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Article

Experimental Research of Concrete with Steel Slag Powder and Zeolite Powder

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Abstract: In order to increase use ratio of steel slag solid waste, the concrete containing steel slag powder and zeolite powder as admixtures was prepared by using the orthogonal test method. The effects of water-binder ratio, sand ratio, steel slag powder content and zeolite powder on working properties, mechanical strength and chloride ion permeability of the concrete was studied. It was found that the early strength of the concrete had a decrease with the mixing of steel slag and zeolite powders, but its later strength approached to pure concrete. Moreover, the physical filling and pozzolanic activity of the admixtures increased the density of the concrete, resulting in the improvement of the durability of the concrete by the migration speed of Cl^{-} reducing. The optimum mix ratio of C40 steel slag powder-zeolite powder concrete is obtained, and which had the slump of 220 mm, the 3 d, 7 d and 28 d compressive strengths of 27.8 MPa, 37.5 MPa and 48.4 MPa, the 6 h electric flux of 950 C and the diffusion coefficient of 1.65×10^{-12} m^2/s.

Keywords: Concrete; steel slag powder; zeolite powder; compressive strength; chloride ion permeability

1 Introduction

Steel slag is one of the main waste slags in the iron and steel metallurgical industry. The annual emissions of steel slag in china are about 100 million tons, which has only about 30% comprehensively utilization [1]. The large number of steel slag piled up not only pollutes the environment and occupies the land, but also causes a waste of resources. The steel slag mainly contains densely structured tricalcium silicate and dicalcium silicate, which has potential hydraulic activity. After mechanical activation, steel slag powder can be used as an extender to modify workability, later strength and microstructure of concrete materials. For instance, Han et al. [2] pointed out that the adding of steel slag powder retained moderate workability of the concrete and reduced temperature rise during the hardening process. Wang et al. [3] indicated that steel slag powder increased the permeability of the concrete. However, due to the low activity and stability, the adding of steel slag powder often causes negative effect on early strength and durability of the concrete [4,5]. Therefore, the utilization of steel slag powder in concrete materials was still the current research issues in building materials.

Zeolite powder is a kind of pozzolanic material after grinding of natural zeolite rock. There are a large amount of active SiO_2 and Al_2O_3 in zeolite powder, of which can react with $Ca(OH)_2$ in cement hyIdration process to promote the formation of C-S-H gel and hydrated aluminate [6]. Rahhal et al. [7] obtained that zeolite powder was contributed to promote the hydration to increase early strength of portland cement. The green concrete filters with low apparent density and high early strength were prepared by the adding of zeolite powder in the study of Azad et al. [8]. In the research of Derogar [9], proper zeolite powder reduced the water transport kinetics to enhance duribility of concrent. It signifies that zeolite powder improves the hydration characteristic, early strength, durability and other properties of concrete materials [10]. Thereby, it infers that zeolite powder could be used to improve the early strength and durability of concrete containing steel slag. However, few literatures have reported the method to prepare concrete with excellent properties by using steel slag and zeolite powders.

In addition, with the increase of concrete consumption, the prices of high-quality resources such as slag powder and fly ash have gradually skyrocketed and even appeared in shortage at present. In order to solve the problems of resource shortage and environmental pollution, and aiming to the low utilization rate of steel slag and abundant natural zeolite resources in Guangxi Province in China, this paper tried to use local steel slag and natural zeolite powders as admixtures to prepare concrete. By using the complementary properties of steel slag and zeolite, the slag powder-zeolite powder concrete was prepared. The working properties, mechanical properties and chloride ion permeability of the concrete were studied. The characteristics of hydration products were researched by microscopic test. It was conducive provide guidance for improving the resource utilization of steel slag.

2 Experimental Section

2.1 Raw Material

(1) Cement: P.O 42.5 grade cement produced by Conch cement Co., Ltd., and its 28 d compressive strength is 48.2 MPa; (2) Sand: Guilin local river sand, with 2.6 fineness modulus; (3) Stone: The local limestone in Guilin, brokening and continuous grading to the particle size of 5–25 mm; (4) Steel slag powder: The steel slag is taken from Liuzhou Iron and Steel Co., Ltd., and which grounds to the specific surface area of 500 m^2/kg; (5) Zeolite powder: Guangxi natural zeolite is ground, with a specific surface area of 610 m^2/kg; (6) Water reducer: Polycarboxylic acid superplasticizer, solid content of 10%; (7) NaCl: Commercially available, analytically pure; (8) NaOH: Commercially available, analytically pure; (9) Water: Tap water and deionized water.

