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Research Paper

Effects of Aging and Rest Periods on the Self-Healing Properties of Asphalt Mixtures

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Abstract

Aging of asphalt mixtures is one of the main causes of reduced durability and performance in flexible pavements. The self-healing ability of asphalt materials plays an important role in extending their service life. This study examines the impact of short-term and long-term aging, using two standard methods (R30 and NCHRP), as well as the influence of different rest periods on the self-healing capacity of asphalt mixtures. Specimens were prepared with PG 64-16 binder and siliceous aggregates, and self-healing was assessed using three indicators: stiffness ratio difference, fatigue life ratio, and failure rate. The results show that longer rest periods significantly improve self-healing indices. Samples aged with the R30 method generally performed better than those aged with the NCHRP method, while unaged samples consistently exhibited the highest self-healing potential. The findings suggest that employing multiple indices provides a more complete picture of asphalt mixture behavior, and systematic comparison of aging methods can serve as a valuable guide for optimizing materials and designing long life pavements.

Keywords: Asphalt Mixtures, Aging, Self-Healing, Rest Periods, Pavement Performance

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1. Introduction

Aging of asphalt mixtures is an inevitable phenomenon in the life cycle of flexible pavements. During this process, the bitumen in the mixture undergoes a series of chemical (mainly oxidation) and physical (hardening, volatilization of light components, and structural rearrangement) changes due to long-term exposure to air and temperature. These changes lead to hardening of the binder and reduced durability of pavements (Petersen & Glaser, 2011). As a consequence, the mechanical properties and service performance of pavements gradually deteriorate. Over time, research in this field has expanded, with a more comprehensive understanding of oxidation mechanisms and the role of oxidation products in the hardening of asphalt binders.

The aging process of asphalt materials is usually divided into two main categories: short-term and long-term aging. Short-term aging primarily occurs during production, mixing, and placement of asphalt mixtures when the binder is exposed to high temperatures and air. This causes volatilization of lighter components and initial oxidation, leading to increased viscosity and initial stiffness of the binder, thereby affecting compaction and workability. In contrast, long-term aging takes place during the service life of pavements under environmental factors such as oxygen, moisture, ultraviolet radiation, and temperature fluctuations (Gholami et al., 2024). This gradual process typically results in increased stiffness, reduced flexibility, and decreased self-healing capacity. Understanding the difference between these two types of aging is essential for predicting long-term pavement performance and developing appropriate maintenance strategies.

In recent decades, in addition to studying the mechanisms of aging, researchers have also focused on the self-healing capacity of asphalt. Self-healing refers to the material's ability to repair part of the damage caused by repeated loading. Various factors, including temperature, rest periods, binder type, and microstructure, can influence this behavior (Lv et al., 2017). Recent studies have shown that the use of specific additives, such as polyphosphoric acid, can significantly enhance the healing capacity of binders even after aging (Li et al., 2023). Moreover, investigations on recycled mixtures have demonstrated that aging reduces both fatigue resistance and healing potential, thereby affecting pavement longevity (Qu et al., 2024).

Several quantitative indices have been developed to evaluate self-healing behavior through laboratory tests, serving as important references in the design of asphalt pavements. Furthermore, continuum damage mechanics models have been proposed for more detailed analysis of fatigue and healing processes (Mannan, 2017). These efforts provide the foundation for defining and applying indices such as 'stiffness ratio difference,' 'fatigue life ratio,' and 'delayed failure rate,' which are employed in this study.

With increasing traffic loads, climate change, and harsher environmental conditions, aging has become one of the most important factors reducing pavement durability and performance. These changes not only raise maintenance costs but also impact road safety and the sustainability of transportation networks. Therefore, a clear understanding of aging processes and the healing capacity of asphalt mixtures is crucial for improving pavement durability and reducing life-cycle costs.

Although many studies have examined the effects of different factors on asphalt self-healing, a comprehensive investigation of the combined influence of aging type (short-term and long-term) and varying rest periods on healing indices has received less attention. Most past research focused on single indices, while the simultaneous use of multiple indices can provide a more accurate and multi-dimensional understanding of healing processes. This scientific gap highlights the need for systematic research addressing these factors together.

Accordingly, the main objective of this study is to investigate the effects of short-term and long-term aging, as well as the role of varying rest periods, on the self-healing capacity of asphalt mixtures. To achieve this, three key indices (stiffness ratio difference, fatigue life ratio, and failure rate) were evaluated and compared to provide a comprehensive picture of material performance under different conditions. The results of this study can form the basis for designing more durable pavements and developing new maintenance approaches in road engineering.

