphalt with different rejuvenator dosages.

3.2 Mixture Volumetric Parameters

Table 3 details the Marshall Stability, Flow, and Air Voids test results for recycled asphalt mixtures under different combinations of RAP content and rejuvenator dosage.

Table 3: Volumetric parameters of recycled asphalt mixtures.

RAP Content (%)	Rejuvenator Content (%)	Stability (kN)	Flow (mm)	Air Voids (%)
0	0	8.45	3.1	4.05
15	0	10.25	22	5.85
15	3	9.65	2.8	5.24
15	6	8.75	4.2	4.55
15	9	7.51	5.3	3.78
15	12	6.65	6.3	2.89
30	0	11.40	1.8	6.45
30	3	10.36	2.5	5.91
30	6	9.68	3.9	5.31
30	9	7.89	5.9	3.84
30	12	6.91	6.1	2.96
45	0	12.15	1.5	6.95
45	3	11.01	1.9	6.12
45	6	10.26	2.3	5.74
45	9	9.58	2.7	5.26
45	12	8.86	3.5	4.65
60	0	13.85	1.0	7.65
60	3	12.63	1.4	6.73
60	6	11.38	1.9	6.31
60	9	10.29	2.2	5.64
60	12	9.36	2.6	5.19

Analysis of the data in Table 3 reveals a significant and opposing interaction mechanism between RAP content and rejuvenator on the volumetric characteristics of the mixture. First, looking at the longitudinal impact of RAP content, the mixture exhibits a clear trend of "stiffness increasing and flexibility decreasing." With a fixed rejuvenator dosage (taking 3% as an example), as RAP content increases from 15% to 60%, Marshall Stability climbs significantly from 9.65 to 12.63 kN, an increase of over 30%; however, the Flow value shrinks sharply from 2.8 to 1.4 mm, and Air Voids worsen from 5.24% to 6.73%. This trend indicates that the severely aged, hard asphalt in the RAP enhances the mixture's deformation-resistant skeletal stiffness (high stability) through its high viscosity but also renders the material extremely dry and brittle, drastically weakening its deformation adaptability (low flow). Furthermore, the high viscosity of aged asphalt significantly increases internal friction between aggregates, hindering particle rearrangement during compaction, resulting in high-RAP mixtures failing to reach design density under standard compaction effort, manifested as higher air voids.

Conversely, the addition of rejuvenator presents significant "softening, lubricating, and toughening" effects in the horizontal dimension. Analyzing data for any single RAP content group, as rejuvenator dosage increases from 3% to 12%, the mixture's stability consistently declines, while flow value increases significantly and air voids decrease substantially. Taking the 15% RAP group, which is most sensitive to the rejuvenator, as an example: when dosage reaches 12%, stability drops to 6.65 kN, flow surges to 6.3 mm, and air voids are suppressed to 2.89%. Macroscopically, the rejuvenator acts as a key lubricant, greatly promoting the compaction density of the mixture (reducing voids) and effectively restoring the material's viscoelasticity and flexibility (increasing flow). Of particular note is the performance under the high-RAP (60%) condition: at a low dosage (3%), the mixture exhibits dangerous brittleness (flow only 1.4 mm) and insufficient compaction (air voids 6.73%), posing high engineering risk; however, when the dosage is raised to 12%, flow recovers to 2.6 mm and air voids drop to 5.19%. Although some strength is sacrificed (stability drops to 9.36 kN), the volumetric indicators are successfully restored to a reasonable range favorable for durability. In summary, for high-RAP mixtures, a sufficient dosage of rejuvenator is essential to balance the excessive stiffness brought by aged asphalt and resolve issues of high low-temperature brittleness and difficulty in compaction.

3.3 Mixture Low-Temperature Cracking Performance

Fig. 8 illustrates the load-displacement curves from Semi-Circular Bend (SCB) tests at −12°C for asphalt mixtures with different RAP contents (15%, 30%, 45%, 60%) and rejuvenator dosages (0%–12%). The geometric morphology of the curves intuitively reflects the failure mode and toughness characteristics of the materials at low temperatures.

