Research Article

Experimental Study and Microscopic Analysis on Frost Resistance of Iron Ore Tailings Recycled Aggregate Concrete

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Freeze-thaw harm is the major factor that reduces the durability of hydraulic concrete buildings at high altitudes and in cold regions. To solve the durability problem of hydraulic buildings in alpine regions, the study prepared sixteen groups of concrete specimens with different replacement ratios of iron ore tailings and recycled aggregate were prepared, and indoor deterioration accelerated tests were designed. Nuclear magnetic resonance (NMR) technology was used to analyze the pore distribution in the structure, and macro indicators of concrete mass loss rate and relative dynamic elastic modulus (RDEM), were selected. Combined with SEM, images, the frost resistance of iron ore tailings sand (IOT), with Recycled aggregate concrete (RAC), was explored. The final analysis shows that when only RCA is replaced, the frost resistance of RAC decreases with the increase of the RCA replacement rate. When only replacing IOT, the frost resistance of IOT concrete with a replacement rate of 50% is better than that of other replacement rates. In addition to ordinary concrete, the combination of 30% iron ore tailings and 30% recycled aggregate concrete (RAC3-IOT3) has good frost resistance. The mass loss of the RAC3-IOT3, specimen increased by 0.09% compared with ordinary concrete. From the microscopic level, with the addition of the dosage of RCA, the number of macropores (0.05–1 μm) and microcracks (>1 μm) in concrete increased. After replacing the appropriate amount of iron ore tailings, the pore space structure of RAC was improved, and some harmful pores spaces were transformed into harmless pores. However, the combination of excess IOT, and RCA, does not improve the interface transition zone of RCA. From the micromorphology, with an increasing dosage of RCA, the bonding force between cementitious material and sand aggregate weakens and there are more pores. The combination of excess IOT, and RCA, does not improve the interface transition zone of RCA but will accelerate the spalling of surface mortar because of its small fineness. All things considered, RAC3-IOT3 is the most suitable concrete for high altitude and cold areas.

1. Introduction

With the rapid development of urban construction, a large number of buildings with overaged service life are demolished in all countries in the world, and the demolished construction waste is piled up and buried arbitrarily, which not only causes serious damage to the environment but also occupies a large amount of land [1]. Iron tailings are a type of waste that cannot be used as ore in the process of mining. Iron ore tailings will fill the microporoids and cracks in concrete, creating the concrete dense and effectively ameliorating the performance of RAC [2]. F-T harm is a common disease of concrete structures of hydraulic concrete buildings at high altitudes and in cold regions, which seriously affects the durability of concrete structures [3, 4]. The application of waste iron ore tailings and discarded construction waste constituting recycled aggregate concrete to hydraulic concrete buildings can not only less include the exploitation of sand and gravel resources and achieve sustainable development, but it can also solve the pollution problems caused to the ecological environment and help to realize green and sustainable development.

After World War II, the Soviet Union, Japan, Germany, and other countries to rebuild their homes on the issue of waste concrete began to study the development and use of RAC and has held three international conferences on the theme of recycling waste concrete. Today, RAC has become a common research topic in developed countries. At present,
an oversized variety of scholars in reception and abroad have performed considerable research on the characteristics and durability of RAC. Many scholars have replaced only the core portion with recycled aggregates [5] and reduced the amount of cement used to prepare ultrahigh-durability concrete. There are also multiple recyclings of concrete for reuse of waste [6, 7], adding admixtures to the use of recycled coarse aggregate to improve some properties that are reduced by the use of recycled coarse aggregate. Jahandari et al. [8] obtained the effect of different fibers on the mechanical properties of RAC and obtained the optimal ratio through the experimental study of steel fiber RAC and silica fiber RAC. His study is mainly on the macroscopic properties of concrete and lacks the corroboration of microscopic properties. By studying the macroscopic mechanical properties of RAC with different replacement rates, Li et al. [9] found that the higher the replacement rate of RCA, the worse the mechanical properties compared to ordinary concrete and constructed the stress-strain equation for reinforced concrete. Wang et al. [10] studied the effect of RAC in complex environments mainly from a microscopic perspective. The causes of durability and failure of RCA were explained in terms of pore structure. Deng et al. [11] analyzed the change process of pore structure of RAC with and without adding A-EA under the F-T environment, and the change of macroscopic flexural strength of RAC was reflected by the change of pore structure. Diamond and Huang [12] analyzed the interface transition zone of concrete from two angles by image analysis and scanning electron microscope. Some researchers have tried to develop new technologies using mineral admixtures, wastes, etc., in combination with recycled concrete to prepare new types of concrete, such as fly ash, waste glass, limestone, rubber granules, nano cotton straw ash, palm leaf ash, and the other new mineral admixtures. The above studies were carried out to replace natural sand with the weight ratio of waste glass and limestone, respectively, which was compared with normal concrete [13]. The recycled coarse aggregate was replaced with coarse and fine aggregates in an equal mass ratio with rubber granules to study the effect of their combination on concrete [14]. Nano cotton straw ash and palm leaf ash to partially replace cement, concrete construction waste prepared as recycled coarse aggregate to replace natural coarse aggregate, not only can achieve the reduction of environmental pollution from the cement industry, reduce CO2 emissions, but also has the effect of improving the performance of concrete [15]. More and more scholars are studying the effects of different wastes on concrete, starting from the replacement of coarse and fine aggregates [16, 17]. Among them, the study of recycled coarse aggregate is the hot topic, which is mixed with the rest of the mechanism sand to make concrete and apply it in practical projects, which is an environmental solution to the continuous consumption of natural aggregates.

