Influence of ion erosion on RHPB strength in brine environment

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Abstract: In order to study the change of dynamic elastic modulus, compressive strength and flexural strength of recycled coarse aggregate high performance concrete (RHPB) specimens during one-year corrosion period in Salt Lake brine, and to explore the failure mechanism of its physical and mechanical behavior, the dynamic elastic modulus and strength of concrete specimens and beam members under the corrosion age of RHPB were studied. Research on the influence of degree and so on. The experimental results show that the longer the corrosion time of RHPB specimens is, the higher the chloride ion content is, the stronger the corrosion strength will become; the coexistence of ions can also affect the corrosion rate; the loss of dynamic elastic modulus will increase with the extension of the corrosion time under 0a-1.0a erosion; and under the same replacement rate of recycled coarse aggregate (RG), R. When the corrosion time of HPB is 0-1.0a, the flexural strength increases continuously with the extension of service time. The compressive strength of specimens with different RG replacement rates decreases as a whole under corrosion. At 1.0a, the compressive strength decreases most obviously with the increase of RG replacement rate, and the strength decreases the most, RG substitution rate of 40% is the best.

1. Introduction
Using recycled aggregates from waste concrete to prepare recycled concrete used in buildings is necessary for reducing construction waste. Although there are many problems in its application in real engineering situations, this method has attracted wide attention due to its characteristics of environmental protection and resource recycling. Therefore, it is necessary to study the material and structural mechanical performance and failure mechanism of recycled concrete in the corrosive bittern surroundings. There is abundant research on single erosion in China, but little on the failure law of multi-factor influence. There are also studies on the influence of sulphate and chlorine salts on the recycled concrete and its structural performance degradation in China. Yu Hongfa et al. [1] studied the stress and non-stress corrosion strength of OPC, HSC and FRHSC concrete specimens in the salt lake brine environment in Xinjiang, Qinghai, Inner Mongolia and Tibet. Yan Hongsheng et al. [2] analyzed the impact of concrete, working conditions and the environment on sulfate erosion based on experiments, and proposed a series of anti-corrosion measures. Shi Feng [3] and Zhang Feng [4] revealed the deterioration law of concrete strength under sulfate attack. Jiang Lei [5] analyzed the concrete damage under different types of sulfate attack, pointing out at longer erosion leads to thinker damaged layer and significantly lower compressive strength.

This experiment explores the change of compressive and flexural strength of RHPB under SO₄²⁻ and Cl⁻ erosion and analyzes the mechanical behavior and failure mechanism of RHPB materials and
components under brine corrosion though brine arrangement.

2. Experiment design

2.1. Raw materials
Cement (C): P.II 52.5 ordinary Portland cement produced by Qilianshan Cement Co., Ltd.; Performance Indicators of Cement is shown in Table 1.

Table 1  Performance Indicators of Cement

| Apparent density (kg/m³) | Specific surface area (m²/kg) | Loss of ignition (%) | Initial/ final setting time (min) | Flexural strength (MPa) | Compressive strength (MPa) |
|-------------------------|-------------------------------|----------------------|----------------------------------|-------------------------|---------------------------|
| 3120                    | 375                           | 1.06                 | 225/320                          | 6.5                     | 8.4                       |
|                         |                               |                      |                                  | 3d 28d                  | 3d 28d                    |

Fly ash (F): Grade I fly ash with fineness of 9.0%; Silica fume (Si): with SiO₂ content of 90.51% and a specific surface area of 26200 m²/kg; Slag (K): S95 slag with a specific surface area of 430 m²/kg; Sand (S): River sand with fineness modulus of 2.65; Stone (S): Granite gravel with the maximum particle size of 20mm, the apparent density of 2780kg/m³, and the bulk density of 1530kg/m³; continuous gradation; Recycled coarse aggregate (RCA): Aggregate particle size of 5mm-45mm; its basic properties are tested using the method provided in Cobble and Gravel for Construction (GB/T14685-2011); The composition of the brine is shown in Table 2.