As seen in Fig. 8, with increasing RAP content, the initial linear slope of the unrejuvenated mixture (black curves, 0% Rejuvenator) increases noticeably, indicating that the low-temperature stiffness modulus rises significantly with aged asphalt content. However, this increased stiffness is accompanied by a severe tendency towards embrittlement: the post-peak curve drops vertically with almost no softening branch, indicating that once cracks initiate, they propagate rapidly through the specimen, causing catastrophic brittle fracture. Particularly at 60% RAP content, the ultimate displacement of the unrejuvenated specimen is only about 0.75 mm, demonstrating extremely poor deformation accommodation. In contrast, the addition of rejuvenator significantly alters the curve topology. As dosage increases from 3% to 12%, the curves shift generally to the upper right or right, with peak displacement increasing significantly. For the 60% RAP group, adding 12% rejuvenator (purple curve) not only lowers the peak load (reflecting modulus softening) but, more importantly, extends the failure displacement to over 1.1 mm, and the post-peak curve exhibits a distinct gradual descending tail. This indicates that the rejuvenator imparts greater flexibility to the binder at low temperatures, enabling the mixture to dissipate more energy in the Fracture Process Zone through aggregate interlock and asphalt bridging, realizing a transition from "hard-brittle" to "quasi-brittle" or even "ductile" failure modes.

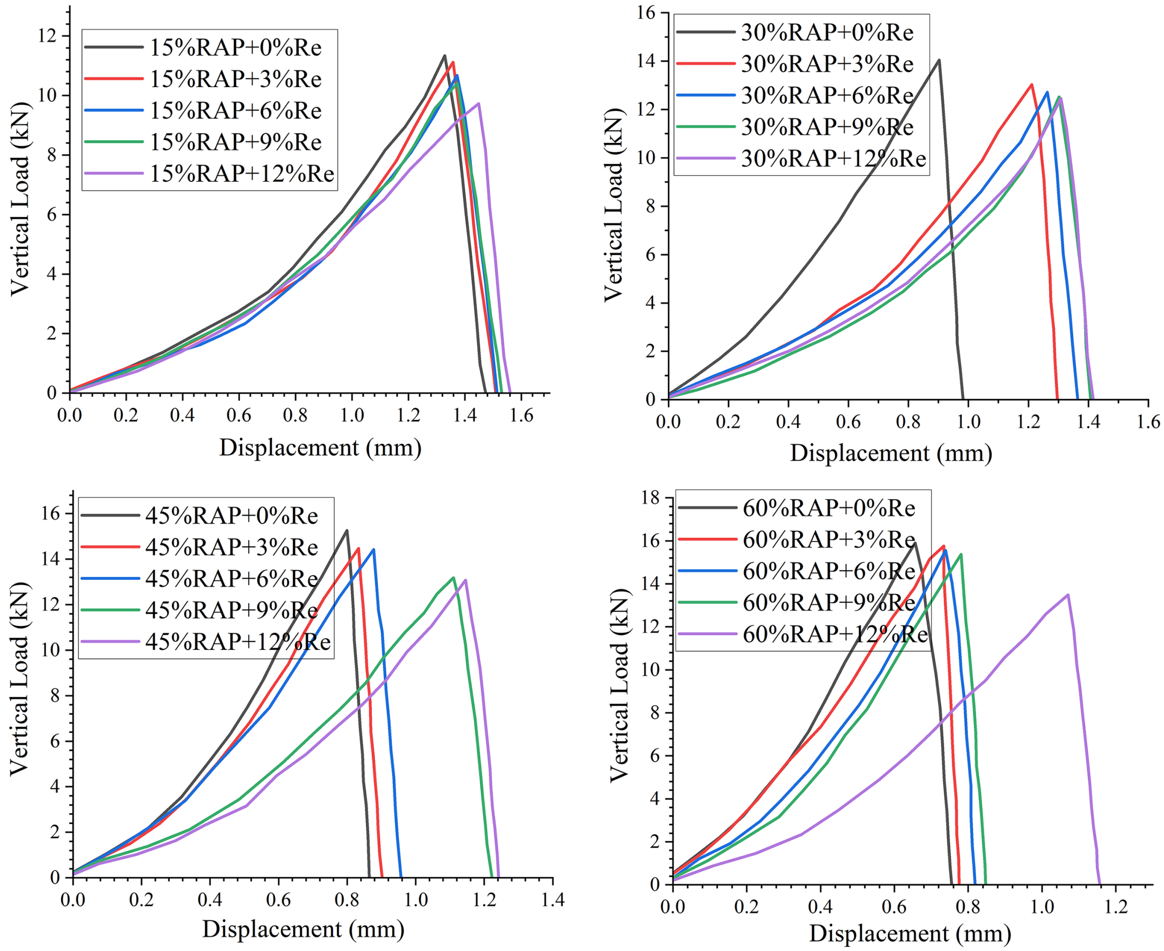

Figure 8: Load-displacement curves of recycled asphalt mixtures under monotonic loading.