After entering the 21st century, with the further increase in demand for iron products, it has led to further increase of iron tailings piles. Therefore, scholars at home and abroad have done a lot of research on this issue. The research on IOT is mostly focused on macroscopic properties and characteristics. By analyzing the performance of natural sand and iron tailings sand in concrete, Shettima et al. [18] analyzed the experimental phenomena from a macro-mechanical point of view and identified the optimal replacement amount of IOT. However, the same verification from the microscopic point of view was missing in that study. Zhao et al. [19] provided a detailed analysis of the literature on concrete with the addition of IOT, illustrating the macroscopic and microscopic postphenomena of concrete after the addition of IOT and understanding the reasons for the different phenomena produced by concrete with different dosages of IOT. Cheng et al. [20] tested the impermeability, frost resistance, and carbonization resistance of mechanochemically active ferrosilicon tailings, respectively, but no coupling test was carried out. Zhang et al. [21] studied the application of cementitious materials with IOT and cementitious materials mixed with IOT in bricks and concrete. Zhao et al. [22] investigated the durability of UHPC by increasing the dosage of IOT during the experiment to obtain the optimal replacement rate of IOT from the perspective of macroscopic mechanical properties.

To sum up, most of the existing researchers focus on the single replacement of coarse aggregates or fine aggregates, but there are few studies on the combined replacement of coarse and fine aggregates. A large number of studies mainly focus on macromechanical properties, while there are few studies on microaspects. Therefore, sixteen groups of concrete with different replacement rates of iron tailings sand and recycled aggregate were prepared, and the apparent phenomena, mass loss, and RDEM of concrete samples were tested under different F-T cycles. NMR technology was employed to observe the variations of the inner pores of the concrete, and SEM was used to observe the microstructure changes of concrete. Frost resistance of iron ore tailings recycled aggregate concrete is revealed from the macro- and microangles to provide a theoretical foundation for the large-scale application of iron ore tailings recycled aggregate concrete in the high altitude and cold regions of the world.

2. Specimen Preparation and Experimental Design

2.1. Materials. The cement used was P.O42.5 ordinary silicate cement produced by Gansu Province Qilianshan Cement Group Co., the alpine province of China, and it had a flexural strength of 7.6 MPa and compressive strength of 48.7 MPa at 28 d. The indices of each parameter are shown in Table 1.

| Material | Flexural Strength | Compressive Strength |
|----------|------------------|----------------------|
| Cement   | 7.6 MPa           | 48.7 MPa              |
| IOT      | 1.58              | 43.2%                 |
| Bulk Density | 1435 kg/m3         |
| Apparent Density | 3426 kg/m3         |
| Moisture Content | 3.3%              |

The admixture iron ore tailings were produced in Jiangxiagou tailings pond in Luonan, Shangluo City, Shaanxi Province, China. Its fineness modulus was 1.58, porosity was 43.2%, bulk density was 1435 kg/m3, and apparent density was 3426 kg/m3. Table 2 shows the chemical composition of iron ore tailings. Figure 1 shows the XRD analysis and real graph of IOT.

The fine aggregate was river sand in Anning District, Lanzhou, China. The apparent density was 2580 kg/m3, the fineness modulus was 3.18, and the moisture content was 3.3%. The air-entraining agent SY-5 type powdered A-EA was used as the admixture.
extracted from the fruit of natural wild plants was selected, and its main active ingredient was triterpenoid saponins.

RCA came from China Lanzhou Delong Ecological Building Materials Co., Ltd. The RCA prepared from a normal C30 concrete building was selected, and this building was not subjected to salt attack. Before concrete pouring, RCA goes through the process of vibration, gradation screening, washing, and so on, and the particles with a size ranging at 5∼25 mm are selected. The RCA was wetted before the concrete was placed to ensure that the water-cement ratio remains the same for the actual situation.

According to the study by Wang et al. [23], it was found that the major reason for moving the performance of recycled aggregate is its ITZ. Contrasted with the interface structure of NAC, the interface structure of RAC is more complex, which was composed of ITZ1, ITZ2, and ITZ3. With the increasing replacement rate of RCA, the channel of water molecules into the concrete is also increased, which can make it reach critical water saturation of F-T harm more quickly. The structure of the multiple interfaces of RCA and the actual diagram is shown in Figure 2. Table 3 shows the performance of RCA and NCA. The NCA adopts the broke stone provided by Lanzhou of China Hualong Shang concrete Company. The particle gradation diagrams of fine and coarse aggregates are shown in Figure 3.

2.2. Experimental Design. According to the research results, three gradients were selected for the replacement rate of RCA and iron ore tailings sand (IOT), which were 0% and 30%, and 50%, respectively. The water-cement quantitative relation was 0.4, and the specifics of the mix ration are shown in Table 4.

This test adopts the quick F-T way and is in identity with the level of Test Methods of Long-term Performance and Durability of Ordinary Concrete (national standard of the People’s Republic of China, GB/T50082-2009). Figure 4 is shown as the flow chart of the F-T cycle.