2. Literature Review

The phenomena of aging and self-healing of asphalt mixtures have been among the central topics of pavement engineering research since the early 20th century. Early studies focused on understanding the chemical and physical mechanisms of aging, while more recent research has expanded to healing behavior, damage modeling, and the development of quantitative indices for performance evaluation.

Initial research revealed that exposure of bitumen to oxygen and elevated temperatures leads to oxidation reactions, formation of polar compounds, and eventual hardening (Petersen & Glaser, 2011). These changes increase modulus, decrease flexibility, and raise susceptibility to cracking. In another study simulating long-term conditions, it was shown that the rate of hardening and reduction in fracture energy increase significantly with aging (Gholami et al., 2024).

More recent studies investigated the impact of environmental factors on the aging process, reporting that cycles of temperature and moisture, as well as combined effects of ultraviolet radiation and oxygen, accelerate oxidation and induce structural changes in bitumen (Lu & Isacsson, 2002).

In the past decades, research has increasingly emphasized the self-healing phenomenon. Some studies have demonstrated that rest periods and temperature play critical roles in healing; higher temperatures enhance molecular mobility of bitumen, resulting in faster recovery (Lv et al., 2017). Polyphosphoric acid has been identified as a key additive for improving healing capacity, as it strengthens the molecular network of the binder and prevents bond breakage after aging (Li et al., 2023).

Another line of research examined the effect of healing additives, such as microcapsules, which were found to improve healing capacity by up to 40% (Zhang et al., 2022). Similarly, the incorporation of nano-silica (SiO_2) particles was studied, and it was reported that proper dispersion of these nanoparticles enhances modulus and improves healing performance at low temperatures (Badroodi et al., 2020).

Modeling of damage and healing behavior has also become prominent. Researchers have developed continuum damage mechanics models, showing that incorporating healing in fatigue equations can improve structural life predictions by more than 30% (Mannan, 2017).

Other researchers studied whether asphalt aging through RTFO and PAV processes significantly affects healing performance. Their results showed that aged mixtures have lower healing potential compared to unaged mixtures (Vo et al, 2020).

A major focus of recent studies has been the development of indices to quantify healing processes. The 'stiffness ratio difference' index captures changes in modulus with or without rest periods (Witczak et al., 2013). The 'fatigue life ratio' is the simplest metric, comparing healing performance of samples under different loading conditions (Qu et al., 2024). More recently, the 'delayed failure rate' index was introduced, enabling analysis of rest period effects on cumulative damage rate (Mannan, 2017).

Overall, literature findings confirm the negative effect of aging on asphalt healing. However, the dependency of this reduction on loading frequency and the role of rest periods have not been systematically studied. Another gap is the simultaneous evaluation of frequency and strain effects on healing indices, which have often been studied separately. Furthermore, detailed comparisons of healing indices for R30- and NCHRP-aged samples are limited. The present study adopts a comprehensive and comparative approach to address these research gaps.

3. Methodology and Modeling

3.1. Materials and Aggregates

In this study, pure PG 64-16 asphalt binder obtained from Akam Refinery and siliceous river aggregates (Shahriar site, Akam Sand Company) with gradation No. 4 (AASHTO specification 234) were used. The properties of the binder and aggregates used are given in Tables 1 and 2, respectively.

Table 1. Properties of the binder used in the study

Aging condition	Property		Unit	ASTM test method	Result PG 64-16
Unaged	Viscosity @ 135 °C		Pa.s	D4402	0.32
	Penetration (0.1 mm)		0.1 mm	D5	68
Long-term aged	BBR	m-value	-	D6648	0.31
		Stiffness	MPa		128.9

3.2. Sample Preparation

The binder content was determined using the Marshall mix design method, yielding an optimal binder content of 5.8% for preparing the asphalt specimens. For specimen preparation, after determining the optimal binder content, asphalt slabs measuring 40×30 cm with a thickness of 6 cm were compacted using a Marshall compactor at the Soil Mechanics Laboratory of Tehran. The compaction arm length and the number of compaction blows were kept constant for all specimens.

Table 2. Properties of the aggregates used in the study

Test method	Property	Value
Coarse aggregate		
Los Angeles abrasion (%)	AASHTO- T96	16
Weight loss against sodium sulfate (%)	AASHTO-T104	0.2
Flat and elongated particles (%)	ASTM- D4791	1.4
Aggregate fracture (two-face) (%)	ASTM- D5821	100
Particle specific gravity (g/cm³)	AASHTO-T85	2.470
Bulk specific gravity (g/cm³)	AASHTO-T85	2.629
Water absorption (%)	AASHTO-T85	2.4
Fine aggregate		
Atterberg limits	AASHTO-T89, 90	Non-plastic
Lost weight against sulphatic sodium (%)	AASHTO-T104	0.9
Angularity of fine aggregate (%)	ASTM-C1252	45.6
Sand equivalent (%)	AASHTO-T176	67
Particle specific gravity (g/cm³)	AASHTO-T84	2.451
Bulk specific gravity (g/cm³)	AASHTO-T84	2.638
Water absorption (%)	AASHTO-T85	2.9
Filler		
Atterberg limits	AASHTO-T89, 90	Non-plastic
Specific gravity (g/cm³)	AASHTO-T100	2.619