The fracture energy (G_f) data calculated based on integration in Table 4 profoundly reveal the non-linear interaction mechanism between RAP and rejuvenator regarding low-temperature cracking resistance. The data show distinct evolution laws across different RAP content intervals: For the 15% low-content group, fracture energy is minimally affected by the rejuvenator, consistently fluctuating within a narrow range of 5.9–6.4 J/m^2, comparable to the virgin mixture (6.12 J/m^2). This is attributed to the dominance of virgin asphalt in the binder system, masking the modification effect of the rejuvenator. In the 30% intermediate-content group, the material exhibits a significant "strengthening-toughening" synergistic effect; with 3% rejuvenator, fracture energy reaches the overall peak of 6.62 J/m^2, surpassing even the virgin level. This results from an ideal balance between the skeletal stiffness provided by RAP aged asphalt and the flexibility restored by an appropriate amount of rejuvenator, thereby maximizing fracture work. However, in the 45% and 60% high-content ranges, the fracture energy of unrejuvenated mixtures decays significantly (dropping to approx. 5.3–5.6 J/m^2), showing obvious brittleness. Here, rejuvenator modification presents a clear "dosage threshold" characteristic. Specifically for the 60% RAP group, dosages up to 9% show limited improvement (Gf remains at 5.32 J/m^2 for the 9% group). Only when the dosage reaches 12% does the fracture energy jump to 6.49 J/m^2, achieving performance reversal. Statistical analysis (one-way ANOVA) confirms that this improvement is significant, with the fracture energy at 12% dosage being statistically higher than that at 9% dosage ($p < 0.05$). This result strongly proves that for high-RAP pavements, a high-dosage rejuvenator strategy

(>9%) must be adopted to effectively overcome low-temperature brittleness risks and achieve full restoration of cracking resistance.

Table 4: Fracture energy of recycled asphalt mixtures.

Mixture Type	Fracture Energy (J/m^2)	SD (J/m^2)	Mixture Type	Fracture Energy (J/m^2)	SD (J/m^2)
0%RAP + 0%Re	6.12	0.59	45%RAP + 0%Re	5.33	0.19
15%RAP + 0%Re	6.43	0.42	45%RAP + 12%Re	5.44	0.55
15%RAP + 12%Re	5.87	0.49	45%RAP + 3%Re	5.76	0.57
15%RAP + 3%Re	5.92	0.38	45%RAP + 6%Re	6.48	0.61
15%RAP + 6%Re	6.28	0.18	45%RAP + 9%Re	6.34	0.53
15%RAP + 9%Re	6.18	0.47	60%RAP + 0%Re	5.57	0.49
30%RAP + 0%Re	5.99	0.39	60%RAP + 12%Re	6.49	0.31
30%RAP + 12%Re	6.37	0.69	60%RAP + 3%Re	5.22	0.57
30%RAP + 3%Re	6.62	0.63	60%RAP + 6%Re	5.40	0.51
30%RAP + 6%Re	6.19	0.71	60%RAP + 9%Re	5.32	0.62
30%RAP + 9%Re	6.52	0.56			

3.4 Mixture Fatigue Cracking Performance

This section aims to systematically evaluate the fatigue resistance of recycled mixtures via Semi-Circular Bend (SCB) tests at an intermediate temperature (20°C). The study first conducted monotonic loading tests to determine the ultimate failure load of the mixtures, establishing the stress baseline for subsequent fatigue testing. Subsequently, stress-controlled repeated loading tests were performed to analyze the cumulative damage evolution law and determine fatigue life, quantifying the restorative effect of rejuvenators on the long-term durability of high-RAP pavements.

