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Model test on the effect of paste-aggregate ratio for chloride ion erosion resistance of tunnel lining concrete

Jie Luo*[1], Ju Feng[2], Zhiguo Zhang[3]
*[*1]Postgraduate, School of Environment and Architecture, University of Shanghai for Science and Technology, 516 Jungong Road, Shanghai 200093, China.*
[2]Postgraduate, School of Environment and Architecture, University of Shanghai for Science and Technology, 516 Jungong Road, Shanghai 200093, China.
[3]Professor, Postdoctor, School of Environment and Architecture, University of Shanghai for Science and Technology, 516 Jungong Road, Shanghai 200093, China
Corresponding Author: Jie Luo. (Email: luojie0803@163.com)

Abstract
Existing studies on the chloride ion erosion resistance of tunnel lining concrete are mostly based on different factors such as admixture materials and early cracks of concrete, and there is a lack of systematic comprehensive analysis on the influence of paste-aggregate ratio. Based on the natural diffusion test of chloride ions, this paper intuitively qualitatively and quantitatively analyzes the change rule of chloride ion erosion resistance of tunnel lining concrete under different paste-aggregate ratio parameters by using AgNO3 color method and chloride ion selective electrode method, and fits out the functional relationship between concrete paste-aggregate ratio and chloride ion diffusion coefficient by using Fick's second law. The results show that with the increase of the paste-aggregate ratio, the depth of concrete chloride ion erosion curve increases, and the resistance of concrete to chloride ion erosion decreases. The chloride ion diffusion coefficient of concrete increases with the increase of the paste-aggregate ratio. When the paste-aggregate ratio is less than 0.44, the percentage content of chloride ions at each measuring point increases slowly with the increase of the paste-aggregate ratio. When the paste-aggregate ratio is 0.44 or above, the resistance of concrete to chloride ions decreases more. The maximum erosion depth of chloride ions on the specimen profile, the concentration of chloride ions at the same point and the diffusion coefficient of chloride ions increase significantly.

Keywords: *Tunnel lining concrete; Paste-aggregate ratio; Free diffusion; Chloride ion.*

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I. INTRODUCTION

High-speed railway plays a more important role in our economic life [1]. However, in view of the complex and varied geological conditions,soil and groundwater contain a large amount of Cl^- iserosive ions [2], which invade the tunnel lining structure and a series of physical and chemical reactions will occur, which will destroy the internal microstructure of concrete and cause the tunnel lining structure to crack and spalling in different degrees, causing a serious impact on the operation safety and transportation efficiency of high-speed railway. So it is very important to explore the performance of tunnel lining concrete against chloride ion erosion.

Laboratory material test is widely used due to its advantages of easy implementation and good test results [3-12]. Zhang et al. [3] considered the correlation between the initial crack width and crack depth of concrete structures, and studied the influence rule of single factor of crack characteristics on chloride ion diffusion characteristics based on AgNO3 color development method and drilling powder extraction. Marsavina et al. [4] studied the influence of cracks on chloride infiltration of concrete structures by comparing the numerical results of transient finite element analysis with the experimental results when the diffusion coefficient of total chloride ion concentration is considered. Nielsen [5] modified the diffusion coefficient of chloride ions in Fick's second Law [6-7] by using Bowers model and composite theory, and established the chloride ion transport model of unsaturated concrete.

Most of the above studies on the chlorine resistance of tunnel lining concrete are based on the types of aggregate of concrete with joint and so on, and there are few systematic studies on this important parameter of concrete paste-aggregate ratio. Based on the natural diffusion test of chloride ions, this paper qualitatively and quantitatively analyzes the variation rule of chlorine resistance of tunnel lining concrete under the influence of different paste-aggregate ratio parameters by using $AgNO^3$ color development method and chloride ion selective electrode method. Meanwhile, based on Fick's second law, the functional relationship between paste-aggregate ratio parameters and chloride ion diffusion coefficient is fitted through experimental data.

II. TEST OVERVIEW

In this paper, five different grades of concrete paste-aggregate ratio ranging from 0.32 to 0.48 are studied, and a total of 15 concrete erosion specimens are designed and manufactured, and the fully enclosed chloride ion natural erosion test is carried out for 120 days.

