

Article

Study on the Self-Healing Performance of Microcapsule-Modified Recycled Asphalt Mixtures

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Abstract

The incorporation of reclaimed asphalt pavement (RAP) in asphalt mixtures improves sustainability but significantly reduces the intrinsic self-healing capacity due to binder aging. This study aimed to quantify whether epoxy-coated rejuvenator microcapsules could restore and enhance the self-healing performance of RAP-containing recycled asphalt mixtures. Four mixture types (AC-10C, AC-13C, AC-16C, and SMA-13C) containing 20% RAP were evaluated using a fracture–healing–refracture bending test (Repair index, R_C) and a splitting healing strength ratio (S_{HSR}) test to determine the effects of healing time, temperature, and microcapsule dosage. R_C increased rapidly during the first 8 h of healing and then approached stabilization, with the growth rate falling below 2%, indicating 8 h as the practical optimum healing duration. R_C increased from 0 °C to 45 °C due to enhanced binder mobility and diffusion, and slightly decreased at 60 °C because temperature-induced softening reduced peak bending strength. The highest self-healing capacity was obtained at a microcapsule dosage of 4% (by RAP mass). Under the optimum healing condition (8 h and 45 °C), R_C increased by 10.38%–13.50% and S_{HSR} increased by 14.35%–25.27% compared with mixtures without microcapsules. Among the mixtures, SMA-13C exhibited the highest self-healing capacity, followed by AC-13C, AC-10C, and AC-16C. The contribution of this study lies in quantifying the healing enhancement in RAP-containing mixtures, identifying practical optimum healing conditions based on a growth-rate criterion, and demonstrating consistent trends between two healing indices across different mixture structures.

Keywords: recycled asphalt mixture; microcapsules; self-healing performance; beam bending test; splitting healing test



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1. Introduction

Recycled asphalt mixture (RAM) technology involves reusing reclaimed asphalt pavement (RAP) through crushing, screening, and blending with virgin asphalt binders and aggregates [1]. This technology effectively reduces the consumption of natural resources and construction costs while mitigating environmental impacts associated with pavement rehabilitation [2–4]. However, the presence of aged asphalt binder in RAP generally leads to inferior cracking resistance [5,6] and fatigue performance [7,8] compared with virgin

asphalt mixtures. This deterioration is mainly attributed to insufficient blending between aged and virgin binders, which results in weak interfacial zones prone to microcrack initiation and propagation under traffic loading and environmental effects [9,10].

Considerable efforts have been devoted to investigating the healing performance of reclaimed asphalt mixtures. González et al. [11] evaluated the healing properties of asphalt mixtures containing different RAP contents and reported that the incorporation of RAP reduced the healing rate of asphalt mixtures. Specifically, the healing rate of mixtures containing 30% RAP was approximately 25% lower than that of virgin mixtures. Kamali et al. [12] found that microwave irradiation applied to RAP materials enhanced the low-temperature cracking resistance and moisture stability of reclaimed asphalt mixtures, which was mainly attributed to the reactivation of aged asphalt under microwave heating. Mullapudi et al. [13] analyzed the influence of initial damage on the healing potential of reclaimed asphalt mixtures using fatigue life and modulus-based healing indices, and demonstrated that both healing indices were negatively correlated with the initial damage level. Gómez-Meijide et al. [14] suggested that the addition of RAP increased the air void content of asphalt mixtures, thereby improving induction heating efficiency. However, the highly stiff aged asphalt in RAP exhibits limited flowability and healing capability, and its adverse effect on healing performance outweighs the benefit induced by increased air voids, ultimately resulting in a reduction in the self-healing capacity of reclaimed asphalt mixtures. Microwave heating results further indicated that higher RAP contents enhanced microwave energy absorption and increased surface temperature; nevertheless, the reduced crack-repairing ability of aged asphalt in RAP led to a decrease in the healing rate of asphalt mixtures [15]. Based on the above findings, it can be concluded that the incorporation of RAP weakens the healing capability of reclaimed asphalt mixtures. Therefore, enhancing the self-healing capacity of reclaimed asphalt mixtures, enabling autonomous repair of microcracks at early stages, is of great significance for the widespread application of recycled asphalt materials.

Previous studies [11–15] have demonstrated that the incorporation of RAP tends to reduce the intrinsic self-healing capability of asphalt mixtures. Although external stimulation methods, such as microwave or induction heating, can partially restore healing performance, the limited flowability of aged asphalt binder remains a critical constraint. Therefore, developing an effective approach to enhance the autonomous healing capacity of recycled asphalt mixtures is of great significance for extending pavement service life.

Microcapsule-based self-healing technology, which involves encapsulating healing agents within protective shells, has shown promising potential in polymeric and cementitious materials [16]. When microcracks propagate, microcapsules rupture and release healing agents that migrate toward the crack interface, thereby enabling autonomous repair [1,17,18]. Nevertheless, the application of this technology in recycled asphalt mixtures remains limited, and the optimal healing conditions and evaluation methods have not yet been systematically established.

Therefore, the objective of this study is to systematically evaluate the self-healing behavior of RAP-containing asphalt mixtures modified with epoxy-coated rejuvenator microcapsules. The effects of healing time, healing temperature, and microcapsule dosage are quantified using a fracture–healing–refracture bending test (R_C) and further validated through a splitting healing strength ratio (S_{HSR}) test. The novelty of the present research is explicitly reflected in three aspects: (i) the application of microcapsule-based rejuvenation technology to recycled mixtures incorporating RAP; (ii) the determination of practical optimum healing conditions based on a quantitative growth-rate criterion; and (iii) the comparative assessment of dense-graded AC mixtures and a stone-on-stone SMA mixture with cross-validation between two healing indices.

2. Materials and Methods

2.1. Raw Materials

The asphalt binders used in this study included a 70# base asphalt and an SBS-modified asphalt, both supplied by Shandong Kunda Highway Materials Co., Ltd. (Linyi, China). Their main physical and rheological properties are summarized in Table 1. Limestone aggregates and mineral filler were provided by Hebei Henghaoda Highway Engineering Co., Ltd. (Baoding, China). Lignocellulosic fibers, supplied by Anfeng New Material Technology Co., Ltd. (Tai'an, China), were incorporated to ensure mixture stability. The key physical and mechanical properties of the limestone aggregates are presented in Tables 2 and 3. The mineral filler and lignocellulosic fiber properties are listed in Table 4.

Table 1. Key technical properties of asphalt binders.

Property	70# Base Asphalt	Specification Requirement	SBS-Modified Asphalt	Specification Requirement
Penetration (25 °C, 100 g, 5 s) (0.1 mm)	66.4	60~80	66.4	40~60
Ductility (5 cm/min, 10 °C) (cm)	33.4	≥20	44.1	≥20
Softening point (Ring-and-Ball) (°C)	48.2	44~54	67.5	≥60
Density (g/cm ³)	1.027	-	1.041	-

Table 2. Key technical properties of coarse aggregates.

