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Research paper

Damage self-healing performance of basalt fiber asphalt concrete in high cold and high altitude area

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Abstract: To explore the self-healing properties of basalt fiber asphalt concrete under different damage levels, freeze-thaw cycles, and ultraviolet radiation aging, a four-point bending fatigue test and scanning electron microscope are used to analyze from macro and micro perspectives. By comparing and analyzing the fatigue damage rate of DV and the cumulative dissipated energy of ECD before and after the specimen healing, the corresponding healing coefficient is obtained respectively. The conclusion shows that basalt fiber has improved damage self-healing properties of ordinary matrix asphalt concrete, and the maximum value of the damage healing coefficient is 96% (mass fraction, the same below); under the same environmental factors, the damage degree of specimens is inversely proportional to the healing coefficient; at the same degree of damage, the freeze-thaw cycle has the greatest impact on the healing performance of the test piece, and the damage healing coefficient decreases by up to 4%; Cumulative dissipated energy can be used as an analysis index to more accurately characterize the damage self-healing performance of asphalt concrete. Through scanning electron microscopy image analysis, the mechanism of the effect of basalt fiber on the self-healing performance of asphalt concrete before and after ultraviolet and freeze-thaw action is further microscopically explained.

Keywords: basalt fiber asphalt concrete, four-point bending fatigue test, damage healing properties, cumulative dissipated energy, scanning electron microscope

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1. Introduction

Asphalt concrete pavement, due to its benefits of openness, has been extensively employed in diverse pavement constructions throughout China. fast traffic, comfortable driving and low noise. Asphalt concrete will produce fatigue cracking under repeated vehicle load and laboratory trials [1]. The fatigue cracks will progressively enlarge, evolving into pits, ruts, displacement, and other road surface defects. if they cannot be effectively maintained and treated.

In foreign research, Yoo DY [2] studied the influence of carbon based materials on the mechanical and self-healing properties of asphalt concrete, and the results showed that carbon nanomaterials were more effective in improving performance. CFs showed the best improvement in flexural performance, and the sample with 0.5% GNFs and CFs added had the best self-healing ability, restoring 40% of the original flexural strength. Grossegger D [3] believes that fatigue damage is the main cause of asphalt pavement degradation, and self-healing can increase the number of load cycles. However, healing is influenced by time and duration, and the unevenness of asphalt introduces uncertainty, which can only estimate the optimal healing time. Pamulapati Y [4] studied the feasibility of using induction heating to repair asphalt materials, and the results showed that induction heating successfully induced eddy currents in the metal fibers. The healing efficiency of the control sample was the highest, and microscopic analysis confirmed the effective healing of cracks. Schlangen [5] reviewed the research progress of self-healing cracks in cement-based materials and asphalt concrete, introduced the self-healing mechanism, and the most advanced results of all projects showed that self-healing can be achieved through material design. Barrasa R.C [6] studied the application of capsule rejuvenators in asphalt mixtures, which can restore the original characteristics of aged pavement and enhance its self-healing ability. Laboratory tests have confirmed the potential of self-healing chemicals to improve the durability of asphalt pavement. Behnia B [7] evaluated the self-healing ability of asphalt concrete under thermal damage using acoustic emission and DCT tests. The results showed that the self-healing ability decreased with increasing cooling cycles, but a 12-hour rest time significantly improved the self-healing ability. The DCT results showed an average increase of 13% in fracture energy. The latest research by Mirzamojeni M [8] reveals that asphalt mixtures have the characteristic of self repairing cracks, but this ability is affected by aging. In order to gain a deeper understanding of the impact of long-term aging on the self repairing performance of asphalt, the research team used FT-IR to conduct a detailed analysis of three service life asphalt road sections.

