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Research Article

Experimental Study on the Properties of Concrete Mixed with Iron Ore Tailings

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The objective of this study is to evaluate the modified performance of concrete with mixing of iron ore tailings in order to solve the shortage of natural sand and make full use of industrial waste. Firstly, the raw materials of mixing were analyzed, and the test ratio was determined. Secondly, the workability and mechanical property of concrete specimens with different amounts of iron ore tailings as replacement were tested. Results show that 35% replacement of natural aggregate by iron ore tailings is optimal. Finally, tests of impermeability, frost resistance, and carbonation resistance were further performed for the concrete specimens with optimal amount of iron ore tailings. The compression performance of the specimens after a durability test was determined. The change in the mechanical properties of the specimens was obtained after seepage, freezing-thawing, and carbonation. Findings showed that the performance of the concrete with 35% replacement of iron ore tailings is basically equivalent to that of natural sand concrete. Hence, it can be utilized in engineering applications.

1. Introduction

With China continuing to increase the investment in the infrastructure construction, the demand for concrete has increased sharply. This results in a shortage of natural sand in some areas and a series of environmental problems due to irrational overexploitation. On the other hand, mining activities not only destroy and occupy lots of land resources but also bring about many serious environmental and social problems, and a lot of waste such as tailings requires disposal [1–5]. It is urgent to solve the shortage of natural sand and make full use of industrial waste. Thus, it is quite significant to vigorously develop the iron ore tailings concrete for the construction.

In recent years, the domestic and oversea scholars have achieved some progress on the preparation and performance testing of concrete with iron mine tailings. Zhao et al. [6] carried out indoor experiments to study the working performance and mechanical behavior of concrete with iron ore tailings and analyzed the test results from micro aspect. Experimental results established by Alwaeli and Nadziakiewicz [7] proved that the shielding effect of concrete with different proportions of scrap steel chips on gamma rays is superior to the ordinary concrete with natural sand. Onoue et al. [8] investigated the fatigue properties of slag concrete and derived the equations for calculating its fatigue life by the theory of fatigue mechanics. A series of laboratory experiments on the mechanical behavior of concrete prepared by abandoned iron ore tailings in Iraq was carried out by Ismail and AL-Hashmi [9], and results revealed that its performance was superior to ordinary concrete and exhibited higher compressive strength and flexural strength. Zhang et al. [10] comprehensively analyzed the disposal and utility circumstance of iron ore tailings in China. Tian [11]

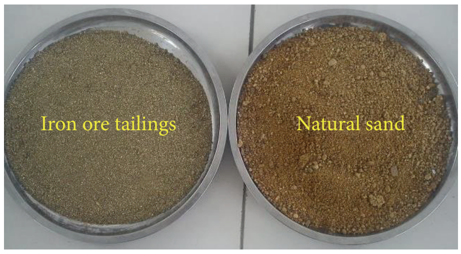


Figure 1: Comparison between iron ore tailings and natural sand.

Table 1: Chemical composition of iron ore tailings.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	Cl^-	Loss amount
70.32	5.1	10.93	4.71	4.51	1.14	1.3	0.26	0.016	1.1

experimentally determined the basic performance of the concrete with iron ore tailings and listed a large number of successful applications of prepared concrete in city construction. He et al. [12] and Davraz and Gunduz [13] prepared the C60 high-strength concrete using iron ore tailings whose performance is superior to the normal concrete.

Many achievements have been made in the research on the utilization of iron ore tailings. However, results of mixing amount of iron ore tailings on the mechanical performance of concrete are not abundant. Thus, the modified performance of concrete with different mixing amounts of iron ore tailings was tested in this study in order to find the optimum one.

2. Raw Material Property

2.1. Iron Ore Tailings. The iron ore tailings were collected from a copper-iron mine in Zibo city. The particles appear as fine gray granular, and the fineness modulus was within 1.9~2.3. Comparison of particle size between the collected iron ore tailings and natural sand from Wen River was shown in Figure 1.

The chemical components of the collected iron ore tailings obtained from phase analysis were shown in Table 1. Obviously, the main components of iron ore tailings are basically the same as natural sand. This indicates that it can be used to prepare concrete.

2.2. Cement. The ordinary Portland cement P.O 42.5 produced from Tai'an was adopted, and its chemical components and property indexes are shown in Table 2.