Property	Particle Size (mm)				Specification Requirement
	16	13.2	9.5	4.75	
Crushing value (%)			19.43		≤26
Los Angeles abrasion loss (%)			12.3		≤28
Apparent density (g/cm ³)	2.726	2.693	2.695	2.731	>2.60
Bulk density (dry) (g/cm ³)	2.715	2.676	2.683	2.712	-
Soundness (%)			7.8		≤12
Flakiness and elongation index (%)			12.6		≤15
Content of particles < 0.075 mm (%)			Qualified		≤1

Table 3. Key technical properties of fine aggregates.

Property	Particle Size (mm)						Specification Requirement
	2.36	1.18	0.6	0.3	0.15	0.075	
Apparent density (g/cm ³)	2.714	2.717	2.713	2.684	2.694	2.732	>2.50
Bulk density (dry) (g/cm ³)	2.711	2.764	2.645	2.598	2.627	2.591	-
Angularity (fine aggregate angularity, FAA) (s)			37				≥30
Sand equivalent (%)			74				≥60

Reclaimed asphalt pavement (RAP) was obtained from the milled surface layer of an expressway. The particle size distribution of RAP is presented in Table 5. Based on sieve analysis, the RAP fractions of 2.36–4.75 mm, 4.75–9.5 mm, and 9.5–13.2 mm accounted for the largest mass proportions. Asphalt content tests were therefore conducted on these fractions using the ignition method. Considering both recycling efficiency and mixture performance, the RAP fraction of 4.75–9.5 mm, which exhibited the highest proportion and the lowest asphalt content, was selected for subsequent experiments.

Table 4. Key technical properties of mineral filler and lignocellulosic fiber.

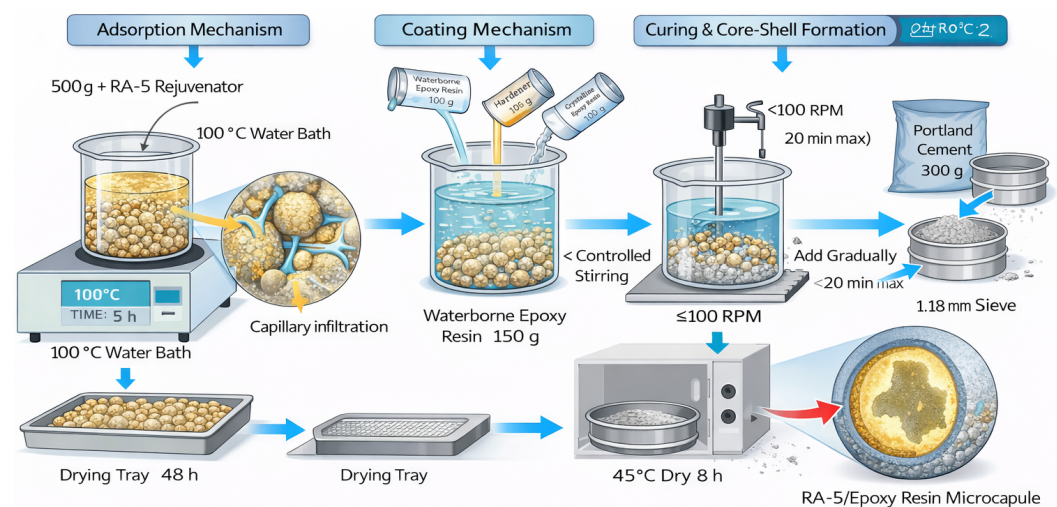
Mineral Filler			Lignocellulosic Fiber		
Property	Test Result	Specification Requirement	Property	Test Result	Specification Requirement
Apparent density (g/cm ³)	2.794	≥2.5	Fiber length (mm)	4.7	≤6
Moisture content (%)	0.51	≤1	Ash content (%)	19.4	13–23
Appearance	No agglomeration	No agglomeration	pH value	7.3	6.5–8.5
Hydrophilic coefficient	0.47	<1	Moisture content (%)	2.3	≤5
Thermal stability	No change after heating	Measured	-	-	-
Plasticity index	3.1	<4	-	-	-

Table 5. Sieve analysis results of reclaimed asphalt pavement (RAP).

Sieve Size (mm)	>16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	<0.075
Mass retained (g)	5717	2425	3244	6062	3027	1550	518	565	260	80	66

2.2. Microcapsule-Based Rejuvenator

Rejuvenator microcapsules were prepared using an adsorption–encapsulation method [19]. The preparation procedure of the microcapsule-type rejuvenator (RA-5/Epoxy Resin) is shown in Figure 1.

**Figure 1.** Schematic illustration of the synthesis process of RA-5/Epoxy Resin (ERM) microcapsule-type rejuvenator.

First, 500 g of porous sand and 500 g of RA-5 rejuvenator were mixed and heated in a 100 °C water bath for 5 h to allow sufficient adsorption of the rejuvenator into the porous matrix. The mixture was then transferred to a dry tray and kept at room temperature for at least 48 h. Subsequently, 150 g of waterborne epoxy resin, 130 g of curing agent, and 100 g of glycidyl ether diluent were premixed thoroughly. Then, 500 g of the porous sand–rejuvenator composite was added into the epoxy system under continuous mechanical stirring. During mixing, 300 g of 42.5R Portland cement was gradually introduced. The entire mixing process was completed within 20 min to prevent premature curing of the epoxy resin. It should be noted that the microcapsule structure was formed in situ during the encapsulation and curing process rather than being mechanically blended after formation. Therefore, no secondary high-shear mixing was applied to preformed capsules. The

mixing speed was carefully controlled to ensure uniform coating while avoiding excessive shear stress. After mixing, the material was kept undisturbed for 48 h to complete curing. The excess cement was removed using a 1.18 mm square sieve, followed by drying at 45 °C for 8 h to obtain the final RA-5/Epoxy Resin microcapsules.

The basic properties of RA-5 are summarized in Table 6. Scanning electron microscopy (SEM) images of the prepared microcapsules at different magnifications are shown in Figure 2, indicating a relatively uniform morphology and intact shell structure.

Table 6. Technical properties of RA-5 asphalt rejuvenator.

Property	RA-5	Specification Requirement
Kinematic viscosity at 60 °C (mm ² /s)	194	176~900
Flash point (°C)	286	≥220
Saturates content (%)	27.84	≤30
Aromatics content (%)	39.87	-
Viscosity ratio before and after TFOT	1.60	≤3
Mass change after TFOT (%)	0.69	−4~+4
Density at 15 °C (g/cm ³)	1.0315	-

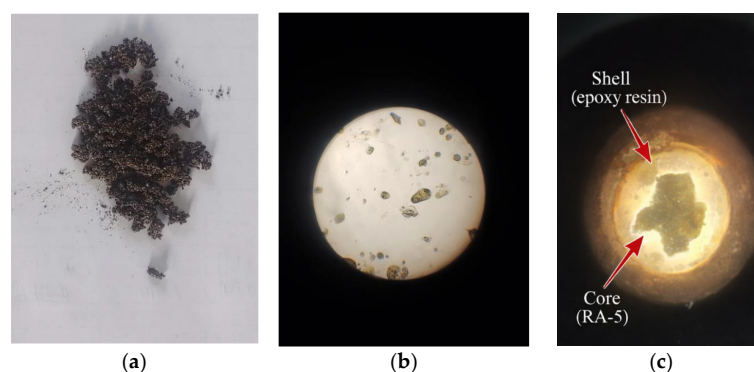


Figure 2. SEM images of RA-5/epoxy resin microcapsules at different magnifications: (a) 1×; (b) 400×; (c) 1000×.