The obtained slabs were then cut into beam specimens measuring 5×6×38 cm (with ± 6 mm tolerance) according to AASHTO T321 (AASHTO, 2003). As illustrated in Figure 1, the Marshall compaction procedure was performed to achieve a fixed target air void content. Specifically, based on the unit weight obtained from the Rice density test and the desired air void percentage, the required mass of the asphalt mixture was calculated and placed in the mold for compaction.

Figure 1. Asphalt mixture compaction

In this study, short-term aging was applied to the un-compacted mixture using the AASHTO R30 procedure (AASHTO, 2002). To implement this, the asphalt mixture was spread to a thickness of 35 mm in specified containers and kept in an oven at 135 °C for 4 hours. Then, long-term aging was applied to half of each sample using the R30 method (compacted mixture) and to the other half using the NCHRP 09-54 method (loose mixture). To simulate long-term aging conditions in the AASHTO method, after performing the short-term aging on the loose mixture and compacting it, the compacted sample was stored in an oven at 85 °C for 5 days. Likewise, for long-term aging of the loose mixture, it was stored in an oven at 95 °C for 8 days.

3.3. Tests

3.3.1. Four-Point Bending Fatigue Test

The four-point bending fatigue test was performed under controlled strain at levels of 500 and 1000 με using a sinusoidal load at frequencies of 5, 10, and 15 Hz, at a temperature of 20 °C. Five loading schemes were used: one without rest and four with different rest periods (from 0.1-0.1 s to 0.1-5.0 s), applied to both aged and unaged specimens. Figure 2 shows the loading jaws of the four-point bending fatigue test setup. A 25 kN UTM (Universal Testing Machine) was used for this test.

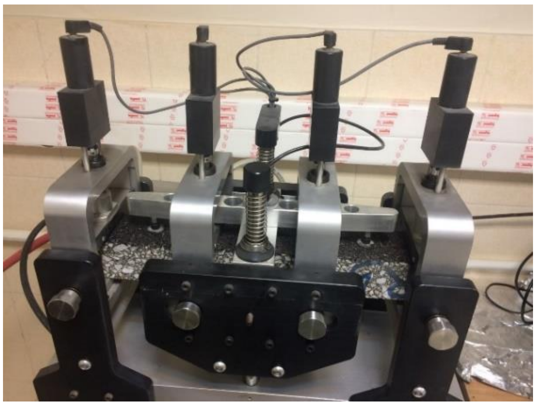

Figure 2. Loading jaws of the four-point bending fatigue test

3.3.2. Self-Healing Indices

In this study, the self-healing indices were calculated using three different methods.

- Method 1: Stiffness Ratio Difference

This method directly reflects the effect of the rest period on the stiffness ratio of the samples. The self-healing index is defined, based on Equation (1), as the difference between the stiffness ratios of specimens tested with and without a rest period (Witczak et al., 2013):

$$HI = [SR_{w/RP} - SR_{w/o\ RP}]_{at\ N_f\ w/o\ RP} \quad (1)$$

Where $SR_{W/RP}$ is the stiffness ratio with a rest period, and $SR_{W/ORP}$ is the stiffness ratio without any rest period.

- Method 2: Fatigue Life Ratio

This is one of the simplest relations for determining the self-healing of asphalt specimens by dividing their fatigue lives. This method directly compares the fatigue performance of the samples. Accordingly, as given by Equation (2), the fatigue life of the specimen with a rest period is divided by the fatigue life of the specimen without rest (Qu et al., 2024):

$$HI = \frac{N_{f-with\ rest}}{N_{f-without\ rest}} \quad (2)$$

Where Nwith rest is the fatigue life with a rest period, and Nwithout rest is the fatigue life without rest.

- Method 3: Failure Rate and Delayed Healing

During the fatigue test of asphalt specimens, self-healing occurs between successive loading cycles (called instantaneous healing). If the sample is kept unloaded during a rest period, the healing that occurs can be considered delayed healing. In four-point bending fatigue tests, only instantaneous healing occurs in the specimens under loading. In this research, fatigue cycles without rest and with various rest periods were defined. According to Equation (3), the average failure rate (D) from the start of the test until a 50% reduction in stiffness is obtained as follows (Mannan, 2017):

$$D = \frac{5S_0}{N_{f50}} \quad (3)$$

Where Sinitial is the initial stiffness modulus and Nf50 is the number of cycles to 50% of the initial stiffness (fatigue life at 50% stiffness reduction).