The chemical composition of the main raw materials is shown in Tab. 1, and the XRD analysis of steel slag and zeolite is shown in Fig. 1.

Table 1: Chemical composition of main raw materials

Name	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	f-CaO	Loss
Cement	23.45	5.56	2.57	60.26	1.46	2.83	/	3.7
Steel slag	29.46	6.70	12.91	34.01	6.89	/	2.63	0.8
Zeolite	54.91	15.68	6.40	9.08	5.39	/	/	4.72

2.2 Experiment Method

(1) Refer to GB/T50080-2016 to test the performance of concrete mixture; (2) Refer to GB/T50081-2016 to test the mechanical properties of concrete at various ages; (3) Refer to GB/T50082-2009 to test the durability of concrete performance.

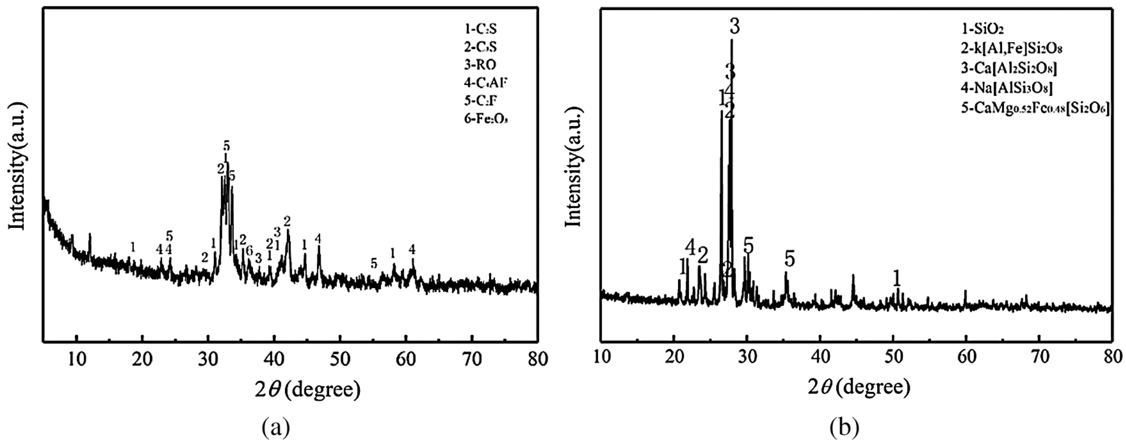


Figure 1: (a) XRD diagram of steel slag powder, (b) XRD pattern of zeolite powder

2.3 Test Plan

On the basis of a large number of preliminary exploratory tests [11–13], the amount of cementing material used 400 kg/m^3 to prepare common C40 strength grade concrete, steel slag powder and zeolite powder were used instead of slag powder and fly ash as concrete admixture, different proportions of steel slag powder and zeolite powder were added to replace cement equivalently, and a high-efficiency water-reducing agent with a mass of 1.2% of the cement material was added. By adjusting the water consumption and sand rate, each component in the concrete can fully exert the comprehensive effect. The L9(34) orthogonal test table in Tab. 2 was used to design the level of each factor.

Table 2: Factor level table

Level	Factor			
	(A) Water-binder ratio	(B) Sand ratio/%	(C) Steel slag powder doping amount/%	(D) Zeolite powder doping content/%
1	0.38	40	5	10
2	0.4	42	10	15
3	0.42	44	15	20

3 Results and Analysis

3.1 Mix Proportion Test

Taking the workability of steel slag powder-zeolite powder concrete, the compressive strength of each age and the 6 h electric flux of at the age of 56 d age were used as the assessment index, the influence rules and significance of various factors on the working performances, the compressive strength and electric flux of each age were analyzed, so as to comprehensively determine the best formula. The results of orthogonal test are shown in Tab. 3.

3.1.1 Performance Analysis

The analysis results of the influence of various factors on the working performance of concrete are shown in Tab. 4. It indicated that the effects of various factors on the working properties of concrete were as follows: water-binder ratio > sand ratio > zeolite powder content > steel slag powder content.

Moreover, the adding of zeolite powder and steel slag powder reduced the slump of concrete to varying degrees, but due to the compactness of steel slag powder has little effect on the working performances of concrete, and the porous structure of zeolite powder lead to a increase of water demand. with the increase of content, the working performances of concrete had a decrease. Taking output slump as the evaluation index, the most suitable combination was regarded as A3B3C1D1, of which contained 0.42 water-binder ratio, 44% sand ratio, 5% steel slag powder and 10% zeolite powder.

