Effect of Curing Age on Chloride Diffusion Coefficient of Recycled Aggregate Concrete Subjected to Compressive Stresses

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Abstract: The effect of curing age on chloride diffusion coefficient of recycled aggregate concrete subjected to different compressive stresses was investigated. A compression loading setup was both designed and fabricated. The chloride diffusion coefficients of recycled aggregate concrete under compressive stresses were measured by the rapid chloride ion migration (RCM) method. The experimental results show that the chloride diffusion coefficients of recycled aggregate concrete (RAC) under different compressive stress ratios generally decrease with the increase of curing age. For RAC subjected to the same compressive stress ratios, the chloride diffusion coefficients approximately have power functions with curing ages and the relationship models are proposed. Moreover, the influence of curing age on chloride diffusion coefficient firstly decreases and then increases as the compressive stress ratio increases.

Key words: recycled aggregate concrete(RAC); chloride diffusion coefficient; curing age; compressive stress ratio; rapid chlorideion migration(RCM) method

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0 Introduction

As one of the pillar industries of the national economy, the construction industry has developed rapidly in recent years, but the construction waste has also increased sharply. Within all of the construction waste, the amount of waste concrete is the largest, which accounts for about 30%—50% by weight [1]. On the other hand, the sources of suitable natural aggregate have been diminished severely. Therefore, the use of recycle aggregate (RA) in the production of new concrete has become increasingly popular and cost-effective[2].

However, compared with natural aggregate (NA), a lot of micro cracks and fissures produced in the process of waste concrete disintegration and fragmentation, as well as old cement mortar that remains attaching to the virgin aggregate of RA, make RA have a higher porosity and more large pores, thus leading to the durability of recycled aggregate concrete (RAC) lower than that of natural aggregate concrete (NAC). Since chloride-induced corrosion is the most prominent cause for the deterioration of reinforced concrete, the durability of concrete is closely related to chloride penetration. The chloride diffusion coefficient has been widely considered as the most important index for evaluating the durability of recycled aggregate concrete.

The micro cracks and pores in concrete significantly influence the chloride diffusion coefficient, and the curing age can affect the resistance to chloride penetration of concrete by changing micro cracks and pores. As the curing age increases, the micro cracks and pores in the concrete decrease and the resistance to chloride penetration improves. Therefore, the influence of curing age on chloride diffusion coefficient should be investigated. Nowadays, the researches on the change trend of the resistance to chloride ion permeability

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of natural aggregate concrete with curing age have been widely conducted and lots of research results have been obtained [3-5]. But the large porosity and the high water absorption of recycled aggregate may deviate the chloride diffusion coefficient of recycled aggregate concrete from that of natural aggregate concrete. To date, the researches on the chloride diffusion coefficient of recycled aggregate concrete have been reported. Limbachiya et al. [6] found that the chloride diffusion coefficient decreased with the increase of the replacement ratio of recycled coarse aggregate. While Zhang et al. [7] observed that the chloride diffusion coefficient of recycled concrete firstly decreased and then increased with the increase of the replacement ratio of recycled coarse aggregate. The results of Ye et al. [8] showed that the decrease of water cement ratio could improve the resistance to chloride ion penetration of recycled concrete. Moreover, the chloride penetration of recycled concrete is done under external loads in practical engineering, so it is significant to study the chloride diffusion coefficient of recycled concrete subjected to external loads. Wang et al. [9] found that the chloride diffusion coefficient of recycled aggregate concrete presents a trend of firstly decreasing and then increasing as the compressive load increases. But the aforementioned research focuses on the influences of the replacement ratio of recycled aggregate, water-cement ratio and compressive load, less information on the relationship between chloride diffusion coefficient of RAC and curing age is available.

In addition, when compressive load is applied to recycled aggregate concrete, the micro cracks and pores may close up and expand, even generating new cracks. Consequently, the chloride diffusion coefficient will change, as well as the change trend of the chloride diffusion coefficient with the curing age. Therefore, the influence of the compressive load should not be neglected.

