Study on self-healing performance of basalt fiber asphalt concrete in road environment

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Abstract. Load crack is one of the main failure forms of asphalt concrete pavement. Basalt fiber has become an important research direction of road fiber modifier. However, the self-healing performance research of basalt fiber asphalt mixture under different road environment factors are rarely. In this paper, the self-healing performance of asphalt pavement in different road environments is studied by combining the self-healing properties of asphalt and the crack resistance of fiber materials. The self-healing test of basalt fiber asphalt concrete was carried out after long and short aging, ultraviolet aging, snow melting and freeze-thaw cycles treatment. By using the damage rate as the evaluation index, the self-healing characteristics of basalt asphalt pavement were analyzed by the method of "fatigue-self-healing - fatigue" under the influence of different road environment. The experiment also compared the self-healing properties with SBS modified asphalt and matrix asphalt and explained the mechanism of basalt fiber mixture self-healing by electron microscope. The results show that the addition of basalt fiber can greatly improve the self-healing level of asphalt concrete under various road conditions.

1. Introduction
Fatigue cracking disease is a typical disease of asphalt concrete. Narasaiah et al. [1] divided the multiphase composite cracking into three stages, namely the microcrack initiation period, the cleavage period, the growth period and the convergence period. During the initiation period, a large number of microcracks are produced; during the cracking period, several microcracks have a competitive advantage; during the growth and convergence period, the dominant cracks converge into one crack, while other microcracks shrink. Fatigue cracking is mainly caused by repeated repetitions in the first two stages. The self-healing properties of asphalt concrete can repair micro-cracks to a certain extent, so the self-healing properties can enhance the fatigue resistance of concrete under certain circumstances. Weidong Huang et al [2] carried out self-healing test results, and show that the healing ability of asphalt concrete depends on the healing time and healing temperature. Hang Zhou [3] four-point bending fatigue test by strain control shows that the self-healing performance of basalt fiber asphalt concrete is stronger than that of matrix asphalt concrete. Under low damage degree, the fatigue resistance of some materials is even better than before healing. During the initiation period, a large number of microcracks are produced; during the cracking period, several microcracks have a competitive advantage; during the growth and convergence period, the dominant cracks converge into one crack, while other microcracks shrink. Fatigue cracking is mainly caused by repeated repetitions in the first two stages. The self-healing properties of asphalt concrete can repair micro-cracks to a certain extent, so the self-healing properties can enhance the fatigue resistance of concrete under certain circumstances. Huang Weidong et al [2] carried out self-healing test results show that the healing ability of asphalt concrete depends on the
healing time and healing temperature. Zhou Hang [3] four-point bending fatigue test by strain control shows that the self-healing performance of basalt fiber asphalt concrete is stronger than that of matrix asphalt concrete. Under low damage degree, the fatigue resistance of some materials is even better than before healing.

As a new type of material, basalt fiber has been recognized by the industry for its good mechanical properties, stable chemical properties and economical performance. Since the fiber additive can form a spatial network structure, it has a certain inhibitory effect on the expansion of the micro crack.

China has a vast territory and different climatic conditions. Different natural and working conditions have certain effects on the self-healing effect of asphalt concrete. The existing self-healing research of asphalt concrete mostly controls the experimental parameters, and there are few studies on the actual environmental factors. Therefore, based on this background, this paper compares the self-healing properties of basalt fiber asphalt concrete under different environments.

2. Test overview

This paper selects the AASHTO T321 experimental standard for strain control four-point bending test. The self-healing performance experiment of asphalt concrete after applying different road environment effects was carried out according to the test procedure of “fatigue-healing-fatigue” the self-healing index selected as evaluation index.