Chung et al. [9] were pioneers in studying fatigue cracking in asphalt concrete and its self-healing characteristics. Wang et al. [10] found that the self-healing properties of fatigue cracks vary depending on the binder used. Chen et al. [11] studied the fatigue and healing performance of asphalt mixtures under aging conditions, finding that aging and damage degree are key factors affecting self-healing. Improving the healing rate of asphalt mixtures requires extending healing time and using appropriate healing temperatures. Cui et al. [12] used macroscopic and microscopic methods to evaluate asphalt mixture healing performance, exploring the effects of aging, damage, and temperature. However, most research has focused on ordinary asphalt concrete, with limited studies on fiber-reinforced asphalt concrete, particularly on the widely used basalt fiber asphalt concrete in recent years [12–15]. Li et al. [16] found that basalt fibers enhance asphalt mixture integrity and crack resistance, with an optimal content of 0.4%. Studies by Zeng et al. [17], and Wang and Wang [18] support the conclusion that basalt fibers delay asphalt pavement cracking and improve fatigue life.

In summary, research has been conducted on the fatigue and freeze-thaw resistance of basalt fiber in asphalt concrete, especially regarding the impact of varying fiber content. However, limited research exists on the self-healing capabilities of basalt fiber asphalt concrete in high-cold, high-altitude environments, especially when exposed to ultraviolet radiation aging and freeze-thaw cycles. To address this gap, this study aims to provide scientific data for the use of basalt fiber asphalt concrete in high-altitude, low-temperature regions by examining its damage self-healing properties after UV aging and freeze-thaw cycles using scanning electron microscopy.

2. Experiment

2.1. Materials and mix proportion

A study comparing three asphalt concretes: basalt fiber, ordinary (control), and modified. Aggregates used are from Zhuozi County, Inner Mongolia, specifically basalt gravel. Asphalt used includes Pan Jin A-grade 90# and polymer-modified asphalt with 4.3% polymer content. Performance indexes detailed in Table 1. Mineral powder primarily limestone, basalt fiber from Zhejiang Shijin, chopped. Concrete gradation follows AC-16C type, composition in Table 2.

Table 1. Performance index of asphalt

Performance index of asphalt	**Matrix asphalt**	**SBS modified asphalt**
Penetration degree (0.1/mm)	86	66
Degree of ductility/cm	88	66
Softening point/°	49	79
Relative density/(g/cm3)	1.04	1.03

Table 2. Asphalt concrete gradation composition

Aggregate size/mm	**0–3**	**3–5**	**5–10**	**10–20**	**Ore fines**
Constituent ratio/%	35	10	25	25	5

A grade #90 base asphalt has a quality grade of "A" and a penetration grade of 90. Penetration is a measure of asphalt's hardness; higher values indicate softer asphalt. A-grade #90 asphalt has a penetration range of 80–100, classifying it as medium to soft with good adhesion, plasticity, and durability.

The optimum asphalt-stone ratio of the three kinds of asphalt concrete is determined through experiments: Base asphalt concrete is 4.3%, basalt fiber asphalt concrete is 4.5%, the optimum dosage of chopped basalt fiber is determined as 0.3% according to existing literature [16], and SBS modified asphalt concrete is 4.9%.

2.2. Specimen preparation and influencing factors

The trabecular specimens of 380 mm × 63.5 mm × 50 mm are prepared by shear compacting molding instrument and large asphalt concrete cutting machine. To investigate the impact of extreme cold temperatures and intense ultraviolet radiation on the self-healing properties of asphalt concrete pavement, trabecular specimens are exposed to alternating high and low temperatures within a controlled chamber, and simultaneously subjected to ultraviolet aging. The freeze-thaw cycle temperature was $-20 \sim 60^\circ$, and the number of cycles is 10. The ultraviolet radiation time is 245 h (the annual ultraviolet radiation is determined by taking the central and western regions of Inner Mongolia as the research sample area), and the temperature is set at 35° (to avoid thermal oxygen aging).

To investigate the self-healing properties of Wuyan fiber-reinforced asphalt concrete, a thorough analysis of its response in varying environments is crucial. Key factors include freeze-thaw cycle duration, UV radiation intensity, UV wavelength range, and UV lab size. Cycle duration can be tailored to experimental needs, with common settings of 24, 48, or 72 hours. By adjusting UV lamp power and object distance, UV radiation intensity can be controlled, simulating real-world lighting conditions. UV wavelength ranges from 100–400 nanometers. The UV lab's size must accommodate specimens, ensuring uniform UV exposure. It must also have tight sealing and temperature control for consistent results.

