A Laboratory Analysis of Chloride Ions Penetration in Recycled Aggregates Concrete Admixed with Ground Granulated Blast Furnace Slag

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Abstract. The corrosion of reinforcements in recycled aggregates (RA) structures could be triggered by chloride attack. Ground granulated blast furnace slag (GGBS) has been recognized a significant cement replacement to improve chloride resistant of concrete. However, the study aimed at time-dependent chloride diffusion of recycled aggregates concrete (RAC) with GGBS was still scarce. Thus, with the data generated at varying immersion durations from long-term bulk immersion tests, the effects of the content of ground granulated blast furnace slag (GGBS) and immersion time on time-dependent chloride diffusion were studied. The results indicated that the apparent diffusion coefficient ($D_{app}$) of recycled aggregates concrete decreases with immersion time. Moreover, the total chloride concentration decreases with the increase of GGBS replacement. When increasing the content of GGBS from 0% to 30%, the value of $D_{app}$ decreases from 28.9% to 52.2%, while 67.2%–40.6% of reduction was observed on $D_{app}$ with the addition of 60% GGBS at different immersion time.

1. Introduction

In recent years, construction waste has increasingly become a potential threat to environmental pollution, and treatment of it seems to be a worldwide problem. Currently, construction waste accounts for about 40 percent of solid waste discharged by urban residents, making it one of the biggest wastes in Chinese rapid urbanization [1]. More and more attention has been paid to it, resulting from that the recycling of construction waste can reduce the discharge of solid waste and the consumption of natural resources. However there are wide variations caused by the differences between natural aggregate and recycled coarse aggregate (RCA) in particle shape, surface structure, water absorption and many other aspects, which restricts the application of RAC in marine environments [2].

Nowadays, much attention has been devoted to studying the durability of RAC in the marine environments. Hu [3] investigated the effects of recycled aggregate, sand ratio, and water-cement ratio on chloride transport in RAC from an unsteady rapid chloride migration test (RCM), which the decrease in the water cement ratio lead to the development in the chloride penetration resistance of RAC. Zhang et al. [4] found that the chloride diffusivity of RAC with high quality recycled fine aggregates seems to be better than that of natural aggregates concrete (NAC), while the impermeability of the RAC with high quality course aggregates is close to that of NAC by using RCM. The existence of recycled aggregate may give rise to concrete having inherent pores and worsen durability actually [5].
Nonetheless, GGBS is capable of improving it by reducing micro pores and cracks, i.e. pozzolanic effect[6]. Du et al. [7] had made some efforts to explore the chloride permeability of RAC containing different pozzolans, such as fly ash and slag through ASTM C1202 test method. It showed that the mineral admixture can improve the chloride diffusivity of RAC effectively, and its chloride resistance gradually increases with the increase of curing age. However, in engineering practice, the time-dependent characteristics of erosion environment and material properties are usually found in NAC, which reflected in the chloride diffusion coefficient, surface chloride ion concentration and other parameters of concrete changing with time [8]. The correlation between chloride diffusion coefficient and time was first discovered by Takewake [9]. Wang et al. [10] analyzed a series of test data of NAC from different long-term fields and laboratory experiments exposed to chloride environment. The results showed that the apparent diffusion coefficient presents an exponential decay with time and tend to be stable at 30 years exposure time. Nevertheless, previous studies focused on the time-dependency of NAC and its influencing factors. Due to the existence of the double interface transition zone, the chloride diffusion of RAC is quite different from that of NAC. Therefore, the time-dependency of chloride ions in RAC needs further study.

In this paper, the effects of the content of GGBS and immersion duration on time-dependent chloride diffusion was studied through the long-term bulk immersion tests. Finally, a theoretical gist for the research on the chloride permeability of RAC Structure was provided.

2. Modeling of Chloride Transport Based on Fick's 2nd Law

The transport of chloride in interior concrete is dominated by diffusion and the concentration of chloride ions decreases with the increase of depth, while there exist the complex chloride transport methods including diffusion, capillary adsorption and convection in the surface of concrete [11]. By assuming the concrete as a semi-infinite homogeneous medium, the transmission of chloride can be expressed by Fick's 2nd law of diffusion [12]:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}$$

(1)

Where $C$ represents the chloride concentration; $t$ represents the exposure time; $D$ represents the chloride diffusion coefficient in concrete; and $x$ represents the distance from concrete surface.

By solving Eq. (1) in a simple mathematical way, the error function solution based on Fick second law can be obtained [13]:

$$C(x,t) = C_0 \left[1 - \text{erf} \left( \frac{x}{2\sqrt{Dt}} \right) \right]$$

(2)

Where $C(x, t)$ represents the concentration of chloride ion at exposure time $t$ and depth $x$; $C_0$ represents the equilibrium chloride concentration on concrete surface; $D$ represents the chloride ion diffusion coefficient of concrete; and $\text{erf}(x)$ represents the error function.

3. Experiment

3.1. Test Materials and Mix Proportion Design

In this study, P•II 42.5 ordinary portland cement supplied by Guangxi Huarun Cement Corporation of China was used, and its apparent density was 3020 kg/m$^3$. A GGBS was obtained from Guangxi Yuansheng Corporation of china and it has a density of 2910 kg/m$^3$. Crushed concrete (C30) was used as the coarse aggregate and the composition of different gradation in RAC was shown in Table 1. Fine aggregate, having a density of 2613.65 kg/m$^3$ and a fineness modulus of 2.725, came from Wuning, Guangxi, China.