2.1. Design and molding of asphalt concrete

The test used 0-2.36mm, 2.36-4.75mm, 4.75-9.5mm, 9.5-26.5mm, 4 basalt gravel and limestone ore. According to JTG F40-2004 "Technical Specifications for Construction of Highway Asphalt Pavement", the median value of AC-16 grades of various grades is selected as the test set. The asphalt concrete design is as follows:

| Sieves size/mm | 26.5 | 19 | 16 | 13.2 | 9.5 | 4.75 | 2.36 | 1.18 | 0.6 | 0.3 | 0.15 | 0.075 |
|----------------|------|----|----|------|-----|------|------|-----|-----|-----|------|-------|
| Passing ratio (by mass)/% | 100 | 100 | 94 | 80 | 76 | 55 | 36 | 20 | 14 | 9.4 | 7.2 | 5.5 |

The specific asphalt index of the modified asphalt with A grade 90# road asphalt and SBS modifier content of 4.5% is as follows:

| Property | Matrix asphalt | SBS modified asphalt | Method |
|----------|----------------|----------------------|--------|
| Penetration/0.1mm | 86 | 66 | JTG E20 T0604 |
| Ductility/(5cm/min)/cm | 86(10°C) | 66(5°C) | JTG E20 T0605 |
| Softening point/°C | 49 | 79 | JTG E20 T0606 |
| Relative density (25°C) | 1.043 | 1.030 | JTG E20 T0603 |
| Flashing point(COC)/°C | 285 | 273 | JTG E20 T0611 |

The basalt fiber is made of chopped basalt fiber produced by Shijin Basalt Fiber Co. Zhejiang province, Ltd. The basalt fiber with a mass fraction of 0.3% is mixed into the matrix asphalt concrete by dry mixing to form basalt fiber concrete. According to the results obtained by the Marshall Mix Design test [4-5], the optimum oil-stone ratio of matrix asphalt and basalt fiber asphalt concrete is 4.3%, 4.5%, and the optimal oil-stone ratio of SBS modified asphalt concrete is 4.9%. The concrete forming was compacted by a shear compactor manufactured by ASC, Italy, and the bulk density was selected as the control index. The size of the cut and formed beam test piece is 380 mm × 63 mm × 50 mm. Before the fatigue test, the test piece was kept at the experimental temperature for more than 4 hours.

2.2. Experimental program

This test presets the following road environmental factors, namely:

(1) Control group: room temperature environment, placed on a plane with a certain rigidity, and ensure no pressure on the top to prevent deformation.
(2) Short-term aging [6-8]: The concrete bulk material was placed in a 135°C ventilated oven for 4 h before molding.

(3) Long-term aging [9-10]: The molded specimens subjected to short-term aging were placed in an oven of 85°C ventilated for 4 d.

(4) Ultraviolet aging [11]: The molded specimen was placed in a UV aging chamber with a radiation dose of 200 W/m² and an increase factor of 1.1. Radiation 292h was finalized to simulate the effect of UV radiation aging on asphalt concrete for half a year [12].

(5) Influence of snow melting agent [13-14]: The sample was immersed in a chlorine salt snow melting agent solution containing 5% mass fraction of MgCl₂, NaCl and CaCl₂. The test temperature was -5 °C for 3 days. The test piece was taken out and allowed to stand for 4 hours to room temperature, and then subjected to a fatigue test.

(6) Freeze-thaw cycle: at -20 °C ambient temperature for 8 h, at 60 °C ambient temperature for 16 h, the above is a freeze-thaw cycle. A total of 10 freeze-thaw cycles were performed on the formed asphalt concrete test piece.

After applying the above environmental factors to the test piece, the trabecular four-point bending fatigue method was used to investigate the self-healing properties of basalt fiber asphalt concrete under different environmental conditions and the matrix and SBS modified asphalt concrete. 18 groups, including: AC-16C matrix asphalt concrete 6 groups prepared with 90# matrix asphalt; SBS modified asphalt concrete 6 groups; basalt fiber asphalt concrete 6 groups. Each set of test pieces has 3 parallel test pieces, which adopt the test method of “fatigue-healing-fatigue”. The introduction of the damage degree index [15] is the key parameter of the test:

\[ D_0 = \left(1 - \frac{E}{E_0}\right) \times 100\% \quad (1) \]

Where: \( D_0 \) is the degree of damage; \( E \) is the stiffness modulus in the non-destructive state; \( \dot{E} \) is the stiffness modulus in the damaged state.