Consequently, the self-healing index for different rest periods is obtained by dividing the failure rates of the specimen with rest by the specimen without rest, according to Equation (4):

$$HI = \frac{D_0}{D_1} * 100\% \quad (4)$$

Where D0 and D1 are the average failure rates of the specimen with rest and without rest, respectively.

4. Results and Data Analysis

In this section, the results from all three methods for evaluating the performance of the samples under various rest period conditions (for strains of 500 and 1000 με) are presented.

4.1. Evaluation Using the Stiffness Ratio Difference

The self-healing index values for different specimens, calculated based on the stiffness ratio difference, are shown in Table 3. As the rest period in the loading cycles increased, the self-healing index based on this metric also increased. This behavior can be attributed to the physical nature of the healing process in bitumen. In fact, longer rest periods provide more time for bitumen molecules to rearrange and partly reform the bonds broken during loading. This effect is especially evident at high strains (1000 με), where the initial damage is greater. At 1000 με, the R30-aged specimens showed higher self-healing indices than the NCHRP-aged specimens. This difference can be attributed to the differences in the nature and severity of aging in the two methods. In the R30 method, because aging is applied to the compacted mixture, some of the lighter components of the binder remain in the mixture during compaction, helping to preserve relative flexibility. As a result, even after aging, the bitumen's capacity for molecular rearrangement and partial healing is higher. In contrast, in the NCHRP method (applied to the loose mixture), a greater portion of the light components is lost, which reduces the healing capacity. However, at 500 με, a different trend was observed. At this strain level, the NCHRP-aged specimens had higher self-healing indices than the R30-aged specimens. This can be interpreted as follows: at lower strains, because the damage per cycle is smaller, the higher stiffness resulting from NCHRP aging provides better resistance to initial cracking, thereby allowing more time for healing. In contrast, in the R30-aged samples, despite having more flexible bitumen, they were more vulnerable at low strains and exhibited a relatively lower healing capacity. This is illustrated in the plots of Figure 3.

Table 3. Self-Healing Evaluation Based on Stiffness Ratio Difference and Fatigue Life Ratio

No.	Strain (εμ)	Rest condition	Aging condition	Fatigue life (cycles) based on 50% reduction in initial stiffness	Stiffness ratio corresponding to fatigue life without rest	Self-healing index (stiffness ratio difference)	Self-healing index (fatigue life ratio)
1	1000	No rest	Unaged	12780	0.50	0	1

No.	Strain (εμ)	Rest condition	Aging condition	Fatigue life (cycles) based on 50% reduction in initial stiffness	Stiffness ratio corresponding to fatigue life without rest	Self-healing index (stiffness ratio difference)	Self-healing index (fatigue life ratio)
2			NCHRP-aged	5330	0.50	0	1
3			R30-aged	2890	0.50	0	1
4		0.1-0.1	Unaged	19610	0.58	0.08	1.53
5			NCHRP-aged	7990	0.58	0.08	1.50
6			R30-aged	5490	0.61	0.11	1.90
7		0.1-0.9	Unaged	22819	0.70	0.20	1.79
8			NCHRP-aged	8514	0.65	0.15	1.60
9			R30-aged	7247	0.67	0.17	2.51
10		0.1-2.5	Unaged	100665	0.82	0.32	7.88
11			NCHRP-aged	10714	0.78	0.28	2.01
12			R30-aged	12233	0.78	0.28	4.23
13		0.1-5	Unaged	137306	0.93	0.43	10.74
14			NCHRP-aged	16708	0.82	0.32	3.13
15			R30-aged	15992	0.84	0.34	5.53
16	500	No rest	Unaged	219610	0.50	0	1
17			NCHRP-aged	93650	0.50	0	1
18			R30-aged	71150	0.50	0	1
19		0.1-0.1	Unaged	505570	0.66	0.16	2.30
20			NCHRP-aged	209675	0.66	0.16	2..24
21			R30-aged	160300	0.63	0.13	2.25
22		0.1-0.9	Unaged	738132	0.80	0.30	3.36
23			NCHRP-aged	234836	0.76	0.26	2.51
24			R30-aged	210289	0.0	0.20	2.96

