The Concrete Performance with Iron Tailings Sand Modified by Polypropylene Fibers under Aggressive Environment

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1. Introduction

How to address and utilize iron tailings sand (ITS) has become an important topic [1–3]. Many scholars regard iron tailings sand as a fine aggregate in concrete, which not only solves the pollution problems but also provides raw materials for construction [4–7]. Lv et al. [8], Umara Shettima et al. [9], and Cheng et al. [10] found that the strength of concrete with iron tailings basically meets the requirements and is higher than that of ordinary concrete.

Some scholars have stated that the concrete with ITS had a poor performance under special conditions. Shettima et al. [11] found that the mass of concrete with ITS decreased faster than that of ordinary cement concrete when exposed to acid and salt solution. Zhang et al. [12] found that, after 200 freeze-thaw cycles, the mass and the compressive strength of the concrete with ITS reduced by 5% and 25%, respectively. Tian et al. [13] found that the impermeability and carbonization resistance of concrete with ITS changed little at low temperatures, but the frost resistance decreased greatly. Sunil et al. [14] have carried the study to test the deterioration of the concrete with tailing material exposed to sulfate solutions. After 56 days, the loss in weight of the concrete cube specimen is of average 1.16% and the increase in strength is of average 4.48%. Zhang et al. found that the expansion variation reached a stable value of 0.052% after 330 days. Therefore, improving the performance of concrete with iron tailings sand under aggressive environment, such as saline soils and salt lake areas, is an urgent problem to be solved.

To make the concrete with iron tailings sand have a good performance under aggressive environment, some scholars have conducted corresponding research on controlling the content of ITS. Umara Shettima et al. [9] and Kuranchie...
et al. [15] found that the performance of concrete can be improved to some extent when the content of iron tailings sand is approximately 30%. Although reducing the content of ITS in concrete can improve the properties of concrete, the demand for natural sand will increase. So, the practical problems have not been solved thoroughly. The other way to ensure the concrete with ITS has good applicability is adding mineral admixtures that can reduce the formation of gypsum and further ettringite. Sunil et al. [14] have found that the concrete blended with 35% Tailings Material in place of river sand and 20% Fly Ash in place of cement has exhibited higher durability characteristics. Xiong et al. [16] added a certain amount of barium carbonate (BaCO₃) to concrete with iron tailings; the sulfate corrosion resistance of the concrete was improved, but this will produce calcium carbonate (CaCO₃) and barium sulfate (BaSO₄). In the recent years, scholars have begun to use fibers to improve the properties of concrete, which is a widely recognized practice by the society. Alavi et al. [17], Awal et al. [18], and Mohammadhosseini et al. [19] found that the compressive strength and flexural strength of concrete with fibers were improved. Blunt et al. [20] found that the concrete with hybrid fibers increased the anticorrosion rate and improved the anticracking performance. Geng et al. [21] found that the sulfate resistance of concrete with fibers increased by 10 times. Murali and Vinodha [22] found that, after 200 freeze-thaw cycles, concrete strengthened by steel fibers had less spalling and fewer cracks. Xu et al. [23] found that polypropylene fibers in concrete can play a role in arresting cracks and bridging, reducing the probability of cracks, and inhibiting the expansion of cracks. Hay and Ostertag [24] found that fibers affect crack widths in concrete and the bridging function of the fiber restricts crack propagation. Li et al. [25] conducted laboratory experiments and found that nanofibers can refine the pore size and improve the frost resistance. So, fibers can be used to modify the properties of the concrete.

However, there are a few research studies on the improvement of the performance of concrete with ITS by adding fibers under aggressive environment. So, based on the abovementioned findings, fibers used as a measure to improve the properties of concrete with ITS may be a good choice. The purpose of this paper is to study whether polypropylene fibers can be used to improve the performance of concrete with ITS. In this study, a series of tests have been carried out for ordinary concrete, concrete with ITS, and concrete with ITS modified by polypropylene fibers under the condition of drying-wetting cycles in 5%Na₂SO₄ solution to analyze whether polypropylene fibers can improve the performance of concrete with ITS. This research also provides a new way to modify the properties of concrete with ITS.

2. Materials and Test Condition

This paper designs three concrete mixes: ordinary concrete, concrete with ITS, and concrete with ITS modified by polypropylene fiber. Tests on the pores distribution, crack width, corrosion products, mass variation, expansion variation, compressive strength, flexural strength, and the diffusion of sulfate ions of the concrete under the condition of drying-wetting cycles in 5% Na₂SO₄ solution are carried out.