2.3. Coarse and Fine Aggregate. The coarse and fine aggregate used in this test are the gravel with a dimension within 5~25 mm in Tai'an area and medium sand collected from Wen River. From particle-size analysis, the grading curves of crushed stone and medium sand are shown in Figure 2.

2.4. Mineral Admixture. Adding admixture, fly ash into raw materials, is an important way to get high-performance concrete. Amorphous active substance of Al_2O_3 in fossil waste of fly ash can react chemically with $Ca(OH)_2$. This form of attack directly leads to the formation of gel component and reduction of the porosity in concrete [14]. As a result, the characteristics of adhesiveness, liquidity, water retention, and pumpability of fresh concrete can be improved. Besides, the choice of commonly available fly ash can also protect the environment and make secondary use of the chemical waste. In this test, Primary grade fly ash provided by power plant in Shandong was adopted, and its chemical composition is listed in Table 3.

2.5. Water Reducer. Polycarboxylic high-performance water-reducing agent of SM-IV was introduced, and its technical indicators were listed in Table 4. This water reducer can reduce levels of chloride iron and is an environmentally friendly additive [15]. Besides, it can also improve the concrete contracting rate.

3. Test to Find the Optimum Mixing Amount of Iron Ore Tailings

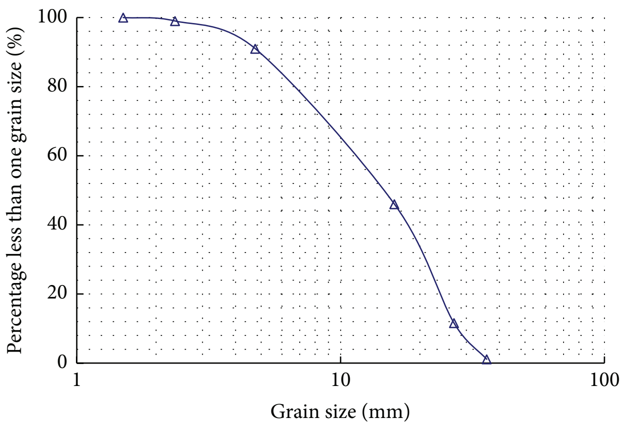
3.1. Workability of Samples with Different Mixing Amount of Iron Ore Tailings. Let the bulk density of C30 concrete be 2400 kg/m^3, and let the mass ratio between iron ore tailings and natural sand be α. Here, the concrete without iron ore tailings was set as reference. On the basis of reference concrete mix, four different mixes (α = 0, 25%, 35%, and 45%) were designed by changing the amount of iron ore tailings. The volume of each sample is 1 m^3. The mixing proportion of each sample was determined by using the overall calculation method [16], as listed in Table 5. Slumps at three different positions for each series were tested. The results are shown in Figure 3.

As shown in Figure 3, the slumps and liquidity of concrete mixed with iron ore tailings decreased compared with that of normal concrete under the same condition (water, mixture ratio, admixture, etc.). This phenomenon arises because the particles of iron ore tailings are rough and occluded with coarse aggregate, so cohesion increases significantly in the tailing mixes. In addition, iron ore tailings have higher water absorption than natural sand. Therefore, the tailing mixes are weak in terms of liquidity. According to the test on the retention value of slumps for 1 h, the loss of slumps had a linear relation with the increase in the proportion of iron tail sand. The loss value of concrete with proportion of 45% for 1 h was 12%, indicating that iron tail sand concrete exhibited improved performance in agglomeration. In the experiment, cement paste easily separated with aggregate as the result of the weak liquidity of the tailing mixes. An inaccurate mix proportion would produce segregation and lead to a reduction in water retention capacity. In all the cases, the slumps are all above 150 mm and can thus be used in practice. In summary, iron tail sand could ensure the workability in transportation and pouring when the proportion is below 45%.