The thermal stability of the microcapsules was evaluated by measuring the mass loss ratio after exposure to temperatures ranging from 150 to 180 °C for 4 h. As shown in Figure 3, the mass loss ratio gradually increased with heating time and stabilized after approximately 2.5 h. Even at 180 °C, the mass loss ratio remained below 10%, demonstrating that the prepared microcapsules possess sufficient thermal stability to withstand asphalt mixture production and compaction processes.

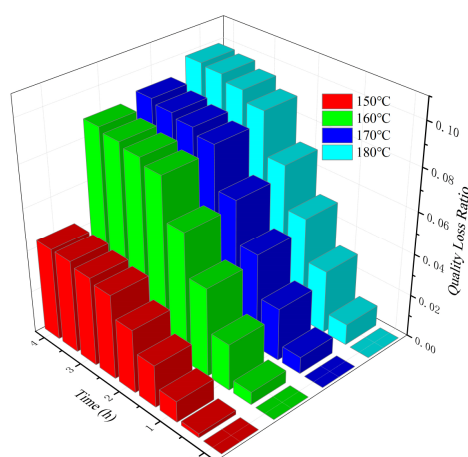


Figure 3. Mass loss of microcapsule-based rejuvenator at different temperatures.

3. Marshall Test

3.1. Marshall Test Program

Four asphalt mixture types (AC-10C, AC-13C, AC-16C, and SMA-13C) were designed in accordance with the Technical Specifications for Construction of Highway Asphalt Pavements (JTG F40-2004) [20]. The aggregate gradation curves are presented in Figure 4. The optimum asphalt contents were determined as 5.2%, 4.7%, 6.0%, and 4.4% for AC-10C, AC-13C, AC-16C, and SMA-13C, respectively.

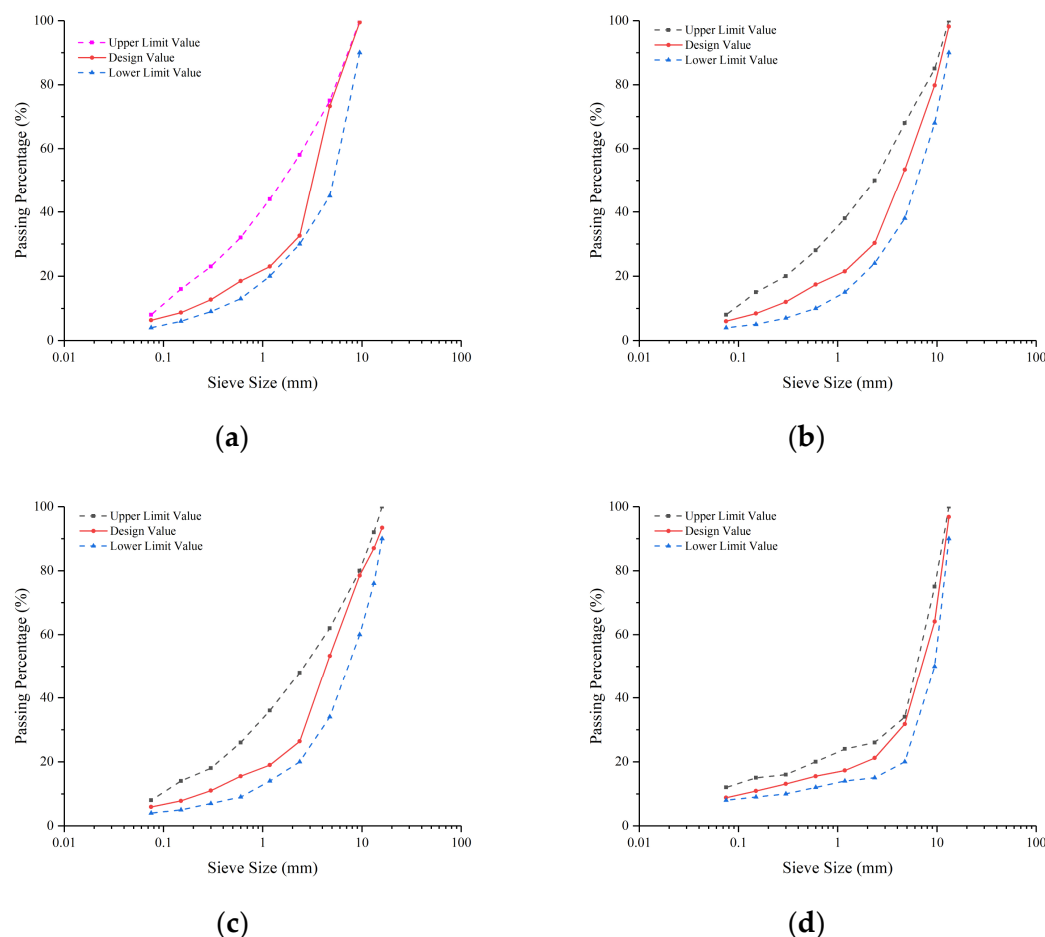


Figure 4. Aggregate gradation curves of the asphalt mixtures: (a) AC-10C; (b) AC-13C; (c) AC-16C; (d) SMA-13C.

For each mixture type, RAP (4.75–9.5 mm) was incorporated at contents of 10%, 20%, and 30%, while mixtures without RAP served as control groups. Marshall stability and flow values were measured to determine an appropriate RAP content. Subsequently, the microcapsule-based rejuvenator was added at contents of 2%, 4%, 6%, and 8% (the dosage of microcapsules (2%, 4%, 6%, and 8%) was calculated as a percentage of RAP mass) to RAP-containing mixtures, and mixtures without microcapsules were also prepared as controls. The Marshall test procedure is illustrated in Figure 5.

3.2. Marshall Test Results

Figure 6 presents the effects of RAP content on Marshall stability and flow values. Marshall stability generally decreased with increasing RAP content, whereas flow values remained within specification limits. When the RAP content reached 30%, the Marshall stability of AC-10C and AC-16C mixtures failed to meet specification requirements. Therefore, the RAP content was limited to 20% in subsequent mixture designs.