2.1. Raw Materials and Mix Ratios

2.1.1. Raw Materials. Ordinary Portland cement with a strength of 42.5 MPa was used in the test. The coarse aggregate is crushed stone with a diameter of 5–20 mm. Tap water in Xi’an city of Shaanxi Province was used as mixing water. Polycarboxylic acid superplasticizer was used in the test. Polypropylene fibers with a diameter of 20 μm, length of 6 mm, tensile strength greater than 486 MPa, modulus of elasticity higher than 4.8 GPa, and an ultimate elongation rate of 4.1% were used in the test. Fine aggregates consisted of natural sand (NS) and ITS. The parameter indexes are shown in Table 1. The apparent density and bulk density of the ITS are obviously higher than those of NS due to the high iron phase minerals in the ITS, which corresponds to the finding by Lv et al. [8] that ITS has a higher specific gravity range from 265 to 340 compared with NS.

The size of the NS and ITS is 0–4.75 mm. The grain size distributions of the ITS and natural sand are shown in Table 2, and their curves are shown in Figure 1. The fineness modulus of the NS and ITS are 2.64 and 1.53, respectively, which is caused by the higher content of 0.0–0.6 mm in ITS.

2.1.2. Mix Ratios. Three concrete mixes were designed: ordinary concrete, concrete with ITS, and polypropylene fibers-modified concrete with ITS. The mass of NS replaced by ITS was 30% according to the literature [9, 12–15, 26], and the volume of polypropylene fibers added as an addition is approximately 0.1% according to the literature [19, 21, 27–29]. They are shown in Table 3.

2.2. Test Conditions. The casting and curing conditions of the concrete mixtures comply with the GB 50081-2002 [30] and GB/T 50082-2009 [31].

2.2.1. Specimen Casting. 150 mm × 150 mm × 150 mm cubic specimens were used to test the pores distribution, crack width, corrosion products, mass variation, expansion variation, compressive strength, and diffusion of sulfate ions. 150 mm × 150 mm × 550 mm prism specimens were used to test the flexural strength. The mixing process details are shown as follows: (1) dry fine aggregates and cement are added into the mixer, the mixer is started for 2 min, and at the same time, the polypropylene fibers are dispersed into the running mixer slowly by hand to ensure uniform distribution. (3) The tap water and superplasticizer are poured into the mixer, and the mixer is run for 2 min. (4) Coarse aggregates are added into the mixer and left on running for 3 min. Once the mixing process is completed, the concrete is poured into the cubic and prism models brushed with isolation oil. Then, the specimens are vibrated at a vibrating table for 3.3 min to make concrete compacting.
2.2.2. Specimens Curing. After curing for 24 hours, the cubic and prism concrete specimens were demolded and, then, cured for 28 days under standard conditions (22 ± 2°C and relative humidity 95 ± 3%). After that, the cubic and prism specimens were exposed to an aggressive environment (140 days of drying-wetting cycles in 5% Na₂SO₄ solution). The process of each cycle is shown in Figure 2. Each cycle takes 14 days. There are 10 cycles. This cycle regime is close to that used by Nehdi et al. [32] and Zhang et al. [33].

It should be noted that, for the cubic specimens, one surface was left for Na₂SO₄ erosion and the five other surfaces were sealed with paraffin [34]. Then, the specimens were placed in a plastic box with 5% Na₂SO₄ solution (Figure 3). The unsealed surface faced up horizontally. The height of the 5% Na₂SO₄ solution exceeded 10 cm of the top surface of the specimens. The prism specimens were cured in this condition without a paraffin cover.

2.2.3. Section Preparation. The procedure to sections preparation is according to the literature [35]. After exposed to 140 days of drying-wetting cycles in 5% Na₂SO₄ solution, the cubic specimen was cut into 5 sections, each of which is 28 mm (2 mm reduction due to cutting wear). Sections 1 and 5 were discarded due to the surface being in direct contact with the solutions to which the specimens were exposed.