Fig. 9 shows the typical vertical load-displacement curve for the control AC-13 mixture (0% RAP + 0% Rejuvenator) under SCB testing at 20°C with a 50 mm/min loading rate. The curve intuitively reflects the viscoelastic mechanical behavior of standard unaged mixtures at room temperature. Initially (displacement < 1.5 mm), the curve shows a steep linear growth, indicating the material is in the linear elastic stage with good initial stiffness. As load increases, the curve gradually deviates non-linearly and reaches a peak, with a measured maximum load (Fmax) of approximately 8.56 kN, representing the ultimate tensile strength. Crucially, in the post-peak stage, the curve exhibits a smooth descending tail rather than a vertical drop, indicating that fresh asphalt binder imparts excellent ductility and toughness, maintaining stress transfer capability during crack propagation. This curve determines the Fmax value used as the strength basis for subsequent repeated load fatigue tests, ensuring the stress level setting (0.25 Fmax) has clear physical significance and comparability.

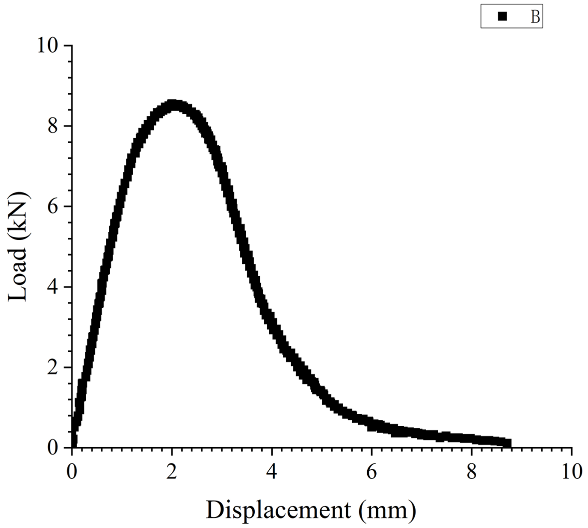

Figure 9: Vertical load-displacement curve of virgin asphalt mixture in SCB test.

Table 5 presents the maximum load (Fmax) results from monotonic SCB tests at 20°C. Data analysis indicates a significant competitive influence of RAP content and rejuvenator on the mixture's ultimate bearing capacity. On one hand, increasing RAP content significantly enhances mixture stiffness and peak strength. Without rejuvenator, as RAP increases from 0% to 60%, Fmax climbs from 8.56 to 13.48 kN. This "stiffening" effect is primarily due to the extremely high viscosity (3550 Pa·s) and low penetration of the aged binder in RAP, which reinforces the skeletal strength against deformation. On the other hand, the addition of rejuvenator acts to "soften" and "reduce stiffness." At the same RAP level, Fmax decreases monotonically with increasing rejuvenator dosage. For the 60% RAP group, adding 12% rejuvenator reduces Fmax from 13.48 to 10.24 kN. This indicates that the light component-rich rejuvenator successfully penetrates and softens the hard aged asphaltenes, reducing the complex modulus of the binder system. Although numerically appearing as a reduction in ultimate strength, this "sacrifice" is necessary, marking a transition from excessive brittleness to a viscoelastic state with certain flexibility, providing the deformation basis for subsequent fatigue performance improvement.

Table 5: Maximum failure load of recycled asphalt mixtures.

RAP Content (%)	Maximum Load (kN)	RAP Content (%)	Maximum Load (kN)
0%RAP + 0%Re	8.56	45%RAP + 0%Re	11.92
15%RAP + 0%Re	9.24	45%RAP + 12%Re	11.25
15%RAP + 12%Re	8.85	45%RAP + 3%Re	10.58
15%RAP + 3%Re	8.42	45%RAP + 6%Re	9.85
15%RAP + 6%Re	8.15	45%RAP + 9%Re	9.15
15%RAP + 9%Re	7.82	60%RAP + 0%Re	13.48
30%RAP + 0%Re	10.45	60%RAP + 12%Re	12.65
30%RAP + 12%Re	9.98	60%RAP + 3%Re	11.72
30%RAP + 3%Re	9.46	60%RAP + 6%Re	10.95
30%RAP + 6%Re	8.92	60%RAP + 9%Re	10.24
30%RAP + 9%Re	8.36		