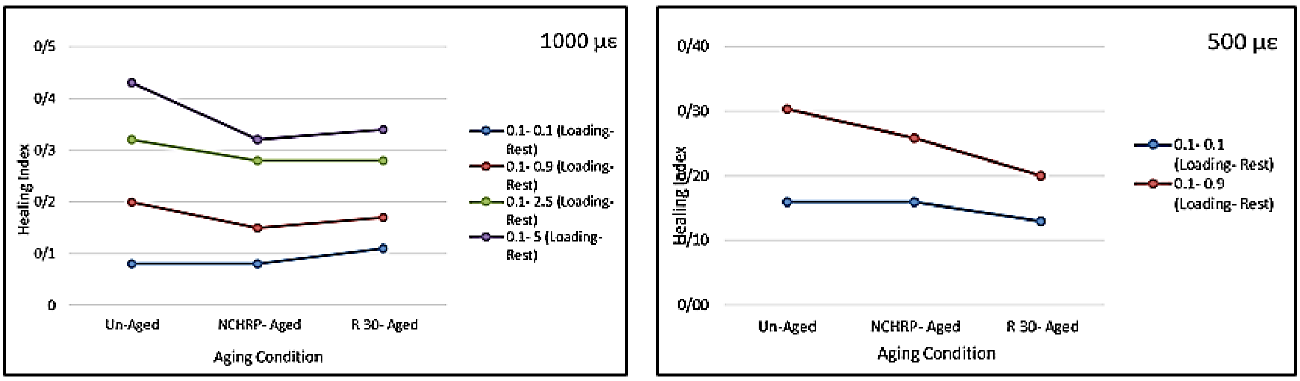

Figure 3. Self-healing index (stiffness ratio difference) at 500 and 1000 microstrain for various rest periods

Figure 4 shows the changes in the self-healing index (first metric) at a strain of 1000 με. As shown, increasing the rest period from 0.1 to 5.0 s results in increases of 438%, 300%, and 209% in the self-healing index for the unaged, NCHRP-aged, and R30-aged specimens, respectively. Conversely, aging caused a 40% and 109% decrease in the self-healing index for the NCHRP-aged and R30-aged specimens relative to the unaged specimen. This outcome is directly due to the reduced molecular mobility of the bitumen after aging. In the unaged binder, the lighter components are still present and the molecular chains can move more freely, thereby facilitating the self-healing process.

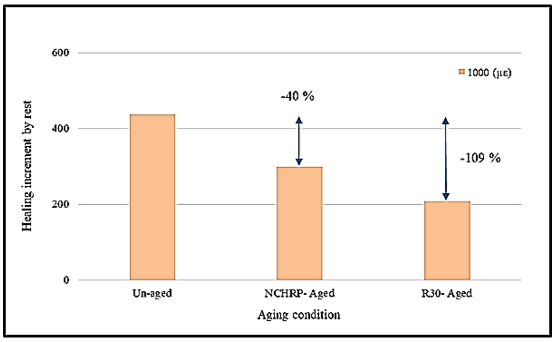

Figure 4. Effect of rest period on the self-healing index (stiffness ratio difference) at 1000 microstrain

Figure 5 compares the self-healing index (stiffness ratio difference) for the 0.1-0.1 s and 0.1-0.9 s rest schemes at strains of 500 and 1000 με. This plot shows that the increase in self-healing is greater at 1000 με than at 500 με. Also, the NCHRP-aged specimens show a larger increase in healing than the R30-aged specimens. These findings indicate that the interaction between aging type and strain level has a determining role in the self-healing mechanism, and one cannot draw a single conclusion valid for all conditions. Therefore, both factors must be considered simultaneously in pavement design.

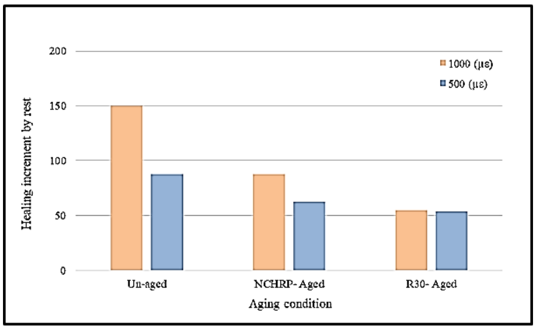

Figure 5. Comparison of self-healing index (stiffness ratio difference) at 1000 and 500 microstrains