Three sets of RAC samples were produced with different content of GGBS (0%, 30% and 60%), as shown in Table 2. The replacement rate of recycle aggregate of all RAC specimens were 100%.
Table 1. The composition of different gradation in recycled aggregate.

| Aggregate type | Gradation(mm) | Volumetric proportions |
|---------------|--------------|------------------------|
| RA            | 5-10         | 0.25                   |
|               | 10-15        | 0.5                    |
|               | 15-20        | 0.25                   |

Table 2. Mix proportion design of recycled aggregates concrete.

| Group | Sample number | Water (kg/m³) | Cement (kg/m³) | Slag (kg/m³) | Sand (kg/m³) | Recycle aggregate (kg/m³) |
|-------|---------------|---------------|----------------|--------------|--------------|--------------------------|
| 1     | RA-0%         | 203.7         | 452.67         | 0            | 701.86       | 931                      |
| 2     | RA-30%        | 201.77        | 313.86         | 134.51       | 701.78       | 931                      |
| 3     | RA-60%        | 199.84        | 177.63         | 266.45       | 701.85       | 931                      |

3.2. Experimental Method

The RAC mixtures were prepared in the laboratory using a 0.2m³ pan mixer. Cubes of 100×100×100mm in dimension were cast in mold and vibrated until suitably consolidated. Then, they were demoulded after 24h and further cured at 20±3℃ and 95% relative humidity until testing. Two faces of cubes exposed to test solution was remained, and other faces were coated with epoxy resin after 28d. Then, samples were immersed in the 165g/L NaCl solution according to NT Build 443[14]. For obtaining the chloride concentration profiles, related powder was collected from cubes specimens at different depths after the immersion period (30d, 60d and 180d). Layers of thickness would be adjusted from 2~3mm to 4~5mm with the increasing of immersion time. Acid-soluble chlorides were taken out from obtained powder by using Improved Volhard Method [15], which giving an indication of the total chloride concentration.

4. Results and Discussion

4.1. Chloride Penetration

The evolution of total chloride concentration for different GGBS contents at immersion ages of 30, 60 and 180 days is represented in Fig.1, and it is found that the total chloride concentration decreases as the content of GGBS increases at different immersion ages. This is primarily attributed to hydration products of C₃A and C-S-H gels which enhancing the physical-chemistry adhesion of concrete to chloride ions, thus decreasing the diffusion coefficient significantly. Also it can be found from Fig.1 that the effect of GGBS on chloride resistance of RAC decreases with time. This may be due to the pozzolanic reaction of GGBS starts at very early age, and GGBS significantly decreases the content of Ca(OH)₂ crystals in the aggregate–mortar ITZ [16], which in turn leads to the insufficient of Ca(OH)₂ for pozzolanic reaction with the increase of immersion time [17].
4.2. Apparent Chloride Diffusion Coefficient

Based on the experimentally obtained chloride concentrations profile, a non-linear regression analysis by means of the least squares fit method (by using Eq. (2)) is performed so as to determine the apparent diffusion coefficient $D_{app}$, as shown in Fig. 2. We can see that $D_{app}$ is a time-dependent parameter, and decreases gradually with the increase of immersion time. Besides, significantly decrease at the early immersion stage can be observed. It can be observed that the increase of immersion time from 30d to 60d produces a decrease of 65.71%, 67.45% and 55.87% on $D_{app}$ for mixes with the content of GGBS equal to 0%, 30% and 60%, respectively, while the change on the immersion time from 60d to 180d results in a reduction of 39.25%, 4.78% and 14.6% on $D_{app}$ with the various GGBS content. The main reason is that RAC mixtures have a high capillary porosity and larger pore size at early age, while the pores are interconnected. Then, as the development of hydration degree, the pore size of RAC will be decreased with the capillary pores being blocked with hydration products [18]. In addition, it can be noticed from Fig.2 that the $D_{app}$ of RAC incorporation 30% GGBS decreases 28.9%-52.2% compared to the control RAC without GGBS at different immersion time, while decreasing 67.2%-40.6% with the addition of 60% GGBS in RAC mixtures.
5. Conclusion
Long-term bulk immersion test is operated to research the time-dependent chloride diffusion coefficient of RAC with different GGBS replacement. The relationship between immersion time and chloride coefficient is investigated. The effect of GGBS replacement on chloride coefficient is derived. The conclusion obtained from the experimental findings are followed:

- Replacing partially the cement with GGBS can reduce the chloride concentration in RAC effectively. However, the improvement of GGBS on impermeability of RAC decreases with time.
- The apparent diffusion coefficient of RAC of long-term bulk immersion tests decreases with immersion time. When the immersion time increases from 30d to 60d, the values of $D_{\text{app}}$ decreases by 65.71%-55.87% with the GGBS content, while an increase of immersion time from 60d to 180d resulted in a reduction of 39.25%-4.78%.
- The reduction of 28.9%-52.2% in $D_{\text{app}}$ can be observed with the increase of GGBS content from 0% to 30% at different immersion time. However, the addition of 60% GGBS resulted in a reduction of 67.2%-40.6% in apparent diffusion coefficient compared to the RAC without GGBS.

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