2.3. Healing test of asphalt mixture damage

The test employs the multi-functional servo test system of UTM-100 and the four-point bending fatigue test. The fatigue damage healing test follows the traditional (damage-healing-re-damage) mode, with a loading frequency of 10 Hz and a test temperature of 15°. When the specimen experiences initial cyclic loading, the bending stiffness modulus (S) decreases to 50% of its initial value (S0), signifying a 50% damage level. The stiffness modulus and cumulative dissipation energy are noted at 10%, 30%, and 50% damage levels. The damaged specimen is then placed in an incubator for 24 hours at 50° for self-healing. Following healing, the specimen undergoes another cyclic loading damage test, with corresponding data recorded.

3. Results and discussion

Asphalt concrete fatigue loading test can obtain a variety of data indicators, including stiffness modulus, fatigue life, phase Angle, dissipated energy. In this study, the damage healing properties of basalt fiber asphalt concrete and its control material are compared from two levels of damage rate DV and cumulative dissipated energy ECD.

3.1. Self-healing performance is evaluated at injury rate level

Asphalt concrete's stress and strain curves under load exhibit nonlinear behavior, deviating from Hooke's law. Stiffness modulus evolves in a concave arc pattern with loading time, as depicted in Fig. 1. The damage rate of D_V is computed by dividing the difference between initial and final stiffness moduli by loading time. The mixture's self-healing ability is evaluated by comparing D_V damage rates before and after healing.

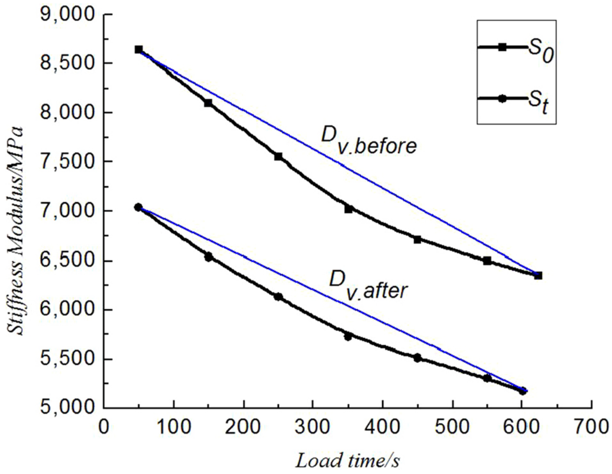


Fig. 1. Variation curve of stiffness modulus with loading time

$$D_V = \frac{S_0 - S_t}{t} \tag{3.1}$$

$$HI_1 = \frac{D_{V.\mathrm{before}}}{D_{V.\mathrm{after}}} \times 100\% \tag{3.2}$$

In Eq. (3.1) and Eq. (3.2), HI_1 is the damage healing coefficient, and the higher the value is, the better the damage self-healing performance of asphalt mixture is. S_0 and S_t are the initial stiffness modulus and termination stiffness modulus, unit: MPa, t is the loading time, unit: S; $D_{V.\mathrm{before}}$ and $D_{V.\mathrm{after}}$ are injury rates before and after healing, respectively. HI_1 obtained in the experiment is shown in Table 3.

Table 3 compares damage self-healing performance of three asphalt concretes under identical conditions. The order is: matrix asphalt concrete <basalt fiber asphalt concrete <SBS modified asphalt concrete. Adding basalt fiber to matrix asphalt concrete boosts its damage healing coefficient by up to 8%, with a peak of 94% in the first degree. Ultraviolet radiation and freeze-thaw cycles reduce the coefficient by 2% and 4% respectively, with freeze-thaw cycles having a greater influence in cold, high UV areas. Basalt fiber asphalt concrete with 50% initial damage has lower coefficients than other damage degrees, showing a direct relationship between initial damage and self-healing properties.