4.2. Evaluation Using the Fatigue Life Ratio

The self-healing index values for various specimens based on the fatigue life ratio are also given in Table 3. In this method, at all strain levels, increasing the rest period in the loading cycles led to an increase in the self-healing index. This clearly indicates that time pauses between loading cycles reduce the accumulation rate of fatigue damage and thus extend the fatigue life of the specimens. In fact, the longer the rest period, the more time the microcracks formed have to close and reorganize, which allows the sample to withstand more load cycles. Using this method, all R30-aged specimens had higher self-healing indices than their counterparts aged by the NCHRP method. This can be attributed to the nature of the fatigue test: in this test, besides the bitumen's healing capacity, its initial ability to resist successive loads is also important. In the R30 method, because some of the lighter binder components remain during compaction, a higher relative flexibility is retained and the specimens can endure more cycles. In contrast, in the NCHRP method, the aging of the loose mixture is so severe that many of the light components evaporate, resulting in a much stiffer binder; thus, both fatigue resistance and healing capacity are reduced. The increase in the healing index for the unaged specimens with longer rest periods is greater than for the aged specimens under both methods. However, the influence of the rest period on increasing the healing index is larger for the R30-aged samples than for the NCHRP-aged ones. This can be attributed to the severity of the initial damage. At lower strain levels, the damage is minor and can be healed even during short rest periods, whereas at higher strains, more severe cracks form that require much longer times to heal, and even long rest periods may not achieve complete healing. Also, at very short rest periods, the difference between aged and unaged samples is almost negligible. This was observed in the previous indices as well, but this index shows it more clearly, indicating that the activation of the true self-healing capacity in the asphalt mixture requires sufficient time, and short rest periods only have a limited effect on reducing the damage rate. The results for this case are shown in Figure 6.

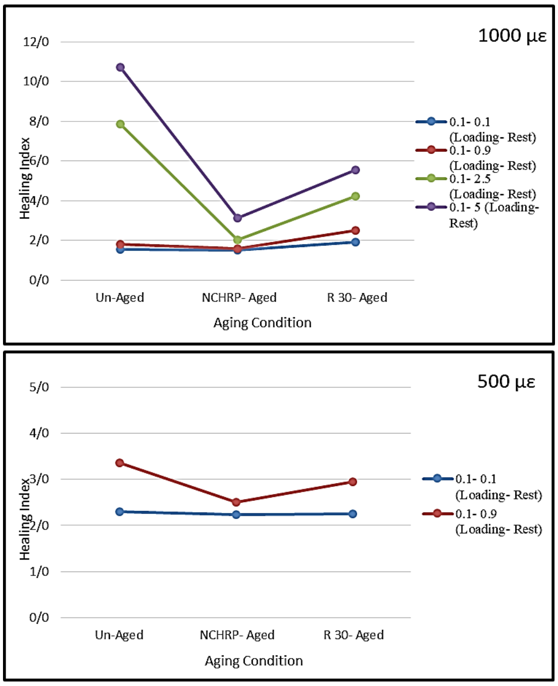

Figure 6. Self-healing index (fatigue life ratio) at 500 and 1000 microstrains for various rest periods

Figure 7 shows the effect of rest period on the self-healing index (fatigue life ratio) at 1000 microstrain. As shown, increasing the rest period from 0.1 to 5.0 s results in increases of 602%, 109%, and 191% in the self-healing index for the unaged, NCHRP-aged, and R30-aged specimens, respectively. Conversely, aging causes a 454% and 215% decrease in the self-healing index for the NCHRP-aged and R30-aged specimens relative to the unaged specimen.

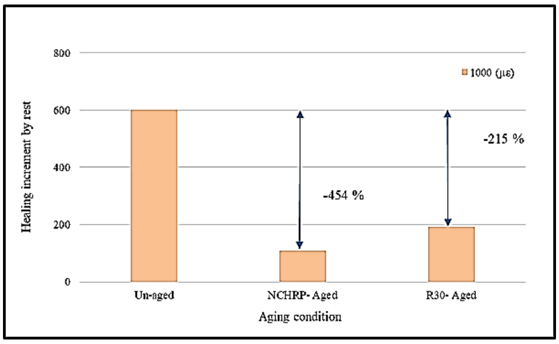

Figure 7. Effect of rest period on the self-healing index (fatigue life ratio) at 1000 microstrain

Figure 8 shows the results for specimens tested at 1000 and 500 microstrain based on the self-healing index (fatigue life ratio) for two rest conditions (0.1-0.1 s and 0.1-0.9 s). From this, it is observed that the increase in self-healing at 500 με is greater than or equal to that at 1000 με. Also, NCHRP-aged specimens exhibit a smaller increase in healing than R30-aged specimens.

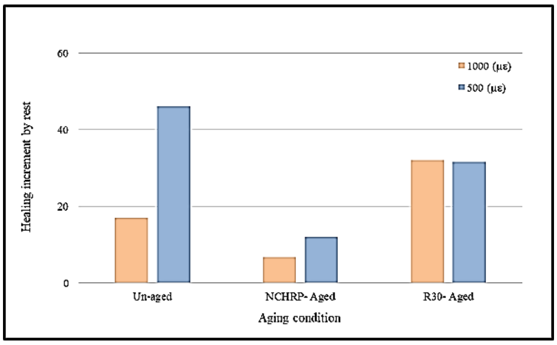

Figure 8. Comparison of self-healing index (fatigue life ratio) at 1000 and 500 microstrains

In summary, the fatigue life ratio is a sensitive and reliable index for evaluating self-healing behavior. In this method, R30-aged specimens showed a relative advantage over NCHRP-aged specimens, and the positive effect of rest time was more pronounced at lower strains. Also, the difference between aged and unaged specimens becomes more pronounced at longer rest periods, clearly highlighting the impact of aging on reducing the self-healing capacity.