The specimen sizes are 100×100×400 mm3 and 100×100×100 mm3. The former was used to test mass loss and RDEM. In this paper, a dynamic elastic modulus tester was accustomed to measure the RDEM of concrete specimens. The pulse speed was affected past the rigidity of the concrete, and the harder the internal structure is, the faster the pulse propagates from the transmitter to the receiver, indicating that the RDEM was higher [24]. The latter was used for microscopic analysis (NMR and SEM). NMR was used to analyze the changes in the internal pore structure of the specimens after damage by F-T cycles. The electron microscopy analysis was performed using a GeminiSEM500 field emission scanning electron microscope, which could be used for ultrahigh resolution microscopic morphological

| Quality parameter index | Detection value | Standard value | Quality parameter index | Detection value | Standard value |
|-------------------------|----------------|---------------|-------------------------|----------------|---------------|
| Specific surface area (m²/kg) | 348 | ≧300 | Chloride ion (%) | 0.012 | ≤0.06 |
| Sulphur trioxide (%) | 2.4 | ≤3.5 | Loss on burn (%) | 1.6 | ≤5.0 |
| Final setting time (min) | 220 | ≤600 | Magnesium oxide (%) | 2.0 | ≤5.0 |
| Safety and security | Qualified | Qualified | Initial setting time (min) | 145 | ≥45 |

Table 2: Chemical composition of IOT.

| Chemical composition | SiO2 | CaO | K2O | LOI | CuO | ZnO | Fe2O3 | Al2O3 | PbO | MnO |
|----------------------|------|-----|-----|-----|-----|-----|-------|-------|-----|-----|
| IOT (%)              | 56   | 4.3 | 1.5 | 3.3 | 0.2 | 0.1 | 8.3   | 10    | 0.4 | 1.7 |

Figure 1: IOT; (a) XRD pattern of IOT; (b) IOT real image.
Table 3: Major performances of RCA and NCA.

| Kinds | Packing density (Kg/m³) | Moisture content (%) | Mud content (%) | Apparent density (Kg/m³) |
|-------|-------------------------|----------------------|----------------|--------------------------|
| RCA   | 1500                    | 2                    | 2              | 2300                     |
| NCA   | 1390                    | 0.15                 | 0.15           | 2660                     |

Figure 2: RCA; (a) Multiple interface structure of RCA; (b) Real graph.

Table 4: Mixed proportions of concrete.

| Kings     | Cement (kg/m³) | Natural sand (kg/m³) | IOT (kg/m³) | Air-entrained agent (A-EA) (%) | NCA (kg/m³) | RCA (kg/m³) | Water (kg/m³) |
|-----------|----------------|----------------------|-------------|-------------------------------|-------------|-------------|---------------|
| RAC0-IOT0 | 512.50         | 504.75               | 0.00        | 0.02                          | 1177.75     | 0.00        | 205.00        |
| RAC0-IOT3 | 512.50         | 353.33               | 151.43      | 0.02                          | 1177.75     | 0.00        | 205.00        |
| RAC0-IOT5 | 512.50         | 252.38               | 252.38      | 0.02                          | 1177.75     | 0.00        | 205.00        |
| RAC0-IOT7 | 512.50         | 151.43               | 353.33      | 0.02                          | 1177.75     | 0.00        | 205.00        |

Figure 3: Coarse and fine aggregate gradation; (a) Coarse aggregate; (b) Fine aggregate.
characterization, microzone structure, and compositional analysis of the samples. Samples with three ITZs (15 mm × 15 mm × 15 mm) were prepared from the specimens by a cutting machine and placed in anhydrous ethanol to terminate hydration. The samples were placed in a vacuum oven at a temperature of 50°C for 2 days, and the samples were gold sprayed before SEM testing. RDEM, NMR, and SEM test instruments are shown in Figure 5. Among them, the mechanical properties were tested every 25 F-T cycles. When its RDEM was less than 60%, the mass change rate was more than 5%; i.e., it reached the prescribed amount of F-T cycles.

3. Results and Discussion

3.1. Analysis of Apparent Damage Phenomenon. Before the F-T cycle of concrete, the main body and end face of concrete were relatively smooth and smooth. Due to the addition of A-EA in the preparation process, semicircular microair bubbles appeared on the surface, and their number and size were not consistent. All the specimens had not failed after the design cycle, but some of them had spalling of surface mortar. The mass and RDEM of concrete did not change indeed in the early cycle (N < 100). After 100 cycles, the change range of mass and RDEM became improved with the increasing amounts of pores and microcracks on the concrete surface. Since the F-T cycle, the concrete specimen with the IOT replacement rate of 30% appeared, as shown in Figure 6. The damage degree of the specimen is multiplied by increasing the replacement rate of RCA. From Figure 6(c) that the change extent of the damage morphology of the specimen is RAC3-IOT3 > RAC0-IOT3 > RAC5-IOT3 > RAC7-IOT3.
3.2. Analysis of Quality Loss. The mass loss behavior of concrete is attributed to the very fact that the expansion stress caused by water freezing is greater than the tensile strength of concrete throughout the F-T cycle, resulting in microcracks and surface spalling within the specimen [25]. In this experiment, 200 F-T cycle tests of concrete specimens with different mix ratios were carried out. The loss of mass of RCA partially replacing NCA and IOT partially replacing natural sand is shown in Figure 7.

The mass loss of concrete was averaged over three specimens. From Figure 7(a), it can be seen that when only RCA replaces some of the NCA (without the addition of IOT), the mass loss decreases continuously with the F-T cycles and the reduction in the mass loss rate of RCA increases after 100 F-T cycles. And the mass loss rate keeps increasing with the increase of recycled coarse aggregate, which is different from the results of Qi et al. [26]. The mass loss rate of normal concrete is 0.8%, while at 70% replacement of recycled coarse aggregate, the mass loss rate reaches 1.53%, which is nearly twice the mass loss rate of normal concrete. The main reason for this phenomenon is that the loose pore structure in the initial mortar hooked up to the RCA is easy to expand and can cause cracks during the F-T cycle, leading to surface spalling and weight loss. The appearance of this phenomenon may be caused by harmful pores and cracks within the RCA and high water absorption [11]. Figure 7(b) shows the replacement of natural sand by IOT only (without the addition of RCA). The maximum mass loss rate of 1.45% was reached for the IOT replacement rate of 70%. The reason for this phenomenon may be the small fineness and poor compatibility of IOT [19]. From this, it can be seen that both replacing only RCA and replacing only IOT have negative effects on concrete, and the negative effects are greater as the replacement rate of RCA increases. And the IOT replacement rate of 50% is better than other replacement rates.