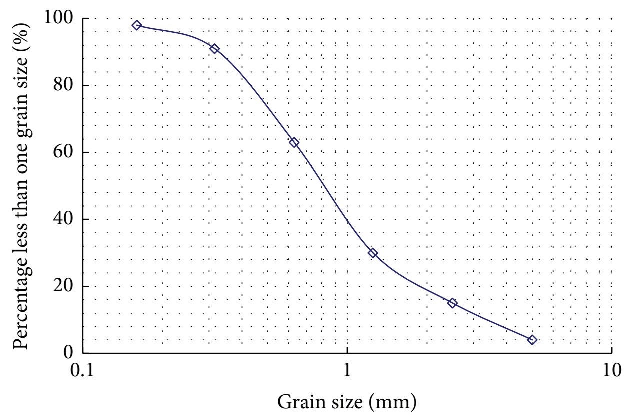
3.2. Compressive Strength of Samples with Different Mixing Amounts of Iron Ore Tailings. Mechanical properties of concrete samples with different mixing amounts of iron ore

Table 2: Chemical components and property indexes of ordinary Portland cement.

Chemical composition (%)					Compressive strength (MPa)		Flexural strength (MPa)		Physical property			
Proj	SO_3	MgO	Loss on ignition	Cl^-	3 d	28 d	3 d	28 d	Soundness	Specific surface (m^2/kg)	Setting time (min)	Final setting (min)
Val	1.62	3.18	3.4	0.028	29.4	49.5	5.5	8.1	Conformity	384	226	288



(a) Grading curve of crushed stone



(b) Grading curve of medium sand

Figure 2: Grading curve of aggregate.

Table 3: Chemical composition of fly ash.

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3
Content	52.38	28.42	5.47	2.57	1.38	0.36	1.84	0.56

tailings were tested in accordance with the national standard GB/T 50081-2002. As shown in Figure 4, standard compressive concrete cube specimens (150 × 150 × 150 mm^3) were fabricated according to different amount of iron ore tailings. Nine test specimens were set for each type of proportion, and a total of three group experiments were conducted.

The test specimens were cured for 3 d, 7 d, and 28 d under standard conditions (20°C ± 2°C, relative humidity of 95%). Then, the compressive strength of the test specimens was tested on the electrohydraulic pressure testing machine (see Figure 5). The results are presented in Figure 6.

Compressive strength results in Figure 6 show that each group is similar. To intuitively compare the compressive properties at different replacement proportions, the average of the test values of the three groups was obtained. The change curve of compressive strength along with age is shown in Figure 7.

Comparison of Figures 6 and 7 shows that under the same experimental conditions, with the increase in the proportion of the iron ore tailings, the compressive strength of the tailing mixes at 3 d increased initially and then decreased subsequently after the first reduction. Specifically, when the replacement of natural aggregate by the tailings in the mixing concrete amount was 35%, the 3 d compressive strength was greater than that of the control mix; the best proportions were 25%, 35%, and 45%. Similarly, with the increase in the proportion of the iron ore tailings, the compressive strength of the tailing mixes at 7 d increased and then decreased subsequently after the first reduction. However, the tailing mixes' compressive strengths of 25%, 35%, and 45% at 7 d were all less than that of the control mix because the surface activity of iron ore tailings is low. After adding iron ore tailings to concrete, more slurry was required to pad the architecture, thereby causing the tailing mixes' compressive strength at 7 d to become lower than that of the control mix. However, with the increase in time, compressive strength increased rapidly. The failure of the specimens indicates that the tailing mixes and the control mix are similar which present a wedge of upper and lower symmetry. After specimen damage, visible defects in the interior, such as the stomata, were observed. With the increase in proportion, the stomatal number increased, but the regularity was weak.