### Table 1: Parameter indexes of NS and ITS.

| Fine aggregate | Apparent density (kg/m³) | Bulk density (kg/m³) | Water absorption (%) | Fine powder composition | Iron phase 6 minerals (%) |
|----------------|--------------------------|----------------------|----------------------|-------------------------|--------------------------|
| Natural sand   | 2650                     | 1410                 | 1.6                  | Soil                    | 2                        |
| ITS            | 3270                     | 1740                 | 3.9                  | Stone powder            | 9                        |

### Table 2: Grain size distribution of NS and ITS.

| Particle size range (mm) | 0~0.15 | 0.15~0.3 | 0.3~0.6 | 0.6~1.18 | 1.18~2.36 | 2.36~4.75 | Fineness modulus |
|--------------------------|--------|----------|---------|----------|-----------|-----------|-----------------|
| NS (%)                   | 8      | 13       | 23      | 23       | 29.5      | 3.5       | 2.64            |
| ITS (%)                  | 30     | 18       | 32      | 12       | 5         | 3         | 1.53            |

### Table 3: Mixture proportion of three concrete mixes.

| Design goal | Sand (%) | Water-cement ratio | Polypropylene fibers volume fractions (%) |
|-------------|----------|--------------------|------------------------------------------|
|             | NS       | ITS                | Polypropylene fibers                     |
| CI0P0       | 100      | 0                  | 0                                         |
| CI30P0      | 70       | 30                 | 0                                         |
| CI30P0.1    | 70       | 30                 | 0.1                                       |

Note: CI30P0.1 represents 30% ITS and 0.1% polypropylene fibers.

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**Figure 1:** Grain size distribution curves of NS and ITS.

**Table 1:** Parameter indexes of NS and ITS.

**Table 2:** Grain size distribution of NS and ITS.

**Table 3:** Mixture proportion of three concrete mixes.
Sections 2 and 4, shown in Figure 4, were selected for the following test.

3. Laboratory Test Design

3.1. Scanning Electron Microscope (SEM) Test. Before the SEM test, a drilling machine with diameters of 5 mm and heights of 3 mm was used to get several samples from section 2 of three concrete after 140 days of drying-wetting cycles in 5% Na$_2$SO$_4$ solution. A sample with few cracks selected from several samples is used to carry out the test. The test were carried by using an S-4800 SEM. Samples used for SEM testing were dried in an oven for 24 hours, then sprayed with gold, and finally scanned by electron microscopy at a 15 kV accelerated voltage. The SEM images were divided into two parts by IPP (Image-Pro Plus). One is the dense part of concrete, and the other is the pore part of concrete.

3.2. X-Ray Diffraction (XRD) Test. Before the XRD test, the powder samples used for the X-ray diffraction analysis were ground from section 2 of three concrete after 28 and 140 days of drying-wetting cycles in 5% Na$_2$SO$_4$ solution. The powder samples were sieved through a 75 $\mu$m sieve. The crystalline minerals were characterized by using a Bruker D8-Advance with Cu-Kα = 1.5406 Å, step size of 0.02°, measuring time of 15 s/step, and the position begins at 5° to 80°.

3.3. Mass Variation Rate. After 28 days of standard curing, the initial mass of the cubic specimens was measured to be $M_0$, which is accurate to 0.001 kg. Then, after 140 days of drying-wetting cycles in 5% Na$_2$SO$_4$ solution, the mass of the cubic specimens at 28, 56, 84, 112, and 140 days was $M_t$. The mass of each specimen was measured 5 times, and the average values were recorded for calculation and analysis. The mass change rate $\Delta M_t$ was calculated by

$$\Delta M_t = \frac{(M_t - M_0)}{M_0}.$$  \hfill (1)

3.4. Expansion Variation Rate. After 28 days of standard curing, the vernier caliper was used to measure the length of the cubic specimens, which is accurate to 0.1 mm. The initial length of the cubic specimens was measured to be $L_0$. Then, after 140 days of drying-wetting cycles in 5% Na$_2$SO$_4$ solution, the length of the cubic specimens at 28, 56, 84, 112, and 140 days was $L_t$. The length of each specimen was measured 5 times, and the average values were recorded for calculation and analysis. The expansion $\Delta L_t$ was calculated by
3.5. Compressive Strength and Flexural Strength. After 28, 56, 84, 112, and 140 days of drying-wetting cycles in 5% Na$_2$SO$_4$ solution, a compression machine was used to test the compressive strength, and the loading speed was 0.3 MPa/s. A three-point loading method was used to test the flexural strength, and the loading speed was 0.5 MPa/s.

