Study on the effect of Acid Rain erosion on the Road performance of Steel Slag Asphalt mixture

Yi Luo Zhang¹, Zhao Wang*, Guo Pu Liu¹, Yuan De Kou¹
¹School of Highway, Chang’an University, Xi’an, Shaanxi, P. R. China
* 2019221202@chd.edu.cn

Abstract—in order to study the influence rules of acid rain erosion on the road performance of steel slag asphalt mixture, the artificial acid rain solution of pH=2 and distilled water of pH=7 were used to carry out periodic immersion erosion test on asphalt mixture with different amount of steel slag (0, 30%, 50%, 70%), then rutting test, low temperature bending test and freeze-thaw splitting test were carried out on the asphalt mixture eroded by acid rain. The results show that after soaking in acid rain solution, the high temperature stability, low temperature crack resistance and water stability of each steel slag asphalt mixture decrease, and the decreasing range increases with the increase of soaking period. The high temperature stability, low temperature crack resistance and water stability of steel slag asphalt mixture soaked in distilled water also decreased, but the decrease was small.

1. INTRODUCTION
In recent years, the highway transportation industry in China has developed vigorously, and more than 150000 kilometers of expressways have been built. With its excellent driving performance, asphalt pavement accounts for more than 80% of it [1]. However, after years of large-scale infrastructure construction, the high-quality stone needed for highway construction has gradually become scarce. At the same time, with the steady progress of the national ecological civilization construction and green development strategy, the application of industrial waste and recycled materials in highway construction will become a major trend in the development of the transportation industry in the future. Therefore, if the industrial waste slag represented by steel slag can be reasonably used in highway construction, it can not only alleviate the shortage of high-quality aggregate, but also solve the problem of environmental pollution and waste of resources caused by a large number of waste slag accumulation. In 2012, Sabrina Sorlini et al studied the physical and chemical properties of steel slag and found that f-CaO is the factor causing the volume stability of steel slag. At the same time, the volume expansion of steel slag decreases with the increase of steel slag shelving time [2]. In 2013, domestic researchers found that the standard area characteristic of steel slag makes steel slag absorb more asphalt than natural stone, and increases the contact area with asphalt, which restrains the volume instability of steel slag to a certain extent [3]. In 2015, Chen ZongWu et al studied the road performance of the mixture after steel slag replaced the fine aggregate in asphalt mixture. the results show that the low temperature crack resistance, water stability and permanent deformation resistance of the mixture after adding steel slag have been significantly improved [4]. To sum up, although many researches on the application of steel slag in asphalt pavement have been carried out at home and abroad, there are few studies on the performance changes of steel slag asphalt mixture under special climatic conditions such as acid rain erosion [5-8]. This paper will study and analyze the change rules of road performance of steel slag asphalt mixture
under acid rain erosion, in order to make a positive contribution to expanding the application range of steel slag asphalt mixture in the future.

2. RAW MATERIALS AND TESTS

2.1. Raw materials.

(1) "SK" No. 90 petroleum asphalt is used in this test. Its main technical performance is shown in Table 1, and all indexes meet the requirements of the specification [9].

(2) Steel slag is made from Shaanxi Longmen Iron and Steel Group. The main technical properties are shown in Table 2.

(3) Diabase is used in the aggregate, and the limestone powder produced in Pucheng county is used as the mineral powder. After testing, all the technical indexes of the coarse and fine aggregate and the mineral powder meet the requirements of the specification. The design gradation of asphalt mixture adopts SMA-13 skeleton dense structure, and the proportion of 4.75~9.5mm and 9.5~16mm steel slag aggregate is used to replace diabase natural aggregate, the substitution ratio is 0,30,50% and 70% respectively. The design grade of asphalt mixture with different amount of steel slag is shown in Table 3.