During the test, there was a mass loss rate of recycled aggregate concrete with IOT of different mix ratios (see Figure 8).

From Figure 8, under the function of F-T cycles, the mass of each group of concrete blocks decreased continuously in a certain range until 125 F-T cycles, when the mass loss of the concrete specimens changed from 150 to 200 cycles, the main reason being that the size of the concrete became smaller; thus, the bond between the concrete and NCA and RCA was not firm and was easy to scale. According to the test results, the incorporation of the A-EA during the preparation of the test block can improve the hydraulic accumulation of concrete earned by the F-T cycle and can slow down the rate of scaling on the surface [18]. As seen in Figure 8(a), considering the dosage of RCA is 30%, it can be found that the lowest quality loss is the replacement rate of IOT of 30%, reaching 0.89%. As shown in Figure 8(b), when the dosage of RCA is 50%, it is obvious that the mass loss lessens with a rise in the dosage of IOT. According to the test results, there is an optimal value between the dosage of RCA and IOT, which is because of the relatively weak interface between the new yet previous mortar within the multi-interface structure of RCA and because the IOT sand particles filled the pores, thereby improving the compactness of the concrete [27]. Excluding ordinary concrete, the concrete of RAC3-IOT3 has higher frost resistance, as the loss rate is 0.89%; the worst is RAC3-IOT7, as the loss rate is 1.72%.

3.3. Analysis of RDEM. The damage to concrete under the function of the F-T cycle is the result of repeated freezing of internal free water. The RDEM of RCA partially replacing NCA and IOT partially replacing natural sand is shown in Figure 9.

From Figure 9(a), it can be seen that the RDEM of ordinary concrete is optimal, and the largest loss of RDEM is RAC5-IOT0. The RDEM is only 79.92% of the initial one, which is 0.38% lower than that of RAC7-IOT0. When replacing only IOT, the largest loss of RDEM is RAC0-IOT7, which is 76.97% of the initial RDEM. As with the mass loss rate, the curve shift is more moderate compared to normal concrete, with no obvious abrupt change points. One of the main reasons for this phenomenon is that IOT also has high water absorption, and the higher water absorption has a negative impact on the F-T cycle [28]. Another reason is due to the poor adhesion between IOT and mortar, which leads to a higher mass loss rate of concrete mixed with IOT than normal concrete [24].

During the test, there was a RDEM rate of recycled aggregate concrete with IOT of different mix ratios (see Figure 10).

From the experiment results, before the F-T cycle, there was little difference in RDEM between concrete with different mix ratios and ordinary concrete. Behind the continuous enhancement of the number of cycles, the RDEM reductions continuously, yet the effects of RCA and IOT with different replacement rates on concrete are also different, as shown in Figure 10. (1) From Figures 10(a) and 10(b) that the decrease of RDEM is the smallest in RAC0-IOT0 ordinary concrete. The optimal mix ratio still appears in the concrete with a dosage of 30% RCA and 30% IOT, and its RDEM decreases to 86.1% and 84.21% after 200 F-T cycles. (2) The reduction of RDEM of concrete increases in the back of 100 F-T cycles, which is mainly because of the increasing number of microcracks within the concrete. However, the pores within the RCA with IOT are more than that of ordinary concrete, and the concrete incorporated with IOT has higher water absorption than ordinary concrete, and the taller water absorption has a destructive impact on the resisting force of F-T cycles [24]. (3) The RDEM data of concrete specimens RAC0-IOT0, RAC0-IOT3, RAC0-IOT5, RAC0-IOT7, RAC3-IOT0, RAC3-IOT3, RAC3-IOT5, RAC3-IOT7, RAC5-IOT0, RAC5-IOT3, RAC5-IOT5, RAC5-IOT7, RAC7-IOT0, RAC7-IOT3, RAC7-IOT5, and RAC7-IOT7 after 200 F-T cycles are 86.1%, 77.29%, 76.97%, 74.97% 81.5%, 84.21%, 83.3%, 78.3%, 79.92%, 78.27%, 76.76%, 78.5%, 77.3%, 81.6%, 80.69%, and 76.5%, respectively. The results show that the appropriate amount of IOT can effectively improve the multiple interfacial transition zone and compactness of RAC, and it can modify the mechanical performance of RAC. Nevertheless, the immediate
replacement rate of IOT can cut back the integrity of the matrix structure and enhance the number of deleterious pores that results in the decreased rate of RDEM [27].

3.4. Changes of Pore Structure Characteristics. The pore structure of concrete can be obtained by an NMR test at totally different stages of the F-T cycle, within which a pore diameter of fewer than 0.01 μm is a micropore, a middle pore radius is 0.01~0.05 μm, yet a large pore semidiameter is 0.05~1 μm microcrack larger than 1 μm in size. Therefore, the pore structure of iron ore tailings recycled aggregate concrete with different mix ratios was measured. The T2 distribution curves before F-T for RCA partially replacing NCA and IOT partially replacing natural sand are shown in Figure 11.

