Research Article

Investigation on the Mechanical Properties and Microscopic Characteristics of Modified Steel Slag Concrete under Sulfate Erosion

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In this study, cement-fly ash composite slurry was used to modify the surface of steel slag aggregate. The evolution law of parameters such as the mass loss rate, dynamic elastic modulus, and compressive strength of the modified material was obtained through the erosion test, and the sulfate erosion was investigated by X-ray diffraction and scanning electron microscopy techniques. The results show that the modification of steel slag aggregate can significantly reduce damage to steel slag concrete during the erosion process. The quality and dynamic elastic modulus of concrete both increased first and then decreased with the erosion time. The compressive strength after erosion was higher than that of ordinary steel slag. Aggregate concrete and ordinary concrete increased by 5.7% and 15.6%, respectively. The microscopic characteristic analysis found that the modified coating filled the pores and microcracks on the surface of the steel slag, making it difficult for SO₄²⁻ to invade. The number of corrosion products inside the sample was significantly reduced. Additionally, the steel slag aggregate and the active components in the modified coating could interact, resulting in the hydration products effectively filling in the pores and microcracks of the modified concrete, so that the compactness of the modified steel slag aggregate concrete was significantly improved.

1. Introduction

In the process of iron and steel smelting, a large amount of steel slag is produced, and about 0.15 tons of steel slag is produced for every 1 ton of steel produced. In 2021, the output of steel slag in China was 169 million tons, and the accumulated steel slag exceeded 3 billion tons. The comprehensive utilization efficiency of steel slag is only 25% [1]. Excessive stacking of steel slag not only pollutes the environment but also occupies land resources. Therefore, it is urgent to improve the utilization rate of steel slag, and this content is also one of the important contents of China’s carbon peaking strategy. The physical properties of steel slag are similar to traditional natural aggregates, and it has the advantages of high compressive strength and high wear resistance. In recent years, the use of steel slag to prepare steel slag aggregate concrete has become a focus for research in engineering and academia. Cheng et al. [2] studied the effect of steel slag coarse aggregate on the sulfate resistance of concrete. The results show that the sulfate corrosion of concrete can be slowed down when the substitution rate of steel slag coarse aggregate is less than 60%. However, because steel slag contains active substances such as free calcium oxide, it can cause poor stability of concrete. Therefore, a large number of scholars have carried out research on steel slag modification [3–6]. Xu [7] used cement-silica mortar slurry, acrylic modified silicone resin waterproofing agent, and silane coupling agent solution to modify the surface of steel slag. The study showed that steel slag formed a dense film on its own surface after surface modification treatment. This film
prevented water from being absorbed into the steel slag, thereby inhibiting the volume expansion of the steel slag, improving the stability, and at the same time, improving the mechanical properties of the steel slag to a certain extent. After the modification of the steel slag, its water absorption and crushing value decreased from 2.02% and 17.6% to 0.56% and 10.1%, respectively, and the water swelling rate decreased from 1.78% to 1.18%. Chen et al. [8] modified the surface of the hydrated steel slag by immersing it in organosilicon. The study showed that the holes existing on the surface of the original steel slag were hydrated and the calcium carbonate crystals obtained after hydration closed the holes to a certain extent, reducing the contact area between slag and water. Compared with the hydrated steel slag, the surface of the steel slag soaked with organosilicon was covered with organosilicon, which blocks the contact between the water and the steel slag. The results of the swelling ratio showed that after hydration treatment and silicone soaking treatment, the water swelling ratio of steel slag decreased from 2.3% to 0.45% and 0.28%, respectively. It can be seen from the above steel slag modification research that the surface modification can effectively improve the stability of the steel slag [9], because the coating formed on the surface of the steel slag after modification plays a role in isolating moisture and preventing moisture intrusion, to achieve the purpose of inhibiting the hydration of F-Cao and the volume expansion of steel slag. Compared with organic modifications such as silicone resins and silicone rubbers, inorganic modifications such as cement pastes have a series of advantages such as low cost, easy operation, no toxic gas generation, and favorable industrialization.

At present, most of China’s steel slag aggregate concrete is used in road engineering [10–12]. With the proposal of the development strategy “The Belt and Road,” the road construction projects in saline soil areas in the west have increased rapidly, resulting in the ever increasing occurrence of road defects which is mainly due to sulfate erosion [13].