Table 3. Damage healing coefficient of HI_1 asphalt concrete

	Degree of damage (%)	**No environmental factors were applied (%)**	**Ultraviolet radiation aging (%)**	**Freeze-thaw cycle (%)**
Matrix Tarmac	10	87	82	82
	30	86	81	81
	50	82	80	75
Basalt fiber tarmac	10	94	92	90
	30	93	91	90
	50	90	89	86
SBS Modified Tarmac	10	96	95	93
	30	96	94	90
	50	95	93	90

3.2. Evaluation of self-healing performance at the level of accumulated dissipated energy

Loading damage of viscoelastic materials is a process of energy transformation. When a certain load is applied to asphalt concrete specimens, the mechanical energy is not transformed into strain energy, but into dissipated energy-heat energy. The damage process is essentially a process of energy dissipation or irreversible thermal process. Sun et al. [19] pointed out that the dissipated energy and the relative change rate of dissipated energy were related to the number of fatigue times, and established the related fatigue equation. Cui et al. [20] studied the self-healing ability of asphalt mixture soil by using fracture energy index and digital speckle technology. Each fatigue loading cycle of asphalt concrete corresponds to a strain of ε and a phase Angle of φ. The dissipated energy of specimens can be determined by the area enclosed by the stress-strain curve formed by fatigue loading.

$$E_{\mathrm{D}} = \int y\mathrm{d}x = \int_0^t \sigma_t \varepsilon_t \mathrm{d}t = \pi \times \sigma_t \times \varepsilon_t \times \sin\varphi \tag{3.3}$$

$$E_{\mathrm{CD}} = \sum_{i=1}^{n} E_{Di} \tag{3.4}$$

In Eq. (3.3) and Eq. (3.4), E_{D} is the dissipation energy of a single loading cycle (J/m^3); E_{CD} is the accumulated dissipated energy (J/m^3) during the fatigue test, σ for stress, t is the time required for a single loading cycle (s). There is a process of energy dissipation before and after the healing of asphalt mixture specimens, $E_{\mathrm{CD.before}}$ – accumulated dissipated energy of loading before healing; $E_{\text{CD.after}}$ – cumulative dissipated energy is loaded after healing. The ratio of accumulated dissipated energy before and after healing is calculated. The ratio is the relationship between the dissipated energy before and after healing, and the healing status of the damaged specimen is evaluated by the ratio.

$$HI_2 = \frac{E_{\text{CD.after}}}{E_{\text{CD.before}}} \times 100\% \tag{3.5}$$

In Eq. (3.5), The ratio HI_2 is also named as the injury healing coefficient, and the data of HI_2 obtained in the test are shown in Table 4.

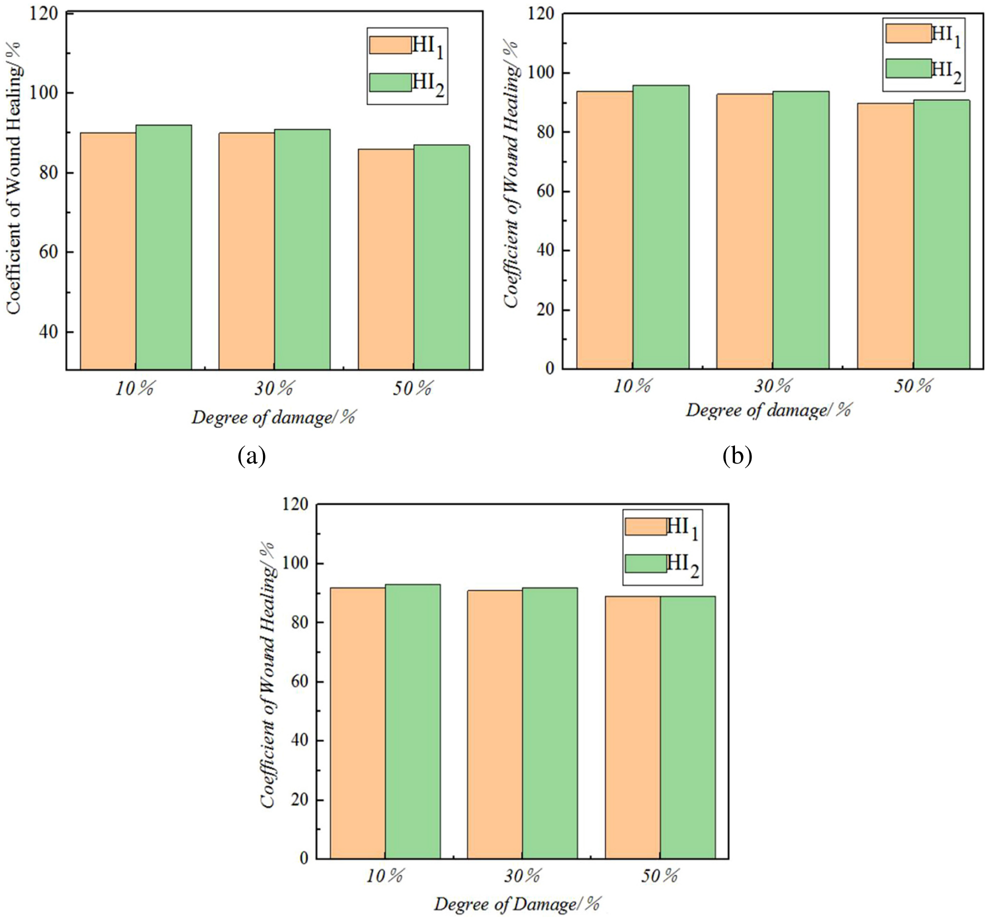
Table 4. Damage healing coefficient of HI_2 asphalt concrete