The objective of this study is to investigate the effect of curing ages on chloride diffusion coefficients of recycled aggregate concrete under different compressive stress levels and to propose the relationship models.

1 Experiment

1.1 Experimental materials

The cement used for the mixes was 42.5R Portland cement supplied by China Nanjing Jiangnan Cement Plant. The fine aggregate (FA) was natural river sand with the fineness modulus of 2.6 and the water content of 3%. The recycled or natural coarse aggregates were used as the coarse aggregate (CA) in the mixtures. The natural coarse aggregate (NCA) was graded gravel with a maximum particle size of 31.5 mm. The recycled coarse aggregate (RCA) with the water absorption of 5.7% and the crushing index of 10.4%, which conform to the requirements of Grade Ⅱ RA in Chinese National Standard GB/T 25177—2010 [10]. The properties of NCA and RCA are shown in Table 1. Based on the design method of mix proportion of NAC, supplementary water needs to be added into the RAC in accordance with water absorption of RCA. The mix proportions and compressive strength of NAC and RAC are shown in Table 2.

Table 1 Properties of coarse aggregate

Aggregate coarse category	Apparent density/ (kg · m^{-3})	Water absorption/ %	Crushing index/ %	Particle size/mm
NCA	2 690	0.82	3.5	5—31.5
RCA	2 700	5.7	10.4	5—31.5

Table 2 Mix proportions and compressive strength of NAC and RAC

Replacement ratio of RA/%	W/C ratio	Cement/ (kg · m^{-3})	Water/ (kg · m^{-3})	supplementary water/(kg · m^{-3})	CA/ (kg · m^{-3})	FA/ (kg · m^{-3})	28-day compressive strength/MPa
0	0.39	513.2	198.3	0	978.8	550.5	43.3
100	0.39	513.2	198.3	55.7	978.8	550.5	35.9

1.2 Concrete casting and curing

Two kinds of concrete specimens were cast here, i.e. 150 mm×150 mm×150 mm cubes and 100 mm×100 mm×400 mm prisms. The cubic specimens were used to measure the compressive strength of concrete at 28 d. The prism specimens were cut into 100 mm×100 mm×50 mm to test the chloride diffusion coefficients of concrete under different compressive stress ratios by RCM method. After casting, the concrete specimens were cured in the water until the age of 14, 28, 56, 90, 135, 180, 270 d, respectively.

1.3 Loading test

The setup for loading test is shown in Fig. 1. The skeleton of the compressive loading setup was made up of two stainless steel bars and three stainless steel plates. In order to ensure enough strength and rigidity of the setup, all parts were made of Q345 high strength stainless steel. The concrete specimens were fixed to the skeleton by a kind of special glue and compressive load was applied by two top nuts. The properties of the special glue are shown in Table 3. Furthermore the applied loadings can be controlled and checked by measuring the displacements of the disc springs during the test. By using this setup, three specimens of 100 mm×100 mm×50 mm can be applied the same loading at the same time, which can shorten the test period and save the test cost.

As shown in Tables 4, 5, after the specimens were cured for 14, 28, 56, 90, 135, 180 and 270 d, respectively, they were subjected to different compressive stress ratios of 0, 0.3, 0.6