### TABLE 1. MAIN TECHNICAL PROPERTIES OF MATRIX ASPHALT

| Technical Index                     | Test Results | Technical Requirements |
|-------------------------------------|--------------|------------------------|
| Needle Penetration (25°C)/(0.1mm)   | 94           | 80~100                 |
| Softening Point (°C)                | 46.2         | ≥45                    |
| Ductility (cm)                      | 71.1         | ≥20                    |
| Density (g·cm⁻³)                    | 1.025        | —                      |
| Flash Point (°C)                    | 275          | ≥245                   |
| Wax Content (%)                     | 1.9          | ≤2.2                   |

### TABLE 2. TEST RESULTS OF PHYSICAL AND MECHANICAL PROPERTIES OF STEEL SLAG

| Index                              | 9.5~16mm   | 4.75~9.5mm  | Technical Requirements |
|------------------------------------|------------|-------------|------------------------|
| Apparent Relative Density          | 3.366      | 3.437       | ≥2.60                  |
| Relative Density of Gross Volume   | 3.226      | 3.273       | —                      |
| Crushing Value                     | 11.5       | 11.5        | ≤26                    |
| Abrasion Volume by Los Angeles Rattler | 12.2        | 12.2       | ≤28                    |
| Water Absorption                   | 2.05       | 1.83        | ≤2                     |
| Soundness                          | 4.1        | 0.6         | ≤12                    |
| Asphalt Adhesion Grade             | 5          | 5           | ≥4                     |

### TABLE 3. DESIGN GRADATION OF ASPHALT MIXTURE WITH DIFFERENT AMOUNT OF STEEL SLAG

| Mesh Size (mm) | SMA-13 (0%) | SMA-13 (30%) | SMA-13 (50%) | SMA-13 (70%) |
|----------------|-------------|--------------|--------------|--------------|
| 16             | 100         | 100          | 100          | 100          |
| 13.2           | 94.3        | 93.1         | 92.6         | 91.6         |
| 9.5            | 66.4        | 58           | 57.2         | 57.3         |
| 4.75           | 26.2        | 28.7         | 30.6         | 31           |
| 2.36           | 22          | 23.2         | 21.4         | 19.7         |
| 1.18           | 18.2        | 18.1         | 16.9         | 15.6         |
| 0.6            | 13.3        | 13.2         | 12.5         | 11.8         |
| 0.3            | 10.8        | 12           | 11.4         | 10.9         |
| 0.15           | 9.4         | 9.4          | 9.1          | 8.9          |
| 0.075          | 7.3         | 7.3          | 7.2          | 7.2          |
2.2. *mix design of asphalt mixture.*

In this paper, the Marshall test is used to determine the best oil-stone ratio of steel slag asphalt mixture, and the mixing ratio of steel slag is 0, 30%, 50% and 70% respectively. Under different amounts of steel slag, the design porosity of asphalt mixture is 4%. The mix design test results are shown in Table 4.

**TABLE 4. TEST RESULTS OF MIX DESIGN OF STEEL SLAG ASPHALT MIXTURE WITH DIFFERENT STEEL SLAG MIXING RATIO**

| Steel Slag Content (%) | 0   | 30  | 50  | 70  |
|------------------------|-----|-----|-----|-----|
| Optimal Asphalt Content (%) | 6.3 | 6.4 | 6.5 | 6.8 |
| Maximum Theoretical Relative Density | 2.65 | 2.865 | 2.708 | 2.728 |
| Bulk Density           | 2.544 | 2.588 | 2.609 | 2.627 |
| Voids in Mineral Aggregate (%) | 17.26 | 17.3 | 17.68 | 18.52 |
| Marshall Stability (KN) | 8.8 | 9.53 | 10.05 | 9.54 |

2.3. *Test methods.*

In this paper, according to the change law of ion concentration of acid rain in typical acid rain control areas in China[10], the laboratory simulated acid rain solution was configured, and the indoor simulated acid rain solution of pH =2 was configured with sulfuric acid, nitric acid and ammonium chloride according to the molar ratio C (SO\(_4^{2-}\)) : C (NO\(_3^-\)) : C (Cl\(^-\)) = 2:1:2, and the contrastive experiment was carried out with distilled water of pH=7.

The scheme of dry-wet cycle immersion was adopted to simulate the erosion of steel slag asphalt mixture by acid rain. The steel slag asphalt mixture was immersed in simulated acid rain solution for 10 days, then dried for 1 day as a cycle, and then continued to carry on the wetting-drying cycle for a total of 5 cycles. In the process of soaking, the pH value of acid rain solution was calibrated by precision pH instrument every 12 hours. When the pH value changed, the pH value was adjusted to the preset value with acid and distilled water in time.