Table 2  Properties of recycled aggregate materials

| Moisture content | Water absorption rate | Sediment percentage | Crushing index | Apparent density | Old mortar content |
|------------------|-----------------------|---------------------|----------------|-----------------|-------------------|
| 3%               | 4.4%                  | 0.6%                | 11.8%          | 2711kg/m³       | 33.1%             |

Water reducing agent (WR): polycarboxylate-type WR; Water (W): tap water meeting national standards. The concrete mix ratio is designed according to the water-binder ratio and water consumption. The design principle is designed according to the “General Concrete Mixing Ratio Design Regulations” JGJ55-2011 [6], is shown in Table 3.

Table 3  Concrete Mix Ratio

| NO.       | RG Substitution rate/% | B/M | M  | C  | F  | K  | Si | S  | G  | RCA | WR | W  | Compressive strength (MPa) |
|-----------|------------------------|-----|----|----|----|----|----|----|----|-----|----|----|---------------------------|
| RHPB-0    | 0                      | 0.30| 500| 325| 60 | 100| 15 | 741| 1159| 11  | 150| 51.6                       |
| RHPB-20   | 20                     | 0.30| 500| 325| 60 | 100| 15 | 741| 927.2| 231.8| 11 | 150| 50.0                       |
| RHPB-40   | 40                     | 0.30| 500| 325| 60 | 100| 15 | 741| 695.4| 463.6| 11 | 150| 48.2                       |
| RHPB-60   | 60                     | 0.30| 500| 325| 60 | 100| 15 | 741| 463.6| 695.4| 11 | 150| 47.3                       |
| RHPB-80   | 80                     | 0.30| 500| 325| 60 | 100| 15 | 741| 231.8| 927.2| 11 | 150| 45.8                       |
| RHPB-100  | 100                    | 0.30| 500| 325| 60 | 100| 15 | 741| 0    | 1159| 11 | 150| 44.6                       |

2.2. Experiment plan

2.2.1. Evaluation method
In order to keep the concentration of the solution constant, it is necessary to seal the solution with a plastic film to prevent volatilization, regularly replace the solution, and keep the temperature and humidity relatively stable. A chloride ion content measuring instrument is used in the experiment. The sulfate content of 7 samples is measured by the barium sulfate weight method (chemical titration method). After completing the flexural test of the 100 mm × 100 mm × 400 mm specimens that are immersed in the same condition for the same period of time, take the sample of the two half blocks, and
take enough concrete at the same depth of the same test block. The sampling holes are located at the corners of the concrete test block and are 20 mm from the edges. The composition of the brine is shown in Table 4. According to Baume meter, the concentration of brine is 1250 g·L⁻¹.

| Name       | NaCl  | Na₂SO₄ | MgSO₄ | CaSO₄ | NaHCO₃ | K₂SO₄ |
|------------|-------|--------|-------|-------|--------|-------|
| Quality /g | 208.98| 43.1   | 5.48  | 1.21  | 0.25   | 0.09  |

2.2.2. Strength analysis method

This experiment takes 6 sets of 100mm × 100mm × 400mm anti-folding specimens, with each set containing 3 pieces, thus making a total of 18 anti-folding specimens; 6 sets of compressive specimens of 100 mm × 100 mm × 100 mm, with each set containing 3 pieces, thus making a total of 18 compressive specimens. This experiment selects 28d standard maintenance (reference specimen), and a total of 3 tracking ages (0.5a, 1.0a). The flexural strength test shall be carried out according to the Standard Test Method for Mechanical Properties of Ordinary Concrete [7]. After maintaining the 100 mm × 100 mm × 400 mm concrete specimens for 28 days (temperature 20±2 °C; relative humidity above 95%), this paper tests the flexural strength of the concrete specimen and uses the result as the benchmark flexural strength of this experiment with the intensity conversion factor being 0.85. Then, test the flexural strength values of concrete specimens after immersion for 0.5a and 1.0a for later analysis.

The compressive strength test adopts the specimen of 150 mm × 150 mm × 150 mm after immersing for 0.5a and 1.0a.

2.2.3. Dynamic elastic mold test

Dynamic elastic mold test is conducted on the specimen of 100 mm × 100 mm × 400 mm with different corrosion ages. The initial dynamic elastic mode and that after erosion are measured according to the Standard Test Method for Long-Term Performance and Durability of Concrete (GB/T50082-2009), using SRDT-60 concrete dynamic-elastic instrument.