2.1 THE SIMULATION

(a) medium sand for the test and (b) gravel for the test

Fig.1 Raw material of concrete test block

Raw materials required for this test: Conch cement (ordinary Portland cement PO42.5); Gravel with a particle size of 5-15mm is selected for coarse aggregate, and high-quality river sand is selected for fine aggregate, as shown in Figure 1. Water (tap water from laboratory of University of Shanghai for Science and Technology, chloride ion content 0.004mol/L); Electrode penetration solution - potassium chloride solution 250ml. C30 concrete is designed according to the "Ordinary Concrete Mix Design Specification" (JGJ 5-2011). The concrete mix is shown in Table 1.

Table 1 Parameters of concrete mix ratio used in the test

material	Water(kg/m^3)	cement(kg/m^3)	Sand(kg/m^3)	Crushed stone(kg/m^3)	paste-aggregate ratio
J1	5.805	9.990	19.602	29.403	0.32
J2	6.264	10.800	19.089	28.647	0.36
J3	6.723	11.610	18.576	27.891	0.40
J4	7.209	12.420	18.063	27.108	0.44
J5	7.668	13.230	17.550	26.352	0.48

2.2 TEST PROCESS

(i) Concrete test blocks are designed and made according to the mix ratio in Table 1, the size of which is 150mm×150mm×300mm. After demoulding, the specimens are labeled respectively, and water culture is carried out uniformly;

(ii) Except for one side of each concrete specimen of 50mm×300mm, the other sides are sealed with epoxy resin to prevent the erosion of chloride ions. After the epoxy resin is completely dried and hardened, the specimen is placed in an erosion chamber containing 5% NaCl solution and soaked. Bubble penetration is carried out for 120 days in the completely closed state. After the bubble penetration is completed, the concrete specimen is taken out, cut and numbered along the center line of the specimen, as shown in Fig.2;

(iii) Section ① after cutting is taken, and color development is sprayed on the cutting surface with the configured 0.1mol/L $AgNO3$ solution. Section ② after cutting is taken, a group of powder sample 2g is taken every 5mm, and 225 samples are taken in the whole test, as shown in Fig.3.

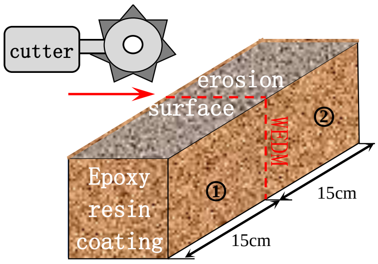


Fig.2 Concrete cutting diagram

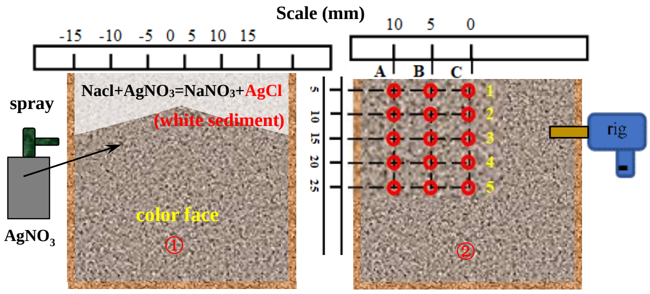


Fig.3. Concrete test block powder color

(ⅳ) The powder sample will be fully ground until it can pass through the 0.65mm screen, and then put in the oven to dry for 48h. After the treatment is completed, the PH value of the corresponding powder sample solution will be tested by the corresponding test instrument, and the corresponding chloride ion concentration of the powder sample will be converted.