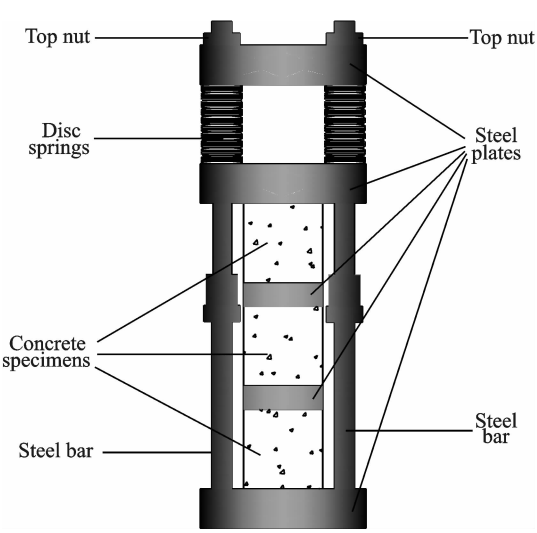

Fig. 1 Setup for loading test [11]

and 0.8. Concrete compressive stress ratio λ was calculated according to the following equation

$$\lambda = \sigma / f \tag{1}$$

where is the compressive strength of 100 mm×100 mm×50 mm specimen and σ the applied stress value.

Table 3 Properties of special glue

Appearance	Viscosity/(cps 25℃)	Mixing ratio (weight ratio)	Operable time (25℃)/h	Bond strength/MPa
White	3 000—5 000	5∶1	1.5—2	>5

Table 4 Stress in NAC specimens subjected to sustained compressive loadings MPa

λ	Age/d			
	14	28	56	90
0.0	0.00	0.00	0.00	0.00
0.3	7.40	10.82	12.36	13.26
0.6	14.80	21.78	24.01	26.43

Table 5 Stress in RAC specimens subjected to sustained compressive loadings MPa

λ	Age/d						
	14	28	56	90	135	180	270
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.3	4.40	8.62	10.30	12.01	12.70	13.15	14.37
0.6	11.80	17.24	20.47	23.93	25.18	26.87	28.55
0.8	16.04	23.20	27.25	32.43	33.90	35.31	37.09

1.4 Concrete chloride diffusion coefficient test

Here, the chloride diffusion coefficient of concrete was tested by RCM method. The test process of RCM method was performed according to NT Build 492 [12]. The test method was selected because of its convenience and reliability [13]. Since the chloride diffusion coefficient of concrete subjected to sustained load was measured, the migration test setup was modified, as shown in Fig. 2. Before the chloride diffusion coefficient test, the specimens under compressive stresses must be immersed in an ultrasonic bath to make the specimens be in a water-saturated state. And to ensure the chloride ion penetration into concrete in one direction, the sides of specimens should be sealed with the special glue mentioned above. Subsequently, the rubber tube was fixed on concrete surface by the special glue, the positive electrode was

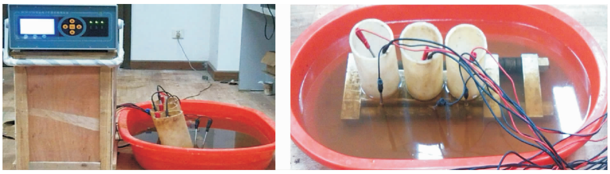

Fig. 2 Modified setup for migration test [9]

placed in the rubber tube and the negative electrode was fixed on concrete bottom. And anodic and cathode electrolytic solution were added in the rubber tube and the plastic pot, respectively.

After the specimens were fixed in the modified setup for migration test, electro-migration test was conducted. After the migration test, the specimens axially splitted and 0.1 mol/L silver nitrate solution was sprayed on the split surface immediately. After about 15 min, the chloride ion diffusion penetration depth was measured according to Fig. 3 and chloride diffusion coefficient was calculated from the following calculation formula proposed by NT Build 492 [12]

$$D_{\mathrm{RCM},0}=2.872\times10^{-6}\,\frac{Th\left(X_{\mathrm{d}}-\alpha\sqrt{X_{\mathrm{d}}}\right)}{t} \quad (1)$$

$$\alpha=3.338\times10^{-3}\sqrt{Th} \quad (2)$$

where $D_{\mathrm{RCM},0}$ is the chloride diffusion coefficient of concrete (m^2/s), T the average anodic electrolytic solution temperature (℃), h the average specimen thickness (mm), X_d the average chloride penetration depth (mm), and α an auxiliary variable.