3. Results and discussion

3.1. Erosion analysis

Analysis of Cl⁻ and SO₄²⁻ Erosion Concentrations of RHPB-40 is shown in Table 5.

After 7d corrosion, the chloride ion content of the concrete beam becomes lower, and the highest chloride ion concentration in the concrete surface is only 1.11%. The content decreases with the sampling depth increases, indicating that the chloride ion corrosion intensity decreases with the increase of depth in a short time. The chloride ion content of RHPB specimens decreases with the increase of depth at any corrosion age, and peaked at 1.0a (1.0a>0.5a). At this time, the chloride ion content of the surface layer reaches 10.13. %, which means that Cl⁻ gradually migrates to the interior of the concrete over time and the erosion intensity weakens with the increase of depth.

The content of SO₄²⁻ of RHPB specimens at any corrosion time decreases with the increase of depth. It peaks when the corrosion time is 1.0a and bottoms out at 0a at each sampling depth. At the same corrosion age, the content of SO₄²⁻ is the highest when the sampling depth is 0-5mm, and then that decreases with the increase of depth. This indicates that the erosion of SO₄²⁻ is stronger over time with less erosion content.

When the corrosion time is 0.5a-1.0a, there is little change in the content of SO₄²⁻ of RHPB specimens over time. SO₄²⁻ erosion is not evident during this time period, but it gets stronger over time, indicating that a certain substance inhibits SO₄²⁻. Jin Yannan et al. [8] also suggested that when SO₄²⁻ and Cl⁻ coexist, Cl⁻ can slow down the sulfate attack. The higher the concentration of the chloride salt solution, the stronger the effect of delaying concrete damage. That is due to the generation of Friedel salt that causes partial pore blockage in concrete reduces the diffusion rate of SO₄²⁻. It also indicates that the
coexistence of ions can affect the corrosion rate.

Table 5  Analysis of Cl\(^{-}\) and SO\(_4^{2-}\) Erosion Concentrations of RHPB-40

| Corrosion time (a) | Depth (mm) | Cl\(^{-}\) concentration (%) | SO\(_4^{2-}\) concentration (%) | Corrosion time (a) | Depth (mm) | Cl\(^{-}\) concentration (%) | SO\(_4^{2-}\) concentration (%) |
|-------------------|------------|------------------------------|-------------------------------|-------------------|------------|------------------------------|-------------------------------|
| 0 (7d)            | 0-5        | 0.011                        | 0.072                         | 0-5               | 0.798      | 0.076                        | 0-5                           | 1.013                        | 0.083                        |
|                   | 5-10       | 0.009                        | 0.022                         | 5-10              | 0.562      | 0.064                        | 5-10                          | 0.743                        | 0.066                        |
|                   | 10-15      | 0.008                        | 0.025                         | 10-15             | 0.33       | 0.05                         | 10-15                         | 0.455                        | 0.059                        |
|                   | 15-20      | 0.007                        | 0.018                         | 0.5               | 0.145      | 0.045                        | 15-20                         | 0.287                        | 0.051                        |
|                   | 20-25      | 0.007                        | 0.022                         | 0.5               | 0.138      | 0.043                        | 20-25                         | 0.164                        | 0.049                        |
|                   | 25-30      | 0.005                        | 0.035                         | 0.5               | 0.084      | 0.039                        | 25-30                         | 0.159                        | 0.038                        |
|                   | 30-35      | 0.004                        | 0.035                         | 0.5               | 0.08       | 0.034                        | 30-35                         | 0.135                        | 0.032                        |

3.2 Dynamic elastic model analysis

Dynamic modulus of RHPB specimens is shown in Table 6 and Fig.1. When water-to-binder ratio remains unchanged, the dynamic elastic modulus of the specimen decreases with the increase of RG substitution rate from 0-100% under the same corrosion conditions. With the increase of RG substitution rate, the dynamic elastic modulus of 0a decreases from 42.2MPa to 36.8 MPa, a decrease of 12.8%; that of 0.5a decreases from 44.5 MPa to 38.6 MPa, a decrease of 13.3%; that of 1.0a decreases from 36.5 MPa to 30.1 MPa, a decrease of 17.5%. It shows that at 0a-1.0a, the dynamic modulus loss increases with the extension of erosion time.