Although many scholars have developed research on the properties of modified concrete materials [14–17], most of the research mainly focuses on the macroscopic mechanical properties. However, there are few studies on durability of modified steel slag aggregate concrete under sulfate attack environment, the macroscopic properties and microstructure changes of modified steel slag aggregate concrete under sulfate erosion were investigated, and the mechanism of their effect on the mechanical properties of steel slag aggregate concrete. The results of the study can provide a basis for the promotion and application of modified steel slag aggregate concrete in practical engineering work.

2. Materials and Methods

2.1. Steel Slag Modification Scheme. To explore the mixture ratio of modified slurry, cement-fly ash slurry with different water-cement ratios was designed for filling and adhesion tests. The mixture ratio and experimental phenomena are shown in Table 1. The fly ash and cement used for modification are the same as those used for mixing concrete in this paper. After the test, the mixture ratio of the modified slurry was determined and the mixture ratio of no. 5 was selected (Table 1). Under this mixture ratio, the modified slurry had high fluidity and strong adhesion, which can fully fill the pores of steel slag and form a protective layer on the surface adhesion. The density of modified steel slag aggregate and ordinary steel slag under no. 5 combination is 2.88 g/cm³ and 2.93 g/cm³, respectively. The reason for the decrease of density is that the density of cement stone after hardening of modified slurry is lower than that of steel slag.

The prepared slurry was applied to the slag aggregate, allowing the aggregate to mix well with the modified slurry to ensure a proper coating on the slag aggregate. The treated steel slag aggregate was placed in the water tank after being naturally air-dried for 24 h. After 7 days of curing, the modified steel slag aggregate was taken out and dried in a 60°C oven for 4 h and allowed to cool naturally to room temperature for concrete preparation. The appearance of the steel slag before and after modification is shown in Figure 1.

2.2. Materials and Specimen Preparation. The cementitious material used in this investigation was conventional Portland cement P-O42.5, and the fly ash was second-grade dry fly ash produced by a fly ash firm. The natural coarse aggregate was continuously graded gravel with particle sizes of 5–20 mm, and the fine aggregate was natural river sand with a fineness modulus of 2.85. The steel slag coarse aggregate was produced by a steel plant in Guangxi Province, with particle sizes ranging from 5 to 20 mm. The steel slag used in the test is converter steel slag. After screening, aggregate with a diameter of 5–20 mm is selected. The screening results of steel slag are shown in Table 2, and the grading is in line with the standards stipulated in Pebble and Gravel for Construction (GBT14685-2011) [18]. The surface of the steel slag was black-gray and rich in voids (see Table 2), so the effect of water absorption of steel slag should be considered when preparing concrete [2].

Based on the, this experiment was designed with a steel slag aggregate substitution rate of 60%. Ordinary steel slag and modified steel slag were used as raw materials. In order to facilitate the experimental comparison, the ordinary concrete specimens without steel slag were prepared in the same working condition to be used as the control group. The spectroscopic analysis of the steel slag using X-ray fluorescence spectrometry yielded the main chemical composition of the steel slag is shown in Table 3, with a free calcium oxide content of 1.19%, which meets the requirements of the standard. The physical properties of the sand, steel slag, and gravel used for the tests are shown in Table 4.

All materials were mixed and injected into 100 × 100 × 100 mm cube molds. The concrete specimens were removed from the molds after one day and cured under standard curing conditions (relative humidity ≥ 95%, temperature 20 ± 1 °C) for 28 days.

2.3. Experimental Methods. The test was designed according to the sulfate erosion section of GB/T 50082-2009 [19], and the test was immersed in sulfate solution for 56 days. The temperature was controlled at 20 ± 2°C during erosion, and the erosion solution was replaced every 30 days. A Na₂SO₄...
solution was used as the erosion solution. To simulate the erosion damage of steel slag concrete by sulfate solution in the actual engineering environment, a Na₂SO₄ solution with a concentration of 10% (mass fraction) was used in the test. The specimen was soaked in Na₂SO₄ solution for 58 h.

The specimen was removed, and the surface was dried, and it was put into the oven and dried for 10 h with the oven set at 60°C. The specimen was removed from the oven and left to cool for 4 h at room temperature, and the process was repeated. The LC-674 dynamic elastic modulus tester was used for the dynamic elastic modulus test.