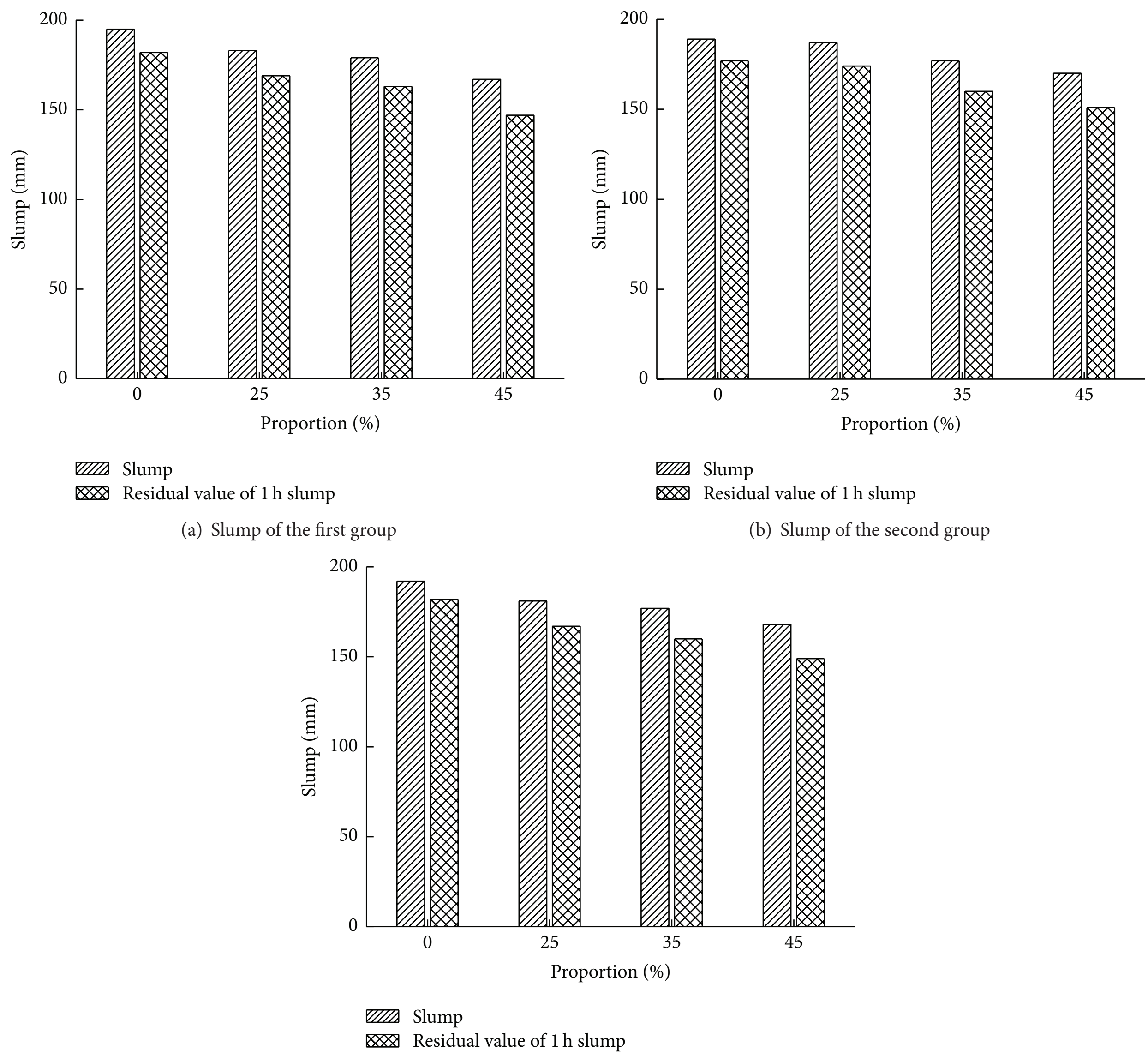
With the increase of the iron ore tailings, the compressive strength of the tailing mixes at 28 d decreased and then increased subsequently after the first reduction. Specifically, when the replacement of natural aggregate by the tailings in the concrete was 35%, the 28 d compressive strength performance was better, and the long-term compressive strength was slightly higher than that of the control mix. The compressive properties of the concrete with 45% replacement of natural aggregate by the tailings were poor mainly because excessive iron ore tailings lead to an increase in harmful voids within the concrete mixture. If mixing is insufficient, the layered bleeding phenomenon easily occurs in the concrete,

TABLE 4: Technical index of water reducing agent.

Items	Density (g/mL)	Solid content (%)	pH level	Neat paste rheology (mm)	Chloride ion content (%)	Alkali content (%)
Test result	1.05	40	7	230	0.01	1

TABLE 5: Proportion of concrete mix with iron ore tailings.

Proportion of iron ore tailings (%)	Iron ore tailings (kg)	Natural sand (kg)	Fly ash (kg)	Cement (kg)	Crushed stone (kg)	Water (kg)	Water-reducing agent (kg)
0	0	1010	94	276	806	204	10.2
25	252	758	94	276	806	204	10.2
35	352	658	94	276	806	204	10.2
45	453	557	94	276	806	204	10.2



(a) Slump of the first group

(b) Slump of the second group

(c) Slump of the third group

FIGURE 3: Comparison of slumps in mixture of different incorporation amounts.

Figure 4: Standard compression specimens.