Table 3: $L_9(3^4)$ test scheme and test results

Serial number	A	B	C	D	Slump/mm	Compressive strength/MPa			Electric flux/C
						3 d	7 d	28 d	
1	0.38	40	5	10	185	31.6	42.3	53.2	1720
2	0.38	42	10	15	175	23.4	36.4	46.9	1280
3	0.38	44	15	20	190	21.7	37.1	48.2	850
4	0.40	40	10	20	200	20.5	31.7	43.5	1130
5	0.40	42	15	10	215	27.7	31.2	41.5	1380
6	0.40	44	5	15	230	24.0	38.2	49.5	1620
7	0.42	40	15	15	215	23.8	35.1	46.0	1220
8	0.42	42	5	20	220	20.2	31.4	41.7	1430
9	0.42	44	10	10	245	23.6	34.6	45.3	1680

Table 4: The influence of various factors on the slump of concrete

Serial number	Slump mm			
	(A) Water-binder ratio	(B) Sand ratio/%	(C) Steel slag powder doping amount/%	(D) Zeolite powder doping content/%
k1	183	200	212	215
k2	215	203	207	207
k3	227	222	207	203
R	44	22	5	12

3.1.2 Analysis of Mechanical Properties

The analysis results of the influence of various factors on the compressive strength of concrete at different ages are shown in Tab. 5. It found that the significant effects of various factors on the 3 d strength of concrete were as follows: zeolite powder doping amount > water-binder ratio > steel slag powder doping amount > sand ratio. The significant influence of various factors on concrete 28 d strength were as follows: water-binder ratio > sand ratio > zeolite powder doping amount > steel slag powder doping amount. It was seen that the addition of zeolite powder had a greater influence on the early compressive strength of concrete, but a smaller effect on the later compressive strength. Because the early hydration of zeolite powder is slow and fails to exert its pozzolanic characteristics. With the increase of $Ca(OH)_2$ amount produced by cement hydration, the pozzolanic reaction occurred gradually to ensure the later strength. Duo to steel slag powder containing cementitious C_2S and a large number of vitreous structure, its hydration activity was more easily excited, and which had less effect on the early and later strength of concrete than zeolite powder [14]. From the effect of the amount of mineral admixtures on the compressive strength of each ages, with the increase of the amount of steel slag powder, the 3 d compressive strength of concrete decreased first and then increased slightly, and the 28 d compressive strength decreased at first and then tends to stabilized. With the increase of zeolite powder adulteration, the 3 d compressive strength of concrete showed a downward trend, and the 28 d compressive strength increased at first and then decreased. Taking the 28 d compressive strength as the main evaluation index, and taking into account the 3 d compressive strength, the most suitable combination was A1B1C3D2. It had 0.38 water-binder ratio was 0.38, 40% sand ratio, 15% adulteration amount of steel slag powder and 15% doping amount of zeolite powder.

Table 5: The influence of various factors on the compressive strength of concrete

Serial number	Compressive strength of each age/MPa											
	(A) Water-binder ratio			(B) Sand ratio/%			(C) Steel slag powder doping amount/%			(D) Zeolite powder doping content/%		
	3 d	7 d	28 d	3 d	7 d	28 d	3 d	7 d	28 d	3 d	7 d	28 d
k1	25.6	38.6	49.4	25.3	36.4	47.6	25.3	37.3	48.1	27.6	36.0	46.7
k2	24.1	38.7	44.8	23.8	33.0	43.4	22.5	34.2	45.2	23.7	36.6	47.5
k3	22.5	33.7	44.3	23.1	36.6	47.7	24.4	34.5	45.2	20.8	33.4	44.5
R	3.1	5.0	5.1	2.2	3.6	4.3	2.8	3.1	2.9	6.8	3.2	3.0

3.1.3 Analysis of Chloride Ion Permeability

The analysis results of the influence of various factors on the resistance of steel slag powder - zeolite powder concrete to chloride ion permeability are shown in Tab. 6. It was seen that the significant influences of various factors on the permeability of concrete chloride ions is: The doping amount of zeolite powder > the doping amount of steel slag powder > water-binder ratio > sand ratio. With the increase of water-cement ratio and sand ratio, the electric flux of concrete increased and the permeability of chloride ion resistance decreased. With the increase of zeolite powder and steel slag powder, the electric flux of concrete decreased obviously and the permeability of chloride ion resistance increased. Taking concrete 56 d chloride ion permeability as the evaluation index, the optimal combination was A1B1C3D3, and its water-cement ratio was 0.38, sand rate was 40%, steel slag powder doping amount was 15%, zeolite powder doping amount was 20%.