When the residual stiffness modulus reaches a preset percentage, the first fatigue test is completed and the rest period is entered. Considering that the self-healing and the load temperature are not much different in the natural state, the same temperature is selected as the fatigue test for self-healing, which is 15±0.5°C, and the time is set to 24h. After the end of the healing, enter the second fatigue test phase, and the degree of damage is reduced again to the first test, which is the destruction, and the test is terminated.

2.3. Determination of healing evaluation indicators

The evaluation index is selected: damage rate \( D \) (damage) [16], and the calculation formula is as follows:

\[ D = \frac{S_0 - S_t}{S_0} \quad (2) \]

\( D \) is the failure ratio to reach the predetermined damage degree; \( S_0 \) is the initial stiffness modulus; \( S_t \) is the termination stiffness modulus; \( t \) is the time required for the stiffness modulus to change from \( S_0 \) to \( S_t \).

The ratio \( HI_D \) of the damage rate is selected as an indicator for evaluating the healing ability of concrete:

\[ HI_D = \frac{D_{\text{before}}}{D_{\text{after}}} \times 100\% \quad (3) \]

The fatigue curve can offset the change in stiffness modulus caused by factors such as temperature. The ratio of the damage rate was used as the evaluation index of the self-healing properties of the concrete after the experiment, and the following is represented by the healing index.

3. Self-healing performance analysis of basalt fiber asphalt concrete

The self-healing results of basalt fiber asphalt concrete are as follows:
Table 3  Statistics of self-healing test data of basalt fiber asphalt mixture under different environmental conditions

| Test conditions       | Before and after self-healing | Time of test/s | Fatigue number | Initial stiffness modulus | Termination stiffness modulus | Damage rate/% | Self-healing index |
|-----------------------|-------------------------------|----------------|----------------|----------------------------|-------------------------------|---------------|-------------------|
| Control group         | Before                         | 978            | 9783           | 4975                       | 3342                          | 1.46          | 1.230             |
|                       | After                          | 1068           | 10680          | 4422                       | 3165                          | 1.27          |                   |
| Short-term aging group| Before                         | 961            | 9607           | 7064                       | 4945                          | 2.21          | 1.110             |
|                       | After                          | 1032           | 10323          | 6825                       | 4777                          | 1.98          |                   |
| Long-term aging group | Before                         | 511            | 4827           | 8812                       | 6168                          | 5.17          | 0.829             |
|                       | After                          | 412            | 4420           | 8567                       | 5997                          | 6.24          | 1.064             |
| Ultraviolet aging group| Before                         | 851            | 8507           | 5341                       | 3739                          | 1.88          |                   |
|                       | After                          | 908            | 9077           | 5354                       | 3748                          | 1.76          |                   |
| Snow-melting treatment| Before                         | 939            | 9390           | 5770                       | 4039                          | 1.84          | 1.089             |
|                       | After                          | 1006           | 10057          | 5678                       | 3975                          | 1.69          |                   |
| Freeze-thaw cycles treatment| Before                         | 718            | 7177           | 5921                       | 4145                          | 2.47          | 0.921             |
|                       | After                          | 687            | 6873           | 6154                       | 4308                          | 2.69          |                   |

Note: The injury degree before self-healing was set as 30% and the control strains are 500μe

It can be seen from the above table that the anti-fatigue ability is the largest under the condition of no environmental factors, and the damage rate is reduced by 13% compared with the first fatigue, followed by the short-term aging by 10.4%, the snow melting agent by 8.2%, and the ultraviolet aging by 6.4%. The anti-fatigue effect of the internal basalt fiber under the influence of freeze-thaw cycles and long-term aging conditions is limited. The fatigue life of basalt fiber asphalt concrete specimens is not greater than that before the damage, and the healing indexes are 0.921 and 0.829. Under the conditions of no environmental factors, short-term aging, ultraviolet light and snow melting agent, the self-healing coefficient decreased by about 0.1, and the self-healing coefficient decreased under the influence of long-term aging and freeze-thaw cycles.

