Investigation on Moisture Damage Resistance of Asphalt Pavement in Salt and Acid Erosion Environments Based on Multi-scale Analysis

Xu Chen [a,b], Dongya Ren [a,b]*, Gangsheng Tian [a,b], Jie Xu [a,b], Rahman Ali [a,b], Changfa Ai[a,b]

a. Civil Engineering School of Southwest Jiaotong University, Sichuan Chengdu, 610031, China

b. Highway Engineering Key Laboratory of Sichuan Province, Sichuan Chengdu, 610031, China

Abstract: The existing research on the moisture damage resistance of asphalt pavement in salt and acid erosion environments is mostly indirect tensile tests based on asphalt mixture scale. There is little comprehensive analysis based on multi-scale. However, for the study of moisture damage resistance of asphalt pavement, different scales have their own advantages and disadvantages. In view of this, this paper comprehensively analyzes the moisture damage resistance of asphalt pavement in salt and acid erosion environments based on three scales namely asphalt binder scale, asphalt-aggregate scale and asphalt mixture scale, and draws the following main conclusions: 1) On the whole, the deterioration tendency of salt and acid solution on the water stability mechanical strength of asphalt pavement is basically the same, and the specific order is acid rain (pH=3) > 16% seawater > 16% NaCl > 8% seawater > 8% NaCl > distilled water > drying, indicating that salt and acid solution will aggravate the moisture damage of asphalt pavement, especially the acid rain with stronger corrosion effects. 2) The moisture damage resistance of asphalt-aggregate scale is weaker than that of asphalt binder scale and asphalt mixture scale. 3) The difference of moisture damage resistance test results between asphalt-aggregate scale and asphalt mixture scale in salt solution environments is smaller than that of other non-salt solutions. 4) The BBS test of asphalt-aggregate scale can effectively evaluate the self-healing performance of asphalt pavement. The self-healing ratio increased as the acid solution concentration increased, but the initial bond strength of BBS after high-concentration acid erosion was too small, so the bond strength after healing was still smaller than that of low-concentration acid solution. 5) The rotational viscosity of asphalt binder at 135°C correlates well with the self-healing performance of asphalt pavement.

Keywords: Asphalt pavement; Multi-scale; Salt and acid erosion environments; Moisture damage resistance; Self-healing performance; Rotational viscosity

1 Introduction

Moisture damage is a key cause of early diseases of asphalt pavement such as pumping slurry, spalling and potholes, and its mechanism mainly includes cohesion failure and adhesion failure [1-3], the specific process of failure is as follows: Moisture reaches asphalt-asphalt interface and asphalt-aggregate interface by infiltration or molecular diffusion, the moisture in the asphalt-asphalt interface softens the asphalt by emulsification, the moisture at the asphalt-aggregate interface causes the asphalt film attached to the aggregate surface to move, separate, break and bubble successively, the cohesive failure of asphalt-asphalt interface and adhesion failure of asphalt-aggregate interface are easy to occur under the drive of external load [4, 5]. The total area of saline-alkali soil in humid areas along the southeast coast of China is 5 million hectares， rainwater can bring a large amount of salt in saline-alkaline soil to asphalt pavement, and frequent salt spray and tide can also bring salt in seawater to asphalt pavement, which aggravates the weakening of adhesion and cohesion of asphalt pavement by moisture [6, 7] . In recent years, with the widespread use of fossil fuels, the average annual pH value of rainfall in China ranges from 4.2 to 8.2, and acid rain (precipitation with pH value less than 5.6) has occurred in 40% of cities, especially in southwest China, where industrial waste gas is not easy to be discharged due to the surrounding mountains. The studies show that acid rain can enter asphalt pavement through cracks and pores, corrode its adhesion and cohesion performance, and aggravate moisture damage [8, 9]. Therefore, it is of great significance to carry out research on moisture damage resistance (adhesion and cohesion performance) of asphalt pavement in salt and acid erosion environments.

Zhang et al. [10] investigated the influence of the number of wet-dry cycles on the indirect tensile strength of asphalt mixture based on the salt erosion environment; Setiadji et al. [11] analyzed the changes of water stability of asphalt mixture after being immersed in seawater in different regions, and the research results showed that the type of chloride played a key role in it; Huang et al. [12] studied the influence of sea salt composition on the high, low temperature, water sensitivity and other properties of asphalt mixture. In order to further explore the coupling effect of dynamic pore water and salt erosion environment, Xiong et al. [13-15] explored the influence of NaCl and Na_2SO_4 concentrations on the moisture damage resistance of asphalt mixture in dynamic pore water environment based on a custom-made apparatus. Amini [16] studied the attenuation characteristics of moisture damage resistance of asphalt mixture in the coupling of salt erosion, dynamic pore water and freeze-thaw environment. In order to explore the influence of acid rain corrosion on the water stability of asphalt pavement, Hu et al. [17] used dilute hydrochloric acid and dilute sulfuric acid mixture to simulate acid rain and studied the attenuation characteristics of acid rain on the moisture damage resistance of asphalt mixture; Wei et al. [18] studied the influence of acid rain on the adhesion and durability of asphalt mixture based on the dry-wet cycle test; Feng et al. [19] studied the influence of solutions with different pH values on the water stability of asphalt mixture based on freeze-thaw splitting test. However, the existing studies on moisture damage resistance of asphalt mixtures in salt and acid erosion environments are few comprehensive studies based on multi-scale.

The binderbond strength (BBS) test is not affected by asphalt mixture gradation and void ratio when it is used to test the bond properties of asphalt and aggregate (including the cohesion properties of asphalt itself and the adhesion properties of asphalt-aggregate interface), based on the material properties of asphalt and aggregates, focusing on the adhesion performance of asphalt-aggregate interface and the cohesion performance of asphalt-asphalt interface, a large number of research results [20-22] show that BBS test has been widely used in the research of moisture damage resistance of asphalt pavement. For the convenience of presentation and understanding, the scale of BBS test is defined as asphalt-aggregate scale in the following.

In summary, previous studies on the moisture damage resistance of asphalt pavement in salt and acid erosion environments, have rarely performed comprehensive analysis based on asphalt binder scale, asphalt-aggregate scale and asphalt mixture scale. However, for the study of moisture damage resistance of asphalt pavement, the above three scale areas have their own advantages and disadvantages: 1) The asphalt mixture scale takes into account the effects of voids and gradation, which has a better correlation with the field pavement. 2) The effects of voids and gradation are not considered in asphalt mixture scale and asphalt-aggregate scale, but only from the bonding characteristics of asphalt and aggregate materials, focusing on the adhesion of asphalt-aggregate performance interface and the cohesion performance of asphalt-asphalt interface, which are more conducive to the research and development of moisture-resistant materials (asphalt and aggregate) for asphalt pavement. Meanwhile, the above two kinds of scale tests are simple, direct and have high repeatability. In view of this, this paper comprehensively analyzes the moisture damage resistance of asphalt pavement in salt and acid erosion environments based on three scales (see Figure 1): asphalt binder scale, asphalt-aggregate scale and asphalt mixture scale, and verifies asphalt-aggregate scale and asphalt mixture scale test results by using SFE (surface free energy) theory. Among them, the study on the asphalt binder scale is realized by the improved BBS test proposed below, the asphalt-aggregate scale is realized by BBS test, and the asphalt mixture scale is realized by indirect tensile test. In addition, to further the above research, this paper also studied the self-healing performance of asphalt pavement after salt and acid erosion environments based on BBS test. It is expected that the research results of this paper can provide a theoretical basis and technical support for the research on the resistance of asphalt pavement to moisture damage in salt and acid erosion environments.

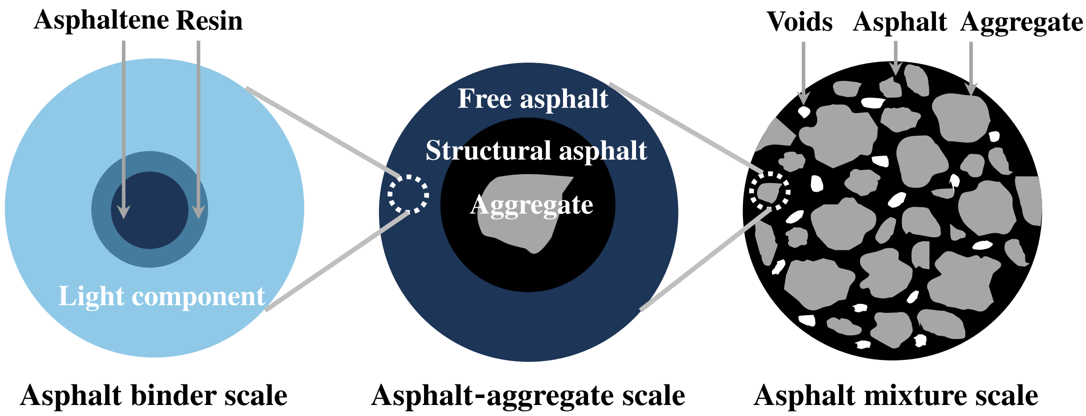


Figure 1 Three scales of asphalt pavement

2 Materials and tests

2.1 Materials

Because of traffic load, the rainwater immersed in the asphalt pavement through pavement pores and cracks is easy to accumulate in the lower layer and the interlayer where the water stability layer is located with poor flatness, especially in the sections where drainage measures fail or are partially failed. Therefore, AC-20, which is common in the lower layer, is selected as the gradation of asphalt mixture in this paper, as shown in Table 2. SBS modified asphalt, which is common in the surface layer, is selected as asphalt, as shown in Table 1. The aggregate used herein was granite.

Table 1 Main technical specifications of SBS modified asphalt

Performance indices	Measured value	Required value
Penetration（25°C, 100 g, 5 s）(0.1mm）	58	⩾50
Viscosity（135°C）(Pa·s）	1.99	⩽3
Ductility（5°C）(cm）	32	⩾20
Softening (°C)	84	⩾75

Table 2 AC-20 grading and volume parameters

The pass rate of (mm) with different sieve pore sizes /%												Asphalt aggregate ratio/%	porosity/%
26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075		
100	92	81	68	55	43	38	16	11	7	5.5	4	4.2	3.8

To simulate salt and acid erosion environments, salt solutions with different concentrations were prepared by selecting NaCl and Na_2SO_4 compounds according to the composition of salt in seawater and acid in acid rain. The molar ratio $C(SO_4^{2-})$:(NO_3^-)=9:1 is used to prepare artificial acid rain. Since the salt concentration of the seawater immersed in the asphalt pavement after evaporation is much higher than that of the sea water (about 3%), the concentration of the salt solution in this paper is chosen to be 1-5 times the salt concentration of the sea water according to relevant literature [6, 7, 13, 14]. In addition, the pH value of acid rain can be as low as 3 [23, 24], so the pH values of acid rain selected in this paper are 3 and 5. The specific solution types and concentrations are shown in Tables 3 and 4.