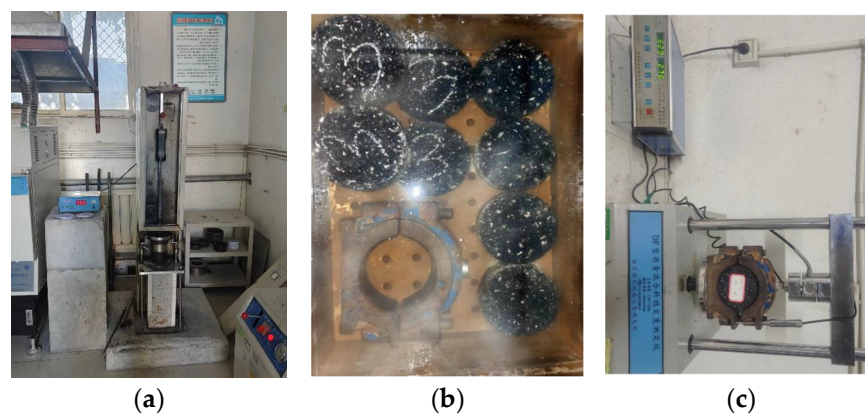


Figure 5. Marshall stability test procedure: (a) compaction; (b) water bath conditioning; (c) measurement of Marshall stability and flow value.

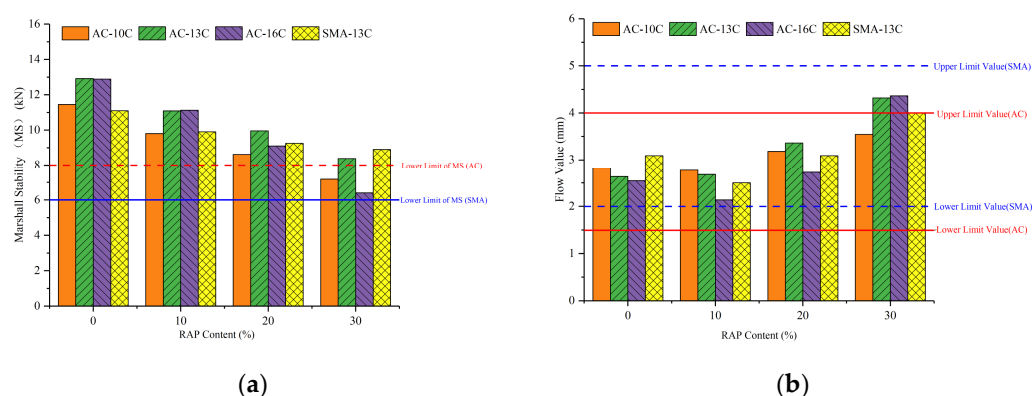


Figure 6. Effects of RAP content on asphalt mixtures: (a) variation in Marshall stability; (b) variation in flow value.

As shown in Figure 7, the incorporation of the microcapsule-based rejuvenator had no adverse effect on Marshall stability or flow values. All mixtures satisfied specification requirements, indicating that the addition of microcapsules at the investigated contents does not compromise the basic mechanical properties of asphalt mixtures.

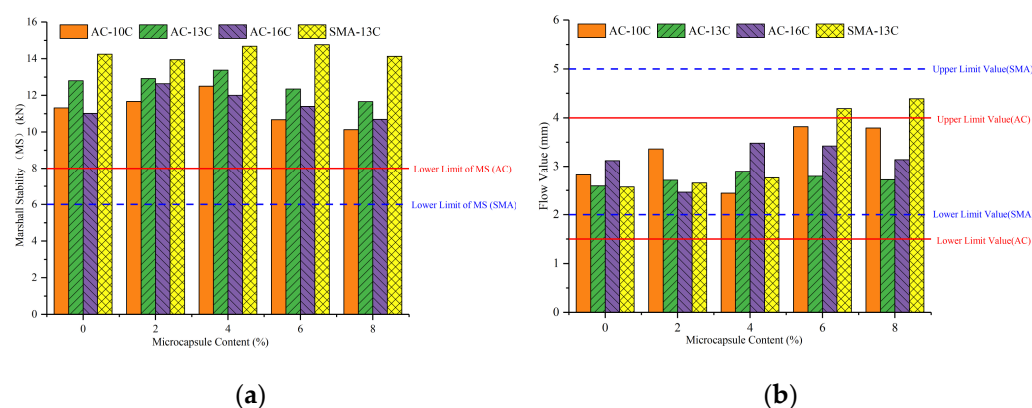


Figure 7. Effects of rejuvenator microcapsule content on asphalt mixtures: (a) Marshall stability; (b) flow value.

4. Determination of Optimal Healing Time and Temperature

4.1. Test Method and Repair Index Definition

Healing time and healing temperature are critical factors governing the self-healing efficiency of asphalt mixtures. To quantitatively evaluate the recovery of load-bearing

capacity after fracture, a beam bending fracture–healing–refracture test was adopted. This test configuration has been widely used to characterize macroscopic healing efficiency in asphalt mixtures.

Standard small beam specimens were subjected to a three-point bending fracture–healing–refracture procedure under displacement-controlled loading at a constant rate [21].

To ensure a consistent initial damage level for healing comparison, the first bending test was terminated using a unified load-drop criterion: the test was stopped when the applied load decreased to 90% of the peak load. The peak load at initial fracture, denoted as F , was extracted from the load–deflection curve.

It should be noted that some specimens did not completely separate into two pieces at peak load. Instead, a dominant macro-crack was formed while the specimen retained partial structural integrity. This condition corresponds to the onset of fracture and is considered appropriate for healing evaluation, as interfacial contact is preserved without introducing additional damage.

Immediately after fracture, the two specimen halves were carefully realigned to restore full contact along the fracture plane. A gentle and short-duration manual pressure was applied solely to achieve intimate interfacial contact, without introducing additional confinement or compaction. The specimen was then promptly transferred to a temperature-controlled chamber and allowed to heal under the prescribed healing temperatures and healing durations.

After the healing period, the specimen was reloaded under the same three-point bending configuration and loading rate. The maximum load at re-fracture, denoted as F' , was obtained.

The Repair index (R_C) was defined as the ratio of the maximum load after healing to that before healing:

$$R_C = F' / F$$

This index reflects the recovery of load-bearing capacity induced by healing and provides a direct measure of macroscopic self-healing efficiency. Each test condition was repeated three times, and the average values are reported.

A schematic illustration of the fracture–healing–refracture procedure is shown in Figure 8, which consists of three stages: (a) initial fracture loading, (b) a healing stage under controlled temperature and time, and (c) reloading after healing.

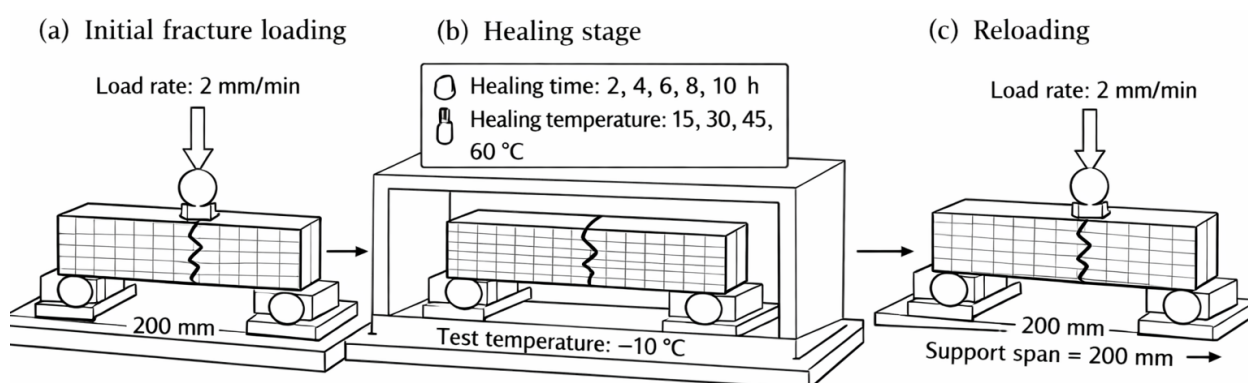


Figure 8. Schematic diagram of the three-point bending fracture–healing–refracture test.