After the freeze-thaw cycle than long-term aging and self-healing process outer seen above 1, which micro-cracks generated inside the self-healing performance obvious. Asphalt concrete is a voided material with numerous voids and microcracks inside. When the specimen is subject to a certain load, the void will be subject to both compressive and tensile stresses. When the asphalt tensile stress around the internal void is within the acceptable range, the void will deform under the compressive stress and close, which enhances the self-healing of the asphalt. The material structure is strengthened; otherwise, when the surrounding asphalt cannot withstand the tensile stress, the voids and microcracks may further damage the material structure. The extent of reinforcement and damage is related to the composition of the material. When the degree of strengthening is greater than the degree of damage, the fatigue life of asphalt concrete is enhanced, and the self-healing index is greater than that before healing.

4. Comparative study on self-healing properties of asphalt concrete with different bonding materials

4.1. Comparison of self-healing properties of matrix asphalt concrete
### Table 4  Statistical table of self-healing test data of matrix asphalt mixture under different environmental conditions

| Test conditions         | Before and after self-healing | Time of test/s | Fatigue number | Initial stiffness modulus | Termination stiffness modulus | Damage rate/% | Self-healing index |
|-------------------------|-------------------------------|----------------|----------------|---------------------------|-------------------------------|---------------|-------------------|
| Control group           | Before                         | 622            | 6220           | 7637                      | 5346                          | 3.68          | 0.979             |
|                         | After                          | 601            | 6010           | 7538                      | 5276                          | 3.76          |                   |
| Short-term aging group  | Before                         | 590            | 5903           | 7201                      | 5040                          | 3.66          | 0.970             |
|                         | After                          | 556            | 5563           | 6990                      | 4893                          | 3.77          |                   |
| Long-term aging group   | Before                         | 354            | 3543           | 5786                      | 4050                          | 4.90          | 0.684             |
|                         | After                          | 239            | 2393           | 5712                      | 3998                          | 7.17          |                   |
| Ultraviolet aging group | Before                         | 520            | 5200           | 7097                      | 4968                          | 4.09          | 0.908             |
|                         | After                          | 454            | 4540           | 6824                      | 4777                          | 4.51          |                   |
| Snow-melting treatment  | Before                         | 615            | 6146           | 7431                      | 5201                          | 3.63          | 0.980             |
|                         | After                          | 587            | 5870           | 7231                      | 5061                          | 3.7           |                   |
| Freeze-thaw cycles treat| Before                         | 375            | 3753           | 6384                      | 4469                          | 5.11          | 0.735             |
|                         | After                          | 321            | 3207           | 7438                      | 5206                          | 6.95          |                   |

Note: The injury degree before self-healing was set as 30% and the control strains are 500µε

It can be seen from the above table:

1. Under the condition of controlled strain and 30% damage, the self-healing index of basalt fiber concrete is basically consistent with the trend of matrix asphalt concrete and is 10% to 25% higher than that of matrix asphalt concrete without basalt fiber, where the maximum is the control group, and the minimum is the snow melting agent treatment group, as shown in Fig.1.

![Figure 1.  Comparison of basalt fiber asphalt mixture Self-healing index improvement](image)

2. The damage rate of unmodified matrix asphalt specimens under the influence of conventional environmental conditions, short-term aging and snow melting agent is relatively low, all of which are about 3.7, the difference is very small, and the self-healing index is very similar to 98%.

3. The damage rate of asphalt concrete mixed with basalt fiber is lower than that of matrix asphalt concrete under the influence of long-term aging conditions. The damage rate under the influence of...
long-term aging conditions is not much different from that of matrix asphalt concrete.

The trend of strength of basalt fiber is explained as: basalt fiber as a mineral fiber, the environment has little effect on itself. When the self-healing environment changes, the deterioration of the asphalt material is mainly caused by the deterioration of the mechanical properties of the mixture. Therefore, the influence of the environment on the self-healing index of basalt fiber reinforced concrete is closely related to the matrix asphalt concrete.