To accurately assess fatigue durability, cyclic SCB tests were conducted at 20°C with a stress ratio of 0.25 based on the determined Fmax. Fig. 10 displays a typical displacement-loading number evolution curve. The cumulative damage process clearly exhibits a "three-stage" non-linear characteristic: Phase I (Initial Densification), where displacement grows rapidly and non-linearly due to void compaction and aggregate rearrangement; Phase II (Stable Development), occupying the majority of fatigue life with quasi-linear growth, where the slope represents the stable crack propagation rate—high RAP mixtures show steeper slopes (faster damage), while rejuvenators flatten the slope (enhanced flexibility); Phase III (Accelerated Failure), where damage reaches a critical threshold, micro-cracks coalesce into macro-cracks, and displacement increases explosively (vertical rise), indicating loss of bearing capacity. The fatigue life (Nf) is defined as the loading cycle count corresponding to the second inflection point (transition from stable growth to accelerated failure), serving as the core parameter for evaluating design life.

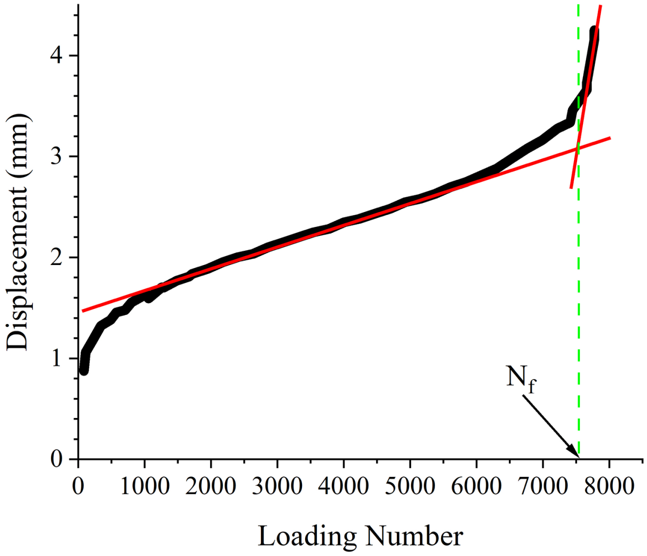

Figure 10: Displacement vs. loading cycles curve of virgin asphalt mixture in fatigue test.

Fig. 11 details the fatigue life (N_f) results for all combinations, with vertical error bars representing the standard deviation to illustrate data variability. Analysis reveals a strong interplay between the "embrittlement effect" of RAP and the "toughening repair effect" of the rejuvenator. First, observing the series without rejuvenator, fatigue life exhibits a precipitous decline as RAP increases: the baseline virgin mixture (0% RAP) has a life of 7566 cycles, whereas the 60% RAP group drops to 1896 cycles, a decrease of over 74%. This significant decay confirms that high proportions of aged asphalt increase stiffness and brittleness, drastically reducing stress relaxation capacity and leading to early structural failure. However, despite the inherent variability of fatigue testing shown by the error bars, the addition of rejuvenator decisively reverses fatigue life. For any fixed RAP content, N_f increases significantly with dosage. For the most severely degraded 60% RAP group, 3% rejuvenator only improves life to 2463 cycles; but at 12% dosage, life surges to 5967 cycles, a 214% increase over the unrejuvenated state. Statistical analysis based on one-way ANOVA confirms that this improvement is significant ($p < 0.05$) compared to the control group, effectively validating the reliability of the high-dosage strategy despite the inherent variability of fatigue testing. Although still slightly lower than the virgin mixture, it has moved out of the dangerous brittle failure zone. Notably, for 15% and 30% RAP mixtures, 12% rejuvenator restores fatigue life to 7536 and 7089 cycles respectively, nearly matching the virgin baseline. This indicates that for low-to-medium RAP content, sufficient rejuvenator (12%) can almost completely eliminate the negative effects of aging through full compatibility. For high RAP content (>45%), while 12% rejuvenator greatly extends life, a “residual deficit” remains due to irreversible damage at the aged aggregate interface and the high proportion of aged asphalt. In summary, to ensure long-term service performance, especially for high-RAP designs, a high-dosage (>9%) rejuvenator strategy is essential to compensate for fatigue defects via superior rheological restoration.