Under the same RG substitution rate, as time prolongs, the dynamic elastic modulus first rises and then falls. It peaks at 0.5a, rises slightly during 0-0.5a, and drops sharply during 0.5a-1.0a. It indicates that under short-time erosion is favorable for the dynamic modulus of the specimen.

Table 6  Dynamic modulus of RHPB specimens

| NO   | Water binder ratio | Standard curing 28d (0a) | Dynamic modulus (GPa) | 0.5a Brine environment | 1.0a Brine environment |
|------|--------------------|---------------------------|-----------------------|------------------------|------------------------|
| RHPB-0 | 0.30                | 42.2                      | 44.5                  | 36.5                   |                        |
| RHPB-20 | 0.30                | 41.3                      | 43.3                  | 35.4                   |                        |
| RHPB-40 | 0.30                | 40.5                      | 41.5                  | 34.3                   |                        |
| RHPB-60 | 0.30                | 39.1                      | 40.9                  | 33.2                   |                        |
| RHPB-80 | 0.30                | 38.7                      | 39.8                  | 31.2                   |                        |
| RHPB-100 | 0.30               | 36.8                      | 38.6                  | 30.1                   |                        |

![Fig. 1 Dynamic modulus curve](image-url)
3.3. Analysis of strength change

Strength of RHPB Brine under Corrosion is shown in Table 7, Fig.2 and Fig.3.

| Type     | Water binder ratio | Flexural strength (MPa) | Compressive strength (MPa) |
|----------|--------------------|-------------------------|---------------------------|
|          |                    | Standard curing 28d     | 0.5a | 1.0a | Standard curing 28d | 0.5a | 1.0a |
|          |                    |                         | Brine environment | Brine environment | Brine environment | Brine environment |
| RHPB-0   | 0.30               | 6.3                     | 7.9 | 8.5 | 51.6 | 59.9 | 46.6 |
| RHPB-20  | 0.30               | 6.0                     | 6.8 | 7.9 | 50.0 | 55.6 | 45.2 |
| RHPB-40  | 0.30               | 5.7                     | 7.7 | 8.6 | 48.2 | 59.4 | 46.3 |
| RHPB-60  | 0.30               | 5.5                     | 6.7 | 7.3 | 47.3 | 57.6 | 40.6 |
| RHPB-80  | 0.30               | 5.2                     | 6.2 | 6.9 | 45.8 | 52.3 | 38.7 |
| RHPB-100 | 0.30               | 5.1                     | 5.9 | 7.1 | 44.6 | 54.1 | 35.7 |

Fig. 2  Flexural Strength Curve

At 0a (intensity of 28d), the flexural strength decreases from 6.3 MPa to 5.1 MPa with the increase of substitution rate from 0% to 100%, a decrease of 19%. At 0.5a, the flexural strength decreases with the increase of substitution rate from 0% to 100%. At the turning point when the substitution rate is 40%, the flexural strength is 7.7 Pa. The flexural strength peaks at 7.9 MPa when the substitution rate is 0% and bottoms out at 5.9 MPa when the substitution rate is 100%, a decrease of 25.3%. At 1.0a, the flexural strength decreases with the increase of substitution rate from 0% to 100%. At the turning point when the substitution rate is 40%, the flexural strength is 8.6 Pa. The flexural strength peaks at 8.5 MPa when the substitution rate is 0% and bottoms out at 6.9 MPa when the substitution rate is 80%, a decrease of 18.8%. The above shows that the change of flexural strength is related to the RG substitution rate and erosion time, but the relationship remains to be further explored.