The YAW-4306 microcomputer-controlled electro-hydraulic servo compression tester was used for the compressive strength test. The maximum load was 3000 kN. The side of the molded surface of the specimen was used as the compressed surface, which was cleaned and coated with appropriate petroleum jelly to reduce friction. The stress controlled mode was used to load the specimen at a rate of 0.3 kN/s until failure.

The equipment selected for the X-ray diffraction (XRD) test was a Bruker D8 analyzer with a test scan angle range of 5-60 degrees and a scan speed of 10°/min. The steel slag aggregate concrete fragments were ground into powder form for the tests.

There are many methods to obtain the internal structure of the sample, such as X-ray computed tomography (X-ray CT) [20] and scanning electron microscope (SEM). In this study, SEM is used to obtain the internal structure of steel slag concrete. A SEM of the TESCAN MIRA4 model with a maximum magnification of 100000 times and an acceleration voltage of 15 keV was chosen. The samples were selected from steel slag aggregate concrete blocks, cut with scissors to make the samples ≤ 1 cm in diameter and <1 cm in thickness and the surface was selected from gold-palladium alloy as the spraying gold target for spraying gold.

Table 1: Mixture ratio of modified slurry (kg).

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Water cement ratio</th>
<th>Water</th>
<th>Cement</th>
<th>The fly ash</th>
<th>The test phenomenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>11.1</td>
<td>22.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
<td>10</td>
<td>8.3</td>
<td>25</td>
<td>Difficult to fill pores</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
<td>10</td>
<td>4</td>
<td>16</td>
<td>Slightly less filling</td>
</tr>
<tr>
<td>4</td>
<td>0.6</td>
<td>10</td>
<td>5</td>
<td>15</td>
<td>Effective void filling and adhesive</td>
</tr>
<tr>
<td>5</td>
<td>0.6</td>
<td>10</td>
<td>4.2</td>
<td>12.4</td>
<td>Adhesion is weak</td>
</tr>
<tr>
<td>6</td>
<td>0.6</td>
<td>10</td>
<td>3.3</td>
<td>13.3</td>
<td>Too dilute</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>5.5</td>
<td>11.1</td>
<td></td>
<td>Can fill the pores with poor adhesion</td>
</tr>
</tbody>
</table>

Table 2: Sieve results of steel slag aggregate.

<table>
<thead>
<tr>
<th>Mesh diameter (mm)</th>
<th>2.36</th>
<th>4.75</th>
<th>9.5</th>
<th>19</th>
<th>Cumulative screen residual (%)</th>
<th>98.21</th>
<th>96.13</th>
<th>63.84</th>
<th>1.89</th>
</tr>
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<tbody>
<tr>
<td>Specification grading range (mm)</td>
<td>95-100</td>
<td>90-100</td>
<td>40-80</td>
<td>0-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Chemical composition of steel slag (%).

<table>
<thead>
<tr>
<th></th>
<th>CaO</th>
<th>SiO₂</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>Mn</th>
<th>Al₂O₃</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>39.86</td>
<td>20.67</td>
<td>20.45</td>
<td>6.77</td>
<td>4.19</td>
<td>3.98</td>
<td>4.08</td>
</tr>
</tbody>
</table>

Figure 1: The morphology of (a) original steel slag and (b) modified steel slag.
which was glued to the sample table with conductive adhesive for testing.

3. Results and Discussion

3.1. The Apparent Deterioration Trend. As can be seen from the results of erosion tests, it can be seen that the apparent deterioration of all groups of concrete under the erosion of the 10% Na₂SO₄ solution increased with the increase of the erosion time. At day 56, the apparent deterioration of modified steel slag aggregate concrete was better than that of steel slag aggregate concrete and worst for ordinary concrete. At day 28 of erosion, whitening appeared on the modified steel slag aggregate concrete and the edge angles were intact; the surface and spread outward without peeling the cement paste on the surface. Ordinary concrete showed holes and sanding and corner dropping on the surface when the erosion time reached 28 days, and at day 56, sanding and corner dropping on the surface were observed, and the cement paste peeled off to show a rough surface. The degree of apparent deterioration of steel slag aggregate concrete was different between the two, which indicates that the use of modified steel slag to prepare steel slag aggregate concrete is beneficial to reduce the degree of apparent deterioration under sulfate erosion.