Figures 11(a) and 11(b) show the NMR T2 distribution curves of concrete with only RCA replacement and only IOT.
replacement. The first and second of the RCA and IOT replacement rate are higher than those of concrete with other replacement rates of 70%. The difference is not so great for 30% and 50% replacement rates of RCA. The volumes of large pores and cracks in the concrete in Figure 11 follow the order of RAC0-IOT0 < RAC5-IOT0 < RAC3-IOT0 < RAC7-IOT0, RAC0-IOT5 < RAC0-IOT3 < RAC0-IOT0 < RAC0-IOT7. This trend suggests that increasing the replacement rate of RCA increases the number of large pores and cracks, which is due to the fact that RCA has more pores and cracks [29]. And IOT has the effect of filling large pores and cracks within the concrete.

Before the F-T cycle, the pore structure of concrete is shown in Figure 12.

As can be seen from Figure 12, different combinations have a good influence on the internal pore structure of concrete. When the T2 spectrum curve is to the left, it shows that the relaxation time is short and that the relaxation speed is fast, indicating that there are mainly small pores in the specimen. When the T2 spectrum curve shifts to the right, it shows that the relaxation time is longer and the relaxation rate is slower, indicating that the internal pores of the specimen become larger. From the experimental results of

**Figure 7:** Mass loss rate of iron ore tailings recycled aggregate concrete during F-T cycle: (a) the dosage of IOT is 0%; (b) the dosage of RCA is 0%.

**Figure 8:** Mass loss rate of iron ore tailings recycled aggregate concrete during F-T cycle: (a) the dosage of RCA is 30%; (b) the dosage of RCA is 50%.
Figure 12(a), it can be seen that the first and second peaks of specimens RAC3-IOT0 and RAC3-IOT5 before the F-T cycle are significantly higher than those of RAC3-IOT3. It is speculated that the major reason for this phenomenon is that IOT can improve the pore structure of RAC. This is thanks to the small particle size and abnormal form of IOT, which might fill the junction region between NCA and RCA and cement mortar. Figure 12(b) shows that when the dosage of IOT is 30%, increasing the replacement rate of RCA can slightly increase the equilibrium of micropores and micro-cracks, reflecting that most of the pores until the F-T cycle are closed pores. Considering the dosage of RCA being 50%, increasing the replacement rate of IOT reduces the number of micro- and macropores. It is speculated that the major reason for this phenomenon is that IOT can improve the pore structure of RAC. This is thanks to the little particle size and abnormal form of IOT, which might fill the link region between NCA and RCA and cement mortar.

The comparative results of the T2 maps of RAC3-IOT0, RAC3-IOT3, RAC3-IOT5, RAC-IOT7, RAC0-IOT3, RAC5-IOT3, and RAC7-IOT3 specimens after the F-T cycle are shown (see Figure 13).
Figure 13 shows the pore distribution of concrete with different mix ratios before yet when the F-T experiment. The area of the left upper peak represents micropores and mesopores, and the area of the right lower peak represents microcracks. It was found that the spectra of the samples moved to the right gradually with the F-T cycle, which indicated that some micropores and mesopores developed into macropores, and the cracks formed between the micropores and macropores, which led to the increase in the number of cracks. It is found from Figure 13(a) that after 200 cycles of F-T, the peak value of micropore distribution of RAC3-IOT3 is surely smaller than that of RAC3-IOT0, RAC3-IOT5, and RAC3-IOT7, and the peak value of micropore distribution is 130.6%, 47.51%, and 133.09% less than that of RAC3-IOT0, RAC3-IOT5, and RAC3-IOT7, respectively. From Figure 13(b), the peak value of micropore distribution of the RAC3-IOT3 specimen was reduced by 40.71%, 28.49%, and 81.24%, compared with that of RAC0-IOT3, RAC5-IOT3, and RAC7-IOT3, respectively. The peak value of macropore distribution of RAC3-IOT3 specimens after the same 200 F-T cycles is clearly smaller than that of other specimens; however, the peak value of macropore distribution in the RAC5-IOT3 specimen increased by 38.32%. The reason for Figure 13 is that the interface structure of the RCA can be effectively improved by the proper amount of IOT, and the reason for the increase of the porosity of the concrete is that the following have negative effects on the porosity of RCA: the conversion zone of the interface structure of the RCA [30], three interfacial transition zones, ITZ1, ITZ2, and ITZ3. However, the surface of NCA is relatively smooth, and the complex surface texture of RCA also causes the high porosity of RCA; the proportion of slender and fatty particles in its interior increases the tendency of water aggregation near its surface, which weakens the interface transition zone. As may be seen from Figure 13(a), the amount of microcracks in the RAC3-IOT3 specimen before the beginning of the F-T cycle is higher than that after the F-T cycle. Two factors could be illustrated in this phenomenon. One is that a proper amount of RCA and IOT sand will effectively ameliorate the pore structure of concrete. The other reason is that the IOT sand belongs to nonactive admixtures. Considering the development of the F-T cycle, the degree of hydration of IOT is continuously happening, and the microcracks are filling constantly [31].

3.5. Deterioration of Microstructure and Properties after the F-T Cycle

3.5.1. Microstructure Performance Deterioration of Iron Ore Tailings Concrete with Replacement Rate of 0% after 200 F-T Cycles. Figure 14 shows the electron microscope scanning images of RAC0-IOT0, RAC3-IOT0, RAC5-IOT0, and RAC7-IOT0 concrete specimens under 200 F-T cycles, respectively.