At the same RG substitution rate, the flexural strength of RHPB does not decline when the corrosion time is 0-1.0a; instead, it increases with the extension of time. This phenomenon indicates that a certain substance is produced during corrosion, which can help to promote the flexural strength. When the RG substitution rate is 0%, the flexural strength increases by 34.9% at 0-1.0a and reaches a maximum value of 8.5 MPa at 1.0a. When the RG substitution rate is 20%, the flexural strength increases by 31.7% at 0-1.0a and reaches the maximum of 7.9 MPa at 1.0a. When the RG substitution rate is 40%, the flexural strength increases by 31.0% at 0-1.0a and reaches the maximum of 7.3 MPa at 1.0a. When the RG substitution rate is 60%, the flexural strength increases by 32.7% at 0-1.0a and reaches the maximum of 6.9 MPa at 1.0a. When the RG substitution rate is
100%, the flexural strength increases by 39.2% at 0a-1.0a and reaches the maximum of 7.1 MPa at 1.0a. As indicated above, when the RG substitution rate is the same, the flexural strength increases with the increase of erosion time during 0-1.0a, with the increase rate greater than 30%. when the substitution rate is 40%, the increase rate peaks at 50.9%, which indicates that brine erosion can promote the flexural strength of the specimen.

![Fig.3 Compressive strength curve](image)

The compressive strength of RHPB specimens shows a downward trend with the prolonged service life in the brine corrosive environment. At 0a, the compressive strength of the specimen at each substitution rate shows a decreasing trend. It reaches the maximum of 51.6 MPa at 0% and the minimum of 44.6 MPa at 100%, a decrease of 13.6%. At 0.5a, the compressive strength of the specimen at each substitution rate decreases first and then increases, then decreases and finally increases, and the overall trend of declining. When the RG substitution rate is 0%, the compressive strength reaches the maximum of 59.9 MPa; when the RG substitution rate is 80%, it reaches the minimum of 52.3 MPa, a decline of 12.7%. At 1.0a, the compressive strength of the specimen under each substitution rate decreases first, then increases and finally decreases, with the overall trend of declining. When the RG substitution rate is 0%, the compressive strength reaches the maximum of 46.6 MPa; when the RG substitution rate is 100%, it reaches the minimum of 35.7 MPa, a decline of 23.4%. The above analysis shows that the compressive strength of the specimens under any RG substitution rate shows a downward trend and it decreases the sharpest at 1.0a.

Under any RG substitution rate, the compressive strength shows trend of 0.5a>0a>1.0a. The compressive strength of RHPB specimens still increases during 0-0.5a, indicating that the hydration lasts for a long time. That is mainly because (1) the micro-aggregate effect of the mineral micro-powder participates in the hydration reaction and fills the tiny pores inside the concrete to make it more compact and stronger; (2) \( \text{Cl}^- \) enters the concrete through diffusion and osmosis and reacts with the hydration product of cement to form hydrated chloroaluminate, which makes the concrete more compact and improves its compressive strength. (3) ettringite is formed during the hydration of concrete, forming a huge expansion stress, thus stronger concrete.

The loss of strength during 0.5a-1.0a is mainly due to the adsorption of ions during the reaction of concrete chemicals in \( \text{Cl}^- \) and \( \text{SO}_4^{2-} \) solutions, resulting in pore expansion and failure in the surface concrete, thus reducing the compressive strength. After the generation of ettringite that increases the compressive strength, this expandable substance eventually damages the the specimen interior, thus lower compressive strength.

The specimen at 0a when RG substitution rate is 40% shows the compressive strength of 48.2 MPa; 0.5a, 59.4 MPa, an increase of 23.2% compared to that at 0a; 1.0a, 46.3 MPa, a decrease of 3.9% compared to that at 0a. The increase rate is the highest among all while the reduction rate is the lowest among all, so the substitution rate of 40% is favorable for the compressive strength.

4. Conclusion
(1) Under the brine corrosive environment and the same substitution rate, the compressive strength of
RHPB specimens decreases with the increase of the flexural strength, indicating that high compressive strength does not lead to strong corrosion resistance.

(2) 40% is the best substitution rate in the test. Under this circumstance, the flexural strength and dynamic elastic modulus of the specimen under any corrosion time reduces the least, while the compressive strength increases the most.

(3) Under the same RG substitution rate, the dynamic elastic modulus first rises and then falls with the extension of erosion time. It reaches the maximum at 0.5a, indicating that short-time brine erosion (within 0.5a) is beneficial to the dynamic modulus of the specimen.

(4) Ion erosion gets stronger with the erosion time and the increase of depth. The coexistence of sulfate and chloride ions in brine makes the corrosion of concrete more complex. Therefore, it is necessary to adopt quantitative and specific research and analysis.

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