3.2. Mass and Relative Dynamic Elastic Modulus. Figures 2 and 3 show the variation curves of the mass loss rate and the relative dynamic elastic modulus of modified steel slag aggregate concrete with erosion time under sulfate erosion. As shown in Figures 2 and 3, the mass and relative dynamic elastic modulus of steel slag aggregate concrete under solution erosion increased and then decreased with time and reached a peak at day 28.

The peak mass loss rates of modified steel slag aggregate concrete and ordinary concrete were 1.99% and 1.37%, respectively, and the peak relative dynamic elastic modulus were 123.72% and 120.13%, respectively. The peak mass loss rate and peak relative dynamic elastic modulus of modified steel slag aggregate concrete were both greater than those of ordinary concrete. This was because modified steel slag aggregate contains SiO₂, CaO, and other active substances that can participate in the hydration reaction compared to natural aggregate. The hydration products such as C₃S-H and Ca(OH)₂ are generated to improve the compactness of steel slag aggregate concrete, making the mass and dynamic elastic modulus of modified steel slag aggregate concrete greater than that of ordinary concrete.

Figures 2 and 3 show that the peak mass and peak relative dynamic elastic modulus of the modified slag aggregate concrete were lower than those of the steel slag aggregate concrete. The mass loss was 0.27% and 0.39% at day 56 of erosion time, and the relative dynamic elastic modulus was 103.16% and 101.57%. The mass loss and relative dynamic elastic modulus of modified steel slag aggregate concrete were both better than those of steel slag aggregate concrete. The reason for this phenomenon is that the surface of steel slag aggregate is porous, so it is easy to form salt crystals in the drying process, modified steel slag surface by the cement slurry soaked, and painted slurry filled the pores, so it is not easy to form salt crystals, which results in a lower growth in mass of modified steel slag aggregate concrete than steel slag aggregate concrete. The modified slag had a small specific surface area, and the modified slurry on the exterior was tightly bonded to the cement slurry. At the same time, this modified slurry inhibits the reaction of SO₄²⁻ in the erosion solution with the active ingredients in the steel slag to form erosion products. This reduces the damage caused by the expansion of the erosion products, resulting in a smaller loss of quality of the modified steel slag aggregate concrete.
3.3. Compressive Strength. Figure 4 shows that the compressive strength of modified steel slag aggregate concrete under solution erosion increased and then decreased with time and reached its peak at day 28. The trend of variation in compressive strength was consistent with the trend of variation in relative dynamic elastic modulus. For modified steel slag aggregate concrete compared with ordinary concrete, the compressive strength at day 0 was 37.4 MPa and 35.1 MPa, and the peak compressive strength was 42.7 MPa and 38.5 MPa, respectively. The compressive strength at day 0 and the peak compressive strength of modified steel slag aggregate concrete were both higher than those of ordinary concrete. At the same time, these scholars also obtained similar experimental results [21, 22]. Analyzing the reasons: modified slurry modified steel slag aggregate surface to form a rough texture, improving the adhesion and bond between the modified steel slag aggregate and cement slurry. Under sulfate erosion, compared with natural aggregates, modified steel slag aggregates contain active substances such as CaO and SiO₂, and these substances can participate in the hydration reaction and promote the consolidation around the aggregate, making the modified steel slag aggregate concrete dense and with continuous transition zone. Additionally, the modified steel slag aggregate concrete had more internal hydration products, which improves the compactness and increases the effective compression area, making the modified steel slag aggregate concrete compressive strength higher than ordinary concrete.

From Figure 4, it can be seen that the peak compressive strength of modified steel slag aggregate concrete was 42.7 MPa and 43.6 MPa and 37.1 MPa and 35.4 MPa at day 56, compared with steel slag aggregate concrete. The peak compressive strength of modified steel slag aggregate concrete was lower than that of steel slag aggregate concrete, while the compressive strength at day 56 was higher than that of the steel slag aggregate concrete. Analyzing the reasons: steel slag aggregate unmodified surface porosity leads to mixing cement slurry cannot be completely wrapped inside the specimen easy to produce cracks, pores make SO₄²⁻ invade and reaction with Ca(OH)₂ in the steel slag, the reaction equation is shown in

\[
Na_{2}SO_{4} + Ca(OH)_{2} + 2H_{2}O = CaSO_{4} \cdot 2H_{2}O + NaOH. \quad (1)
\]