Table 6: Influence of various factors on concrete electric flux

Serial number	6 h Electric flux/C			
	(A) Water-binder ratio	(B) Sand ratio/%	(C) Steel slag powder doping amount/%	(D) Zeolite powder doping amount/%
k1	1283	1357	1590	1593
k2	1377	1363	1363	1373
k3	1443	1383	1150	1137
R	160	26	440	456

3.2 Optimum Proportioning Test

Taking the compressive strength of steel slag powder-zeolite powder concrete at each age and 56 d chloride ion electric flux as the main evaluation index, combined with the test goal to prepare C40 strength grade concrete, A1B1C3D2 was selected as the most suitable combination, that was, the water-binder ratio of 0.38, sand ratio of 40%, doping amount of steel slag powder of 15%, doping amount of zeolite powder of 15%. Considering that the influence results of various factors on working performance were quite different from the influence rules of strength and electric flux, the working performances of concrete were adjusted by increasing the doping amount of superplasticizer. It was verified by experiments that when the adulteration amount of superplasticizer increased to 1.3%, the slump of concrete could reach to 220 mm, to meet the requirements of pumping construction performance. Therefore, the most suitable mix ratio was 280 kg/m^3 cement, 60 kg/m^3 steel slag powder, 60 kg/m^3 zeolite powder, 756 kg/m^3 sand, 1134 kg/m^3 macadam, 152 kg/m^3 water consumption and 5.2 kg/m^3 superplasticizer.

The most suitable mix ratio of steel slag powder-zeolite powder concrete and the ratio of pure cement were used for the comparative test. The test results are shown in Tab. 7. From the comparative test, it was seen that the influence of steel slag powder and zeolite powder on the working performances of concrete was solved by appropriately increasing the amount of water reducing agent, and the two groups of concrete could get better construction performance. The compressive strength results of each age showed that the early strength of steel slag powder-zeolite powder concrete was obviously lower than that of base concrete, but with the increase of age, the 28 d compressive strength was close to the standard concrete.

Table 7: Optimum proportioning test

Serial number	Concrete material consumption/(kg/m^3)							Slump/mm	Compressive strength/MPa		
	Cement	Zeolite powder	Steel slag powder	Pebbles	Sand	Water	Superplasticizer		3 d	7 d	28 d
C40-1	400	/	/	1134	756	152	4.8	215	33.6	42.5	50.2
C40-2	280	60	60	1134	756	152	5.2	220	27.8	37.5	48.4

3.3 Chloride Ion Permeability Test

The chloride ion permeability of the two groups of concrete was compared by electric flux method and chloride ion diffusion coefficient method. The permeability test parameters and experimental results are shown in Tab. 8.

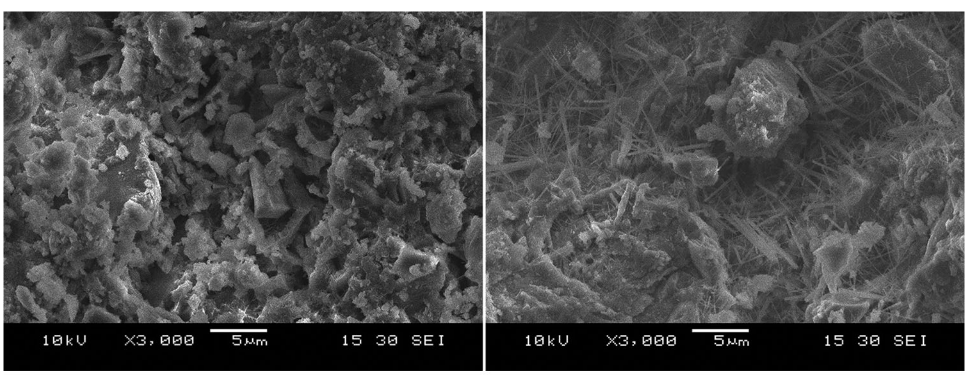
Table 8: Test results of chloride ion permeability of concrete after curing for 56 d