3.6. Sulfate Ion Diffusion Test. After finishing the concrete compressive strength test in each curing time, the specimens could be cut into 5 sections, shown in Figure 4, and section 2 and section 4 were used to test the sulfate concentrations, rather than thrown away. The sulfate concentrations at different time were determined by chemical titration. This method has been used by Blunt et al. [20]. The detailed process of sulfate concentrations test is shown in Figure 5.

4. Analysis of the Test Results

4.1. The Results of the SEM Test

4.1.1. The Pores Distribution. The SEM images were analyzed by IPP software, which made black represent the number of pores. The results show that the number of pores in each size and the percentage of pore content of three kinds of concrete were distributed according to Table 4 and Figure 6.

From Table 4, after 140 days of drying-wetting cycles in 5% Na$_2$SO$_4$ solution, it is known to us that the ranked order of the total number of pores is CI0P0 > CI30P0 > CI30P0.1. At the same time, the number of pores in CI0P0 is the highest, but the number of pores in CI30P0.1 is the lowest. This is mainly because the erosion of concrete is restrained by polypropylene fiber, which makes the pore structure of concrete in a relatively dense state. The pores caused by expansion stress are considered, which is different from the research by Yang et al. [36].

As shown in Figure 6, the pores diameter is mostly 0–20 μm. According to Rasheeduzzafar et al. [26, 37], pores with a diameter of 0.1 μm are defined as the threshold that influences permeability properties, so the pores with a diameter larger than 0.1 μm are harmful to the concrete. The proportion of pores (>0.1 μm) in CI0P0, CI30P0, and CI30P0.1 was more than 69%, 61%, and 54%. This indicates that the proportion of pores diameters (>0.1 μm) in CI30P0.1 is lower than that in CI0P0 and CI30P0. This is mainly because large amounts of expansive AFT and gypsum cause the formation of harmful pores. It is similar to the observations of other researchers for concrete with fly ash [38, 39].

In other words, the proportion of pore diameter (<0.1 μm) in CI30P0.1 is higher than that in CI0P0 and CI30P0. This is mainly because the polypropylene fibers restrain the pores diameter to enlarge [25], further making the whole structure of the concrete more complete [9, 20, 22–40].

4.1.2. Crack Width Analysis. The SEM images analyzed by IPP software are two dimensional, and the crack can only expand along the horizontal direction, so there only exists the crack width, and the crack width is shown in Figures 7(a)–7(c).

Figures 7(a)–7(c) show that CI0P0, CI30P0, and CI30P0.1 all produce cracks. The widths of the cracks are approximately 3, 5, and 2 μm, respectively. This is mainly because in the process of 140 days of drying-wetting cycles in 5% Na$_2$SO$_4$ solution, the sodium sulfate reacts with hydrates to form AFT and gypsum, which will fill up large amounts of pores, making volume expansive. When the expansion stress is bigger than the concrete tensile stress, the concrete begins to crack.

As shown in Figures 7(a)–7(c), the crack width of CI30P0 is larger than that of CI0P0. This is mainly because ITS has the rough particles, which can be embedded in the coarse aggregates, making the concrete compact [9]. With the accumulation of expansive corrosion products, the expansion pressure cannot be consumed by the tensile stress of CI30P0, so that the concrete surface peels off and forms longer and wider cracks, as shown in Figure 7(b). This phenomenon has been observed in the research by Zhang et al. [33]. Figures 7(b) and 7(c) show that the crack width of CI30P0 is larger than that of CI30P0.1. This is mainly because the tensile stress of polypropylene fiber can consume a part of expansion stress of gypsum and AFT in pores, which makes CI30P0.1 not crack easily. Polypropylene fibers play a role in bridging the crack, alleviating the sulfate ion attack on concrete [41], as shown in Figure 8. This is similar to the research by Mohammadhosseini et al. [19]; they found that cracks were very fine and small in size compared to those of the specimens without any fibers.
4.2. The Results of the XRD Test. After 28 and 140 days of drying-wetting cycles in 5% Na$_2$SO$_4$ solution, the changes of crystalline minerals of corrosion products are as shown in Figure 9.