The reaction produces gypsum, while CaO in the steel slag aggregate in direct contact with water will also produce gypsum. In the preerosion period, gypsum can fill the internal pores of the specimen to increase the effective compression area and make the strength of slag aggregate concrete rise. The volume of gypsum formed inside the pores increased by 1.24 times at a later stage, and the pores broke down due to excessive expansion stress. After modification, the surface of the slag was wrapped by the modified slurry to reduce the pore space while the slurry formed a covering film on the surface of the slag aggregate to inhibit SO₄²⁻ intrusion and reduce the generation of erosion products such as gypsum. Although the peak strength of modified steel slag aggregate concrete was lower than that of steel slag aggregate concrete due to fewer erosion products and less expansion damage in the later phases of erosion, the residual compressive strength was larger than that of steel slag aggregate concrete.

3.4. XRD Analysis. The XRD samples used for the analysis were finely ground modified steel slag aggregate concrete samples, which allowed a comparative analysis of the number of various products generated based on the height and width of their diffraction peaks. In order to prevent carbonization reaction between CO₂ in air and sample, affecting test results. In this paper, the XRD test samples were ground into powder from concrete pattern and immediately sealed.
with sample bag. They were sent to the laboratory for XRD test within 6 hours.

As shown in Figure 5, there were several obvious diffraction peaks in the X-diffraction atlas of the modified steel slag aggregate concrete after sulfate attack. Through the analysis of their corresponding characteristic angles, these diffraction peaks were A-Fe at 9.23° (2θ), CH at 18.15° (2θ) and 34.12° (2θ), gypsum at 20.97° (2θ), SiO$_2$ at 26.76° (2θ), albite at 29.46° (2θ), and dolomite at 31.10° (2θ). SiO$_2$ was the main component of fine aggregate sand.

Figure 5 shows that the diffraction peak of calcium hydroxide in modified steel slag aggregate concrete was higher than that in ordinary concrete, which indicates that the amount of calcium hydroxide generated in modified steel slag aggregate concrete was more than that in ordinary concrete under solution erosion. The hydration products generated by the reaction of the modified steel slag aggregate with water were mainly CH and C-S-H, and CH is calcium hydroxide crystal and C-S-H is gel. Therefore, there was an obvious diffraction peak of calcium hydroxide in Figure 5, while C-S-H had no obvious diffraction peak.

The main contributor to the strength of the specimen was C-S-H with its great specific surface area and rigid gel properties. In addition, these hydration products filled in the cracks and pores between the steel slag aggregate, modified coating, and cement slurry to improve the interface transition zone, so that the surrounding cement slurry compactness was improved. Thus, the modified steel slag aggregate concrete had increased dynamic elastic modulus and strength. This is consistent with the trend shown in Figures 2 and 3.

From Figure 5, the calcium alumina diffraction peak and gypsum diffraction peak of modified steel slag aggregate concrete were lower than those of steel slag aggregate concrete, which indicates that the amount of both calcium alumina and gypsum generated inside the modified steel slag aggregate concrete under solution attack was less than that of steel slag aggregate concrete. This was because the steel slag aggregate concrete underwent chemical erosion in Na$_2$SO$_4$ solution and SO$_4^{2-}$ reacted with Ca$^{2+}$ to form gypsum. Calcium hydroxide is slightly soluble, and the formation of gypsum breaks the ion balance of calcium hydroxide, causing its continuous decomposition into Ca$^{2+}$ and OH$.^-$. Due to the modified steel slag surface having a uniform layer of cement slurry wrapped, SO$_4^{2-}$ could not react directly with the steel slag aggregate to generate calcium alumina, which results in less calcium alumina than steel slag aggregate concrete in modified steel slag aggregate concrete specimens under sulfate attack.

3.5. Microstructural Characteristics. To further investigate the damage deterioration mechanism of modified steel slag aggregate concrete under sulfate erosion, scanning electron microscopy tests were conducted on the interior of modified steel slag aggregate concrete under sulfate erosion. In this paper, each SEM test sample was taken from the central position of the erosion specimen with a depth of 30-35 mm from the sample surface and removed after cutting by a cutting machine. This study only offers the SEM results of modified steel slag aggregate concrete, steel slag aggregate concrete, and ordinary concrete eroded in 10% Na$_2$SO$_4$ solution for 28 days and 56 days, as shown in Figure 6, all at 10,000 times magnification.