From Figure 14(a), when the dosage of RCA and IOT is 0%, the cement paste is closely bonded, there are a large number of ettringite crystals, and some large cracks exist. As is often seen from Figure 14(b), when the dosage of RCA is 30%, there are fewer harmful macropores and more harmless small pores. The main reason for this phenomenon is that a suitable number of A-EA is added to the concrete, and the A-EA has improved a large amount of pores with a radius of 0.01–1 μm [32]. Compared with the specimen with 0% replacement rate of RCA, there are small cracks in the pores, the cracks are narrower in width and shorter in length, and there are no penetrating cracks. The cause is the frost heaving of the water in the pores, resulting in cracks in the pores. From Figure 14(c), cracks that run through the pores occur once the dosage of RCA is 50%. Due to the F-T cycle, the concentration of Ca(OH)2 within the cement stone decreases continuously, which promotes the
decomposition and dissolution of hydrates, resulting in structural damage; in addition, the bonding of cement stone is not as good as that of other specimens. The macroscopic phenomenon is that the mass loss is large, and the RDEM decreases rapidly. In contrast, when the RCA mixture reaches 70%, it is found from Figure 14(d), that the concrete as a whole presents a loose and porous state. One of the main reasons for this phenomenon is due to the RCA itself, and another reason is due to the freezing and swelling of the water in the pores [33].

3.5.2 Microstructure Performance Deterioration of Iron Ore Tailings Concrete with Replacement Rate of 30% after 200 F-T Cycles. Figure 15 is shown using the RAC0-IOT3, RAC3-IOT0, RAC3-IOT3, RAC3-IOT5 and RAC3-IOT7.
IOT, RAC5-IOT3, and RAC7-IOT3 scanning electron microscope images of concrete specimens with a 30% replacement rate of iron tailings.

In Figure 15(a), the micromorphology shows that the overall number of pores is less, but the number of cracks is larger and wider, and most of them are penetrating cracks. The reason for the analysis is that there are many micropores and potential microcracks within the RCA, which will release the freeze-thaw pressure in the pores in time, resulting in less frost heave pressure on the pores of the concrete, thus, the smaller the level of F-T harm. Because the content of SiO2 and Al2O3 in IOT is as high as 60%, which has a pozzolanic effect, it gradually reacts with Ca(OH)2 within the process of cement hydration to make hydration products like C-S-H, C-A-H, and Ettringite [34], which are compared in the three pictures in Figure 15. The number of cracks in Figure 15(b) is the least of the four specimens, with the narrowest crack width and fewer pores. It shows that increasing a suitable number of IOT can effectively improve the compactness of RAC and improve the mechanical performance of RAC. From Figure 15(c), the micromorphology is loose and porous as a whole, and the internal structure is loose and flocculent. Figure 15(d) shows that a large number of hydration products are generated inside the concrete pores and show a more sparse phenomenon. The major reason is the larger dosage of RCA is compared with the other two specimens; there are more pores, the pores are rougher, and the integrity is the worst. The surface is uneven and fragile, which has an important effect on the mechanical performance and durability of the concrete.

3.5.3. Microstructure Performance Deterioration of Recycled Concrete with a Replacement Rate of 30% after 200 F-T Cycles. Figure 16 is shown the RAC3-IOT0, RAC3-IOT3, and RAC3-IOT5 electron microscope scanning of the concrete specimen with a 30% replacement rate of RCA.

As is seen from Figure 16(a), its micromorphology is composed of Monosulfate aluminate plate structure bonding; there are many pores between the sheets, and its density is low. The main reason is that C-A-H is formed in the primary stage of hydration. With the subsequent hydration reaction of cement, C-A-H will become unstable, thus creating a
Figure 15: Microscopic damage characteristic diagram of samples (IOT replacement rate is 30%) under 200 F-T cycles: (a) RAC0-IOT3; (b) RAC3-IOT3; (c) RAC5-IOT3; (d) RAC7-IOT3.

Figure 16: Continued.
monosulfate aluminosilicate plate structure [35]. Macroscopically, it is relatively brittle, and it easily appears as a phenomenon of surface cracking and cement mortar shedding. The major reason for this phenomenon is that there are many pore structures of the original mortar on the shallow of the RCA, and the expansion of cracks, penetrating cracks, and microexpansion are more likely to occur in the process of F-T [36]. From Figure 16(b) that there are higher amounts of rod ettringite and C-S-H, indicating that the reaction between the substances is basically completed with the F-T cycle. From Figure 12(c), compared with Figure 16(b), the crack width of Figure 16(c) changes. Obviously, the number of cracks is higher, and the overall morphology changes less. This shows that when the replacement rate of IOT is high, its ability to resist the F-T cycle decreases. Macroscopically, the mass loss and RDEM of RAC3-IOT5 were much greater than that of the other two specimens. From the microscopic point of view, it shows that the acceptable quantity of iron ore tailings recycled aggregate concrete will well fill the pores and improve the interface transition area of RAC. The comparison of Figure 16(d) with Figure 16(a) reveals that the RAC mixed with IOT did not generate a significant monosulfate aluminosilicate plate structure inside. The reason for this phenomenon is analyzed to be the high content of alumina in the IOT. Aluminum oxide has the effect of preventing the reaction of C-A-H to produce a monosulfate slab structure [35].

4. Conclusions

The macroscopic performance and microstructure of iron ore tailings recycled concrete with different mix ratios before and when the F-T cycles are studied, and the main conclusions are as follows.