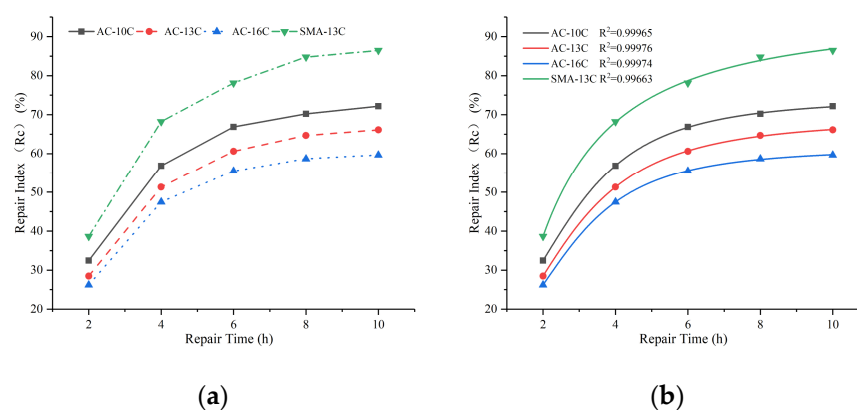
4.2. Effect of Healing Time

To investigate the influence of healing time, healing durations of 2, 4, 6, 8, and 10 h were selected, while the healing temperature was kept constant. The corresponding healing indices of the four asphalt mixtures are summarized in Table 7.

Table 7. Repair index of asphalt mixtures at different healing times.

Asphalt Mixture Type	Repair Index R_C (%)				
	2 h	4 h	6 h	8 h	10 h
AC-10C	32.457	56.867	66.887	70.203	72.180
AC-13C	28.484	51.332	60.602	64.666	66.123
AC-16C	26.214	47.482	55.492	58.689	59.663
SMA-13C	38.647	68.228	78.129	84.765	86.462

As shown in Figure 9a, the R_C increases rapidly at the early stage and gradually approaches a plateau with increasing healing time for all mixture types. This trend indicates that asphalt molecular diffusion and interfacial wetting dominate the early healing process, whereas the healing rate diminishes as the crack interface becomes progressively saturated. It should be emphasized that R_C represents the recovery of peak load capacity across the crack interface under controlled laboratory conditions; because specimens were terminated near the onset of fracture (without enforcing complete separation), interfacial contact was preserved and relatively high R_C values can be achieved after sufficient time.

**Figure 9.** Variation in the Repair index R_C with healing time: (a) measured values; (b) fitted curves.

To further quantify this behavior, the relationship between R_C and healing time was fitted using empirical functions, as shown in Figure 9b. The fitted curves exhibit high coefficients of determination, indicating good agreement with the experimental data.

Figure 10 presents the growth rate of R_C with healing time, which continuously decreases as healing time increases. When the healing time exceeds 8 h, the growth rate of R_C drops below 2% for all mixtures, suggesting that further extension of healing time contributes marginally to additional recovery. Therefore, considering both healing efficiency and practical feasibility, the optimal healing time for the investigated asphalt mixtures was determined to be 8 h.

4.3. Effect of Healing Temperature

The effect of healing temperature was examined at 0, 15, 30, 45, and 60 °C, while the healing time was fixed at 8 h. The corresponding healing indices are listed in Table 8.

Table 8. Repair index of asphalt mixtures at different healing temperatures.

Asphalt Mixture Type	Repair Index R_C (%)				
	0 °C	15 °C	30 °C	45 °C	60 °C
AC-10C	10.653	49.786	72.667	80.232	73.807
AC-13C	12.961	41.553	60.724	73.484	65.321
AC-16C	14.773	39.393	52.814	67.286	61.091
SMA-13C	16.686	58.804	76.896	86.542	80.617

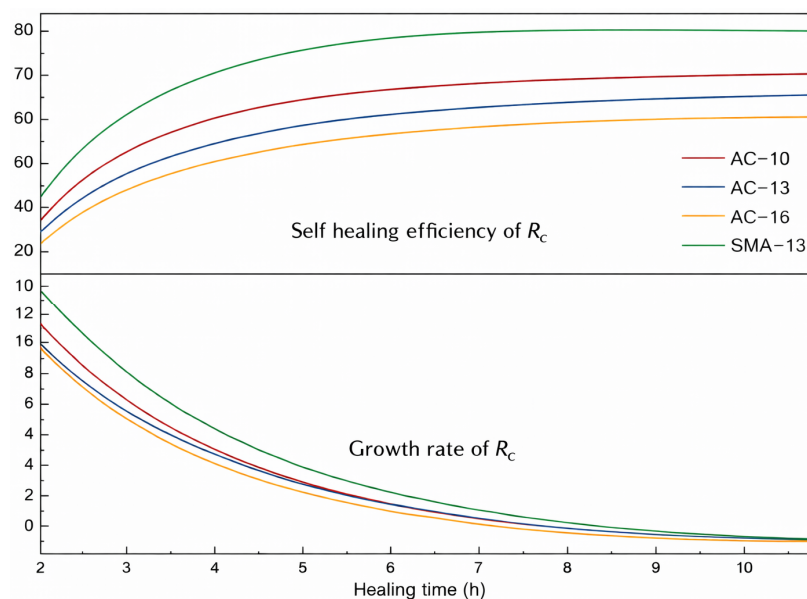


Figure 10. Variation in the growth rate of the Repair index R_C with healing time.

As illustrated in Figure 11a, R_C initially increases and then decreases with increasing healing temperature. When the healing temperature increases from 0 to 45 °C, the Repair index exhibits a pronounced increase, which can be attributed to enhanced asphalt binder mobility and accelerated molecular diffusion at elevated temperatures. This behavior explains the partial healing of low-temperature cracks during warmer service periods.

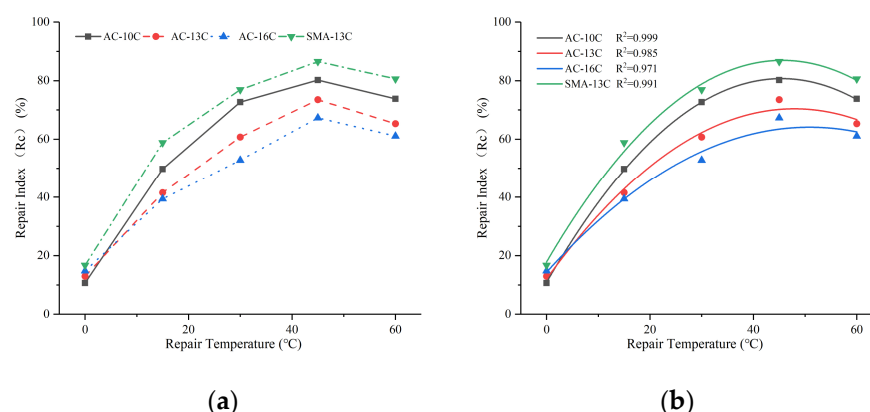


Figure 11. Variation in the Repair index R_C with healing temperature: (a) measured values; (b) fitted curves.