The matrix asphalt concrete has little difference under the influence of conventional environmental conditions, short-term aging and snow melting agent. The reason is that the contact area between asphalt and air is small in asphalt concrete mixing and transportation, although it needs to be mixed with asphalt concrete during the 4h aging process. It is in contact with air, but there is not much evaporation, oxidation and polymerization inside. The aging of asphalt concrete will not be very serious. The effect of snow melting agent on asphalt concrete is mostly the corrosion of chloride ion on its surface, its influence depth is shallow, limited to the surface, and the test specimens are densely mixed with concrete for the four-point bending standard test piece, the size is relatively large and the porosity is small. Therefore, the influence of the snow melting agent on the asphalt mixed test piece is minimal. Ultraviolet light has certain influence on asphalt concrete. The damage rate is about 1.1 times larger than that of the specimen without environmental factors, and the healing index is 0.908, which is about 10% less than the influence of conventional environmental conditions. Studies have shown that [17], in the ultraviolet aging process of asphalt, the soft component content decreases, the hard component content increases, the composite modulus increases, the phase angle decreases, and the rheological properties of the asphalt deteriorate, thereby affecting the concrete self-healing performance.

The freeze-thaw cycle has a great influence on the two types of asphalt concrete. The damage rate is about 1.7 times that of the unapplied environmental factors, while the self-healing index is only 0.735, which is 24% smaller than the uncoated environmental factors. This shows that the freeze-thaw cycle has a greater impact on the inside of the test piece. Long-term aging has the most serious impact on the specimens, and the damage rate is larger than that of the conventional environmental conditions. The difference is mainly due to the damage rate after the second self-healing. The self-healing index is only 0.684, which is lower than the environmental factors. The test piece is 30% smaller. The conclusions obtained from the above data can explain the majority of the traditional matrix asphalt concrete roads after long-term use or experience the occurrence of cracks in the cold and heat road surface, and the addition of basalt fiber can effectively improve the self-healing performance.
4.2. Comparison of self-healing properties of SBS modified asphalt concrete

Table 5  Statistical table of self-healing test data of SBS modified asphalt mixture under different environmental conditions

| Test conditions    | Before and after self-healing | Time of test/s | Fatigue number | Initial stiffness modulus | Termination stiffness modulus | Damage rate/% | Self-healing index |
|-------------------|-------------------------------|----------------|----------------|---------------------------|-----------------------------|---------------|-------------------|
| Control group     | Before                        | 6081           | 60810          | 6936                      | 4855                        | 0.34          | 1.200             |
|                   | After                         | 6575           | 65747          | 6244                      | 4301                        | 0.28          |                   |
| Short-term aging group | Before                     | 5508           | 55083          | 6678                      | 4675                        | 0.36          | 1.175             |
|                   | After                         | 5793           | 57930          | 5978                      | 4185                        | 0.31          |                   |
| Long-term aging group | Before                      | 4240           | 42407          | 4166                      | 2916                        | 0.29          | 0.911             |
|                   | After                         | 3866           | 38660          | 4169                      | 2918                        | 0.32          |                   |
| Ultraviolet aging group | Before                     | 5392           | 53917          | 5369                      | 3758                        | 0.30          | 1.152             |
|                   | After                         | 5749           | 57493          | 4970                      | 3479                        | 0.26          |                   |
| Snow-melting treatment | Before                      | 5427           | 54273          | 5792                      | 4054                        | 0.32          | 1.135             |
|                   | After                         | 5807           | 58067          | 5461                      | 3823                        | 0.28          |                   |
| Freeze-thaw cycles treatment | Before                | 5303           | 53033          | 4346                      | 3042                        | 0.25          | 0.960             |
|                   | After                         | 5021           | 50213          | 4288                      | 3002                        | 0.26          |                   |

Note: The injury degree before self-healing was set as 30% and the control strains are 500με

It can be seen from the above table that the SBS modified asphalt concrete has the lowest damage rate and is uniform and has no obvious change. This shows that after the matrix asphalt is added with the SBS modifier, the asphalt itself greatly increases the elastic modulus and the external pressure. It has little effect on the deformation of itself and its elastic modulus decreases slowly. It has been found through experiments that SBS modified asphalt will produce a healing index greater than 1 under 30% damage, controlled strain, no applied factors, short-term aging, UV influence and snow melting agent soaking conditions. Long-term aging and freeze-thaw cycles, like basalt fiber, have a healing index of less than one.