Table 3 Types and concentrations of salt and acid solutions

Solution type	Concentration
Distilled water	/
NaCl	4%, 8%, 12%, 16%
$MgCl_2$	2%, 4%, 8%, 12%
Na_2SO_4	2%, 4%, 8%, 12%
Seawater	4%, 8%, 12%, 16%
Acid rain	pH=3, pH=5

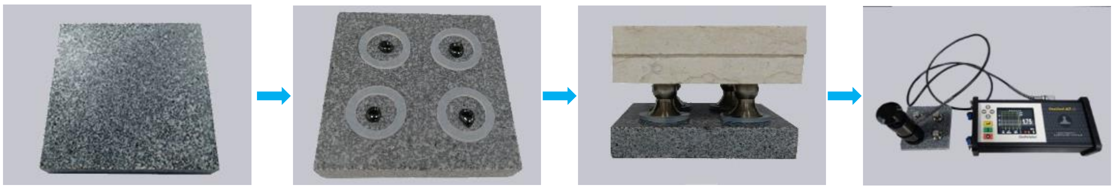
Table 4 Volume concentration of salt in seawater (g/L)

Type of salt solution	NaCl	$MgCl_2$	Na_2SO_4	KCl_2
Volume concentration	122.7	26.0	20.5	3.5

2.2 Test methods

2.2.1 Asphalt-aggregate and asphalt Mixture Scale

The BBS test is suitable for the bonding performance test of asphalt and aggregate, and has been applied to the study of moisture damage resistance in asphalt-aggregate scale by a large number of research results [20, 25, 26] . In this paper, the PosiTest AT-A equipment produced by DeFelsko was used to conduct BBS test to study the moisture damage resistance of asphalt-aggregate scale. Test parameters and specific operation process (see Figure.2) refer to the study of ASTM D45411[27], AASHTO TP-91 [28], Huang et al. [29] and Du et al. [30], drawing rate and asphalt film thickness are 0.7 MPa/s and 0.2 mm, respectively. Test results are denoted as bond strength $POTS_{\mathrm{Bond}}$ (*POTS*, *pull-off tensile strength*). The indirect tensile test of asphalt mixture can characterize its bonding performance, so the study on moisture damage resistance of asphalt mixture scale is realized by the indirect tensile test. For the specific operation method, see JTG E20-2011[31], and the test result is denoted as the indirect tensile strength *ITS*.



(a) **(b)** **(c)** **(d)**

Figure 2 Steps of BBS test

2.2.2 Asphalt binder scale

After effect of water environment, BBS test results are usually the adhesive and bonding failure (the coexistence of adhesion and cohesion) shown in Figure 3(b) and (c). It is difficult to fully characterize the cohesion attenuation characteristics of asphalt binder after effect of water environment. The result of this test is that the moisture effect on the adhesion of asphalt-aggregate interface is much greater than that of asphalt-asphalt interface [32, 33]. In this paper, the BBS test base was replaced from rock to stainless steel with better adhesion to asphalt. A circular groove with a radius of 0.1 mm is excavated on the surface of the base to increase the difficulty of moisture entering the asphalt-stainless steel base interface. Meanwhile, in order to keep the thickness of asphalt film unchanged at 0.2 mm, the notch depth of BBS test head was changed from 0.2 mm to 0.1 mm, as shown in Figure 4. Therefore, the study of moisture damage resistance in the scale of asphalt binder was carried out by the improved BBS test, and the test result was denoted as the cohesion strength $POTS_{co}$.

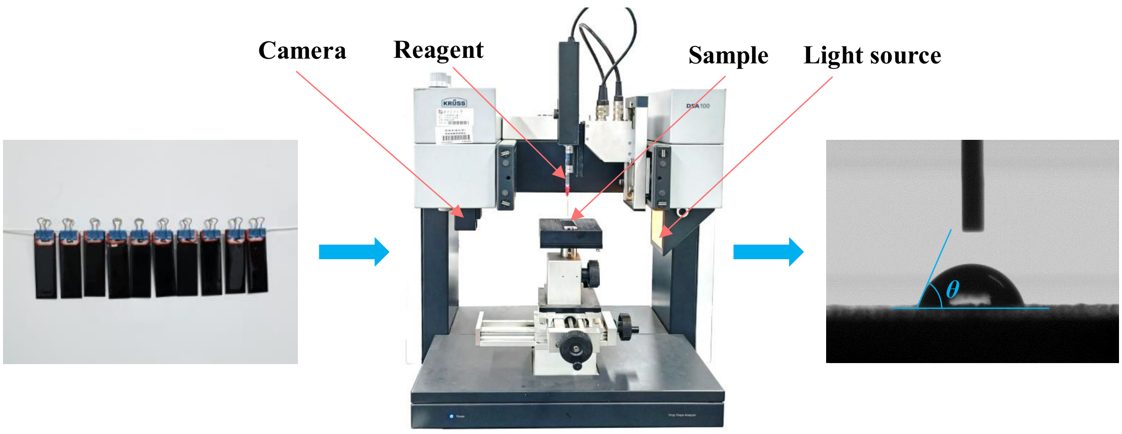
(a) Cohesion failure **(b) Adhesion failure** **(c) Bond failure**

Figure 3 Failure types of BBS test

Figure 4 Schematic diagram of the improved BBS test

2.2.3 Surface free energy test

Figure 5 and equations (1)-(3) illustrate the SFE test process [34].



(a)Sample **(b) Contact angle measuring instrument** **(c) Contact angle**

Figure 5 Contact Angle test method [34]

$$\gamma = \gamma^{LW} + \gamma^{AB} \qquad (1)$$

$$\gamma^{AB} = 2\sqrt{\gamma^{+}\gamma^{-}} \qquad (2)$$

$$\frac{(1+COS\theta)\gamma_L}{2} = \sqrt{\gamma_S^+\gamma_L^-} + \sqrt{\gamma_S^-\gamma_L^+} + \sqrt{\gamma_S^{LW}\gamma_L^{LW}} \tag{3}$$

In Equations (1-3), γ、γ^{LW}, and γ^{AB} represent surface energy, dispersion component and polarity component, respectively. θ, γ+, and γ- represent contact Angle, acidic component, and basic component, respectively. The subscripts S and L indicate the type of material to be tested.

Table 5 Surface free energy parameters of chemical droplets and aggregate(mJ/m^2)

Liquids/ Aggregate	γ^+	γ^-	γ^{AB}	γ^{LW}	γ
Distilled water (H_2O)	25.5	25.5	51	21.8	72.8
Formamide (CH_3NO)	2.28	39.6	19	39	58
Glycerol ($C_3H_8O_3$)	3.92	57.4	30	34	64
Granite	9.87	0.56	4.70	45.69	50.39

2.2.4 Salt and acid erosion environments

To simulate the corrosion of asphalt mixture by salt and acid environments, the formed specimens of different scales were put into salt and acid erosion solutions of different concentrations as shown in Table 3, and the dry-wet cycles were carried out several times. One cycle was soaking in 25°C solution for 12h and curing in 40°C oven for 12 h. In addition, because ordinary stainless steel is easy to be corroded by acidic environments, copper drawing head that does not react with acidic solution is used in BBS test in this paper, the improved BBS test uses copper drawing head and copper plate, as shown in Figure 6.

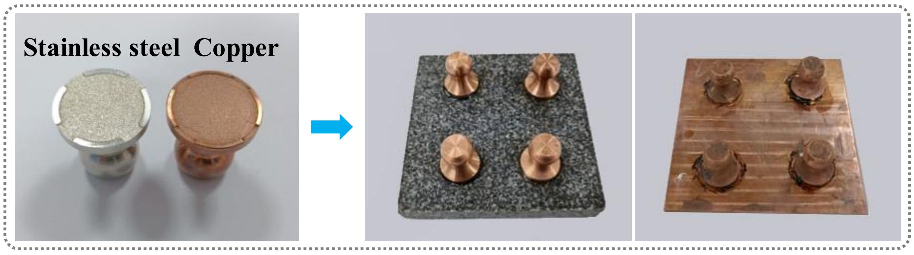


Figure 6 Copper drawing head and copper plate

2.2.5 Self-healing performance of asphalt pavement

Since BBS test can characterize the adhesion of asphalt-aggregate interface and the cohesion of asphalt-asphalt interface, it has the characteristics of intuitionistic, simple and rapid measurement [35, 36]. Therefore, in this paper, referring to relevant literature [37-39] , BBS test in asphalt-aggregate scale was used to characterize the self-healing performance of asphalt pavement after effect of salt and acid erosion. The specific test operation process was as follows: ① The position of BBS drawing head after effect of salt and acid erosion was marked with a marker; ② The bond strength of the labeled BBS specimens was tested and denoted as the initial bond strength $POTS_0$ (Healing strength 0); ③ According to the marked position of the drawing head, put the drawing head back to the original position, and weight; ④ The BBS specimen after step 3 was put into an oven at 40°C for curing for 24h, and after temperature control at 25°C for 1h, the bond strength after the first self-healing was tested, denoted as $POTS_1$ (Healing strength 1); ⑤ Repeat steps ②-④ to test the bond strength after self-healing for the second and third times, denoted as $POTS_n$ (Healing strength *n*), where *n* is the number of self-healing times, as shown in Figure 7. The self-healing ratio H_n was used to evaluate the self-healing ability. The larger the value, the stronger the self-healing ability; otherwise, the weaker the self-healing ability, as shown in Equation 4.

$$H_n = \frac{POTS_n}{POTS_0} \tag{4}$$

Figure 7 Testing of self-healing performance

2.3 Test scheme

The asphalt binder, asphalt-aggregate and asphalt mixture scale specimens were treated with salt and acid erosion environments as shown in Table 3, and then the SFE test was used to verify the test results. In addition, the self-healing performance of asphalt pavement after several dry-wet cycles was tested. The specific test process is shown in Figure 8.