Figure 5: Electrohydraulic pressure testing machine.

the development of the bond strength between the paste and aggregate is not uniform, and the overall compressive strength of concrete decreases [17].

3.3. The Optimum Mixing Amount of Iron Ore Tailings. By the comparison and analysis of the test data, the mixing amount of 35% is the most appropriate among all the proportions. When the amount of the admixture exceeded 45%, the initial strength of the tailing mixes was lower than that of the control mix, and its long-term compressive strength decreased significantly. It is thus unsuitable for use as C30 concrete in building engineering.

4. Further Durability Test on the Properties of the Concrete with Optimum Mixing Amount of Iron Ore Tailings

To evaluate the durability of the concrete mixed with 35% iron ore tailings, three tests of resistance to penetration, frost resistance, and carbonation resistance were performed.

4.1. Research on Permeability Resistance. According to the standard JGJ/T193-2009 for concrete antipenetration test, cylindrical specimens with 150 mm diameter and height were prepared. Four groups were established, and each group included six specimens. One group (KS-0), which was regarded as the control mix, was not mixed with tailings. The other three groups (KS-1, KS-2, and KS-3) were concrete with 35% iron ore tailings. As shown in Figure 8, the specimens were placed on a permeability tester for the concrete antipenetration test.

Water pressure was increased to 0.1 MPa every 8 h, until three concrete specimen surfaces exhibited seepage. Then, the test was stopped. The measured concrete anti-infiltration test data are shown in Table 6.

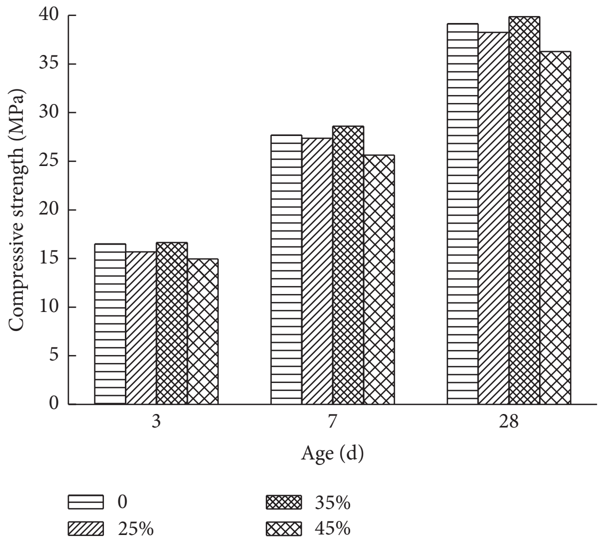
Table 6: Analysis of concrete anti-infiltration test data.

Number	Water pressure during third specimen seepage	Anti-infiltration level
KS-0	0.7 MPa	6
KS-1	0.7 MPa	6
KS-2	0.7 MPa	6
KS-3	0.8 MPa	7

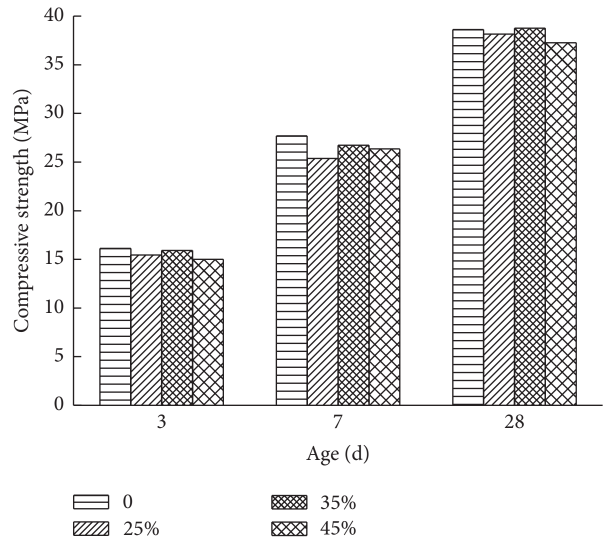
As revealed in Table 6, the impermeability grade of concrete with 35% iron tailings and that of natural sand concrete are basically the same. The incorporation of iron tailings did not affect the impermeability of concrete. However, the impermeability grade of concrete with the incorporation of iron tailings is not high, and its impermeability can only be used as an adjunct. In engineering application, the concrete must be added to concrete admixtures to improve impermeability.