2.3 TEST CHLORIDE ION CONCENTRATION CALCULATION

(a) Test concrete powder sample **(b) test instrument**

Fig.4 Test equipment and samples

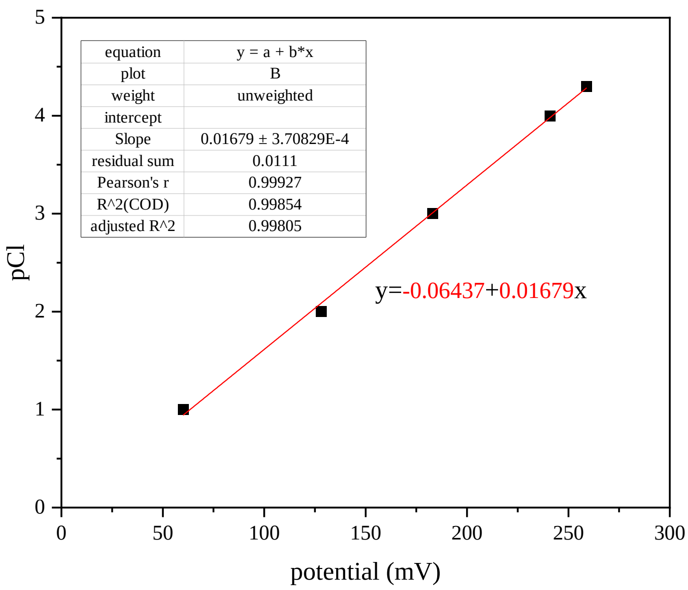


Fig.5 Relational standard curve

A PHS-3E PH meter combined with a PCL-01 chloride ion electrode and a 217-01 double salt bridge reference electrode is used to test the potential value of the powdery solution, as shown in Fig.4. The first salt bridge electrode uses saturated KCl solution, and the second salt bridge uses 2mol/L KNO3 solution. The two electrodes are activated to improve sensitivity. At the same time, the collected concrete powder samples are dissolved in 100ml deionized water, and then stand for 48h for chloride ion extraction after full mixing. Finally, the standard curve of "mV-pCl" relationship measured by standard solution with the obtained PH value is shown in Fig.5. The ordinate concentration value mol/L of the powder sample is obtained, and the weight of chloride ion in the concrete powder sample is converted into the equation of the standard curve as follows:

$$pCl = -0.06437 + 0.01679mV \tag{2}$$

Where pCl=-lgCCl-, CCl-is the chloride ion concentration measured in powdered solution.

The standard curve is drawn by linear regression after measuring 5 groups of NaCl solutions with different concentration gradients. The corresponding potential value and pCl of each group of NaCl solutions are shown in Table 2:

Table 2 Parameters of NaCl solution

NaCl	potential(mV)	pCl
0.1mol/L	60	1
0.01mol/L	128	2
0.001mol/L	183	3
0.0001mol/L	241	4
0.00005mol/L	259	4.301

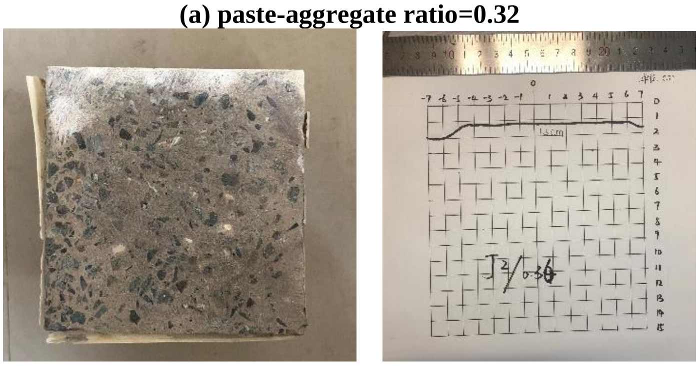
III. ANALYSIS OF TEST RESULTS

Through color rendering of concrete specimens with different paste-aggregate ratio and powder extraction by drilling, the chloride ion erosion area, chloride ion content and corresponding chloride ion permeability coefficient of concrete specimens are obtained.

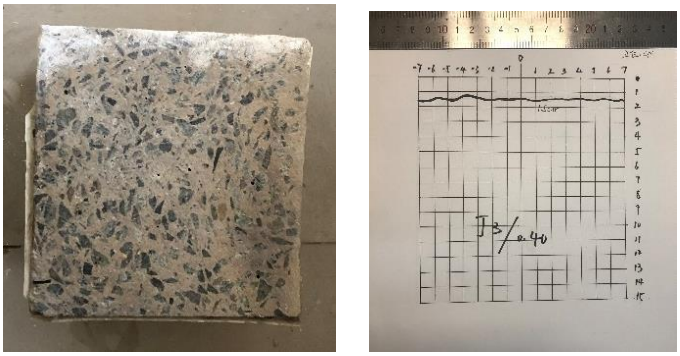
3.1 SAMPLE SECTION CHLORIDE ION EROSION AREA

As can be seen from Fig.6, the chloride ion erosion curve on the concrete section plane basically presents a slightly convex curve on both sides and a flat curve with concave in the middle. This is because in the process of artificial epoxy resin sealing concrete, there are always gaps on both sides of the top surface of concrete, resulting in the one-dimensional diffusion of the four-corner concrete to a certain extent, so the erosion depth is slightly greater than that on both sides of the middle area.