4.3. Evaluation Using the Failure Rate Index

The self-healing index values for different specimens based on the failure rate index are given in Table 4. In this method, at all strain levels, increasing the rest period in the loading cycles resulted in an increase in the self-healing index. This clearly shows that pausing the loading, even for a few cycles, reduces the damage rate of the specimen. The general mechanism is similar to the previous explanations: it is due to stress release and providing an opportunity for the bitumen components to rearrange and flow. Also, all R30-aged specimens had higher healing indices than the NCHRP-aged specimens. Although the same pattern was observed with the stiffness difference and fatigue life indices, the difference between R30 and NCHRP is more pronounced in the failure rate index. This can be explained by the relatively stiffer and more brittle binder produced by the NCHRP method; due to loss of lighter components in the loose stage, the binder has a lesser capacity to withstand and heal successive damage. In contrast, R30-aged specimens retain some of their flexibility, and thus they exhibit a more noticeable reduction in damage rate.

Table 4. Self-Healing Evaluation Based on Damage Rate Index

No.	Strain (εμ)	Rest condition	Aging condition	Initial Stiffness (MPa)	Fatigue life (cycles) based on 50% reduction in initial stiffness	D	Self-healing index
1	1000	No rest	Unaged	3145	12780	1.23	1
2			NCHRP-aged	5404	5330	5.07	1
3			R30-aged	4829	2890	8.36	1
4		0.1-0.1	Unaged	2994	19610	0.76	1.61
5			NCHRP-aged	5328	7990	3.33	1.52
6			R30-aged	4203	5490	3.83	2.18
7		0.1-0.9	Unaged	3275	22819	0.72	1.71
8			NCHRP-aged	5591	8514	3.28	1.54
9			R30-aged	4811	7247	3.32	2.52
10		0.1-2.5	Unaged	2771	100665	0.14	8.94
11			NCHRP-aged	5249	10714	2.45	2.07
12			R30-aged	4009	12233	1.64	5.1
13		0.1-5	Unaged	2507	137306	0.09	13.48
14			NCHRP-aged	4028	16708	1.21	4.21
15			R30-aged	3871	15992	1.21	6.90
16	500	No rest	Unaged	3824	219610	0.09	1
17			NCHRP-aged	5176	93650	0.28	1
18			R30-aged	4104	71150	0.29	1
19		0.1-0.1	Unaged	2944	505570	0.03	2.99
20			NCHRP-aged	4295	209675	0.10	2.70
21			R30-aged	3405	160300	0.11	2.72
22		0.1-0.9	Unaged	3773	738132	0.03	3.41

No.	Strain (εμ)	Rest condition	Aging condition	Initial Stiffness (MPa)	Fatigue life (cycles) based on 50% reduction in initial stiffness	D	Self-healing index
23			NCHRP-aged	4078	234836	0.09	3.18
24			R30-aged	3193	210289	0.08	3.80

As seen in Figure 9, comparing strain levels (as mentioned in Sections 4.1 and 4.2), the positive effect of rest is more significant at 500 με than at 1000 με. However, one point highlighted by this index is that at higher strains, even with rest periods, the damage rate still increases rapidly and the bitumen's healing capacity cannot keep pace with the severity of damage. Another point is that at very short rest periods (e.g., 0.1 and 0.9s), the difference between aged and unaged specimens is hardly noticeable. This behavior was also seen in the previous indices, but it is more evident in this index, indicating that the healing mechanisms require a minimum amount of time to activate.

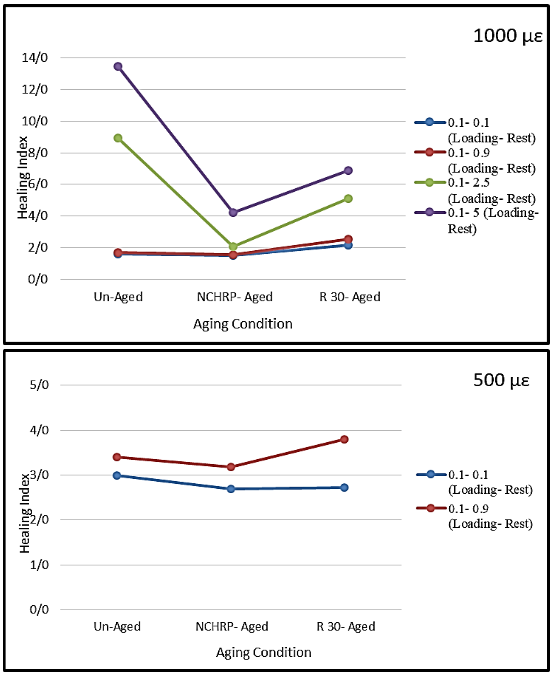

Figure 9. Self-healing index (failure rate) at 500 and 1000 microstrains for various rest periods