4.2. Research on Frost Resistance. The frost resistance test for long-term performance and durability of ordinary concrete was carried out based on the national standard GB/T50082-2009. Four groups of concrete cube specimens were used. Their length, width, and height were 100 mm, and each group has two specimens (one was used in the frost resistance test, and the other was used in the compression test after freezing and thawing). Similarly, one group (KD-0) was set as the reference specimen, and the other three groups (KD-1, KD-2, and KD-3) contained 35% iron tailings. The freezing-thawing test was carried out by the −40 DW/200 low temperature box (see Figure 9), and detection of quality loss was conducted every 25 freezing-thawing cycles. The quality loss curve of the four groups when the number of freezing-thawing cycles is 200 is shown in Figure 10.

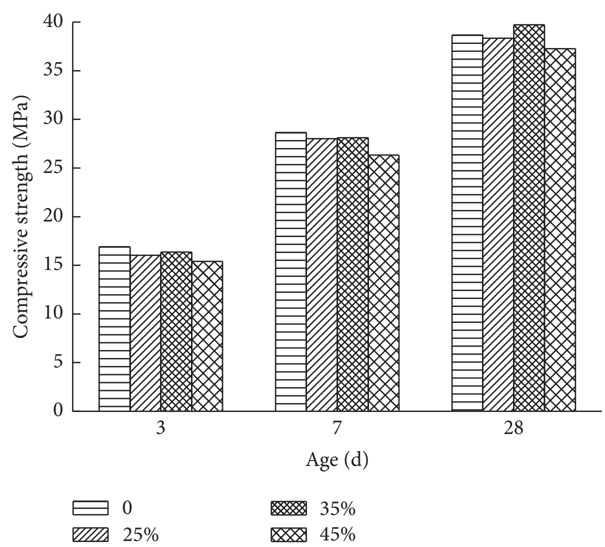
Results show that the mass loss of concrete containing 35% iron ore tailings is higher than that of the reference concrete. The frost resistance of the concrete decreased to 16.2% because of the iron tailings sand. The bonding properties of certain minerals in iron tailings sand are weak at low temperatures, and some of the sand on the surface falls off. The four experimental curves show that the concrete specimens' mass increased in the early part of the freezing-thawing test because the concrete specimens exhibited micro cracks and water came in. However, as the freezing-thawing



(a) Compressive strength of the first group



(b) Compressive strength of the second group



(c) Compressive strength of the third group

Figure 6: Compressive strength of concrete specimens.

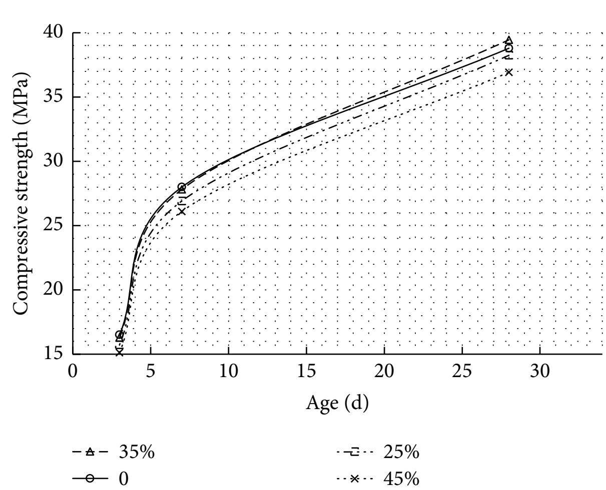


Figure 7: Change curve of compressive strength with age.

Figure 8: Antipermeability apparatus for concrete.

Figure 9: Low temperature box.

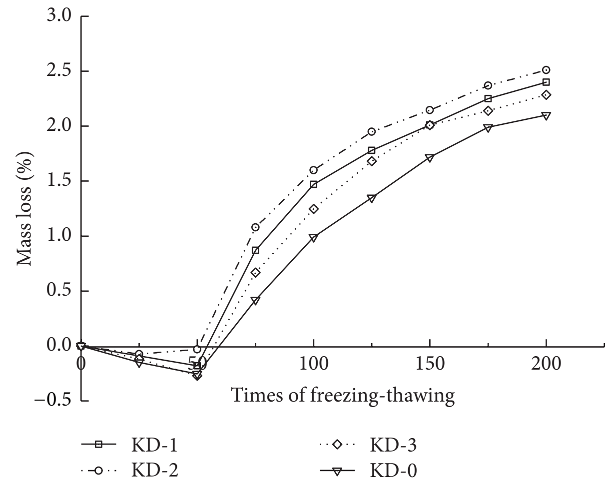


Figure 10: The mass loss rate varies with the number of cycles.