As shown in Figure 9, after 28 and 140 days of drying-wetting cycles in 5% Na$_2$SO$_4$ solution, there are crystalline phases identified from XRD patterns, such as Portlandite, Quartz, Calcite, Ettringite, Gypsum, and others. This is mainly due to the chemical reactions between hydrates and Na$_2$SO$_4$. The reactions are shown in the following equations [21, 35, 42]:

\[ 3(\text{CaSO}_4 \cdot \text{H}_2\text{O}) + 4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 12\text{H}_2\text{O} + 14\text{H}_2\text{O} \rightarrow 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 31\text{H}_2\text{O} + \text{Ca(OH)}_2 \]  

\[ \text{Ca(OH)}_2 + \text{SO}_4^{2-} + 2\text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot 32\text{H}_2\text{O} + 2\text{OH}^- \]

Figure 9 shows that the characteristic peak area of AFT and gypsum at 140 days is greater than that at 28 days. This is mainly because at 140 days, the sulfate ions concentration diffused into concrete is the highest, which can provide enough SO$_4^{2-}$ to react with hydrates. However, it is obvious that the characteristic peak area of Portlandite at 140 days is lower than that at 28 days. This implies that the calcium hydroxide is consumed after the specimen is exposed to 140 days of drying-wetting cycles in 5% Na$_2$SO$_4$ solution [20]. So, the production of AFT and gypsum and the consumption of calcium hydroxide are in accordance with the law of conservation of mass.

From Figure 9(b), compared CI30P0.1 with CI0P0 and CI30P0, the characteristic peak area of AFT and gypsum in CI30P0.1 is the lowest. This indicates the content of ettringite
Figure 6: Pore size distribution of section 2 in CI0P0, CI30P0, and CI30P0.1.

Figure 7: Concrete crack width. (a) CI0P0. (b) CI30P0. (c) CI30P0.1.
and gypsum of the concrete with ITS modified by polypropylene fiber is the lowest. This is mainly because the polypropylene fiber plays a role in bridging the aggregates more tightly and inhibiting the crack development, alleviating the sulfate ion attack on concrete [39]. These results can be used to explain the following test phenomenon.

4.3. The Results of Mass Variation. Figure 10 shows that, from 28 to 56 days, the mass variation rate of CI0P0, CI30P0, and CI30P0.1 is positive. This indicates that the mass of CI0P0, CI30P0, and CI30P0.1 is increasing. This phenomenon is caused by the increase of AFT and gypsum, which can be inferred from equations (3) and (4) [42]. From 56 to 140 days, the mass variation rate of CI0P0, CI30P0, and CI30P0.1 are change from positive to negative. This indicates that the mass of CI0P0, CI30P0, and CI30P0.1 are decreasing. The reason for this change is that, with the sulfate ions in the concrete increasing, the amount of AFT and gypsum produced by the reaction of the sulfate ions with the
hydrates is increasing. The concrete begins to peel and crack for the increasing expansion stress from AFT and gypsum, which makes the mass of three concrete decrease [22].

As shown in Figure 10, when it was at 56 days, the mass variation rate of CI0P0, CI30P0, and CI30P0.1 reaches a maximum, 0.43%, 0.38%, and 0.32%, respectively. This is mainly because the pores of CI0P0, CI30P0, and CI30P0.1 have been filled by AFT and gypsum completely. This similar phenomenon has been observed by the research [16]. When it was at 84 days, the mass of CI0P0 and CI30P0 begins to be less than that of the initial stage of drying-wetting cycles in 5% Na$_2$SO$_4$ solution. This is mainly because the mass loss of concrete by peel and crack is larger than the amount of AFT and gypsum increase. However, the mass of CI30P0.1 is still higher than that of the initial stage of drying-wetting cycles in 5% Na$_2$SO$_4$ solution, which is attributed to the existence of polypropylene fiber bridging the aggregates, restricting the peel and crack of the concrete. At 140 days, the mass of CI0P0, CI30P0, and CI30P0.1 decreased by 1.35%, 1.46%, and 0.83%, respectively, compared with the initial mass; that is to say, the mass variation rate of CI30P0.1 is the smallest. This indicates that the polypropylene fiber can reduce the mass loss of concrete with ITS.

4.4. The Results of Expansion Variation. From Figure 11, it can be seen that the expansion variation rate of CI0P0 and CI30P0 all show a gradual increasing trend; however, the expansion of CI30P0.1 shows an increasing trend first and, then, becomes moderate. The expansion variation rate of CI0P0, CI30P0, and CI30P0.1 reaches a maximum at 140 days, and they are 0.0560%, 0.0612%, and 0.0352%, respectively. This is mainly because the diffusing sulfate ions reacts with cement hydrate to produce AFT and gypsum, and it expands the volume up to about 3.0 times the original volume. The similar observations have also been obtained by many other researchers [20, 32–34].