In summary, the failure rate index not only confirms the trends observed in the two previous indices but also has a higher discriminating power in comparing different aging methods. In other words, although the overall patterns are similar to Sections 4.1 and 4.2, the magnitude and clarity of the differences are greater in this index, highlighting the importance of using it in comprehensive studies of self-healing.

Figure 10 shows the effect of rest period on the self-healing index (failure rate) at 1000 microstrain. As shown, increasing the rest period from 0.1 to 5.0 s results in increases of 737%, 177%, and 217% in the self-healing index for the unaged, NCHRP-aged, and R30-aged specimens, respectively. Also, aging caused a 317% and 241% decrease in the self-healing index for the NCHRP-aged and R30-aged specimens relative to the unaged specimen.

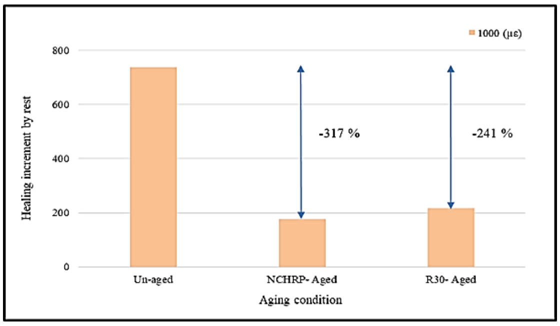

Figure 10. Effect of rest period on the self-healing index (failure rate) at 1000 microstrain

Figure 11 presents the results for specimens tested at 1000 and 500 microstrain based on the failure rate index, for two rest conditions (0.1-0.1 s and 0.1-0.9 s). It is observed that the increase in self-healing at 500 με is larger than at 1000 με. Also, the NCHRP-aged specimens exhibited a smaller increase in healing compared to the R30-aged specimens.

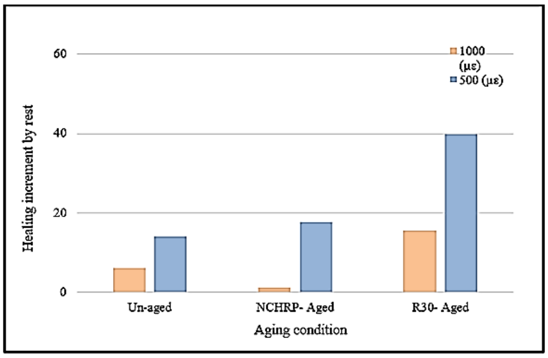

Figure 11. Comparison of self-healing index (failure rate) at 1000 and 500 microstrains

5. Conclusion

In this study, the effects of short-term and long-term aging — specifically using the R30 and NCHRP methods — and the role of varying rest periods on the self-healing capacity of asphalt mixtures were investigated. The results from the three different indices (stiffness ratio difference, fatigue life ratio, and failure rate) showed that rest periods play a key role in enhancing the healing ability of the specimens. In general, the self-healing capacity improved with longer rest periods, which is attributed to the greater opportunity for molecular rearrangement and reduction of accumulated damage in the bitumen.

The comparison between the two aging methods showed that the severity and nature of the aging process significantly affect the self-healing ability. In the stiffness ratio difference index, the R30-aged specimens performed better at high strains than the NCHRP-aged specimens, whereas at lower strains, the self-healing index of the NCHRP-aged specimens was higher. In the fatigue life ratio and failure rate indices, the R30-aged specimens outperformed the NCHRP-aged specimens under almost all conditions. These differences are due to the differences in the loss of light binder components and the relative stiffness of the binder matrix in the two methods.

It was also observed that even at short rest periods, unaged specimens had higher self-healing indices than aged specimens, indicating the negative effect of aging on the healing capacity. These findings emphasize that controlling the level of aging and including appropriate rest periods in the design of flexible pavements can help increase durability and reduce life-cycle costs.

Overall, the results of this study show that using multiple indices simultaneously to evaluate self-healing provides a more comprehensive and accurate picture of asphalt mixtures' behavior. A systematic comparison between different aging methods can serve as an effective guide for optimizing materials and designing more durable pavements. Finally, it is emphasized that when choosing one of the two aging methods for practical use, it is necessary not only to examine the effects of these methods on other distresses, such as rutting and thermal cracks, but also to conduct field studies.

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