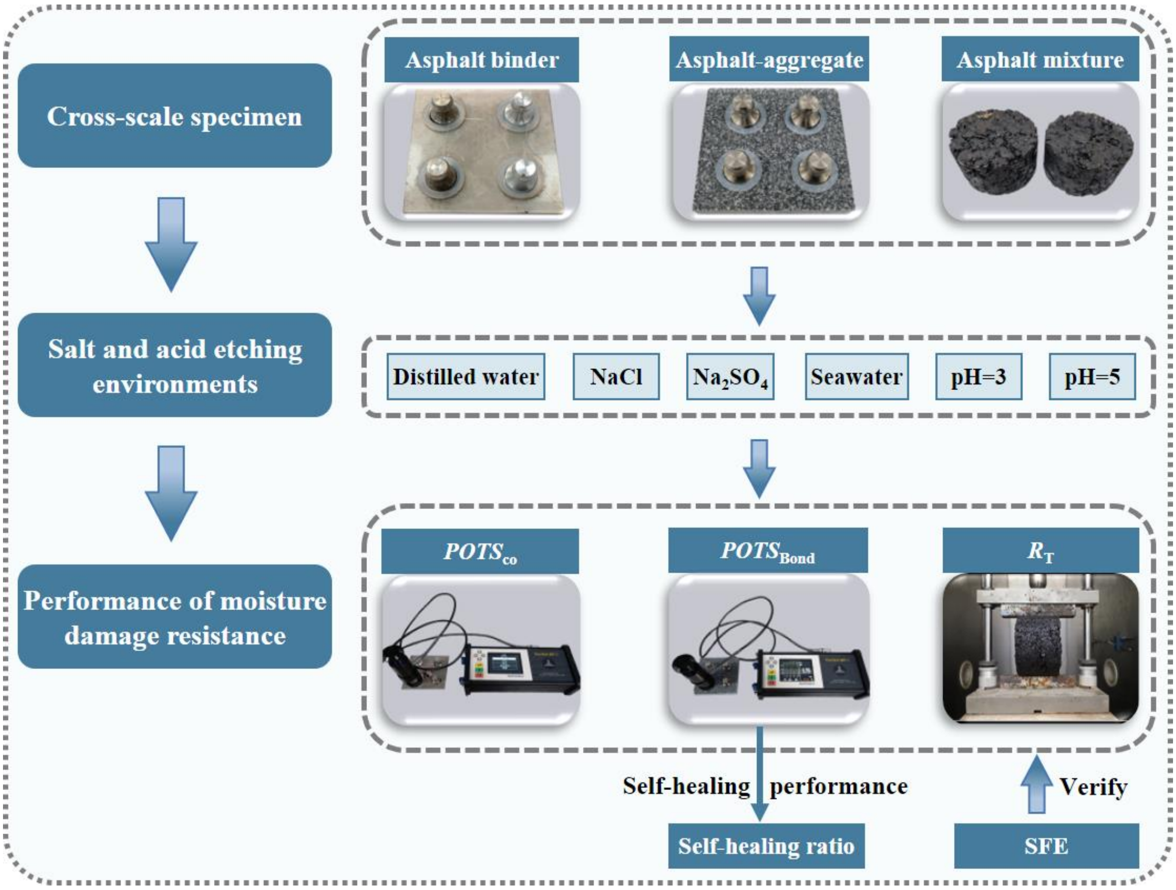


Figure 8 Test flow

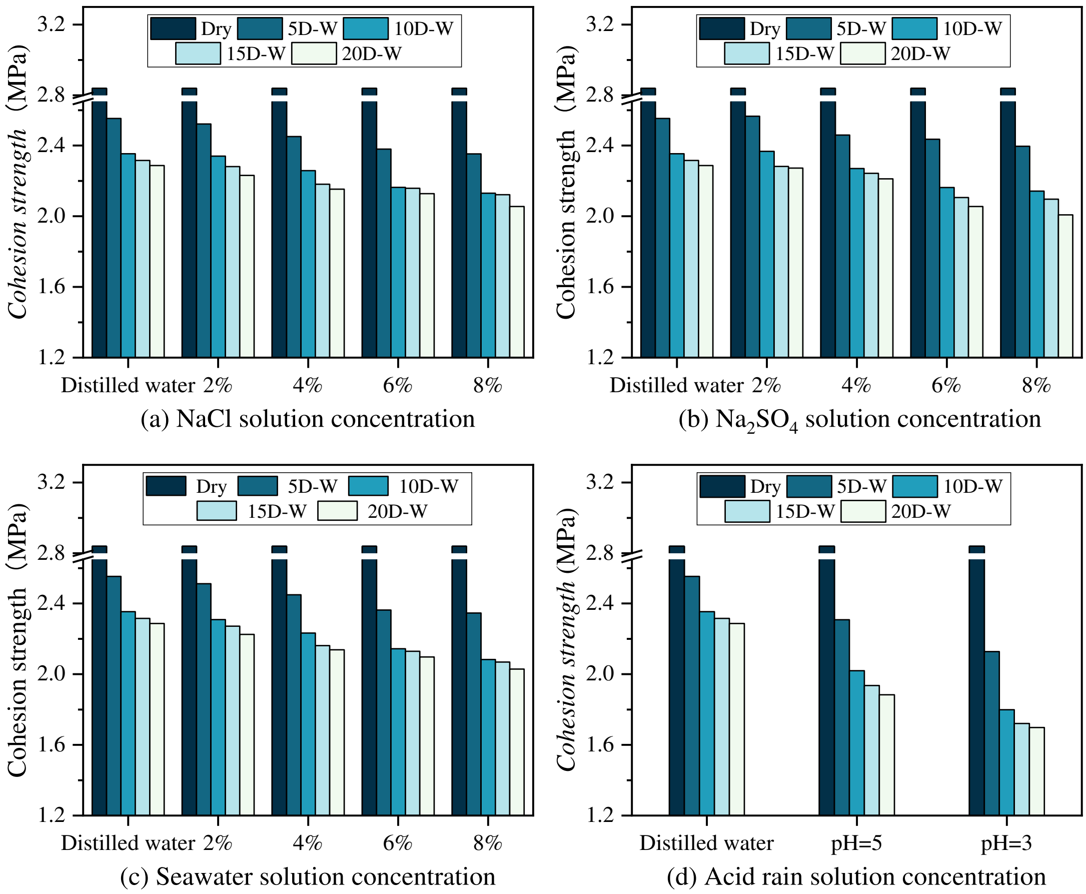
Note: *POTS*$_{CO}$, *POTS*$_{Bond}$ and *ITS* represent cohesion, bond and indirect tensile strength, respectively

3 Results and discussion

3.1 Moisture damage resistance of asphalt pavement in multi-scale

3.1.1 Decay characteristics of mechanical strength for water stability

Figure 9-11 shows the results of improved BBS test of asphalt binder scale, BBS test of asphalt-aggregate scale and indirect tensile test of asphalt mixture scale, respectively. The corresponding mechanical strength of water stability is cohesion strength, bonding strength, and indirect tensile strength. As can be seen from Figure 9-11, the following common test conclusions can be obtained for the asphalt binder, asphalt-aggregate and asphalt mixture scale: 1) With the increase of salt and acid solubility concentration, the cohesion, bond and indirect tensile strength gradually decrease, indicating that NaCl, Na_2SO_4, seawater and acid rain can corrode asphalt pavement in different scales, thereby weakening its moisture damage resistance, and the corrosion ability is positively proportional to the solution concentration, which is similar to the experimental results in the literature [10, 13, 14]. The main reasons are as follows: ① Alkali metal ions such as Na^+ and K^+ in seawater are easy to react with carboxylic acids in asphalt to generate water-soluble saponification material, leading to asphalt emulsification, which reduces the adhesion of asphalt-aggregate interface and the cohesion strength of asphalt itself [6, 10, 40, 41]; ② The inorganic salts can increase the surface tension of aqueous solution, which makes it easier for the salt solution to enter the asphalt-asphalt interface and asphalt-aggregate interface, and further weakens the water damage resistance of the asphalt pavement [10, 41, 42]; ③ Under the action of the dry-wet cycle, the salt in the salt solution crystallizes and dissolves repeatedly (see Figure 12). The crystallization stress generated by crystallization leads to the increase of void fraction and the destruction of internal structure, which is shown as the weakening of adhesion and bond properties on a macroscopic level [10, 14]； ④ At the microscopic level, literature [7, 41, 43] found that salt erosion could reduce the roughness index of asphalt slurry surface based on AFM (Atomic Force Microscope), which resulted in lower adhesion strength between asphalt and aggregate interface； ⑤ Acid rain can dissolve and ionize acidic substances in asphalt to a certain extent, resulting in a decrease in the resin content in asphalt, which weakens the adhesion of asphalt and aggregate interface. In addition, acid rain can react with asphalt by esterification and alkylation to generate longer-chain isomeric alkanes, which can increase the content of light components such as saturates in asphalt, thus softening asphalt and reducing modulus, resulting in lower bond properties of asphalt mixture [19, 44, 45]. 2) With the increase of the number of dry-wet cycles, NaCl, Na_2SO_4, seawater and acid rain solutions weaken the mechanical strength (cohesion, bond and indirect tensile strength) of asphalt pavement water stability gradually, and gradually stabilize after 10 dry-wet cycles.

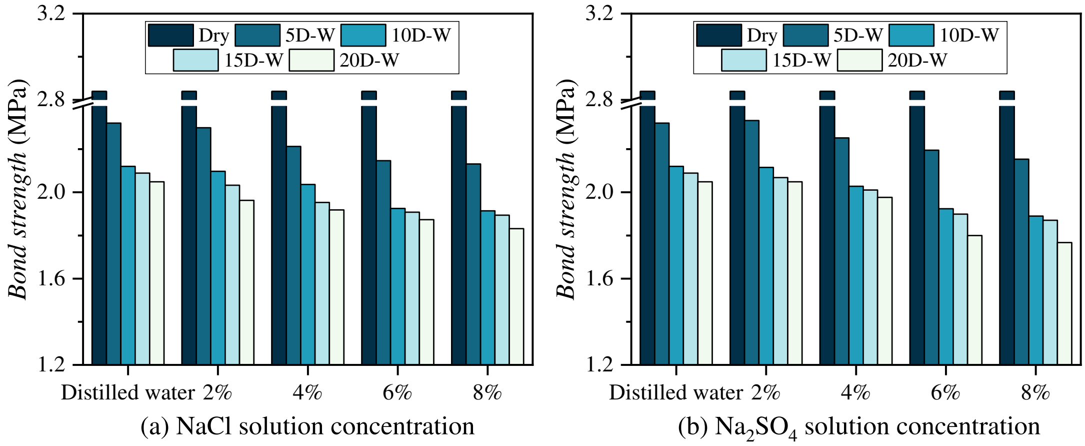


(a) NaCl solution concentration (b) Na_2SO_4 solution concentration

(c) Seawater solution concentration (d) Acid rain solution concentration

Figure 9 Cohesion strength of the asphalt binder scale

Note: ①n D-W represents n dry-wet cycles; ②The datas in the first column of horizontal coordinate are the test result of dry state, the same as below.