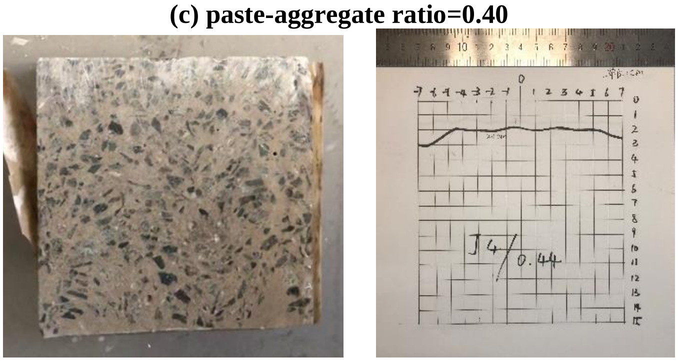
(a) paste-aggregate ratio=0.32



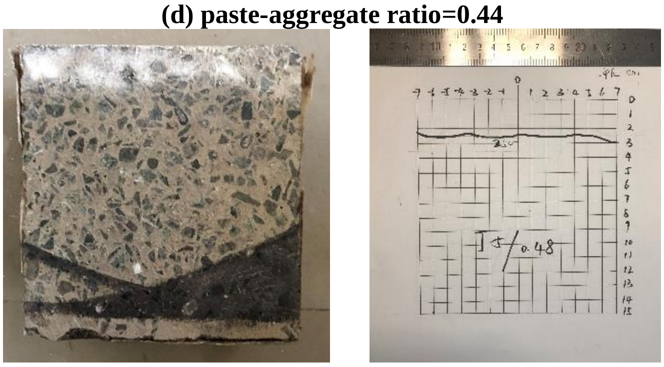
(b) paste-aggregate ratio=0.36



(c) paste-aggregate ratio=0.40



(d) paste-aggregate ratio=0.44

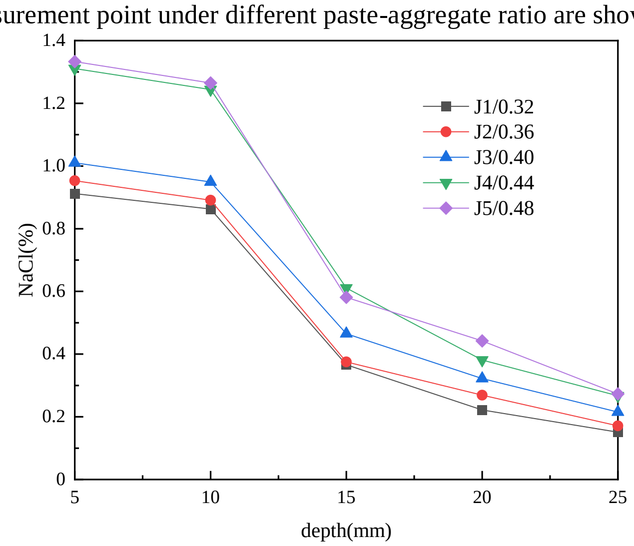


(e) paste-aggregate ratio=0.48

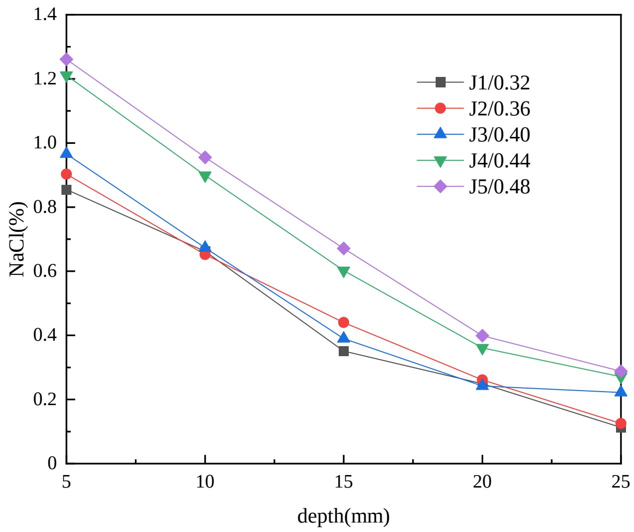
Fig.6. Curves of color development and erosion depth of specimen