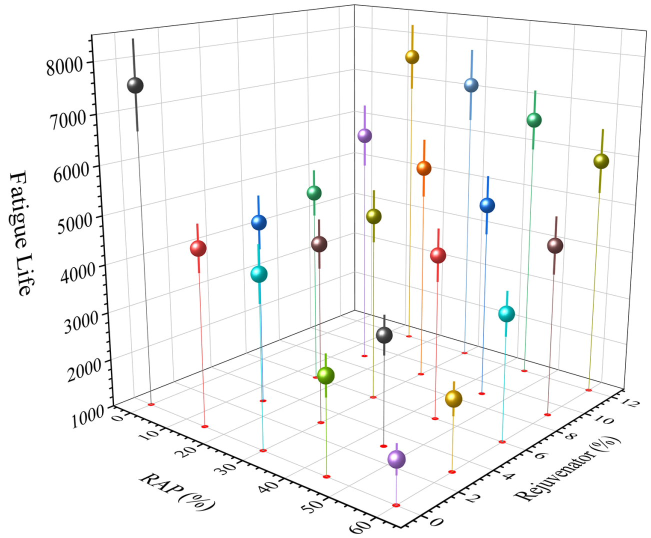

Figure 11: Fatigue life of recycled asphalt mixture.

4 Conclusions

Based on the systematic study of binder rheology, volumetric parameters, low-temperature cracking resistance, and intermediate-temperature fatigue performance of AC-13 recycled asphalt mixtures, the main conclusions are as follows:

(1) Repair Mechanism of Rejuvenator on Aged Binder Fatigue: LAS tests and VECD analysis show that the YJ rejuvenator significantly improves the rheological properties of aged asphalt, reducing complex shear modulus and restoring flexibility. Rejuvenator dosage is linearly correlated with binder fatigue life; at 12% dosage, fatigue life increases by approximately 56%. Damage characteristic curves (C-D) show that high-dosage rejuvenator effectively slows the decline rate of pseudo-stiffness with accumulated damage, thereby retarding micro-crack propagation.

(2) Interactive Effect of RAP and Rejuvenator on Volumetric Characteristics: High RAP content (>45%) significantly increases compaction difficulty, leading to higher air voids and lower flow values. The rejuvenator exhibits excellent lubricating and softening effects, balancing the high viscosity of aged asphalt. For 60% RAP mixtures, adding 12% rejuvenator reduces air voids from 6.73% to 5.19% and recovers flow from 1.4 to 2.6 mm, successfully restoring volumetric indicators to a reasonable range meeting specifications.

(3) “Threshold Recovery” Characteristic of Low-Temperature Cracking: −12°C SCB tests indicate a complex non-linear synergistic effect. At 30% RAP, 6% rejuvenator achieves an optimal “stiffness-toughness” balance, peaking fracture energy (6.69 J/m^2). However, for 60% high RAP content, a distinct dosage threshold exists: low dosages improve performance minimally, and 12% rejuvenator is required to lift fracture energy from 5.56 to 6.45 J/m^2, effectively reversing brittle risks.

(4) Significant Reversal of Fatigue Durability: 20°C cyclic SCB tests reveal that high RAP content causes a cliff-like decay in fatigue life (60% RAP group drops >74% vs. virgin). Rejuvenator addition is decisive

for recovery. For 60% RAP mixtures, 12% rejuvenator increases fatigue life from 1896 to 5967 cycles (214% increase). Although slightly lower than virgin levels (~7500 cycles), this proves the necessity of high-dosage rejuvenator for guaranteeing long-term service.

(5) Recommended Optimal Dosage Strategy: Considering mechanical performance and volumetric stability, for low-to-medium RAP content (≤30%), a rejuvenator dosage of 3%–6% is recommended; for high RAP content (≥45%), a dosage of no less than 9%–12% is suggested to ensure optimal low-temperature cracking resistance and fatigue durability.

Finally, it should be noted that this study primarily focused on the cracking resistance and fatigue durability of high-RAP mixtures. The potential influence of high-dosage rejuvenators on other performance dimensions, such as moisture susceptibility and high-temperature rutting resistance, was not covered due to the scope of this research. These aspects will be systematically investigated in our future work to provide a more comprehensive evaluation for engineering applications.

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Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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