	Degree of damage (%)	**No environmental factors were applied (%)**	**Ultraviolet radiation aging (%)**	**Freeze-thaw cycle (%)**
Matrix Tarmac	10	89	87	86
	30	87	86	84
	50	83	82	81
Basalt fiber tarmac	10	96	93	92
	30	94	92	91
	50	91	89	87
SBS Modified tarmac	10	98	96	93
	30	97	96	95
	50	95	94	90

Table 4 indicates that the cumulative dissipated energy of the three asphalt concretes decreases following healing, with the base asphalt concrete experiencing a more pronounced decrease than the other two. The damage healing coefficient of HI_2 reveals that the decrease is due to concrete damage resulting from initial fatigue cracking. The surface energy of asphalt and aggregate at the cracking point, post-rehealing, does not fully recover. This implies that the energy loss of specimens indirectly reflects the self-healing capacity of asphalt concrete.

Asphalt concrete mixed with basalt fiber experiences slight variations in cumulative dissipated energy before and after healing. The damage healing coefficient (HI_2) increases under different environmental factors, peaking at 96%. However, HI_2 decreases due to ultraviolet radiation and freeze-thaw cycles, with the largest decrease of 4% due to freeze-thaw cycles. When damage reaches 50%, HI_2 is 87%. Since the initial damage causes significant energy loss and healing conditions are the same as for 10% and 30% damage, molecular potential energy is not effectively recovered at 50% damage, resulting in the lowest self-healing performance.

Figure 2 demonstrates a comparative analysis of the damage healing coefficient of two-stage basalt asphalt concrete, taking into account various environmental factors. The two damage healing coefficients of basalt fiber asphalt concrete are compared and analyzed. It can be seen from Fig. 2 that two damage healing coefficients obtained by damage rate of D_v and cumulative dissipated energy of E_{CD} can reflect the self-healing performance of asphalt concrete, and the difference is small, and the maximum difference is 2%. The value of HI_1 is lower than that of HI_2 under different environmental factors and damage degrees. This is because HI_1 is the ratio of the damage rate of D_v before and after healing. As asphalt concrete is a typical viscoelastic material, its stiffness modulus does not decrease linearly when subjected to fatigue load.



(a)

(b)

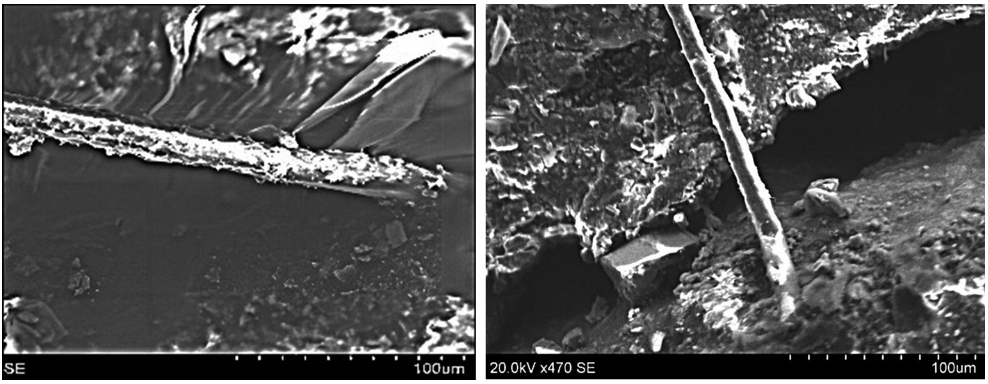
(c)