Under the conditions of short-term aging, ultraviolet aging and snow melting agent soaking, the self-healing ability of SBS modified asphalt concrete is slightly stronger than that of basalt fiber asphalt concrete. The fatigue life of both concretes is higher than that before the damage, which is 5.8%, 8.3%, and 4.2% respectively. The self-healing properties of basalt fiber asphalt concrete are stronger than that of matrix asphalt concrete, which are 14.4%, 17.2% and 11.1%, respectively.

![Figure 2. Comparison of basalt fiber and SBS mixture](image-url)
According to the self-healing contrast diagram of basalt fiber and SBS, although the self-healing ability of basalt fiber modification is not as good as that of SBS under various environmental influences, basalt fiber asphalt concrete self-healing without the influence of environmental factors. The effect is the best, 2.5% higher than SBS modified asphalt concrete. It shows that the self-healing properties of asphalt concrete are not just the material itself but the internal structure of concrete can play a big role.

The asphalt concrete under the influence of freeze-thaw cycles and long-term aging cannot be completely healed. The self-healing ability of SBS modified asphalt concrete is 4.3% and 9.9% higher than that of high basalt fiber asphalt mixture respectively; 30.6% and 33%. The self-healing ability of basalt fiber asphalt concrete is stronger than that of matrix asphalt concrete by 25.2% and 21.2%.

When the damage degree of asphalt concrete is small, the internal defects will be compensated to some extent when it under pressure. At the same time, because of the asphalt material's own reasons, the matrix asphalt has poor fluidity, small modulus of elasticity, and poor fatigue properties and self-healing properties. After being incorporated into the basalt fiber, the fiber can form a spatial network structure inside the test piece to improve the fatigue performance of the asphalt itself. In the self-healing process, the spatial network structure can promote the flow of asphalt, make up for micro-cracks, and improve its self-healing properties. Before the crack is enlarged, the effect of the fiber lifting asphalt fatigue performance is obvious. SBS modified asphalt concrete has the strongest anti-fatigue performance due to its high elastic modulus and the strongest resistance to environmental influences. SBS modified asphalt itself is less affected by the environment, its self-healing performance fluctuates little, the self-healing index approaches 1 and the self-healing effect is the best.

5. Microscopic electron microscopic scanning analysis of self-healing properties of basalt fiber asphalt concrete

Cracks can cause stress concentration, which leads to cracks, and the presence of fibers can inhibit the development of cracks and create conditions for the self-healing of asphalt concrete. It can be seen from the following electron micrographs how the fiber inhibits the development of cracks and explains the self-healing effect of the fiber asphalt concrete.

![Figure 3. The working condition of basalt fiber in asphalt mixture](image-url)
Asphalt concrete cracks in the initiation stage, basalt fiber can play a role in preventing the blocking crack from continuing to develop, changing the crack direction and expanding the range of stress, as shown in Fig. 2(a). When the crack enters the cracking stage, the basalt fiber can act as a reinforcement to inhibit the crack from continuing to expand, increasing the tensile properties of the material at the microscopic level and reducing the stress concentration at the crack tip, as shown in Fig. 2(b). According to the observation of the two stages of basalt fiber, it can be concluded that the basalt fiber has an inhibitory effect on the crack in the case of less damage, thereby enhancing the self-healing effect.

It can be seen from Fig. 2(c) that the fiber still does not completely fail when the crack reaches about 3000 μm. Figure 2(d) shows that when the crack develops to a certain width, the fiber breaks or is pulled out of the asphalt. It can be seen that for the crack with relatively large damage, the fiber basically fails, and the self-healing effect cannot be improved.

6. Conclusion

- The addition of basalt fiber under various environmental impact conditions can greatly improve the self-healing level of matrix asphalt concrete, especially in new pavement.
- By comparing the SBS modified asphalt concrete with the basalt fiber asphalt concrete, it is found that the material itself and the internal structure of the concrete can promote the self-healing of the asphalt concrete under the condition that the environmental factors are weak.
- There is a strong correlation between the self-healing ability of basalt fiber asphalt concrete and matrix asphalt concrete. This shows that more serious of the effective environmental factors, the performance of the asphalt itself more severity, and smaller effect on the self-healing of concrete.
- Basalt fiber can only act on self-healing when the crack width is small, and the fiber fails when the crack is wide.

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