However, when the healing temperature further increases from 45 to 60 °C, R_C shows a slight decrease. This trend does not indicate a loss of healing ability; rather, it reflects pronounced high-temperature softening of the asphalt mastic, which reduces mixture stiffness and peak load capacity in bending even though interfacial diffusion is accelerated. In field pavements, temperatures may approach 60 °C in hot seasons; therefore, the application of microcapsule-based rejuvenators should be considered together with high-temperature performance and mixture structural confinement. Overall, 45 °C represents a balanced condition where binder mobility is sufficiently enhanced while adhesive bonding and mixture strength remain stable. Notably, R_C values at 60 °C remain substantially higher than those at low temperatures, indicating that healing is still active; however, high-temperature pavement performance (e.g., rutting resistance) should be evaluated in parallel for practical implementation.

Figure 11b shows that the fitted R_C –temperature curves exhibit coefficients of determination exceeding 0.98. The corresponding growth-rate analysis (Figure 12) indicates that the growth rate of R_C approaches zero at healing temperatures close to 45 °C for all mixtures. Consequently, 45 °C was identified as the optimal healing temperature.

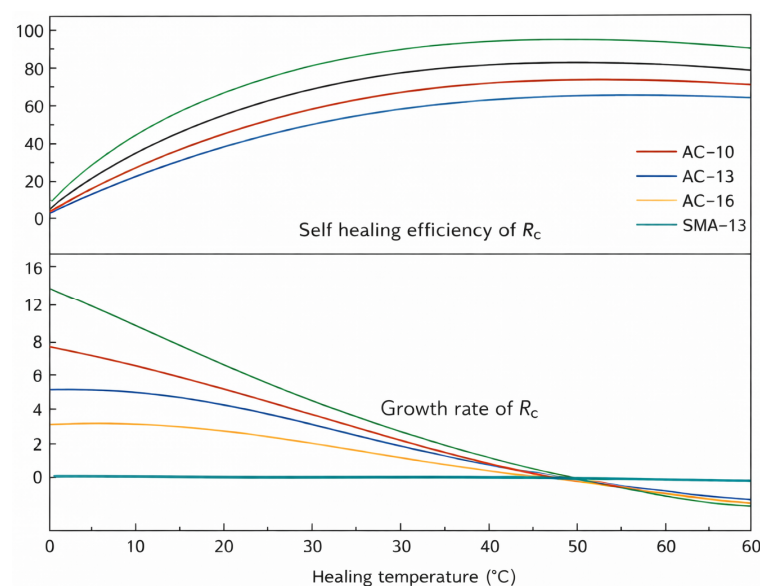


Figure 12. Variation in the growth rate of the Repair index R_C with healing temperature.

Representative crack morphologies of beam specimens healed at different temperatures for 8 h are presented in Figure 13, providing visual evidence consistent with the quantitative healing indices.

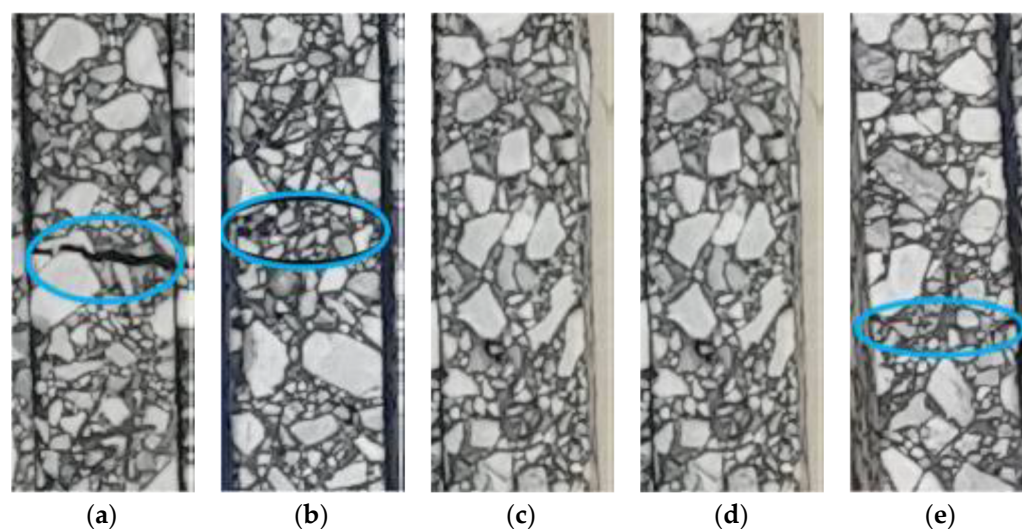


Figure 13. Crack-healing performance of beam specimens at different healing temperatures: (a) 0 °C; (b) 15 °C; (c) 30 °C; (d) 45 °C; (e) 60 °C.

5. Self-Healing Performance Evaluation

5.1. Beam Bending Fracture–Healing–Refracture Test

Under the optimal healing conditions (healing time of 8 h and healing temperature of 45 °C), beam specimens incorporating different contents of microcapsule-based rejuvenator were evaluated using the beam bending fracture–healing–refracture test. Representative crack-healing morphologies are shown in Figure 14, while the corresponding healing

indices (R_C) are summarized in Table 9. The increase rates of R_C relative to the mixtures without microcapsules are presented in Table 10.