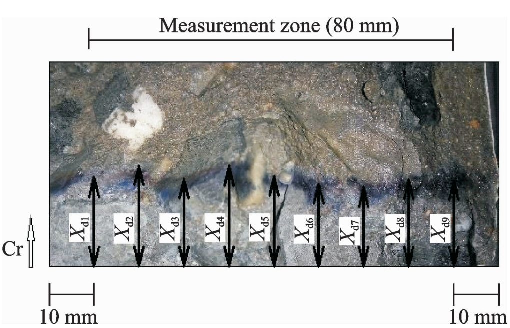

Fig. 3 Concrete chloride diffusion penetration depth test

2 Analysis and Discussion

2.1 Effect of curing age with no stresses

For natural aggregate concrete, Mangat et al. [4] and Zhou et al. [14] have given the relationship between the chloride diffusion coefficient and curing age. In this study, the relationship between D/D_0 and t/t_0 in recycled aggregate concrete was explored, and D was the chloride diffusion coefficient (m^2/s), D_0 the chloride diffusion coefficient at the reference period (m^2/s), and t_0 the reference period (t_0 refers to 28 d). In Fig. 4, the experimental results from other researches[15-20] were compared with that of this paper.

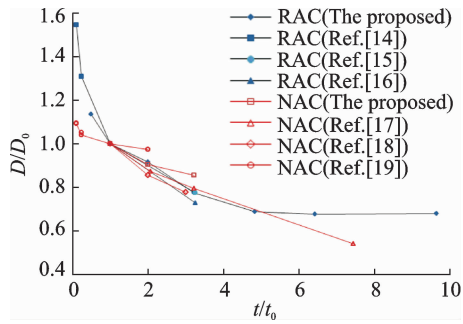

Fig. 4 Curing age vs chloride diffusion coefficient of recycled aggregate concrete and natural aggregate concrete under no stresses

In Fig. 4, recycled and natural aggregate concretes with the same water-binder have the similar experimental results, i.e., for both RAC and NAC, the chloride diffusion coefficient decreases with the increase of curing age. It was widely accepted that the setting and hardening of recycled aggregate concrete are the result of the chemical and physical reaction between cement and water[21]. At the beginning of hydration, many large capillary pores exist in the recycled aggregate concrete and total pore volume is large. As the curing time increases, the fine degree of the capillary system increases, and the amount of gel, pore volume and through-pore structure decrease. Therefore, chloride diffusion coefficient decreases with the help of deepening the degree of hydration. In addition, for both NAC and RAC, the chloride diffusion coefficient decreases quickly at the beginning and then slows down obviously with the increase of curing age. It can be implied that the chemical and physical reactions mostly occur in the earlier stage of curing and seldom occur during the later ages, which leads the resistance to chloride ion penetration to improve initially significantly but then a little. This is consistent with the conclusion of Wang et al. [22] on the change trend of NAC chloride diffusion coefficient with age.

It should be noted that before the age of 28 d ($D/D_0<1$), the chloride diffusion coefficients of recycled concrete are larger than those of natural concrete. Nevertheless, during the period of 28 to 90 d ($1<D/D_0<3.21$), the chloride diffusion coefficients of recycled concrete are lower than those of natural concrete, indicating that before 90 d, the chloride diffusion coefficient of recycled aggregate concrete decreases larger when compared with that of natural aggregate concrete. The larger decrease in chloride diffusion coefficient of RAC is attributed to the fact that with the high water absorbing ratio of recycled aggregate, recycled aggregate concrete absorbs a certain amount of water in the process of mixing, and part of the water was gradually released in the hydration. The process increased concrete curing humidity, produced a kind of "internal curing" effect on RAC, made cement hydration full, and increased the compactness of recycled concrete, thus promoting the recycled aggregate concrete resistance to chloride ion diffusion [23]. Additionally, the result would suggest the importance of the early-age curing to improve the RAC resistance to chloride ion permeability.