As shown in Figure 11, compared CI30P0 with CI0P0, the expansion variation rate of CI30P0 is lower than that of CI0P0 from 0 to 84 days. This is mainly because the ITS makes the structure of CI30P0 denser than that of CI0P0, retarding migration of sulfate ions and expansion of pastes. However, from 84 to 140 days, the expansion variation rate of CI30P0 is higher than that of CI0P0. This is because the sulfate ion in CI30P0 reacts with cement hydrates to form expansive gypsum and AFT in pores, which only fill the pores of pastes initially. With the accumulation of expansive corrosion products, the expansion pressure formed in the limited pore space, thus forming expansion deformation [43]. In addition, it is known that the expansions variation rate of CI30P0.1 and CI30P0 is basically increasing from 0 to 56 days, which indicates that the expansive gypsum and AFT is forming in CI30P0.1 and CI30P0, and the polypropylene fibers do not play the role inhibiting the expansion of CI30P0.1 at this time. Mardani-Aghabaglou et al. [44] obtained the similar experimental result; that is, within the first 30 days after production, the expansion values of all specimens were close to each other.

However, from 56 to 140 days, the expansion variation rate of CI30P0.1 begins to be stable, and the expansion variation rate of CI30P0 is still increasing fast. This is mainly because a part of expansion stress of gypsum and AFT in pores is consumed by the tensile stress of polypropylene fiber, which makes CI30P0.1 not crack easily. This is basically consistent with the research results of Mardani-Aghabaglou et al. [44], who have found that by adding polypropylene fiber as 0.8% of total volume into the concrete, there were significant differences in expansion especially after 60 days, and the expansion value of this mixture was determined to be approximately 25% lower than that of the control.
mixture. So, the amount of sulfate ion diffusing into CI30P0.1 will be limited, which restricts the expansive gypsum and AFT to generate in concrete pores. As shown in Figure 11, the expansion variation rate of the concrete with ITS modified by polypropylene fibers compared with that of the concrete with ITS decreases by 40%, at 140 days. Polypropylene fibers make the concrete structure more compact and slow down the speed of sulfate ions entering, restraining the volume expansion of the concrete [45]. So, the expansion of the concrete with ITS is limited by polypropylene fibers.

4.5. The Results of Compressive Strength and Flexural Strength. As shown in Figure 12, the compressive strength and flexural strength of CI0P0, CI30P0, and CI30P0.1 all exhibit two distinct stages. In stage 1, from 28 to 84 days, the strengths of the concrete increase. There are two reasons to explain this phenomenon. Firstly, the cement hydrates make the concrete structure dense. Secondly, the diffusing sulfate ions react with cement hydrates to form expansive gypsum and AFT filling in pores, making the strength improve. In stage 2, from 84 to 140 days, the compressive strength and flexural strength of the concrete decrease. This is mainly because after 140 days of drying-wetting cycles in 5% Na₂SO₄ solution, the internal pore structure of concrete cannot bear the expansion stress of gypsum and AFT, and the concrete compressive strength and flexural strength begin to decrease [34]. At the same time, the compressive strength and flexural strength of CI30P0.1 have the least reduction. This is mainly because a part of expansion stress of gypsum and AFT in pores is consumed by the tensile stress of polypropylene fiber, which makes CI30P0.1 not cracked easily. So, it has the most complete structure and the highest compressive strength and flexural strength.

From 28 to 84 days, the compressive strength and flexural strength of CI0P0 and CI30P0 are increasing, and the compressive strength and flexural strength of CI30P0 are higher than those of CI0P0. This is mainly because the ITS has the rough particle, which can embed in the coarse aggregates and increase the friction between the aggregates so that the compactness of the concrete is good [6, 7, 46]. Hence, the concrete with ITS has higher compressive strength and flexural strength than ordinary concrete. However, from 112 to 140 days, the compressive strength and flexural strength of CI0P0 and CI30P0 are decreasing, and the compressive strength and flexural strength of CI30P0.1 are lower than those of CI0P0. The reason for this transition is that the concrete with ITS is denser than ordinary concrete, and the expansion stress of gypsum and AFT released by CI30P0 is smaller than that of CI0P0, which makes the concrete with ITS crack easily and have lower compressive strength and flexural strength [12]. As shown in Figure 12, when polypropylene fibers are used to reinforce the concrete with ITS, the compressive strength and flexural strength of CI30P0.1 are always higher than those of CI30P0 and CI0P0. This is because the polypropylene fibers can provide enough tensile stress to consume the expansion stress of gypsum and AFT. At the same time, the fibers also bridge the cementitious materials and aggregates, making it difficult for sulfate ions to invade, which is conducive to the integrity of the concrete structure [34, 45]. Therefore, the concrete with ITS modified by polypropylene fiber always keeps the highest compressive strength and flexural strength during the 140 days of drying-wetting cycles in 5% Na₂SO₄ solution.