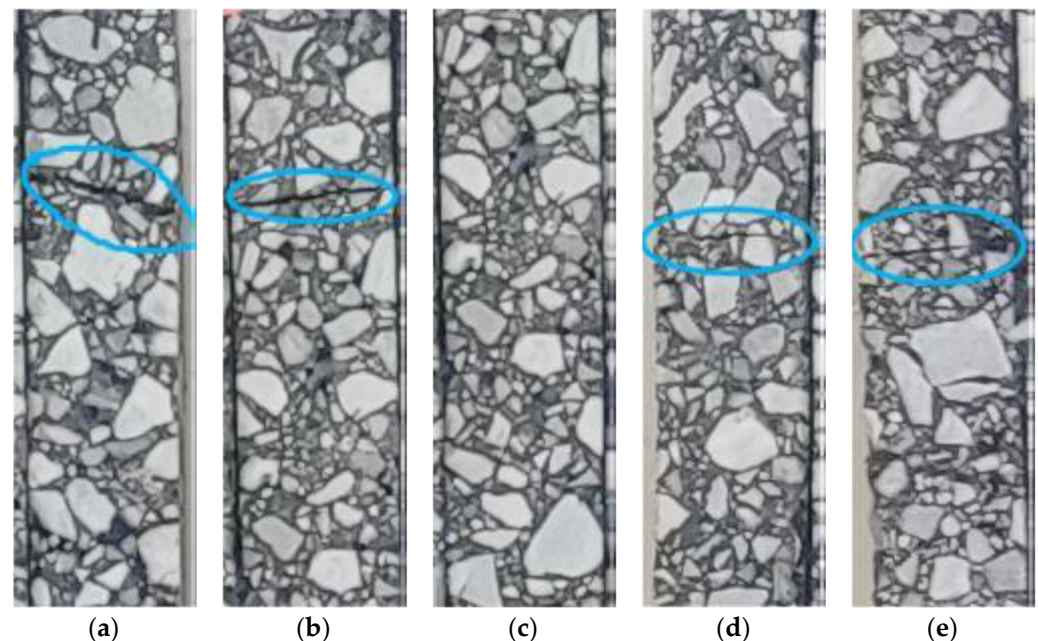


Figure 14. Crack-healing performance of beam specimens with different microcapsule contents under optimal healing conditions: (a) 0%; (b) 2%; (c) 4%; (d) 6%; (e) 8%.

Table 9. Repair index of asphalt mixtures with different microcapsule contents.

Asphalt Mixture Type	Repair Index R_C (%)				
	0%	2%	4%	6%	8%
AC-10C	75.86	81.87	89.36	82.18	77.09
AC-13C	73.16	78.66	84.66	82.05	76.68
AC-16C	72.98	75.63	83.36	81.52	76.21
SMA-13C	79.18	87.41	90.36	86.17	80.92

Table 10. Increase rate of Repair index of asphalt mixtures with different microcapsule contents.

Asphalt Mixture Type	Increase Rate of Repair Index R_C (%)				
	0%	2%	4%	6%	8%
AC-10C	0	6.01	13.5	6.32	1.23
AC-13C	0	5.5	11.5	6.89	1.52
AC-16C	0	2.65	10.38	8.54	3.23
SMA-13C	0	8.23	11.18	6.99	1.74

As shown in Figure 15, the Repair index R_C of all four asphalt mixtures initially increases and then decreases with increasing microcapsule content, reaching a maximum at a microcapsule content of 4%. When the microcapsule content is relatively low ($\leq 4\%$), microcapsules rupture during fracture and release rejuvenator, which migrates toward the crack interface. This process enhances asphalt binder mobility and interfacial wetting, thereby promoting crack closure and accelerating the recovery of load-bearing capacity. As a result, the healing efficiency of the asphalt mixtures is significantly improved.

However, when the microcapsule content exceeds 4%, R_C decreases for all mixtures. This reduction is attributed to over-dosage: additional solid capsules may disrupt the original aggregate skeleton and asphalt mastic distribution and reduce the continuity of

the binder film, offsetting the benefit of extra rejuvenator release. The inclusion of 6% and 8% dosages was intended to identify this upper boundary and confirm the existence of an optimum; for engineering applications, a dosage around 4% (by RAP mass) is recommended based on the peak R_C values.

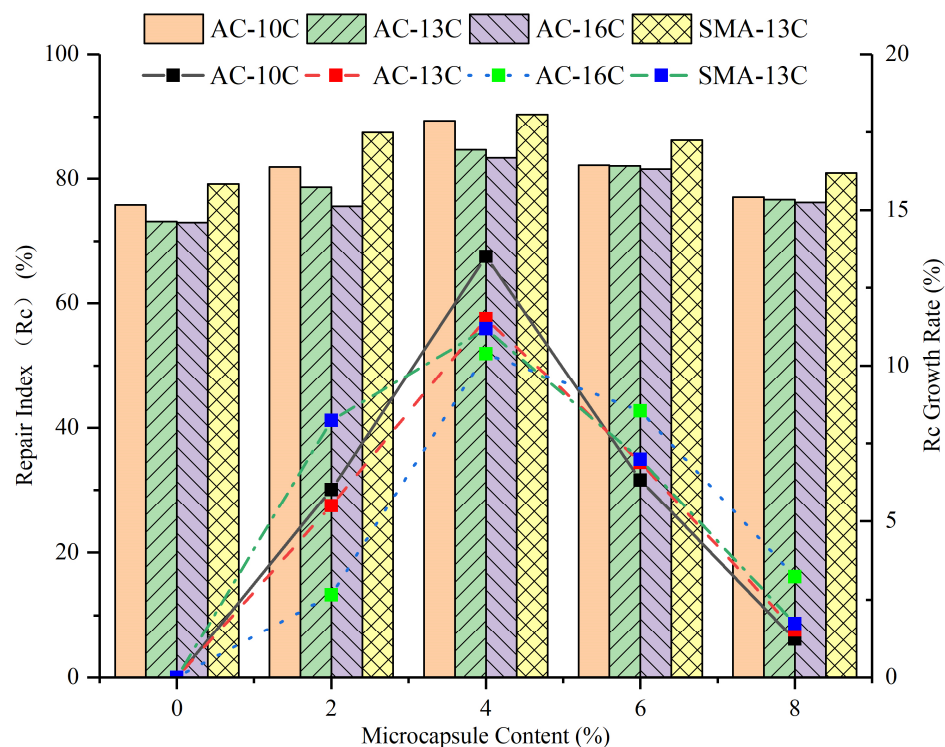


Figure 15. Variation in the Repair index R_C with microcapsule content.

At the optimal microcapsule content of 4%, the healing indices of the four asphalt mixtures decrease in the following order: SMA-13C > AC-13C > AC-10C > AC-16C. This trend highlights the strong dependence of healing efficiency on both asphalt binder content and mixture structure. Mixtures with higher binder content and well-developed asphalt mastic films provide more favorable conditions for rejuvenator diffusion and crack-interface restoration, resulting in superior healing performance.

5.2. Splitting Healing Test

To further evaluate the self-healing performance under a different loading mode, indirect tensile (splitting) healing tests were conducted. After the initial splitting test, specimens typically developed a dominant crack. The specimens were then promptly transferred to a temperature-controlled chamber and heated at 60 °C for 12 h. This condition was selected to promote binder flow and diffusion and to minimize the influence of insufficient healing on comparisons among mixtures with different microcapsule contents. Subsequently, a second splitting test was performed, and the splitting healing strength ratio (S_{HSR}) was calculated.

The variation in S_{HSR} with microcapsule content is illustrated in Figure 16. Similar to the trend observed for the Repair index R_C , S_{HSR} initially increases and then decreases with increasing microcapsule content, with the maximum value occurring at a content of 4%. Compared with the mixtures without microcapsules, the S_{HSR} of AC-10C, AC-13C, AC-16C, and SMA-13C increased by 14.35%, 25.27%, 22.56%, and 20.70%, respectively, at the optimal microcapsule content.