Serial number	Electric flux method voltage/V	6 h Electric flux/C	Applied voltage by diffusion coefficient method/V	Test time of diffusion coefficient method/h	Diffusion coefficient/ (10^{-12} m^2/s)
C40-1	60.0	1980.0	40.0	24.0	3.20
C40-2	60.0	950.0	40.0	24.0	1.65

It was found that the 6-hour electric flux value and chloride ion diffusion coefficient of the concrete containing 15% steel slag powder and 15% zeolite powder were significantly lower than that of the base concrete after 56 d of standard curing. According to the relationship between the diffusion coefficient and anti-chloride ion permeability proposed by Li et al. [15], when concrete chloride ion diffusion coefficient $D_a < 8 \times 10^{-12}$ m^2/s, its anti-chloride ion permeability was better. When concrete chloride ion diffusion coefficient $D_a < 2 \times 10^{-12}$ m^2/s, its anti-chloride ion penetration performance was very good. According to the evaluation criteria of the electric flux results [16], the chloride ion permeability of concrete was lower when the electric flux was in the range of 1000–2000 C, and the chloride ion permeability of concrete was very low when the electric flux was in the range of 100–1000 C. The test results was seen that the diffusion coefficient of C40 steel slag powder-zeolite concrete was 1.65×10^{-12} m^2/s, and which had the 6 h electric flux of 950 C. It was indicated that the C40 steel slag powder-zeolite concrete had very low chloride ion permeability and very good resistance to chloride ion permeability. Compared with the standard concrete, the resistance to chloride ion permeability was improved by one grade. The results of the two methods had a good correlation, which showed that steel slag powder and zeolite powder could significantly improve the chloride ion permeability of concrete.

3.4 Microscopic Analysis

Fig. 2 are SEM pictures of two kinds of concrete at 56 d. By comparison, it was seen that a large number of hydration products CSH gel and flake $Ca(OH)_2$ were distributed in the base concrete, and the hydration products were dense, but there were still a few tiny voids having not be filled completely. In addition to the large amount of gel-like hydration products produced in the steel slag powder-zeolite powder concrete, at the same time, a large number of needle-like hydration products were seen between the gaps, and flake $Ca(OH)_2$ products were rarely found, and the overall structure was more compact. This was because steel slag powder and zeolite powder were finer than cement, of which filled between cement particles as admixtures to make the cementitious system more compact. In addition, steel slag and zeolite powders with potential pozzolanic activity could gradually react with $Ca(OH)_2$ of cement hydration to form the gelatinous calcium silicate hydrate and acicular calcium sulphoaluminate, accompanying with the consumtion of $Ca(OH)_2$ products. The physical filling effect and secondary hydration reaction of steel slag powder and zeolite powder made the internal structure of concrete more compact, leading to the capillary path of the slag powder-zeolite powder concrete was less than the base concrete. Since the micro-void and capillary path of concrete are the main ways of harmful ion infiltration [17], the migration speed of Cl^- in the steel slag powder-zeolite powder concrete was much slower than the base concrete. Because the chloride ion permeability of concrete was an important index to evaluate its durability, it was speculated that the double adding of steel slag powder and zeolite powder greatly improved the durability of concrete.



(a) (b)

Figure 2: (a) 56 d SEM image of pure cement concrete, (b) 56 d SEM image of steel slag powder-zeolite powder concrete

4 Conclusions

1. The early strength of the concrete containing steel slag powder and zeolite powder had a decrease while its later strength approached to pure concrete. In addition, the chloride ion permeability of concrete obviously reduced with the adding of steel slag powder and zeolite powder. The C40 concrete with 220 mm slump, 48.4 MPa compressive strengths after 28 d curing age, 950 C

electric flux of 6 h and 1.65×10^{-12} m^2/s diffusion coefficient was prepared by double adding of steel slag and zeolite powders.

2. The physical filling effect and secondary hydration reaction of steel slag and zeolite powders led the internal structure of concrete to be more compact, which endowed the steel slag powder-zeolite powder concrete with good later strength. Moreover, the density of the concrete increasing could reduce the capillary path to slow down the he migration speed of Cl^-. It was benefited to improve the chloride ion permeability and durability of the concrete.
3. Steel slag powder and zeolite powder instead of high-priced admixtures such as slag and fly ash to prepare green concrete with good working performances, satisfactory strength, low chloride ion permeability, economical and practical, as a guiding significance for the preparation of marine concrete.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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