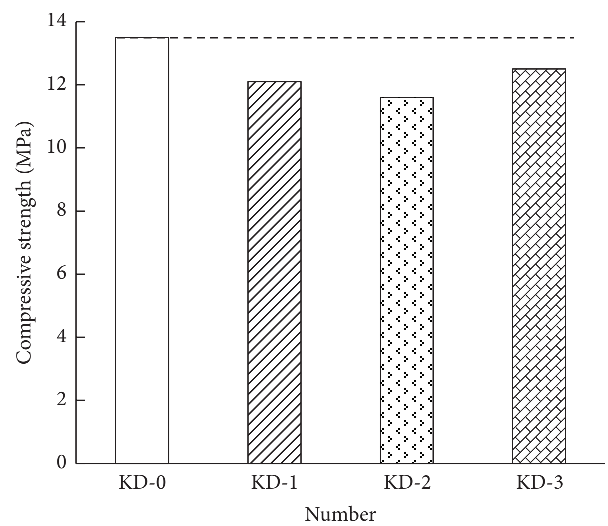


Figure 11: Compressive strength of concrete specimen after freezing-thawing test.

test went on, cement slurry and coarse and fine aggregates fell off from the specimens' surfaces. Then, the weight of the specimens decreased, but their mass loss was less than 3% in all the tests. A compression experiment was performed after freezing-thawing, and the results are shown in Figure 11. The compressive strength of the concrete specimens decreased by more than 60% after 200 cycles of freezing-thawing. The loss of the tailing mixes is larger than that of the control mix. The compressive strength of the concrete with iron ore tailings after freezing-thawing was approximately 90% that of the reference concrete; hence, the compressive strength of the tailing mixes after freezing-thawing had some degree of discount [18]. When used in buildings with antifreeze requirements, the concrete needs to be combined with an air-entraining agent to increase the antifreeze performance.

4.3. Research on Carbonation Resistance. Test code for hydraulic concrete (DL/T 5150-2001) was applied in the carbonation test. Similar to the frost resistance test, one group (KT-0) of concrete specimens was set as the reference, and three groups (KT-1, KT-2, and KT-3) of concrete specimens contained iron ore tailings. Each group has two specimens. The concrete specimens were placed in a carbonation tank at 23°C with 22% CO_2 concentration and 70% relative humidity (RH). After the concrete specimens were carbonated, we split the specimens and sprayed 1.0% phenolphthalein ethanol solution on the fracture surface. Multipoint distance was measured at each side, and the average value was regarded as the carbonation depth. The degree of carbonation of concrete at 3, 7, and 28 d is shown in Figure 11.

As shown in Figure 12, with the development of the ages of carbonation, the carbonation depth of the concrete specimens exhibited a nonlinear variation. The carbide growth rate decreased mainly because the produced $CaCO_3$ in the early carbonation process formed a layer of protection membrane on the surface of carbonation and prevented CO_2 from entering to a certain extent. Hence, the rate of carbonation decreased. However, after fly ash partly replaced cement, the $Ca(OH)_2$ generated by cement hydration reacted with SiO_2 and Al_2O_3 in fly ash and produced hydrated calcium. Therefore, late carbonation resistance of the concrete decreased

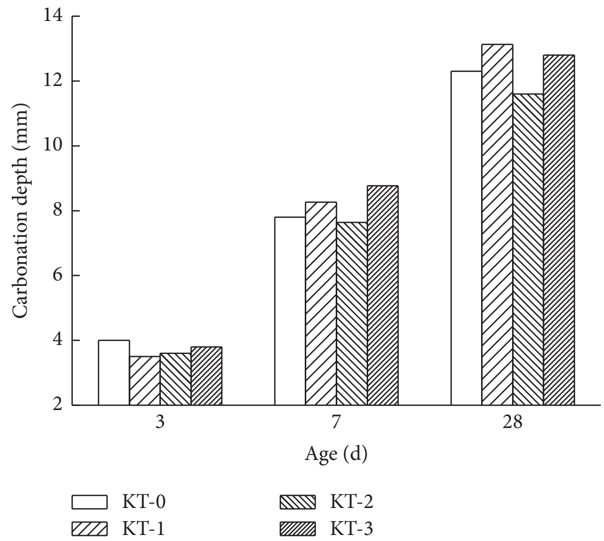


Figure 12: Carbonation depth change with time.