3. **RESULTS AND ANALYSIS**

3.1. *Analysis of the influence of high temperature stability.*

The 60℃ rutting test is used as the test method for high temperature performance of steel slag asphalt mixture [11]. According to the requirements of the regulations, the test results of rut board specimens are shown in fig.1.

![Dynamic stability of steel slag asphalt mixture soaked in Ph=2 acid rain solution](attachment:image.png)
Dynamic stability of steel slag asphalt mixture soaked in Ph=7 distilled water

Fig 1. Effect of acid rain solution on dynamic stability of steel slag asphalt mixture

It can be seen from fig.1 that the dynamic stability of different steel slag asphalt mixtures soaked in acid rain solution of pH=2 and distilled water of pH=7 for 1-5 cycles decreases to a certain extent, and the dynamic stability decreases continuously with the increase of immersion age, and the damage of neutral solution of pH=7 to high temperature stability of mixture is obviously less than that of acid rain solution. When the mixture is not soaked in acid rain solution, the dynamic stability of each steel slag content asphalt mixture is $50% > 30% > 70% > 0$, the initial stability of steel slag asphalt mixture increases at first and then decreases with the steel slag content. When the steel slag content is 50%, the dynamic stability of the mixture reaches the maximum, so when the steel slag content is 50%, the initial high temperature stability of the asphalt mixture is the best. There is a negative correlation between the dynamic stability of the mixture and the soaking age of acid rain, and the dynamic stability of each steel slag content of asphalt mixture decreases with the increase of soaking time. Compared with the asphalt mixture that is not soaked by acid rain, after 1-5 cycles of acid rain erosion, the attenuation value of dynamic stability of mixture is $30% > 70% > 0 > 50%$ respectively. The analysis of the attenuation law of the dynamic stability of the mixture with the immersion age shows that the rate at which the dynamic stability of the steel slag asphalt mixture decreases with the increase of the acid rain soaking time shows that the damage rate of the acid rain on the high temperature performance of the steel slag asphalt mixture decreases continuously.

3.2. Analysis of the effect of low temperature crack resistance.

The low temperature crack resistance of steel slag asphalt mixture was evaluated by trabecular bending test at -10°C. The trabecular specimens were formed according to the Test rules for Asphalt and Asphalt mixtures in Highway Engineering. The flexural tensile strength and flexural strain at -10°C were measured after the given immersion age. The test results are shown in fig.2 and fig.3.
Fig 2. Effect of acid rain solution on flexural tensile strength of steel slag asphalt mixture

(a) Flexural tensile strain of steel slag asphalt mixture soaked in Ph=2 acid rain solution

(b) Flexural tensile strength of steel slag asphalt mixture soaked in Ph=7 distilled water

Fig 3. Effect of acid rain solution on bending tensile strain of steel slag asphalt mixture

(a) Flexural tensile strain of steel slag asphalt mixture immersed in Ph=7 distilled water

(b) Flexural tensile strain of steel slag asphalt mixture immersed in Ph=7 distilled water
It can be seen from fig.2 that the flexural tensile strength of each steel slag content asphalt mixture decreases to a certain extent after soaking in Ph=2 acid rain solution and pH=7 distilled water solution for one to five cycles, and the flexural tensile strength of each steel slag content asphalt mixture decreases with the increase of solution immersion age. When the steel slag content increases from 0 to 30%, the flexural tensile strength of the mixture increases slightly, and then when the steel slag content continues to increase, the flexural tensile strength of the mixture decreases continuously, that is, when the steel slag content is 30%, the flexural tensile strength of the asphalt mixture is the highest. Under this addition, the mixture has the best crack resistance at low temperature when immersed in neutral aqueous solution. The flexural tensile strength of each steel slag content asphalt mixture decreased greatly after soaking in pH=2 acid rain solution for 1-5 cycles, and the decrease was in the order of 30% > 50% > 0 > 70%. Among them, the flexural tensile strength of 30% steel slag asphalt mixture decreased by 23.0%. The strength loss ratio of 70% steel slag asphalt mixture is the smallest, so the low temperature crack resistance of 70% steel slag asphalt mixture decreases the least under the action of long-term immersion erosion in acid rain.