(a) NaCl solution concentration (b) Na_2SO_4 solution concentration

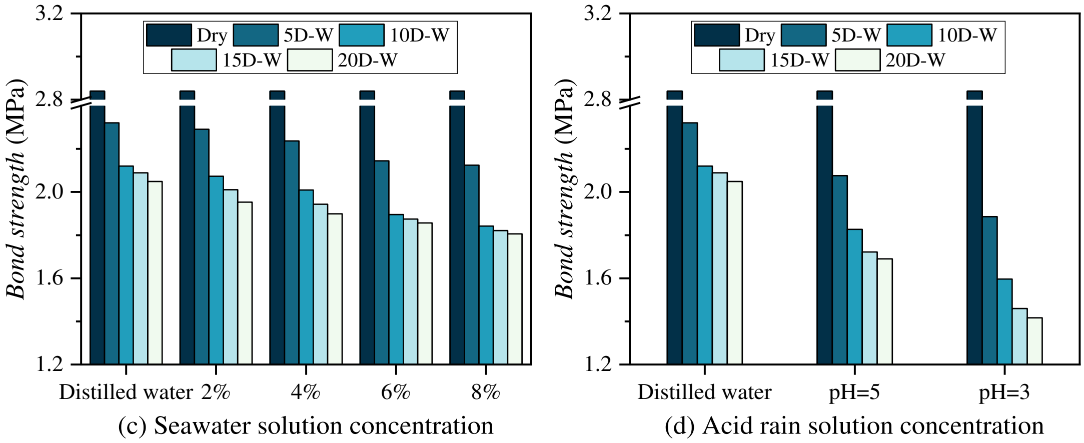


Figure 10 Bond strength of the asphalt-aggregate scale

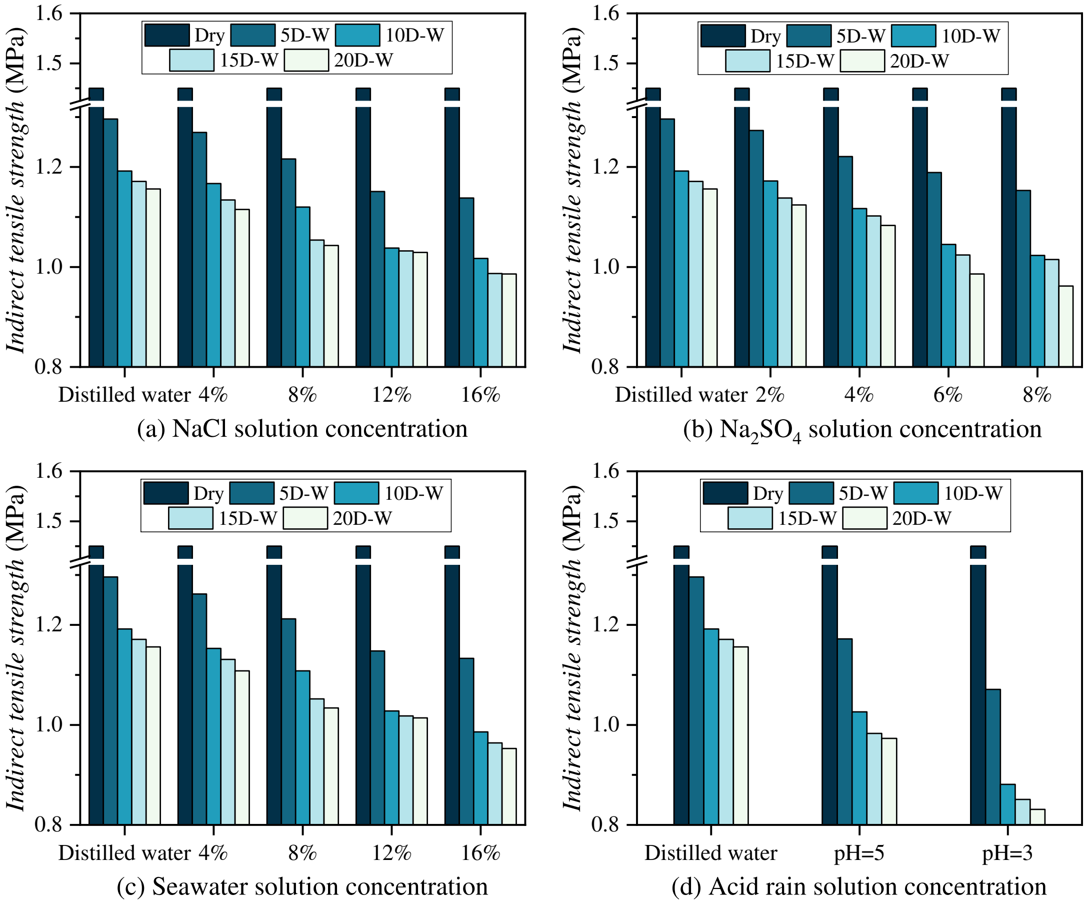


Figure 11 Indirect tensile strength of the asphalt mixture scale

Figure 12 The phenomenon of "salt crystallization"

To further analyze the attenuation characteristics of the mechanical strength of water stability of different solution types and multi-scale in Figure 9-11, the mechanical strength of water stability of representative solutions subjected to 10 wet and dry cycles in Figure 9-11 (the mechanical strength of water stability tends to be stable) was sorted into Figure 13. It can be seen from Figure 13 that: 1) The mechanical strength of water stability of asphalt binder scale is greater than that of asphalt-aggregate scale, indicating that water weakens the adhesion property of asphalt-aggregate interface more than that of asphalt-asphalt interface cohesion property. The reason is as follows: the essence of the adhesion of asphalt is that asphalt has polarity and can adhere to the surface of strongly polar aggregate. However, the moisture immersed in the asphalt-aggregate interface is more polar than asphalt because of hydrogen bonds, which is easy to replace asphalt and adhere to the surface of aggregate [46] . In addition, since the failure type of asphalt-aggregate scale and asphalt binder scale are cohesion failure during drying, the bonding strength of asphalt-aggregate scale is the same as cohesion strength of asphalt binder scale, both of which are 2.84 MPa. This is due to the chemical reaction between the acidic components in the asphalt and the alkaline active centers on the aggregate surface, resulting in the adhesion strength of the asphalt-aggregate scale during drying being greater than the cohesion strength of the asphalt binder scale. 2） Mechanical strength of water stability of asphalt mixture scale is quite different from that of asphalt binder and asphalt-aggregate scale. This is due to the inconsistency between the test conditions of the (improved) BBS test and the indirect tensile test, such as the drawing speed and the thickness of the asphalt film. 3） On the whole, the weakening of mechanical strength of asphalt pavement water stability by different solution types in multi-scale are basically the same as: ① Acid rain (pH=3) has the strongest weakening ability, at the same concentration: Na_2SO_4 > seawater > NaCl, specifically: Acid rain (pH=3) > 16% seawater > 16% NaCl > 8% seawater > 8% NaCl > distilled water > dry, indicating that the acid rain with stronger corrosion ability should be paid more attention than the above salt solution, which is similar to the experimental results in the literature [19, 44]; ② The order of the weakening of the mechanical strength of water stability caused by 8% Na_2SO_4, 16% seawater, 16% NaCl and acid rain (pH=5) varies slightly in different scale. This is due to the inconsistency of the weakening ability of the mechanical strength of water stability caused by the "salt crystallization" phenomenon in different scales. For example, the "salt crystallization" phenomenon has a greater impact on the scale of asphalt mixture with more pores and fractures than that of asphalt binder and asphalt-aggregate scales.

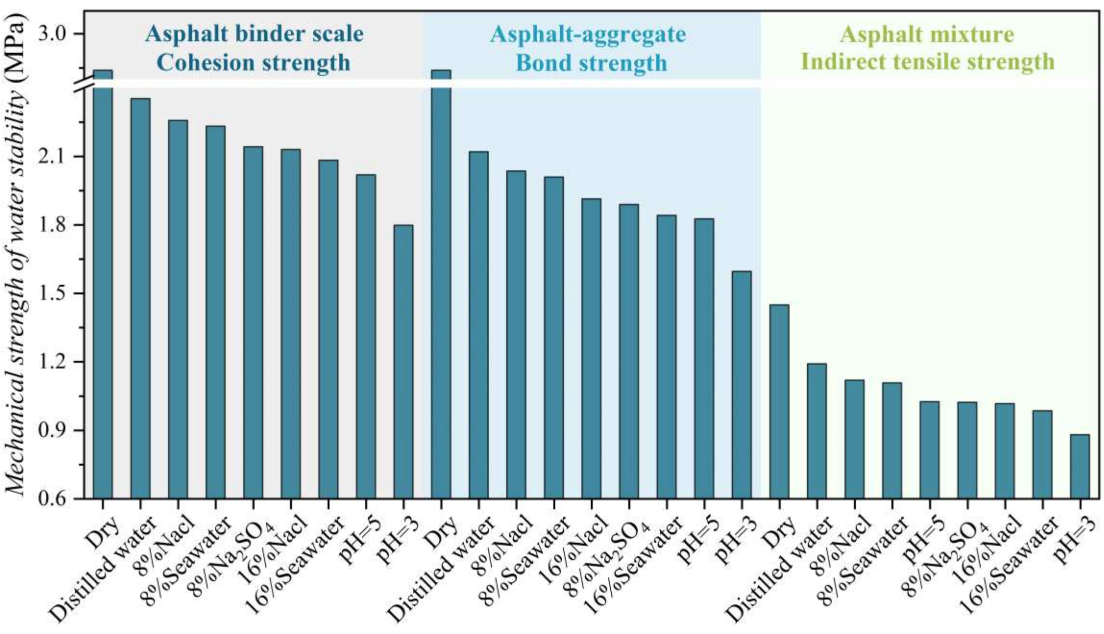


Figure 13 Decay tendency of mechanical strength of water stability in multi-scale