The compressive strength and flexural strength of CI0P0, CI30P0, and CI30P0.1 all reach a maximum at 84 days and, then, begin to decrease. The degree of decay of the concrete strength is calculated by equation (5). The attenuation is shown in Figure 13.

$$\Delta F = \frac{(F_t - F_0)}{F_t},$$  \hspace{1cm} (5)

where $\Delta F$—decay degree of compressive strength and flexural strength of the concrete. $F_t$—compressive strength and flexural strength of the concrete at 84 days.
It is shown in Figure 13 that the compressive strength and flexural strength of CI0P0, CI30P0, and CI30P0.1 all decrease under 140 days of drying-wetting cycles in 5% Na₂SO₄ solution, and the compressive strength and flexural strength of CI30P0.1 had minimum attenuation values of 12.9% and 2.4%, respectively. The ranking of the degree of attenuation of the compressive strength and flexural strength of the concrete is in the order of CI30P0 > CI0P0 > CI30P0.1. This similar observation has also been found by researchers in reference [23], and the compressive strength and flexural strength of concrete increased by approximately 20% after adding polypropylene fibers. Therefore, the polypropylene fiber can improve the performance of the concrete with ITS.

4.6. The Results of Sulfate Ion Diffusion. The distribution of sulfate ions in concrete is attributed to the existence of pores in concrete. During the 140 days of drying-wetting cycles in 5% Na₂SO₄ solution, the sulfate ions diffuse into concrete through pores. Analysis of sulfate ion in sections 2 and 4 of concrete can determine the degree of sulfate corrosion of concrete.
The distribution of sulfate ions in concrete is shown in Figure 14.

As shown in Figures 14(a) and 14(b), with the change of curing time, the sulfate ions concentration in section 2 and section 4 of CI0P0, CI30P0, and CI30P0.1 is increasing gradually, and the trend can be divided into three stages. The stage of 0–56 days is slow growth. This is attributed to that the concrete structure is relatively dense, and it is difficult for the sulfate ions to diffuse into the concrete. The stage of 56–112 days is rapid growth. This is mainly because the dense concrete begins to be damaged partly by the stress of gypsum and AFT, leading to cracks. So, it is easy for the sulfate ions to diffuse into the concrete. The stage of 112–140 days is mild growth. This is mainly because the gap of sulfate ion concentration between inside and outside of concrete is small. So, there is a small amount of sulfate ions that can diffuse into the concrete.

In CI0P0, CI30P0, and CI30P0.1, the concentration of sulfate ions in section 2 was always higher than that in section 4. At 140 days, in section 2, the concentrations of sulfate ion are 1.677%, 1.512%, and 1.365%, and in section 4, they are 1.210%, 1.010%, and 0.965%. This is mainly because, during the drying-wetting cycles in 5% Na₂SO₄ solution, the diffusion of sulfate ion is easily affected by the pore structure and erosion distance of concrete, which conforms to Fick’s second law [42, 47]. Figures 14(a) and 14(b), also show that comparing CI30P0.1 with CI0P0 and CI30P0, the concentration of sulfate ion in sections 2 and 4 is the lowest all the

**Figure 14:** The distribution of sulfate ions. (a) Section 2. (b) Section 4.

**Figure 15:** Black-and-white diversification diagram after IPP processing.
time. This is mainly because polypropylene fibers inhibit the cracks caused by expansion stress of concrete and bridge the aggregates in concrete, further decreasing the porosity of concrete. Therefore, the polypropylene fibers have an effect on the diffusion of sulfate ion in concrete with ITS.