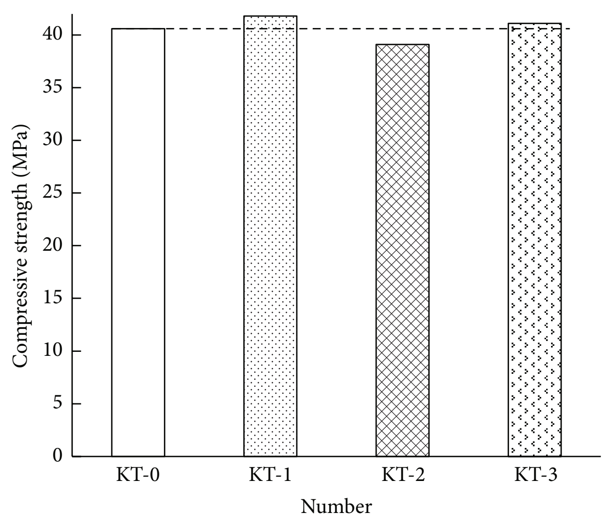


Figure 13: Mass loss rate change of cycles.

partly because the secondary reaction of the concrete mixed with fly ash consumed large amounts of $Ca(OH)_2$ and made the pH value decrease [19]. By contrast, the carbonation speed of the tailing mixes was lower than that of the control mix in the early stage. When the carbonation age was more than 7 d, the carbonation speed of the tailing mixes was higher than that of the control mix. With the increase in time, the carbonation depth of the two groups was greater than that of the control mix. The average of the three group tests is basically equal to that of the control mix; 28 d carbonation depth was less than 20 mm. These test results show that carbonation resistance performance is good in the early stage, and replacement of natural aggregate by the tailings is not related to carbonation resistance. The tailing mixes of 35% meet the requirement for carbonation resistance in engineering design.

After the carbonation test, we used another specimen in the compressive experiment. The result is shown in Figure 13. Compared with that in Figure 4, the compressive strength of the specimen after the carbonation experiment increased by about 5%. The main reason is that concrete absorbed CO_2 from the air in the process of carbonation and generated $CaCO_3$ to make the concrete surface denser. During the compression test, the ultimate deformation capacity of the specimen decreased significantly. The concrete specimen's brittleness increased after carbonation.

For plain concrete, carbonation is relatively favorable. However, for reinforced concrete, the corrosion of reinforcement is more serious because the alkalinity of concrete after carbonation is reduced. Clearly, the specification for the minimum cover thickness of steel has a regulation: when the carbonation depth is larger than the thickness of the protective layer, the strength of the steel bar in concrete decreases sharply, thereby affecting the overall strength of the reinforced concrete [20].

5. Conclusions

Based on previous studies, the modified performance of concrete with different mixing amounts of iron ore tailings was evaluated in detail in order to solve the shortage of natural sand and make full use of industrial waste. The following conclusions are reached:

(1) Tests on workability and mechanical property of concrete specimens with different amounts of iron ore tailings were carried out. It was found that the strength development law of the tailings mixes is basically equivalent to that of natural sand concrete according to the compressive strength at 3 d, 7 d, and 28 d age. With the increasing of substitutive ratio of iron ore tailings, the mobility of mixture becomes worse, the water retention of mixture is lower than that of reference concrete, and the excreting water phenomenon may occur. The compressive strength of concrete without iron tailing reaches the highest at 7 d age, while the 35% replacement peaks at 3 d and 28 d age.

(2) From the durability experiment on the concrete with 35% replacement of natural aggregate by ore tailings, the permeability resistance of the tailing mixes is equal to that of the control mix. Its frost resistance is slightly lower than that of the control mix, and its carbonation resistance is equivalent to that of the control mix.

(3) Altogether, iron ore tailings can be utilized as a partial substitute for natural sand to prepare concrete. It reduces the amount of natural sand, solves the environmental pollution problem of iron ore tailings, and promotes the development of green building projects.

Competing Interests

The authors declare that they have no competing interests regarding the publication of this paper.

Acknowledgments

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