1. The mass loss rate, RDEM of concrete prepared by replacing NCA with RCA only increases with the increase in the replacement rate of RCA. At a replacement rate, the mass loss rate increases by 1.53%, and the relative dynamic modulus of elasticity is 77.3% of the initial rate. The number of macropores and cracks also increases with the increase of the replacement rate.

2. Concrete prepared using only IOT to replace natural sand, in addition to ordinary concrete, have the smallest mass loss rate of 1.05% with 50% IOT admixture and a RDEM of 76.97% of the initial. And concrete with 30% and 50% IOT admixture has a lower number of large holes and cracks than normal concrete, indicating that the appropriate amount of IOT has a better filling effect on large holes and cracks.

3. After the start of the freeze-thaw cycle, the mass and RDEM of iron ore tailings recycled aggregate concrete with sixteen different mix ratios decreased slowly at the beginning and then decreased rapidly. After the F-T cycles, the mass loss rate of the RAC0-IOT5 specimens reached 1.67%, and the RDEM loss rate reached 23.03%, with the largest decrease. The mass loss rate of the RAC3-IOT3 specimen is 0.89%, and the RDEM is reduced by 15.79%, which is the smallest except for ordinary concrete. Therefore, the RAC3-IOT3 specimen has the best mechanical properties, except for ordinary concrete.

4. The porosity of RAC will increase with increasing RCA content, and therefore the proportion of micropores and cracks increases. The incorporation of IOT reduces the number of enormous pores and cracks in RAC, yet also the peak distribution of micropores in RAC3-IOT3 is 56.64% lower than that in RAC3-IOT0. The peak distribution of large holes in RAC3-IOT5 is 108.63% higher than that in RAC3-IOT3, which leads to an increase in the amounts of large holes in concrete and influences the corresponding mechanical performance of concrete.

5. Through SEM micromorphology analysis, the basic structure of concrete is analyzed from the microlevel of the IOT and RCA replacement rates, and their
macroscopic mechanical properties are verified. With the increasing dosage of RCA, the bonding force between cementitious material and sand aggregate weakens, and there are more pores. The combination of excess IOT and RCA does not improve the interface transition zone of RCA but will accelerate the spalling of surface mortar because of its small fineness. Considering RAC3-IOT3 can meet the mechanical properties, make full use of waste materials, and reduce environmental pollution; thus, it is the most suitable concrete for high altitudes and cold regions.

**Nomenclature**

RAC: Recycled aggregate concrete  
IOT: Iron ore tailings sand  
NAC: Natural aggregate concrete  
ITZ2: Old aggregate–new mortar  
RCA: Recycled coarse aggregate  
APAC: Air-entrained RAC  
C-S-H: Calcium silicate hydrated  
SEM: Scanning electron microscope  
ITZ: Interface transition zone  
UHPC: Ultra-high-performance concrete  
ITZ1: Old mortar–new mortar  
A-EA: Air-entrained agent  
ITZ3: Old aggregate–old mortar  
F-T: Freeze-thaw  
C-A-H: Calcium aluminate hydrated  
NMR: Nuclear magnetic resonance  
RDEM: Relative dynamic elastic modulus  
NCA: Natural coarse aggregate.

**Data Availability**

The data used to support the findings of this study are included within the article.

**Conflicts of Interest**

The authors declare no conflicts of interest.

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**References**

[1] B. Jiwen, Y. Zhihao, and Z. Peng, "Review on frost resistance property of recycled coarse aggregate concrete and its structural components," *Journal of Building Structures*, vol. 04, no. 43, pp. 142–157, 2022.

[2] Y. Zheng, J. Zhuo, and P. Zhang, "A review on durability of nano-SiO2 and basalt fiber modified recycled aggregate concrete," *Construction and Building Materials*, vol. 304, Article ID 124659, 2021.

[3] L. Deren, Z. Dong, and Z. Shimin, "Increase insulation effect of polyurethane board pasting on closed aqueduct surface in cold regions," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 29, no. 9, pp. 70–75, 2013.

[4] G. L. K. Chuntao and W. Hong, "Mechanism of aqueducts in cold and dry areas under effect of salt-frozen coupling erosion," *China Safety Science Journal*, vol. 30, no. 11, pp. 43–52, 2020.

[5] K. Robalo, R. do Carmo, H. Costa, and E. Júlio, "Experimental study on the interface between low cement recycled aggregates concrete and ultra-high durability concrete," *Construction and Building Materials*, vol. 304, Article ID 124603, 2021.

[6] S. Silva, L. Evangelista, and J. de Brito, "Durability and shrinkage performance of concrete made with coarse multi-recycled concrete aggregates," *Construction and Building Materials*, vol. 272, Article ID 121645, 2021.

[7] M. Abed, R. Nemes, and B. A. Tayeh, "Properties of self-compacting high-strength concrete containing multiple use of recycled aggregate," *Journal of King Saud University - Engineering Sciences*, vol. 32, no. 2, pp. 108–114, 2020.

[8] S. Jahandari, M. A. Mohammadi, A. Rahmani et al., "Mechanical properties of recycled aggregate concretes containing silica fume and steel fibres," *Materials*, vol. 14, no. 22, p. 7065, 2021.

[9] A. Li, G. Zhou, X. Zhang, and E. Meng, "Compressive mechanical properties of a novel recycled aggregate concrete with recycled lightweight Aggregate," *Advances in Materials Science and Engineering*, vol. 2021, Article ID 2134082, 13 pages, 2021.

[10] J. Wang, J. Zhang, and D. Cao, "Pore characteristics of recycled aggregate concrete and its relationship with durability under complex environmental factors," *Construction and Building Materials*, vol. 272, Article ID 121642, 2021.