3.2 CHLORIDE ION CONCENTRATION OF EACH PART OF THE SAMPLE POWDER

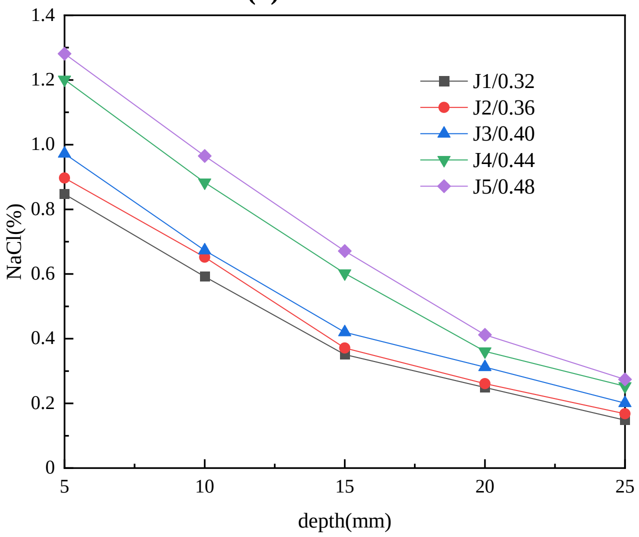
The powder extraction solution is drilled in the specified position of the concrete section, and the mass percentage of chloride ions in the concrete powder samples is converted by Eq.(1) The concentration curves of chloride ions at each measurement point under different paste-aggregate ratio are shown in Fig.8.



(a) column A



(b) column B



(c) column C

Fig.7 Chloride ion concentration curves under different paste-aggregate ratios

As can be seen from Fig.7, the trend of chloride ions changing with powder depth under different paste-aggregate ratios in column B and C at powder depth is consistent, and the chloride resistance of concrete specimens decreases with the increase of paste-aggregate ratio. When the paste-aggregate ratios is between 0.32 and 0.40, the chloride resistance of concrete decreases slowly, and the concentration of chloride ions in powder samples of each paste-aggregate ratio approaches at the same powder depth. When the paste-aggregate ratio is 0.44 or above, the chlorine resistance of concrete decreases significantly, and the concentration of chloride ions in the powder samples with the same depth increases significantly, indicating that the chlorine resistance of concrete specimens decreases significantly at this time, and the concentration of chloride ions in the powder position A is significantly different from that in column B and C within the depth range of 0~10mm. This is due to the gap defects around the concrete specimen during the artificial epoxy resin seal.

3.3 CHLORIDE ION DIFFUSION COEFFICIENT OF SPECIMENS

Based on the measured chloride ion concentration at each measuring point on the profile, it is assumed that the initial chloride ion concentration inside the concrete is zero, and Fick's simplified second law [3] is adopted to ignore the initial chloride ion concentration in the concrete. The formula is as follows:

$$C(x,t) = C_s(1-\mathrm{erf}(\frac{x}{2\sqrt{Dt}})) \tag{2}$$

where C is the concentration of chloride ions at the measured points; x is the corresponding depth of the measured points; t is the test time (120d in all experiments); Cs is the concentration of chloride ions on the exposed surface of concrete; D is the diffusion coefficient of chloride ions, which is the error function.