3.1.2 Correlation of moisture damage resistance in multi-scale

To analyze the correlation of water damage resistance of asphalt pavement in multi-scale, the ratio of mechanical strength of water stability after water damage and before water damage (residual ratio) is taken as the evaluation index of moisture damage resistance of asphalt pavement, as shown in Equations (5) to (7).

$$POTS\ Ratio_{Co} = \frac{POTS'_{Co}}{POTS_{Co}} \times 100\% \quad (5) \qquad POTS\ Ratio_{Bond} = \frac{POTS'_{Bond}}{POTS_{Bond}} \times 100\% \quad (6)$$

$$ITS\ Ratio = \frac{ITS'}{ITS} \times 100\% \quad (7)$$

In Equations (5)-(7), $POTS\ Ratio_{\mathrm{Co}}$, $POTS\ Ratio_{\mathrm{Bond}}$ and *ITS Ratio* are respectively the residual ratio of cohesion, bond and indirect tensile strength. The larger the value, the better the water damage resistance is, and the worse it is; $POTS'_{\mathrm{Co}}$, $POTS'_{\mathrm{Bond}}$ and ITS'_{T} respectively represent the cohesion, bond and indirect tensile strength after moisture damage; $POTS_{\mathrm{Co}}$, $POTS_{\mathrm{Bond}}$ and *ITS* respectively represent the cohesion, bond and indirect tensile strength before moisture damage.

Figure 14 shows the evaluation indexes of moisture damage resistance in different scales after 10 dry-wet cycles when the mechanical strength of water stability tends to be stable. It can be seen that: 1) The residual ratios of cohesion, adhesion and indirect tensile strength were 63.33-82.87, 56.2-74.67 and 60.76-82.21, respectively, indicating that the moisture damage resistance of asphalt-aggregate scale was weaker than that of asphalt binder and asphalt mixture scale. The reasons are as follows: The asphalt mixture moisture damage includes two stages (moisture transmission and moisture weakening on the bonding performance). The asphalt mixture scale includes the above two stages, and the asphalt-aggregate scale only includes the moisture weakening on the bonding performance. Therefore, the ability of salt and acid liquid to enter the asphalt-aggregate scale is easier to asphalt mixture scale, which is determined by their different scale, seeing Figures 1 and 15. In addition, since water weakens the adhesion strength of the asphalt-aggregate interface more than the cohesion strength of the asphalt-aggregate interface, the moisture damage resistance of the asphalt-aggregate scale is also weaker than that of the asphalt binder scale, which has been similarly described above and will not be repeated here. 2) On the whole, difference one (the difference between the residual ratio of indirect tensile strength and the residual ratio of bonding strength) of non-salt solutions such as distilled water, pH=5 and pH=3 are 7.5%, 6.4% and 4.6%, respectively. For salt solution, with the increase of salt concentration, the difference one gradually decreases. Among them, difference one the high concentration salt solution of 16% NaCl, 16% seawater and 8% Na_2SO_4 are 2.7%, 3.1% and 4.0%, respectively. It is shown that the difference of moisture damage resistance test results between asphalt-aggregate and asphalt mixture in the scale in salt solution is smaller than that of other solutions. This is because the size of the asphalt-aggregate scale is smaller than that of the asphalt mixture scale, which leads to its weaker moisture damage resistance than that of the asphalt moisture scale. However, the phenomenon of "salt crystallization" in the asphalt mixture scale is stronger than that in the asphalt-aggregate scale, which reduces the difference in the test results of moisture damage resistance. 3) The Difference two (the difference between the residual ratio of cohesion strength and the residual ratio of bonding strength) of all salt and acid solutions ranges from 6.8% to 8.9%, indicating that the difference between the moisture damage resistance test results of the asphalt binder scale and the asphalt-aggregate scale in the environment of salt and acid solutions is relatively stable. This is because the effect degree of "salt crystallization" phenomenon in above two kinds of asphalt pavement scale is relatively consistent.

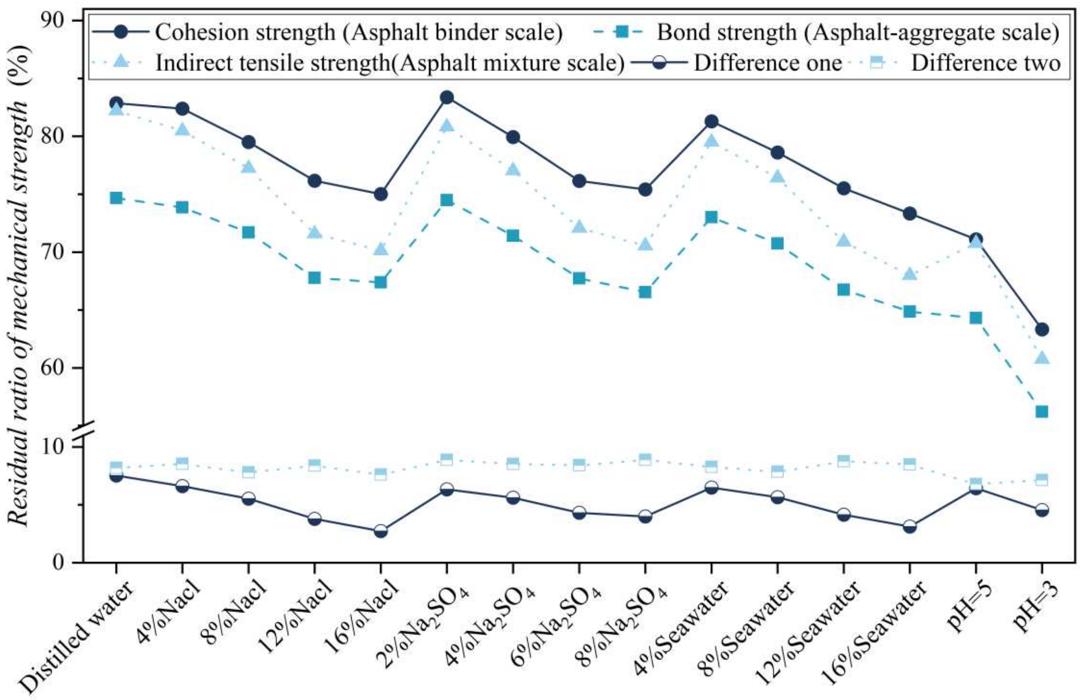


Figure 14 Moisture damage resistance of asphalt pavement in multi-scale

Note: ① Difference one represents the difference between the residual ratio of indirect tensile strength and the residual ratio of bonding strength; ② Difference two represents the difference between the residual ratio of cohesion strength and the residual ratio of bonding strength.

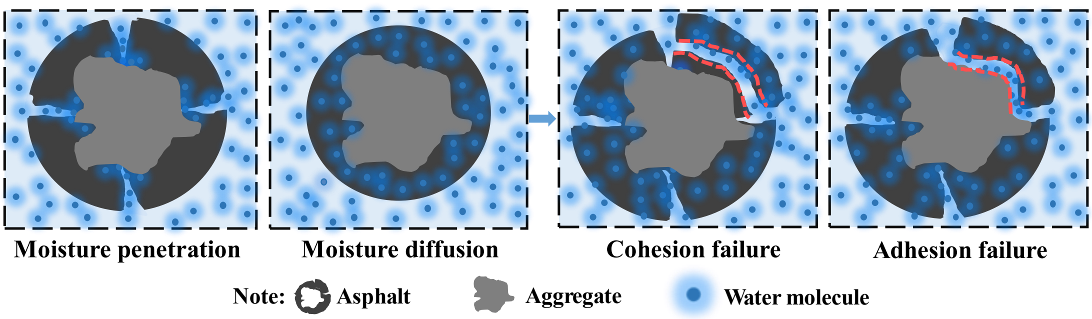
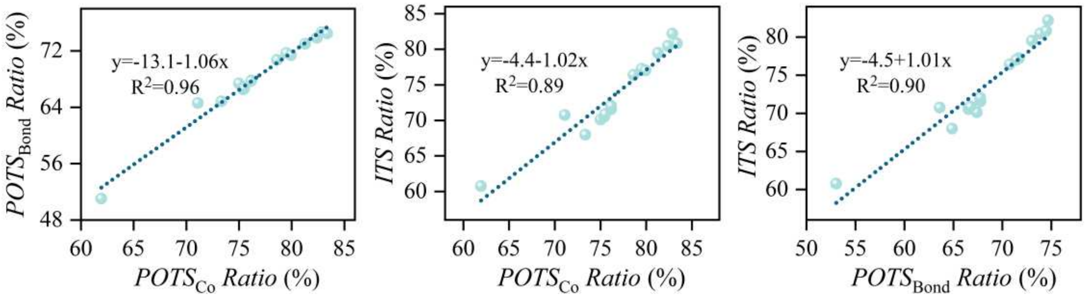


Fig. 15 Diagrams of moisture-induced damage in an asphalt pavement

Figure 16 shows the correlation of moisture damage resistance in multi-scale. It can be seen that: 1) The linear correlation coefficient of asphalt binder and asphalt-aggregate scale is as high as 0.96, indicating that in various salt and acid erosion environments, the dry-wet cycle effect has a good correlation with the deterioration tendency of the moisture damage resistance of the above two scales, only the degree of weakening is different. It can be seen from the above that the difference interval of the evaluation index of moisture damage resistance in the above two scales is 6.8%-8.9% (difference two of Figure 14); 2) The correlation coefficient of moisture damage resistance between the asphalt mixture and the asphalt binder scale is 0.89, and the correlation coefficient of the asphalt-aggregate scale is 0.90. It shows that the correlation between the moisture damage resistance of the asphalt binder and the asphalt-aggregate scale is greater than that between them and the asphalt mixture scale respectively, which is due to the size of the scale and the phenomenon of "salt crystallization", which has been elaborated above and will not be repeated here. In addition, although the "salt crystallization" phenomenon in the asphalt mixture scale can reduce its correlation with the moisture damage resistance performance of the other two scales, the correlation coefficients are still as high as 0.89 and 0.9, indicating that based on asphalt binder and asphalt-aggregate scale, the research on the moisture damage resistance of asphalt pavement in salt and acid corrosion environments still has high accuracy.