As shown in Figures 6(a)–6(c), flake material in Figures 6(b) and 6(c) was calcium hydroxide (Ca(OH)$_2$). It can be seen that there was no obvious crack in the cement stone of modified steel slag aggregate concrete when the erosion time reached 28 days, and there was a large amount of Ca(OH)$_2$ accumulation in steel slag aggregate concrete and ordinary concrete, and the Ca(OH)$_2$ in ordinary concrete was loose and porous. The surface coating of modified steel slag aggregate and the steel slag aggregate itself contained a large number of active substances which react with water to generate hydration products, leading to the improvement of sample compactness and lower erosion degree of cement stone by SO$_4^{2-}$ ion. The hydration products in ordinary concrete were less dense and less vulnerable to SO$_4^{2-}$ ion erosion. Ca(OH)$_2$ has poor stability, and it was the first part to be eroded, becoming loose and porous. In terms of macroscopic properties, the compressive strength and dynamic elastic modulus of modified steel slag aggregate concrete were greater than that of ordinary concrete, which is consistent with the trend reflected in Figures 2 and 3.

As shown in Figures 6(d)–6(f), the acicular crystal in Figure 6(d) is ettringite (AFt), and the short columnar substance in Figures 6(e)–6(f) is gypsum (CaSO$_4$). For the modified steel slag concrete, at day 56 erosion time, there was a small amount of ettringite. For the steel slag concrete, internal short columnar gypsum stacked together with very a dense cement surface and no obvious cracks. While for the ordinary concrete, internal obvious cracks appeared. Accumulations of short columnar gypsum were found in and around the cracks. This was because SO$_4^{2-}$ in the erosion solution reacted with Ca$^{2+}$ to form CaSO$_4$ after entering the material. In the modified steel slag aggregate concrete, there was a layer of modified coating on the aggregate surface, and the steel slag reacted with water to generate Ca(OH)$_2$ to fill the cracks and pores between the aggregate and cement slurry, which improved the compactness of the
surrounding cement slurry. The interface transition zone was improved, \( \text{SO}_4^{2-} \) was difficult to invade, and \( \text{Ca}^{2+} \) released by steel slag was difficult to diffuse outwards. Under the dual action of the two, \( \text{CaSO}_4 \) was rarely found in modified steel slag aggregate concrete and AFT was in small quantities. The porous \( \text{SO}_4^{2-} \) on the surface of unmodified steel slag reacted with it to generate \( \text{CaSO}_4 \) and accumulated in it, and the compactness of ordinary concrete was the worst. \( \text{SO}_4^{2-} \) invaded the fracture and formed \( \text{CaSO}_4 \), which expands and causes the fracture to expand, resulting in loss of bond between aggregate and cement slurry. This indicates that concrete prepared by steel slag modification can effectively reduce the number of erosion products generated in the material under sulfate erosion environment and thus reduce the damage caused by the expansion stress of erosion products, which is consistent with the conclusion of previous macroscopic properties research.

4. Conclusion

(1) The variation trend in compressive strength of modified steel slag aggregate concrete under sulfate attack can be divided into two stages: (a) strength improvement stage: modified steel slag reaction generated by hydration products and erosion products filling, modified steel slag aggregate concrete strength increased. (b) Strength reduction stage: the expansion force of erosion products acting around the pore wall leads to pore expansion, crack penetration,
and modified steel slag aggregate concrete strength reduction.

(2) Modified steel slag had a large effect on the apparent deterioration degree and compressive strength of concrete. Compared with steel slag aggregate concrete and ordinary concrete, the modified steel slag aggregate concrete specimens showed the lowest degree of deterioration, and the compressive strength increased by 5.7% and 15.7%.

(3) Modified steel slag can reduce the deterioration of concrete microstructure damage under sulfate erosion environment to a certain extent. The modified coating fills the pores of the steel slag surface and strengthens the bond between the aggregates and the cement slurry, which makes the density of the specimen improve with low internal erosion products and it is difficult for SO$_4^{2-}$ to intrude.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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