2.2 Effect of curing age under different compressive stress ratios

The relationships between the chloride diffusion coefficient of NAC and RAC and curing age under compressive stresses are shown in Figs. 5, 6, respectively. With the increase of the curing age, the chloride diffusion coefficients of both NAC and RAC generally decrease, no matter how large compressive stress ratios are applied. This is due to the fact that with the growth of curing age, the degree of hydration of concrete increases and the internal micro cracks decrease continuously. Additionally, the chloride diffusion coefficients of NAC and RAC decrease fast at the be-

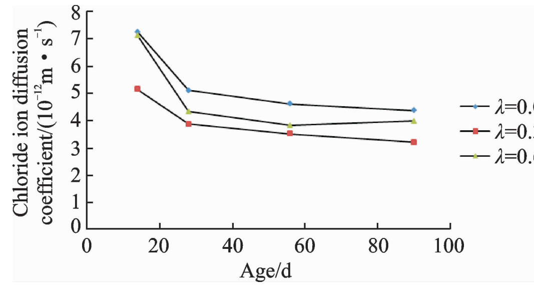

Fig. 5 Curing age versus chloride diffusion coefficient of natural aggregate concrete under different compressive stress levels λ

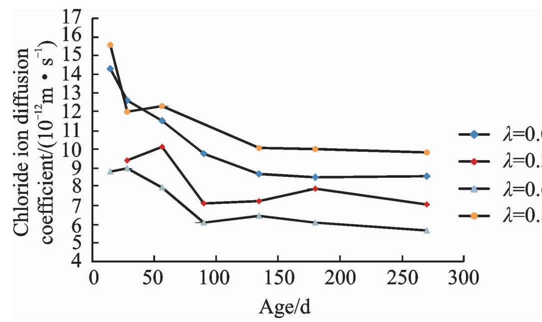

Fig. 6 Curing age versus chloride diffusion coefficient of recycled aggregate concrete under different compressive stress levels

ginning and then slow down with the increase of curing age. But the chloride diffusion coefficient of NAC decreases slowly after 28 d, while the chloride diffusion coefficient of RAC decreases slowly after 90 d. It is due to the internal curing effect of recycled aggregate concrete mentioned above, which promotes the improvement of the resistance to chloride ion penetration of RAC from 28 d to 90 d.

2.3 Relationship between curing age and chloride diffusion coefficient of recycled aggregate concrete under compressive stresses

According to the above analyses, the chloride diffusion coefficient of RAC has a good correlation with the curing age, which is consistent with the research results of NAC chloride diffusion coefficient obtained by Mangat et al. [4] and Hong et al. [5]. For RAC and NAC under different compressive stress ratios, the relationships between the chloride diffusion coefficient D/D_0 and curing age t/t_0 are nearly suitable to power functions. The fitting formulas and curves are shown in Table 6 and Figs. 7, 8, respectively.

Table 6 The fitting formulas

Category	Compressive stress level	Fitting formula	Correlation coefficient R^2
NAC	0.0	$D/D_0 = (t/t_0)^{-0.264}$	0.886 2
	0.3	$D/D_0 = (t/t_0)^{-0.244}$	0.937 9
	0.6	$D/D_0 = (t/t_0)^{-0.308}$	0.760 4
RAC	0.0	$D/D_0 = (t/t_0)^{-0.195}$	0.957 1
	0.3	$D/D_0 = (t/t_0)^{-0.120}$	0.852 9
	0.6	$D/D_0 = (t/t_0)^{-0.170}$	0.870 2