(a) (b) (c)

Figure 16 Correlation of moisture damage resistance in multi-scale

Note: (a) Correlation for the asphalt binder and asphalt–aggregate scales; (b) correlation for the asphalt binder and asphalt mixture scales; (c) correlation for the asphalt–aggregate and asphalt mixture scales

3.2 Surface free energy

3.2.1 The Debonding work

The Debonding work of surface free energy theory (W_{AWG}) refers to the energy required to form asphalt-water and aggregate-water interfaces when the asphalt-aggregate interface fails under the action of water. The larger the absolute value of energy, the easier the reaction will be, as shown in Figure 17 and Equation 8. In order to verify and analyze the accuracy of mechanical strength of water stability of multi-scale asphalt pavement in salt and acid erosion environment from the perspective of energy, the W_{AWG} of asphalt binder under different salt and acid erosion solutions was tested.

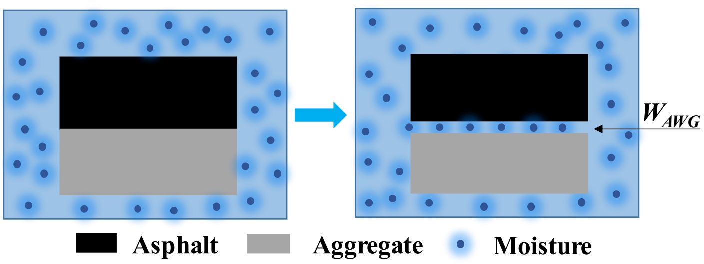


Figure 17 Schematic diagram of debonding work

$$W_{AWG} = 2\left[\sqrt{\gamma_A^{LW}\gamma_W^{LW}} + \sqrt{\gamma_G^{LW}\gamma_W^{LW}} + \sqrt{\gamma_W^{+}}\left(\sqrt{\gamma_A^{-}} + \sqrt{\gamma_G^{-}}\right) + \sqrt{\gamma_W^{-}}\left(\sqrt{\gamma_A^{+}} + \sqrt{\gamma_G^{+}}\right) - 2\sqrt{\gamma_W^{+}\gamma_W^{-}} - \sqrt{\gamma_A^{+}\gamma_G^{-}} - \sqrt{\gamma_A^{-}\gamma_G^{+}} - \sqrt{\gamma_A^{LW}\gamma_G^{LW}} - \gamma_W^{LW}\right] \tag{8}$$

In Equation (8), W_{AWG} represents debonding work, γ^{LW} and γ^{AB} represent dispersion and polarity components, γ^{+} and γ^{-} represent acid and basic components, and the subscripts A, W and G represent asphalt, moisture and aggregate, respectively.

Figure 18 shows the debonding work after 10 dry-wet cycles (the mechanical strength of water stability tends to be stable) in the salt and acid erosion environments. It can be seen from Figure 18 that: 1) W_{AWG} of asphalt samples are all negative values, indicating that external negative work is required for adhesion failure of asphalt-aggregate interface after environmental action, that is, the reaction is spontaneous, which is similar to the experimental results in the literature [52]; 2) With the increase of salt and acid solution concentration, the absolute value of debonding work of asphalt binder increases, indicating that the asphalt-aggregate interface is more prone to adhesion failure. Among them, pH=3 and pH=5 acid rain adhesion failure is the easiest, dry and distilled water environments are the most difficult, and the salt solution adhesion failure under the same concentration is in the order of Na_2SO_4 > Seawater > NaCl, specifically pH=3 acid rain > pH=5 acid rain > 16% seawater > 16% NaCl > 8% seawater > 8% NaCl > distilled water > dry. The ordering rule is basically the same as the mechanical strength of water stability of asphalt binder, asphalt-aggregate and asphalt mixture scales.

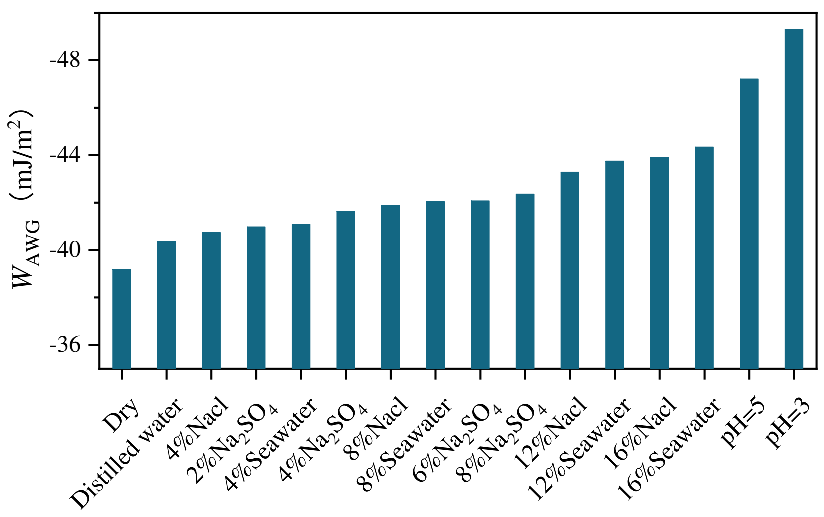


Figure 18 Debonding work after salt and acid erosion environment

3.2.2 Correlation between debonding work and mechanical strength of water stability

Since the debonding work (W_{AWG}) only represents the weakening characteristic of moisture on the adhesion performance of asphalt-aggregate interface, this paper only analyzes the correlation between debonding work and bond strength (asphalt-aggregate scale) and indirect tensile strength (asphalt mixture scale) after the action of water environment, as shown in figure 19. It can be seen that after the action of salt and acid etching environment, the correlation coefficients between the debonding work and the water stability strength of asphalt-aggregate and asphalt mixture are 0.83 and 0.75, respectively.

It is shown that the surface free energy theory has a good correlation with the mechanical strength of water stability in the above two scales, which verifies the accuracy of the test results. Among them, for SFE theory, the correlation with asphalt mixture scale is slightly lower than that of asphalt-aggregate scale, which may be due to the "salt crystallization" phenomenon of asphalt mixture scale being stronger than asphalt-aggregate scale under dry-wet cycles action, and the surface free energy theory is difficult to characterize this phenomenon.

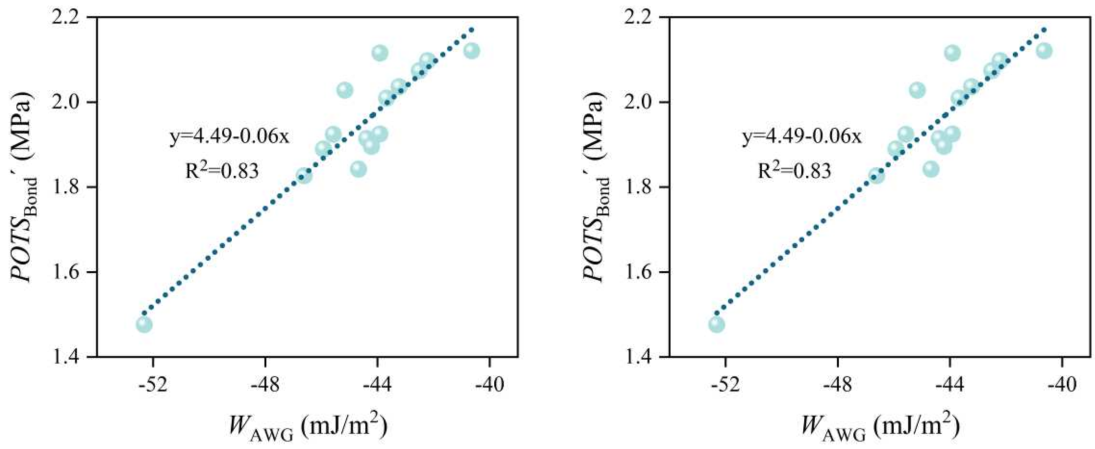


Figure 19 Correlation between debonding work and mechanical strength of water stability

3.3 Self-healing performance of asphalt pavement

Asphalt pavement usually has different degrees of bond failure under multiple working conditions, but the bond performance of asphalt-aggregate interface is not one-time, and it will recover to a certain extent under appropriate conditions, that is, the self-healing performance of asphalt pavement. Therefore, it is of great significance to explore the self-healing mechanism of asphalt pavement after moisture damage, and improve the self-healing performance of asphalt pavement after moisture damage in an appropriate way to extend the service life of asphalt pavement. Compared with the indirect tensile test in the asphalt mixture scale, the BBS test in the asphalt-aggregate scale is simple and intuitive. Compared with the improved BBS of asphalt binder scale, BBS test can simultaneously characterize the adhesion and cohesion properties. This research is based on the BBS test to study the self-healing performance of the asphalt pavement after the action of salt and acid corrosion. The initial BBS specimen was subjected to 10 dry-wet cycles (the mechanical strength of water stability tends to be stable). The specific test method is shown in above 2.2.5.

3.3.1 Healing strength and self-healing ratio

Figure 20 shows the healing strength ($POTS_n$) and self-healing ratio (H_n) of BBS test. It can be seen that: BBS test in asphalt-aggregate scale can effectively evaluate the self-healing performance of asphalt pavement, which are as follows: 1) With the increase of healing times, both the healing strength and self-healing ratio decreased significantly. Among them, the distribution intervals of self-healing rates 1, 2 and 3 were 72.5-92.2%, 31.1-53.2% and 24.5-36.3%, respectively, indicating that the bond strength lost after the second self-healing was greater than that after the first self-healing, and the bond strength lost after the third self-healing was smaller than that after the second self-healing. The distribution interval of self-healing rate 3 is more stable than that of self-healing ratio 1 and 2. 2) With the increase of the concentration of salt solution, the H_1, H_2 and H_3 decreased; With the increase of pH value of acid rain solution, the $POTS_1$, $POTS_2$ and $POTS_3$ increased, but the initial bond strength of BBS after acid erosion was too small, so the bond strength after healing was still smaller than that of low-concentration acid solution (or distilled water). The order of the specific self-healing ratio was pH=3 > pH=5 > drying > …… > 8% Na_2SO_4 > 16% NaCl > 16% seawater. This is because the asphalt has different mobility after the action of different solutions, resulting in different self-healing ratio, which will be elaborated in detail below. 3) With the increase of healing times, the self-healing ratio of asphalt binder treated with different solutions is inconsistent, leading to the order of healing strength is from $POTS_0$ (initial strength) : dry > distilled water >……> 16% NaCl > 16%

seawater > acid rain (pH=5) > acid rain (pH=3), to convert to *POTS*3: dry > distilled water >······> acid rain (pH=5) > 16% NaCl > acid rain (pH=3) > 16% seawater.