[11] X. Deng, X. Gao, W. Rui et al., "Investigation of micro-structural damage in air-entrained recycled concrete under a freeze-thaw environment," *Construction and Building Materials*, vol. 268, Article ID 121219, 2021.

[12] S. Diamond and J. Huang, "The ITZ in concrete ± a different view based on image analysis and SEM observations," *Cement and Concrete Composites*, vol. 23, no. 2–3, pp. 179–188, 2001.

[13] S. M. S. Taher, J. H. Haido, and B. A. Tayeh, "Behavior of geopolymer concrete deep beams containing waste aggregate of glass and limestone as a partial replacement of natural sand," *Case Studies in Construction Materials*, vol. 15, Article ID 600744, Dec. 2021.

[14] M. Elsayed, B. A. Tayeh, M. Mohamed, and M. A. H. Elmany, "Punching shear behaviour of RC flat slabs incorporating recycled coarse aggregates and crumb rubber," *Journal of Building Engineering*, vol. 44, Article ID 103363, 2021.

[15] M. Amin, A. M. Zeyad, B. A. Tayeh, and I. Saad Agwa, "Effects of nano cotton stalk and palm leaf ashes on ultrahigh-performance concrete properties incorporating recycled concrete aggregates," *Construction and Building Materials*, vol. 302, Article ID 124196, Oct. 2021.

[16] P. Saloni, Y. Y. Parveen, Y. Y. Lim, and T. M. Pham, "Effective utilisation of ultrafine slag to improve mechanical and durability properties of recycled aggregates geopolymer concrete," *Cleaner Engineering and Technology*, vol. 5, Article ID 100330, 2021.
[17] B. Ali, S. S. Raza, R. Kurda, and R. Alyousef, “Synergistic effects of fly ash and hooked steel fibers on strength and durability properties of high strength recycled aggregate concrete,” *Resources, Conservation and Recycling*, vol. 168, Article ID 105444, May 2021.

[18] A. U. Shettima, M. W. Hussin, Y. Ahmad, and J. Mirza, “Evaluation of iron ore tailings as replacement for fine aggregate in concrete,” *Construction and Building Materials*, vol. 120, pp. 72–79, Sep. 2016.

[19] J. Zhao, K. Ni, Y. Su, and Y. Shi, “An evaluation of iron ore tailings characteristics and iron ore tailings concrete properties,” *Construction and Building Materials*, vol. 286, Article ID 105444, May 2021.

[20] Y. Cheng, F. Huang, S. Qi, and W. R. G. Li, “Durability of concrete incorporated with siliceous iron tailings,” *Construction and Building Materials*, vol. 242, Article ID 118147, May 2020.

[21] N. Zhang, B. Tang, and X. Liu, “Cementitious activity of iron ore tailing and its utilization in cementitious materials, bricks and concrete,” *Construction and Building Materials*, vol. 288, Article ID 123022, 2021.

[22] Y. Zhao, X. Gu, J. Qiu, and W. X. Zhang, “Study on the utilization of iron tailings in ultra-high-performance concrete: fresh properties and compressive behaviors,” *Materials*, vol. 14, no. 17, p. 4807, 2021.

[23] Y. Wang, Y. Peng, M. M. A. Kamel, and L. Gong, “Modeling interfacial transition zone of RAC based on a degenerate element of BFEM,” *Construction and Building Materials*, vol. 252, Article ID 119063, Aug. 2020.

[24] F. Xu, S. Wang, T. Li, and B. B. Y. Liu, "The mechanical properties and resistance against the coupled deterioration of sulfate attack and freeze-thaw cycles of tailing recycled aggregate concrete," *Construction and Building Materials*, vol. 269, Article ID 121273, Feb. 2021.

[25] F. Xu, S. Wang, T. Li, and B. B. Y. Liu, "The mechanical properties of tailing recycled aggregate concrete and its resistance to the coupled deterioration of sulfate attack and wetting-drying cycles," *Structures*, vol. 27, pp. 2208–2216, Oct. 2020.

[26] B. Qi, J. Gao, F. Chen, and D. Shen, “Evaluation of the damage process of recycled aggregate concrete under sulfate attack and wetting-drying cycles,” *Construction and Building Materials*, vol. 138, pp. 254–262, May 2017.

[27] T. Li, S. Wang, F. Xu, and X. B. M. Meng, “Study of the basic mechanical properties and degradation mechanism of recycled concrete with tailings before and after carbonation,” *Journal of Cleaner Production*, vol. 259, Article ID 120923, Jun. 2020.

[28] D. Chan and P. C. Sun, “Effects of fine recycled aggregate as sand replacement in concrete,” *HKIE Transactions*, vol. 13, no. 4, pp. 2–7, 2006.

[29] H. Liu, C. Liu, G. Bai, and C. Zhu, “Study on the effect of chloride ion ingress on the pore structure of the attached mortar of recycled concrete coarse aggregate,” *Construction and Building Materials*, vol. 263, Article ID 120123, Dec. 2020.

[30] Y. Zhang, X. Lin, J. Zhou, and H. Z. Sun, “Numerical simulation of mechanical properties of recycled concrete based on characterization of interfacial transition zone characteristics,” *Journal of Physics: Conference Series*, vol. 1865, no. 3, Article ID 032013, 2021.

[31] Z. Ding, B. Kong, X. Wei, and M. B. F. Zhang, “Laboratory testing to research the micro-structure and dynamic characteristics of frozen-thawed marine soft soil,” *Journal of Marine Science and Engineering*, vol. 7, no. 4, p. 85, 2019.