Fig. 2. Comparative analysis chart depicting the performance of HI_1 and HI_2 in basalt asphalt concrete: (a) Inactive environmental conditions, (b) Ultraviolet radiation conditions, (c) Freeze-thaw cycle acting parts

However, the formula of $S_0 - St/t = D_v$ reflects that D_v is the slope of the stiffness modulus variation of asphalt concrete during a period of loading time and presents a linear relationship, which cannot accurately reflect the nonlinear damage characteristics of viscoelastic materials. The loading process of specimens is a process of mechanical energy being transformed into dissipated energy, and the accumulated dissipated energy is the sum of dissipated energy formed by multiple stresses and strains in the fatigue loading cycle of specimens. The ratio of accumulated dissipated energy before and after healing (HI_2) is suitable to evaluate the damage self-healing performance of specimens.

4. Microscopic analysis of damage self-healing mechanism mechanism of basalt fiber asphalt concrete

The internal structure of asphalt concrete is complex due to the colloid that binds coarse and fine aggregates [21–23]. This spatial structure has varying sizes of airtight and penetrating pores, reducing its load resistance. Basalt fiber's strengthening effect enhances asphalt concrete's cracking resistance. Fracture mechanics indicates that material fracture development aligns with strain, and resistance is tied to component arrangement and combination [24–26]. To assess the influence of basalt fiber asphalt concrete's components on damage self-healing, scanning electron microscopy (SEM) analyzes cracking surfaces. UV radiation and freeze-thaw cycle effects on damage performance are compared. Figs. 3, 4, and 5 depict component arrangements at the cracking point before and after healing.

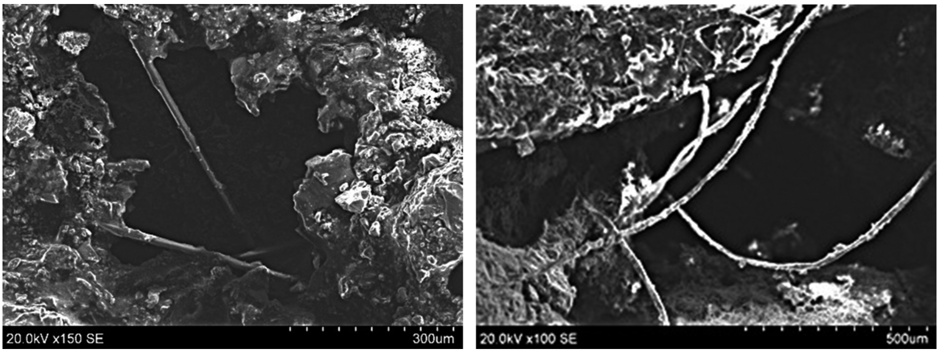


(a) (b)

Fig. 3. Microscopic morphology images of self-healing specimens before (a) and after (b) environmental effects

Figure 3 clearly demonstrates that the adhesive spatial reticulated structure of basalt fiber and asphalt remains intact post-healing. Adding basalt fiber to asphalt concrete reduces internal voids and enhances crack resistance. This prevents micro-cracks from propagating during loading due to the fiber's tensile strength. Chemically, basalt fiber's properties adjacent to cracks exhibit lipophilicity. This fiber applies tensile force to concrete cracks, enhancing local concrete defects and overall integrity.

Figure 4 is the SEM of the specimen before and after ultraviolet radiation. It can be seen from Fig. 4 that asphaltene, colloids and fiber filaments in basalt fiber reinforced asphalt concrete exhibit a separation state after UV irradiation. Due to ultraviolet aging, the fluidity of asphalt is reduced, and the aggregate is not well wrapped. There is uneven distribution of fibers in asphalt concrete, in which there is a certain agglomeration phenomenon. When the amount of asphalt is less than the wrapped fiber, the integrity of the mixture is affected to some extent.