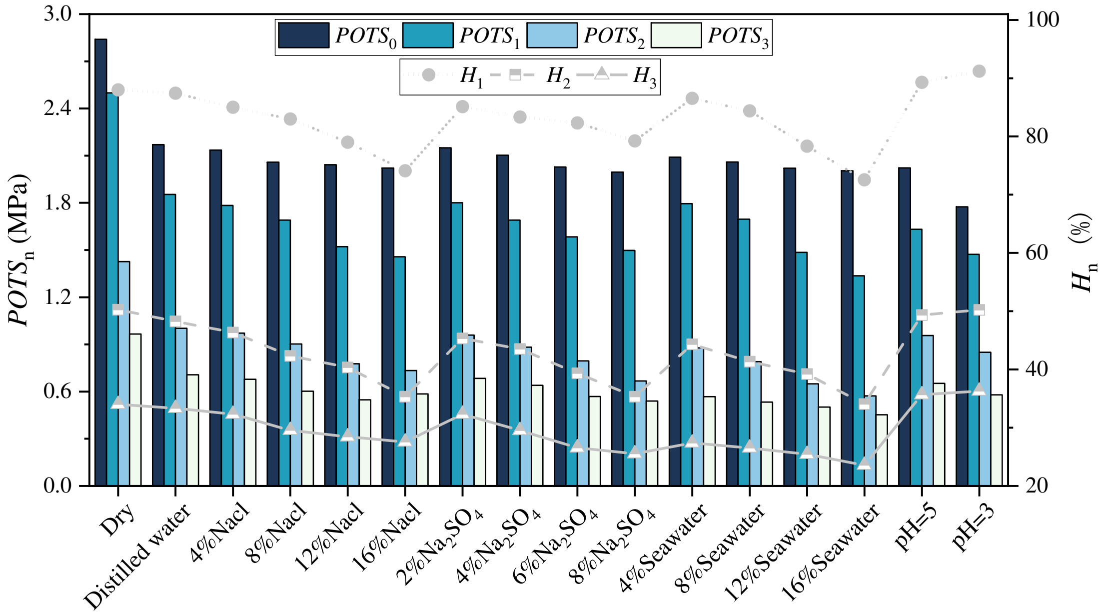


Figure 20 Self-healing performance of asphalt pavement

3.3.2 Correlation between self-healing performance and rotational viscosity

Genes et al. [47] , Kim et al. [48] and Qiu et al. [49] revealed that the self-healing property of asphalt mixture was related to the diffusion property of asphalt, Huang et al. [37], Zhou et al. [38] and Lv et al. [39] revealed that the self-healing property of asphalt mixture was related to the flow property of asphalt. Asphalt viscosity refers to the resistance or internal resistance formed when asphalt flows under specified conditions, which can characterize the flow performance of asphalt [31] . Therefore, in order to study the influence of salt and acid corrosion environments on the self-healing performance of asphalt pavement, the 135°C rotational viscosity of asphalt binder after being exposed to various salt and acid solutions as shown in Figure 20 was analyzed.

As can be seen from Figure 21, with the increase of salt and acid solution concentration, the rotational viscosity of asphalt binder at 135°C increases and decreases respectively, and the specific order is 16% seawater > 16%NaCl > 8%Na_2SO_4 >⋯⋯ > distilled water > dry > acid rain (pH=5) > acid rain (pH=3). The reasons are as follows: 1) Alkaline metal ions such as Na^+ and K^+ in salt solution form water-soluble saponites with light oxygen-containing compounds such as carboxylic acid in asphalt, and carboxylic acid is easy to ionize and dissolve in water, which reduces the content of light components such as saturates and aromatic in asphalt and increases the content of heavy asphaltene. 2) Acid rain can react with asphalt by esterification and alkylation to generate isomeric alkanes with longer chains and increase the content of light components such as saturation in asphalt [19, 44, 45]. To sum up, the salt solution can reduce the content of light components such as saturates and aromatic components and increase the content of heavy components such as asphaltenes, while the acid solution can increase the content of light components such as saturates and aromatic components, and reduce the content of heavy components such as asphaltenes. However, asphaltene is a black or brown solid insoluble in water, which can harden asphalt, increase the internal resistance of asphalt molecules, and increase the viscosity of asphalt [50, 51]; Saturated and aromatic are the substances with the lowest molecular weight in the asphalt component, which play the role of softening and lubricating, and can reduce the viscosity of asphalt. Therefore, salt and acid solutions increase and decrease the 135°C rotational viscosity of asphalt binder respectively, which is basically consistent with the trend of the self-healing ratio of asphalt pavement, indicating that there is a certain correlation between the 135°C rotational viscosity of asphalt binder and the self-healing ratio of asphalt pavement. In addition, Figure 22 shows the correlation coefficients between the rotational viscosity at 135°C and the self-healing ratio of asphalt pavement after salt and acid erosion. It can be seen that the correlation coefficients between the rotational viscosity at 135°C and H_1, H_2, H_3 are 0.79, 0.81 and 0.66, respectively, which again indicates that they have a good correlation.

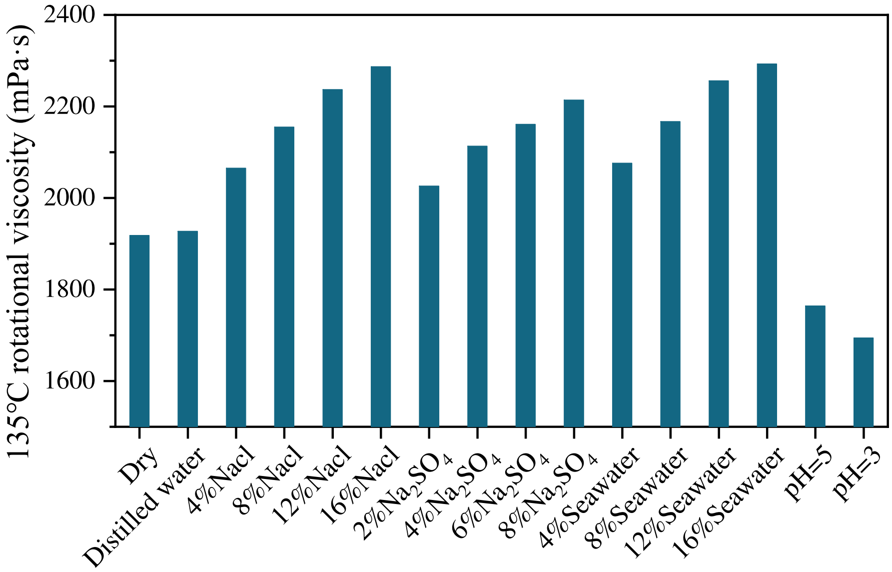


Figure 21 Rotational viscosity of asphalt at 135°C

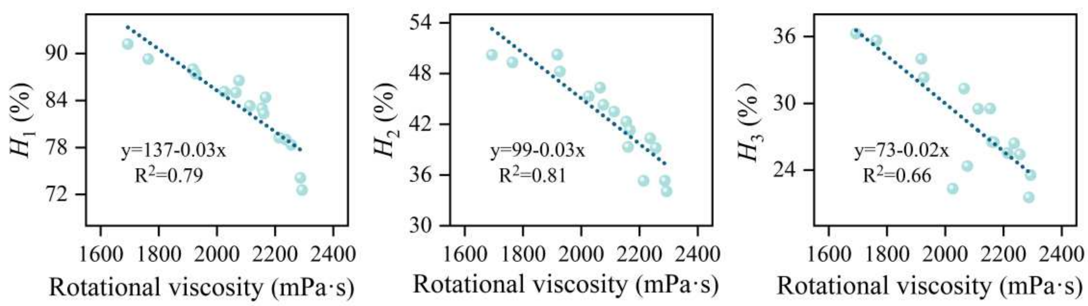


Figure 22 Correlation between 135°C rotational viscosity and self-healing ratio

Note: H_1, H_2 and H_3 represent self-healing ratio 1, 2 and 3, respectively

4 Conclusions

(1) Salt and acid solutions, especially acid rain that has strong corrosion effects, can aggravate the moisture damage of asphalt pavements because of the various physical and chemical reactions of the solutions with asphalt binder.

(2) The asphalt–aggregate scale exhibited a lower moisture damage resistance than those of the asphalt binder scale and asphalt mixture scale; this may be attributed to the differences in size and structure.

(3) The difference in moisture damage resistance between the asphalt-aggregate scale and asphalt mixture scale in salt solution environments is smaller than that in nonsalt environments. This may be attributed to the size of the scale of asphalt pavement and to the phenomenon of "salt crystallization".

(4) The results of SFE analysis indicated the high accuracy of the moisture damage resistance test of the asphalt–aggregate scale and the asphalt mixture scale in salt and acid erosion environments.

(5) With the increase in the concentrations of salt and acid in solution, the self-healing rate decreased and increased, respectively; this may be attributed to the changes in asphalt composition in salt and acid solutions.

(6) The self-healing performance of asphalt pavements is strongly correlated with liquidity and is thus strongly correlated with the rotational viscosity of asphalt binders at 135°C.

Declaration of Competing Interest

The authors have no potential conflict of interest to report.

Acknowledgments

Authors would like to acknowledge the following financial support:

1. Supported by the National Natural Science Foundation of China (No. 51878574);
2. Supported by Sichuan Science and Technology Program (No. 2021YJ0065, No. 2021JDTD0023);
3. Supported by Science and Technology Project of Sichuan Transportation Department (2021-ZL-016).

References

[1] Sulejmani P, Said S, Agardh S, et al. Moisture sensitivity of asphalt mixtures using cycling pore pressure conditioning[J]. Transportation Research Record, 2019, 2673(2): 294-303.

[2] Chen X, Xiao H, Cao C, et al. Study on Moisture Diffusion Behavior in Asphalt Binder Based on Static and Dynamic Pore Water Conditions[J]. Journal of Materials in Civil Engineering, 2022, 34(8): 4022183.