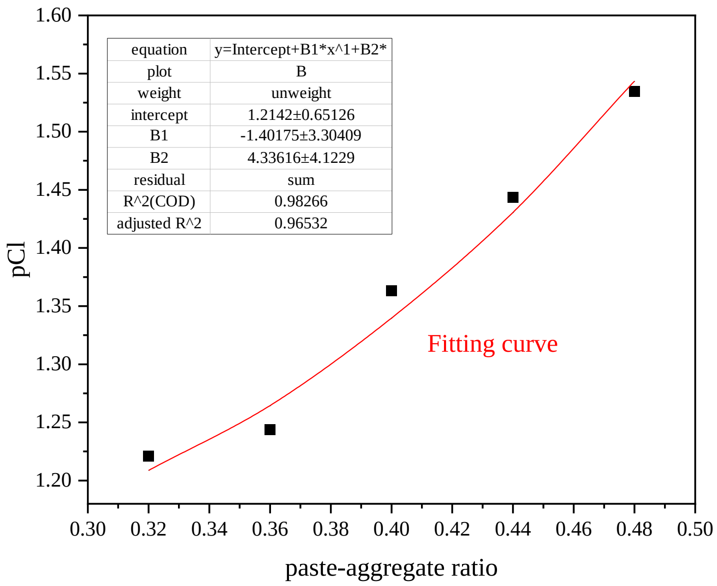


Fig.8 Fitting curve of paste-aggregate ratio and diffusion coefficient

The chloride ion diffusion coefficient under different paste-aggregate ratios is fitted, and the functional relationship between chloride ion diffusion coefficient D and concrete paste-aggregate ratio J is established, as shown in Fig.8. The relationship is as follows:

$$D = 1.2142 - 1.40175J + 4.33616J^2 \tag{3}$$

According to the fitting results, the quadratic polynomial fitting curve has a good fit with the actual data, which can describe the process of the increase of chloride ion diffusion coefficient with the increase of concrete paste-aggregate ratio J between 0.32 and 0.48.

A total of 20 groups of different paste-aggregate ratio parameters between 0.3 and 0.5 are selected, and corresponding concrete chloride ion diffusion coefficients are calculated according to Eq.(2), as shown in Table 3. According to the data in the table, consistent with the trend of the test, the concrete chloride ion diffusion coefficient increased with the increase of the paste-aggregate ratio, but compared with the test data, the chloride ion diffusion coefficient obtained by fitting formula is slightly larger. Concrete as a whole is less resistant to erosion.

Table 3 Chloride ion diffusion coefficient under different paste-aggregate ratio

paste-aggregate ratio	D×10-11(m2·s-1)	Water(kg/m3)	Cement(kg/m3)	Sand(kg/m3)	Crushed stone(kg/m3)
0.3	1.1839	5.489	9.464	19.938	29.908
0.31	1.1964	5.629	9.705	19.786	29.679
0.32	1.2097	5.767	9.942	19.636	29.455
0.33	1.2238	5.902	10.176	19.489	29.233
0.34	1.2389	6.036	10.406	19.343	29.015
0.35	1.2548	6.167	10.633	19.200	28.800
0.36	1.2715	6.297	10.856	19.059	28.588
0.37	1.2892	6.424	11.076	18.920	28.380
0.38	1.3077	6.550	11.293	18.783	28.174
0.39	1.3270	6.674	11.507	18.647	27.971
0.4	1.3473	6.796	11.718	18.514	27.771
0.41	1.3684	6.917	11.926	18.383	27.574
0.42	1.3904	7.036	12.131	18.254	27.380
0.43	1.4132	7.153	12.332	18.126	27.189
0.44	1.4369	7.268	12.532	18.000	27.000
0.45	1.4615	7.382	12.728	17.876	26.814
0.46	1.4869	7.495	12.922	17.753	26.630

0.47	1.5132	7.605	13.113	17.633	26.449
0.48	1.5404	7.715	13.301	17.514	26.270
0.49	1.5685	7.823	13.487	17.396	26.094

IV. CONCLUSION

Based on the natural diffusion test of chloride ions, this paper qualitatively and quantitatively analyzes the variation rule of chlorine resistance of tunnel lining concrete under the influence of different paste-aggregate ratio parameters by using AgNO3 color development method and chloride ion selective electrode method. The main conclusions are as follows:

(ⅰ) The chloride ion erosion resistance of concrete decreases with the increase of the paste-aggregate ratio;

(ⅱ) The diffusion coefficient of chloride ions in concrete increases with the increase of the paste-aggregate ratio, that is, the increase of the paste-aggregate ratio will lead to the diffusion of chloride ions into the interior of concrete more easily. Moreover, through software fitting, the quadratic polynomial functional relation between the paste-aggregate ratio and the diffusion coefficient of chloride ions is obtained;

(ⅲ) There will be a mutation in chlorine resistance of concrete when the paste-aggregate ratio is near 0.44. When the paste-aggregate ratio is less than 0.44, the chlorine resistance of concrete decreases slowly with the increase of the paste-aggregate ratio, and the chloride ion concentration at the same point within the concrete approaches; when the paste-aggregate ratio is greater than 0.44, the chlorine resistance of concrete attenuates significantly, and the maximum erosion depth of chloride ion on the specimen profile, the chloride ion concentration at the same point and the chloride ion diffusion coefficient increase significantly.

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