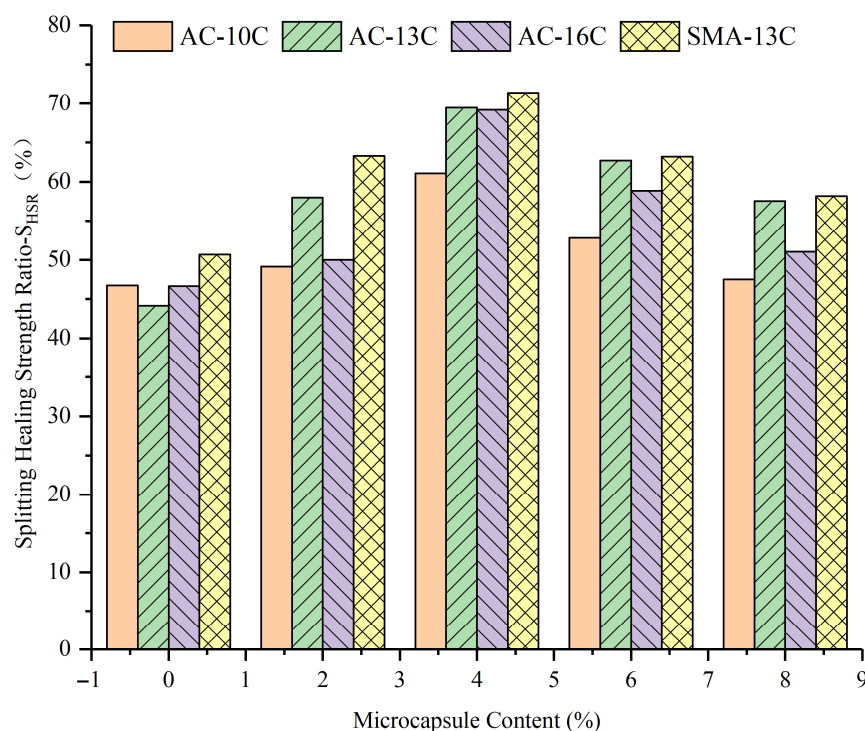


Figure 16. Variation in the S_{HSR} with microcapsule content.

For dense-graded asphalt mixtures, S_{HSR} generally decreases with increasing nominal maximum aggregate size. This phenomenon can be attributed to the reduction in asphalt binder content associated with larger aggregate sizes, which results in a lower volume of asphalt mastic and thus limits the crack-healing potential. When comparing AC-13C and SMA-13C mixtures with the same nominal maximum aggregate size, SMA-13C exhibits a higher S_{HSR} . This difference arises from the stone-on-stone skeleton-dense structure of SMA mixtures, which facilitates asphalt binder flow and crack-interface reconnection after splitting failure.

5.3. Consistency Between Healing Indices

A comparison between the Repair index R_c obtained from the beam bending fracture–healing–refracture test and the splitting healing strength ratio is presented in Figure 17. Both indices exhibit consistent trends with respect to microcapsule content, characterized by an initial increase followed by a decrease, with maximum values occurring at a microcapsule content of 4%.

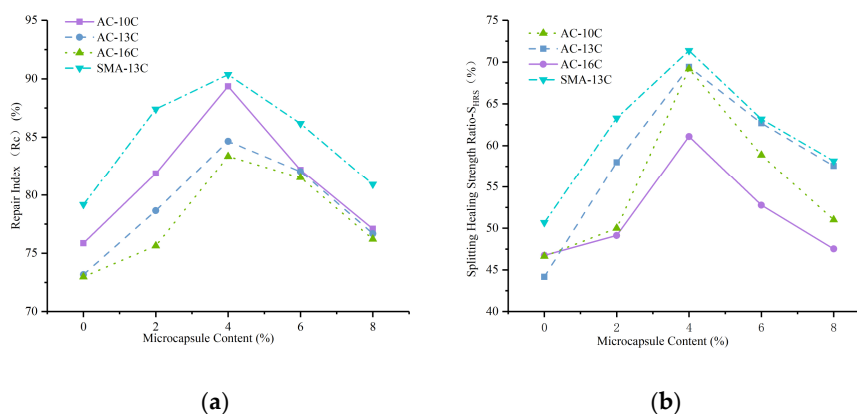


Figure 17. Comparison of self-healing evaluation methods: (a) beam bending fracture–healing–refracture test; (b) splitting healing test.

Moreover, the ranking of self-healing performance among the four asphalt mixtures obtained from the two evaluation methods is identical, namely SMA-13C > AC-13C > AC-10C > AC-16C. This consistency confirms the reliability and robustness of R_C and S_{HSR} as complementary indicators for evaluating the self-healing performance of recycled asphalt mixtures under different loading conditions.

The superior healing performance of SMA-13C and the comparatively lower healing efficiency of AC-16C can be attributed to differences in aggregate gradation and internal structural characteristics.

SMA-13C possesses a stone-on-stone skeleton structure with a relatively higher effective binder film thickness and greater voids in mineral aggregate. This structural configuration promotes crack formation predominantly within the binder-rich regions, preserving sufficient interfacial contact for molecular diffusion during healing. The thicker binder film and enhanced binder continuity facilitate crack closure and strength recovery.

In contrast, AC-16C, characterized by a coarser gradation and larger nominal maximum aggregate size, exhibits a more open aggregate skeleton with thinner binder films. Cracks in AC-16C are more likely to propagate through aggregate-dominated paths, leading to reduced effective contact area at the crack interface and limiting diffusion-driven healing. Consequently, its macroscopic healing index is lower.

Therefore, the observed differences in healing performance are closely related to mixture gradation, binder distribution, and crack morphology rather than solely binder content.

6. Conclusions

In this study, the self-healing performance of RAP-containing asphalt mixtures modified with epoxy-coated rejuvenator microcapsules was evaluated using both bending-based and splitting-based healing indices. Practical optimum healing conditions and dosages were identified, and the influence of mixture type was interpreted from a structural perspective. The following conclusions can be drawn:

The Repair index (R_C) increased with healing time and gradually approached a stable value. The growth rate decreased to below 2% after 8 h, indicating that 8 h can be considered a practical optimum healing duration.

With increasing healing temperature, R_C increased from 0 °C to 45 °C due to enhanced molecular diffusion and binder mobility. A slight decrease at 60 °C was observed, which was mainly attributed to temperature-induced softening affecting peak bending strength rather than a reduction in healing potential. Therefore, 45 °C was identified as the optimum healing temperature.

The self-healing capacity increased with microcapsule dosage up to 4% (by RAP mass) and then decreased at higher dosages. Excessive microcapsules were considered to disrupt aggregate interlocking and binder continuity, offsetting the benefit of additional rejuvenator release. Under the optimum healing condition, R_C increased by 10.38%–13.50% compared with control mixtures.

The S_{HSR} results exhibited trends consistent with R_C , and S_{HSR} increased by 14.35%–25.27% at the optimum dosage. The agreement between the two indices confirms the robustness of the identified optimum dosage.

Among the investigated mixtures, SMA-13C exhibited the highest self-healing capacity, followed by AC-13C, AC-10C, and AC-16C. The differences were attributed to variations in aggregate skeleton structure and effective binder film thickness, which influence crack path characteristics and contact conditions during healing.

The findings provide quantitative guidance for the design of RAP-containing self-healing asphalt mixtures incorporating microcapsule-based rejuvenators.

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