[3] Cong P, Guo X, Ge W. Effects of moisture on the bonding performance of asphalt-aggregate system[J]. Construction and Building Materials, 2021, 295: 123667.

[4] Hamedi G H, Sohrabi M, Sakanlou F, et al. Investigating the Effect of Various Fillers on Cohesive Failure Mechanism in Asphalt Mixtures[J]. Periodica Polytechnica Civil Engineering, 2020, 64(1): 144-155.

[5] Cui X Z, Huang D, Liu L. A review of mechanics of asphalt pavement disease[J]. Journal of Shandong University, 2016, 46(5): 68-83.

[6] Chu C, Liu K, Li K, et al. Research on road performance of asphalt mixture under salt erosion [J]. Bulletin of Silicate, 2018, 37(12): 7. Doi: 10.16552/j.cnki.issn1001-1625.2018.12.033.

[7] Zhang Q L. Study on water damage mechanism of multi-factor environmental asphalt mixture in southern coastal area [D]. Zhejiang university, 2020. Doi: 10.27461/d.cnki.gzjdx.2020.002487.

[8] Wang X. The Research on the Erosion Damage Mechanism of the Acid Rain on the Asphalt an d Asphalt Mixture [D]. Changsha University of Science and Technology, 2014. https://kns.cnki.net /KCMS/detail/detail.aspx?dbname=CMFD201601&filename=1015394468.nh

[9] Zeng X, Li Y, Ran Y, et al. Deterioration mechanism of CA mortar due to simulated acid rain[J]. Construction & Building Materials, 2018: S2127439206.

[10] Zhang K, Li W, Han F. Performance deterioration mechanism and improvement techniques of asphalt mixture in salty and humid environment[J]. Construction and Building Materials, 2019, 208: 749-757.

[11] Setiadji B H, Utomo S. Effect of chemical compounds in tidal water on asphalt pavement mixture[J]. International Journal of Pavement Research and Technology, 2017, 10(2): 122-130.

[12] Huang Xin, Sha A, JIANG Wei, et al. Effect of salt erosion on properties of asphalt and mixture and its action mechanism [J]. Journal of Chang 'an University: Natural Science Edition, 2017, 37(3): 7. Doi: 10.19721/j.cnki.1671-8879.2017.03.005.

[13] Xiong R, Chu C, Qiao N, et al. Performance evaluation of asphalt mixture exposed to dynamic water and chlorine salt erosion[J]. Construction and Building Materials, 2019, 201: 121-126.

[14] Xiong R, Chu C, Guan B, et al. Performance damage characteristics of asphalt mixture suffered from the sulphate–water–temperature–load coupling action[J]. International Journal of Pavement Engineering, 2022, 23(5): 1368-1377.

[15] Li C, Xiong R, Li S, et al. Performance damage evaluation of asphalt mixture under salt-corrosion-hydrodynamic conditions [J]. Journal of Materials Science and Engineering, 2022, 40(2): 6. Doi: 10.14136/j.cnki.issn1673-2812.2022.02.018.

[16] Amini B, Tehrani S S. Simultaneous effects of salted water and water flow on asphalt concrete pavement deterioration under freeze–thaw cycles[J]. International Journal of Pavement Engineering, 2014, 15(5): 383-391.

[17] Hu C, Zhou Z, Chen G. Effects of different types of acid rain on water stability of asphalt pavement[J]. Construction and Building Materials, 2022, 322: 126308.

[18] Wei J, Chen Q, Du J, et al. Study on the Durability of Acid Rain Erosion-Resistant Asphalt Mixtures[J]. Materials, 2022, 15(5): 1849.

[19] Feng X J, Tang X, Xiong X. Study on influence of acid rain on pavement performances of asphalt mixtures[J]. Journal of Wuhan University of Technology, 2015.

[20] Bionghi R, Shahraki D, Ameri M, et al. Correlation between bond strength and surface free energy parameters of asphalt binder-aggregate system[J]. Construction and Building Materials, 2021, 303: 124487.

[21] Lv Q, Huang W, Tang N, et al. Comparison and relationship between indices for the characterization of the moisture resistance of asphalt–aggregate systems[J]. Construction and Building Materials, 2018, 168: 580-589.
[22] Li J, Chen Z, Xiao F, et al. Solution soaking pretreatments of crumb rubber for improving compatibility of rubberized asphalt[J]. Journal of Materials in Civil Engineering, 2022, 34(1): 4021377.
[23] Zou Y, Amirkhanian S, Xu S, et al. Effect of different aqueous solutions on physicochemical properties of asphalt binder[J]. Construction and Building Materials, 2021, 286: 122810.
[24] Simonović A T, Tasić Z Z, Radovanović M B, et al. Influence of 5-chlorobenzotriazole on inhibition of copper corrosion in acid rain solution[J]. ACS omega, 2020, 5(22): 12832-12841.
[25] Yee T S, Hamzah M O. Evaluation of moisture susceptibility of asphalt-aggregate constituents subjected to direct tensile test using imaging technique[J]. Construction and Building Materials, 2019, 227: 116642.
[26] Hu M, Sun D, Lu T, et al. Laboratory investigation of the adhesion and self-healing properties of high-viscosity modified asphalt binders[J]. Transportation Research Record, 2020, 2674(1): 307-318.
[27] ASTM D4541-09, Standard Test Method for Pull-Off Strength of Coatings using Portable Adhesion Testers, American Society of Testing and Materials, West Conshohocken, PA, 2009.
[28] AASHTO TP-91. Standard Method of Test for Determining Asphalt Binder Strength by Means of the Binder Bond Strength (BBS) Test[S]. American Association of State Highway and Transportation Officials, Washington, D.C., 2011.
[29] Huang W, Lv Q. Investigation of critical factors determining the accuracy of binder bond strength test to evaluate adhesion properties of asphalt binders[J]. Journal of Testing and Evaluation, 2017, 45(4): 1270-1279.
[30] Du X, Liu S, Zhang H, et al. A test method to evaluate the fuel oil corrosion resistance of asphalt binders[J]. Construction and Building Materials, 2021, 292: 123416.
[31] Ministry of Communications of the People's Republic of China. Test code for asphalt and asphalt mixture in highway engineering: JTG E20-2011 [S]. Beijing: People's Communications Publishing House, 2011.

[32] Azarhoosh A, Hamedi G H, Azarhoosh M J. The influence of cohesion and adhesion parameters on the moisture sensitivity of modified Asphalt mixtures with polymer additive[J]. The Journal of Adhesion, 2021, 97(16): 1486-1508.

[33] Canestrari F, Cardone F, Graziani A, et al. Adhesive and cohesive Properties of Asphalt-Aggregate Systems Subjected to Moisture Damage[J]. Road Materials and Pavement Design, 2010, 11(sup1): 11-32.

[34] Wang W, Nili A, Rahman A, et al. Effects of wax molecular weight distribution and branching on moisture sensitivity of asphalt binders[J]. Materials, 2022, 15(12): 4206.

[35] Zhou L, Huang W, Lv Q. Evaluation and Mechanism analysis of self-healing properties of asphalt under Wet and dry conditions [J]. Journal of Building Materials, 2021, 24(01): 137-145. Doi: 10.3969/j.issn.1007-9629.2021.01.019

[36] Mogawer, Walaa, Austerman, et al. Evaluating the effect of warm-mix asphalt technologies on moisture characteristics of asphalt binders and mixtures[J]. Transportation Research Record Journal of the Transportation Research Board, 2011.

[37] Huang W, Lv Q, Xiao F. Investigation of using binder bond strength test to evaluate adhesion and self-healing properties of modified asphalt binders[J]. Construction & Building Materials, 2016, 113(jun.15): 49-56.

[38] Zhou L, Huang W, Zhang Y, et al. Evaluation of the adhesion and healing properties of modified asphalt binders[J]. Construction and Building Materials, 2020, 251: 119026.

[39] Lv Q, Huang W, Xiao F. Laboratory evaluation of self-healing properties of various modified asphalt[J]. Construction & Building Materials, 2017, 136(APR.1): 192-201.

[40] Zhang Q L. Study on water damage mechanism of multi-factor environmental asphalt mixture in southern coastal area [D]. Zhejiang university, 2020. Doi: 10.27461/d.cnki.gzjdx.2020.002487.

[41] Feng B, Wang H, Li S, et al. The durability of asphalt mixture with the action of salt erosion: A review[J]. Construction and Building Materials, 2022, 315: 125749.

[42] Zhang K, Luo Y, Xie W, et al. Evaluation of road performance and adhesive characteristic of asphalt binder in salt erosion environment[J]. Materials Today Communications, 2020, 25(4): 101593.

[43] Zhang K，Luo Y． Chemical component and performance evolution of asphalt binder in salt erosion environment[J]. Science Technology and Engineering, 2020, 20(36): 15081-15087

[44] Hu C, Zhou Z, Chen G. Effects of different types of acid rain on water stability of asphalt pavement[J]. Construction and Building Materials, 2022, 322: 126308.

[45] Saba R G. Response and Deterioration Mechanism of Bitumen under Acid Rain Erosion[J]. Materials, 2021, 14.

[46] Shen Jin 'an. Road performance of asphalt and asphalt mixture [M]. Road performance of asphalt and asphalt mixture, 2001.

[47] De Gennes P. Reptation of a polymer chain in the presence of fixed obstacles[J]. The journal of chemical physics, 1971, 55(2): 572-579.

[48] Kim Y H, Wool R P. A theory of healing at a polymer-polymer interface[J]. Macromolecules, 1983, 16(7): 1115-1120.

[49] Qiu J, van de Ven M, Molenaar A. Crack-healing investigation in bituminous materials[J]. Journal of materials in civil engineering, 2013, 25(7): 864-870.

[50] Ding Z, Li P, Zhang J, et al. Analysis of viscosity test conditions for crumb-rubber-modified asphalt[J]. Construction and Building Materials, 2020, 245: 118454.

[51] Ding Z, Zhang J, Li P, et al. Analysis of viscous flow properties of styrene–butadiene–styrene-modified asphalt[J]. Construction and Building Materials, 2019, 229: 116881.

[52] Cheng Z, Zhang X, Kong F, et al. Analysis of peel behavior of asphalt film by surface energy theory and pull-off test [J]. Materials Review, 2021, 34(Z2): 288-294.