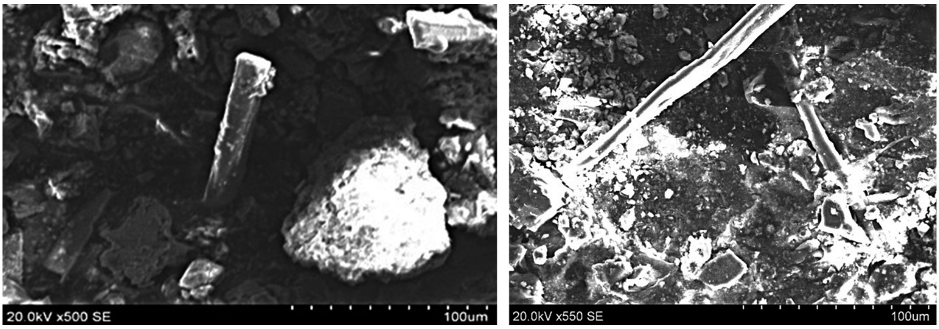


(a) (b)

Fig. 4. Microscopic morphology photos of specimens before (a) and after (b) self-healing under UV radiation conditions

It is found that basalt fiber has strong radiation resistance, its morphology is relatively intact, and the fiber is integrated into the asphalt concrete again to form a whole. This makes the asphalt concrete mixed with fiber still have a certain damage self-healing ability after ultraviolet radiation.

It can be seen from Fig. 5 that the freeze-thaw cycle causes water to enter the pores of asphalt concrete, and the pores become larger and penetrate due to frost heave. After freeze-thaw, the aggregate and asphalt on the cracking surface of basalt fiber asphalt concrete show a relatively loose separation state, which makes the joint surface of asphalt and aggregate rough when the damage heals. Under the action of freeze-thaw cycle, the pores in asphalt concrete tend to become larger, which affects theadhesion between asphalt and fiber, but the effect is not obvious.



(a) (b)

Fig. 5. Microscopic morphology photos of specimens before (a) and after (b) self-healing under freeze-thaw cycling conditions

Basalt fiber, distinct from regular fibers, boosts asphalt concrete's resistance to cracking in low temperatures. Evenly distributed fibers connect the concrete at crack surfaces, forming a spatial grid that reinforces it. When loaded, the fiber's toughness prevents crack propagation. Basalt fiber-reinforced concrete also exhibits self-healing properties.

5. Conclusions

1. The damage self-healing performance of matrix asphalt concrete mixed with basalt fiber is improved to a certain extent under the influence of different damage degrees and different environmental factors. The maximum increase of damage healing coefficient is 7%, which is close to the modified asphalt concrete of SBS.
2. Under the same damage degree, the freeze-thaw cycle has the most significant effect on the damage self-healing performance of basalt fiber asphalt concrete, and the maximum value of the decline range of damage healing coefficient is 4%; Under the influence of the same laboratory trials, the higher the initial damage degree of the specimen, the lower the damage self-healing performance; When the damage degree of the specimen is 50%, the damage healing coefficient is the lowest.
3. The cumulative dissipated energy is used as the evaluation index of damage self-healing, which avoids the error caused by the feedback of damage healing coefficient by damage rate. Therefore, the cumulative dissipated energy of HI_2 before and after healing can more accurately express the damage self-healing performance of asphalt concrete.
4. After basalt fiber asphalt concrete is affected by ultraviolet radiation and freeze-thaw cycle, the molecular structure between asphalt colloid and aggregate is damaged to a certain extent, and the freeze-thaw cycle is the largest influence factor, which causes a large area of irreparable peeling state between asphalt and aggregate, and finally leads to the reduction of its damage self-healing performance.
5. After in-depth research on the self repair performance of basalt fiber matrix asphalt concrete, we have reason to believe that its future evaluation methods will continue to be improved and enhanced. At present, significant progress has been made in using cumulative dissipated energy as an evaluation indicator, but further optimization and standardization are still needed. Looking ahead, we will actively explore more effective evaluation methods, such as those based on microstructure analysis and mechanical properties, in order to comprehensively and accurately evaluate the damage self-healing performance of basalt fiber reinforced asphalt concrete.

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