It can be seen from fig.3 that the flexural tensile strain of asphalt mixture with each amount of steel slag decreases with the increase of solution soaking time, and the decrease of flexural tensile strength of asphalt mixture in acid rain solution of pH=2 is obviously greater than that in neutral aqueous solution of pH=7. The initial low temperature crack resistance of steel slag asphalt mixture increases with the increase of steel slag content. Compared with 0 steel slag asphalt mixture, the flexural tensile strain of 70% steel slag asphalt mixture is increased by 15.3%. Similar to the variation of the flexural tensile strength of the mixture with the immersion age, the flexural tensile strain of each content of asphalt mixture is negatively correlated with the solution soaking age, with the increase of solution soaking time, the flexural tensile strain of the mixture decreases gradually, at the same time, the decreasing rate of bending strain also decreases gradually. The ultimate value of flexural tensile strain of asphalt mixture with steel slag content is 70% > 50% > 30% > 0, so the crack resistance at low temperature and long-term acid rain resistance of 70% steel slag asphalt mixture is the best. The change law of flexural tensile strain of each steel slag asphalt mixture in Ph=7 distilled water solution with immersion time is consistent with that of flexural tensile strength with immersion time, and the erosion immersion of neutral aqueous solution has little effect on the low temperature crack resistance of steel slag asphalt mixture.

3.3. Influence analysis of water stability.

The freeze-thaw splitting test was used to evaluate the water stability of asphalt mixture. The Marshall specimen (50 times of double-sided compaction) of steel slag asphalt mixture treated by periodic immersion in acid rain solution was tested by freeze-thaw splitting test. Immediately after freezing, the splitting test was carried out after being kept in a water bath at 60 ℃ for 24 hours. The test results are shown in fig.4.

(a) Freeze-thaw splitting strength ratio of steel slag asphalt mixture soaked in Ph=2 acid rain solution
It can be seen from fig. 4 that the freeze-thaw splitting strength ratio of each steel slag content asphalt mixture decreases with the extension of acid rain solution soaking time, and in the initial state, the freeze-thaw splitting strength ratio of the four asphalt mixtures was 50%, 30%, 70% and 0 from the largest to the smallest successively, this law shows that the addition of steel slag can effectively improve the initial water stability of asphalt mixture. With the increase of the content of steel slag, the freeze-thaw splitting strength ratio of the mixture increased at first and then decreased, and reached the peak when the content of steel slag was 50%. After 5 cycles of soaking, the freeze-thaw splitting of the four asphalt mixtures is lower than the initial state, and the decreasing range is 70%>50%>30%>0, which shows that there is a negative correlation between the acid rain resistance of steel slag asphalt mixture and the amount of steel slag. The addition of steel slag can not only improve the initial water stability of asphalt mixture, but also improve the ability of asphalt mixture to resist long-term immersion in neutral aqueous solution, and the improvement effect increases with the increase of steel slag content. To sum up, the addition of steel slag aggregate weakens the resistance to long-term acid rain immersion of asphalt mixture to a certain extent, but significantly improves the resistance of asphalt mixture to neutral aqueous solution.

4. CONCLUSION
(1) The addition of steel slag can significantly improve the high temperature performance of asphalt mixture, and the high temperature stability of asphalt mixture with steel slag content of 50% is the highest than that of asphalt mixture with steel slag content of 0. Under long-term acid rain erosion, the high temperature stability of 0 steel slag mixture is the best, followed by the asphalt mixture with steel slag content of 50%.

(2) The addition of steel slag enhances the initial low temperature crack resistance of asphalt mixture, but the strengthening effect is obviously regular with the content of steel slag. The erosion and immersion effect of acid rain greatly attenuates the low temperature performance of each steel slag content asphalt mixture. After 5 cycles of immersion in acid rain solution, the low temperature crack resistance of 30% steel slag content asphalt mixture is the largest, and 70% steel slag content asphalt mixture has the strongest acid rain resistance.

(3) The addition of steel slag effectively improves the initial water stability of asphalt mixture, and the water stability of asphalt mixture decreases with the increase of acid rain soaking time, and the decrease is positively correlated with the content of steel slag. However, the addition of steel slag has a significant effect on improving the corrosion resistance of asphalt mixture to neutral aqueous solution.

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