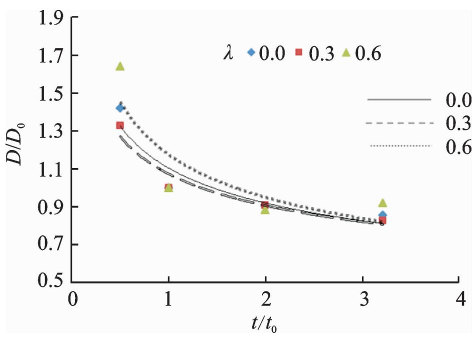

Fig. 7 D/D_0 versus t/t_0 for NAC

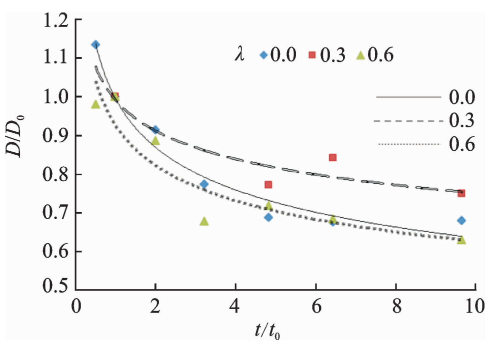

Fig. 8 D/D_0 versus t/t_0 for RAC

For both NAC and RAC, the slope of the curve under the compressive stress ratio 0.3 is gentler than that of the curves under the compressive stress ratio 0.0 and 0.6, which indicates that the compressive stress ratio can change the level of involvement of the curing age on the concrete chloride diffusion coefficient. This might be related to the closure and expansion of micro cracks in concrete subjected to compressive stresses. Under smaller compressive stress ratio, the closure of micro cracks in concrete will lead to the lower influence of the curing age on the chloride diffusion coefficient. While under larger compressive stress ratio, as the micro cracks in concrete expands, the improvement of the curing age on the internal structure of the concrete become significant, which could lead to an obvious decrease in chloride diffusion coefficient as the curing age increases [11].

Furthermore, to verify the validity of the fitting formulas of concrete in Table 6, the experimental results from Refs. [15-17] are compared with the calculated values of D/D_0 based on the proposed fitting formulas. Table 7 shows the validation results.

In Table 7, the calculated values concur with the experimental ones. Therefore, the empirical formulas of this study can express the relationships between chloride diffusion coefficient and age of concrete well.

Table 7 Validation results of the fitting formulas of concrete

Researchers	Concrete category	λ	Age/d	D/D_0 experimental value	D/D_0 calculated value	Relative error/%	Relative error variance
Ref. [15]	RAC	0	3	1.571	1.546	1.62	
	RAC	0	7	1.381	1.310	5.41	
The proposed	RAC	0	90	0.774	0.796	−2.76	0.002 4
Ref. [16]	RAC	0	90	0.773	0.796	−2.89	
Ref. [17]	RAC	0	90	0.727	0.796	−8.67	

3 Conclusions

The influence of curing age on chloride diffusion coefficient of recycled aggregate concrete under different compressive stress levels is investigated and the following conclusions can be drawn:

(1) With no stresses, the chloride diffusion coefficient of recycled aggregate concrete decreases with the increase of curing age and the rate of

descent evidently presents "fast followed by slow" type, which is consistent with the result of natural aggregate concrete. Whereas compared with the natural aggregate concrete, the chloride diffusion coefficient of recycled aggregate concrete drops sharply in the earlier stage of curing.

(2) Under different compressive stress ratios, the chloride diffusion coefficient of recycled aggregate concrete generally decreases with the increase of curing age. And the internal curing effect of recycled aggregate concrete promotes the improvement of the resistance to chloride ion penetration of RAC from 28 d to 90 d.

(3) For both the recycled aggregate concrete and the natural aggregate concrete, the chloride diffusion coefficient approximately has a power function with the curing age and the relationship models are proposed under the compressive stress levels of 0, 0.3, and 0.6, respectively and the performance of the relationship models was verified by the experimental data of other researchers. And the influence of curing age on chloride diffusion coefficient of concrete under higher compressive level is more remarkable than that under lower compressive level.

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