5. Correlation Analysis of Plane Porosities and Mechanical Strengths

The mechanical properties of the concrete are closely related to its microstructures. Chen et al. [48] has estimated the degree of deterioration of the macro mechanical properties of concrete by testing the changes in the plane porosity of the concrete. In this study, after 28, 84, and 140 days of drying-wetting cycles in 5% Na₂SO₄ solution, the plane porosities of the CI0P0, CI30P0, and CI30P0.1 samples are calculated by

\[ K_a = \frac{S_{black}}{(S_{white} + S_{black})} \]  \hspace{1cm} (6)

where \( K_a \) is the plane porosity, \( S_{white} \) and \( S_{black} \) represent the concrete area and the plane porosity area, respectively, as shown in Figure 15.

The influence of the plane porosity of CI0P0, CI30P0, and CI30P0.1 on the mechanical strengths of the concrete is analyzed. The results are shown in Figure 16.

As shown in Figure 16, from 28 to 84 days, the plane porosity of CI0P0, CI30P0, and CI30P0.1 show a decreasing trend, but the compressive strength and flexural strength of CI0P0, CI30P0, and CI30P0.1 increase. This is mainly because the pores of CI0P0, CI30P0, and CI30P0.1 are filled gradually by AFT and gypsum. From 84 to 140 days, the plane porosity of CI0P0, CI30P0, and CI30P0.1 show an increasing trend, but the compressive strength and flexural strength of CI0P0, CI30P0, and CI30P0.1 decrease. This is mainly because in the late stage of drying-wetting cycles in 5% Na₂SO₄ solution, there are many peels and cracks caused by the expansion stress, leading to lots of holes and pores, which destroy the structure of concrete gradually [44, 47]. It is noted that the plane porosity of CI30P0.1 is the minimum at 140 days compared with the plane porosity of CI0P0 and CI30P0. This is attributed to that a part of expansion stress of gypsum and AFT is consumed by the tensile stress of polypropylene fiber, and polypropylene fiber also can bridge the aggregates and restrict the peel and crack of the concrete, so that the compressive strength and flexural strength are improved. Based on the analysis given above, in the process of drying-wetting cycles in 5% Na₂SO₄ solution, the ranked order of plane porosity is CI30P0 > CI0P0 > CI30P0.1, and the ranked order of mechanical properties is CI30P0.1 > CI0P0 > CI30P0. This similar observation has been obtained by Zhao et al. [26]. He has found that the coefficient of determination (\( R^2 \)) of the linear fit is 0.90 between the experimental compressive strength and the total porosity.

6. Conclusions

In this paper, the performance of the ordinary concrete, concrete with ITS, and the concrete with ITS modified by polypropylene fiber under 140 days of drying-wetting cycles in Na₂SO₄ solution is investigated. Based on the experimental results reported in this study, the following conclusions can be drawn.

The results show that polypropylene fibers can refine the pores development and inhibit the crack development of the concrete with ITS, further alleviating the rate of sulfate ion attack on concrete and the rate of increase of corrosion.
products, so that the mass variation, the expansion variation, and the reduction of compressive strength and flexural strength can be limited effectively. Furthermore, in the concrete with ITS modified by 0.1% polypropylene fibers, the content of sulfate ions diffused is always the lowest.

(1) In the process of the corrosion of sodium sulfate solution, the formation of gypsum and ettringite (AFT) has an important impact on the harmful pores (>0.1 μm), cracks, mass variation, expansion variation, compressive strength, and flexural strength of the three concrete.

(2) Polypropylene fibers have a positive impact on the properties of the concrete with ITS and refine the pores development and inhibit the crack development of the concrete with ITS, further alleviating the rate of sulfate ion attack on concrete and the rate of increase of corrosion products, so that the the mass variation, the expansion variation, and the reduction of compressive strength and flexural strength can be limited effectively.

(3) The variation of concentration of sulfate ion of three kinds of concrete can be divided to three stages: the slow growth stage, the rapid growth stage, and the mild growth stage. Furthermore, the concentration of sulfate ion of the concrete with iron tailings sand modified by polypropylene fibers is always the lowest due to polypropylene fibers bridging the aggregates refining the pores development and inhibiting the crack development to restrain the diffusion of sulfate ion.

(4) The relationship between the macromechanics and the plane porosity of three kinds of concrete is negatively correlated, especially the concrete with ITS modified by polypropylene fibers.

(5) There are still some shortcomings in this research. First, the content of polypropylene fibers is determined by the literature. Second the different size of polypropylene fibers is not considered. Third, improving the content of iron tailings sand and polypropylene fibers together can be considered in later research.

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

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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