A Multi-factor Model of Chloride Diffusion Coefficient of 180d Cured Concrete with High-volume Mineral Admixture

Zheng Chen, Zhiyu Xia*, Yuhao Tang, Zhiqiang Wang, Tianhai Zhao and Fan Fan

ABSTRACT

This paper describes a multi-factor model of chloride diffusion coefficient of long-age (180d) cured concrete with high-volume mineral admixture. The RCM (rapid chloride migration) tests were conducted on 15 specimens with different mixtures proportions to analyze the effect of the water/binder ratio, the total content of mineral admixture, the different combination of FA (fly ash) and GGBS (ground granulated blast-furnace slag) on the chloride diffusion coefficient. Based on the data of orthogonal experiments, a multi-factor coupling model of chloride diffusion coefficient of 180d cured concrete is developed through regression analysis, which can be verified by the data in full range design. The experimental results show that the water/binder ratio, the content of FA and GGBS have a certain impact on the chloride diffusion coefficient, and the predicted values from multi-factor coupling model of chloride diffusion coefficient is in good agreement with the experimental data.1

KEYWORDS

High-volume Mineral Admixture, long-age cured concrete, Chloride Diffusion Coefficient, Multi-factor Model

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INTRODUCTION

Under the chloride surrounding such as marine environment and where deicing salts are applied, chloride will invade the interior of concrete and destroy the covering layer over, embedded steel corrosion and the durability damage of concrete structure [1]. Thus, the service life of the concrete structure under the chloride environment usually depends on how long it takes for the chloride diffuse into the surface of the steel in the concrete, and this interval is directly related to the chloride diffusion coefficient of the concrete [2]. There are several experimental methods to obtain the chloride diffusion coefficient in concrete, natural immersion, electro migration, and rapid chloride penetration test (ASTM) [3] and so on. In view of the chloride diffusion coefficient calculated from RCM can be directly used to describe the durability of concrete structure, it is a trend that RCM becomes a popular method all over the world.

Justness et al. [4] carried out the curing time, the water/binder ratio and the mineral admixture are the major factors affecting the chloride diffusion coefficient. Due to mineral admixture can be equally used as an admixture to replace cement and its environmentally friendly, this concrete has been widely used, and the mineral admixture content in the concrete is also higher than ever before. Nowadays, a lot of researches about the high-volume mineral admixture concrete have been done. Some studies have shown that the chloride diffusion coefficient is decreasing with the proportion of mineral admixture [5]. Other studies [6], which are focus about durability of the high-volume mineral admixture concrete cured for 7 days, 28 days and 90 days. The result showed that the chloride diffusion coefficient will down with a smaller water/binder ratio. Moreover, when the total content of mineral admixture is fixed, the coefficient for fly ash content is negative. On the other study, Guimarães [7] studied the durability of concrete cured for 90d and found that the diffusion coefficient had a good linear relationship to the water/binder ratio. In addition, the incorporation of mineral admixtures can effectively strengthen the resistance to chloride ion penetration. Therefore, it is necessary to study the regularity of the chloride diffusion coefficient of concrete with long-term curing time.

The predictive model of chloride diffusion coefficient can be established following the concrete mixtures proportions. C.C. Yang and Mahmoud Khashaa, et al [8] presented that the incorporation of mineral admixtures has influence on the linear relationship between the chloride diffusion coefficient and the water/binder ratio. The multi-factor coupling model of chloride diffusion coefficient about concrete cured for 28d can accurately reflect the coupling effect of the water/binder ratio, content of FA and GGBS on the coefficient, which has a good application in practical engineering. However, the data of specimens cured for 28 days is unable to accurately reflect the true durability of concrete, and it is recommended to test on concrete cured for long time to evaluate the accurate performance of concrete, reported by studies of Yasser Khodair [9].
In this study, based on orthogonal design, the RCM tests were conducted to analyze the influence of the water/binder ratio, the total content of mineral admixture and the different combination of FA and GGBS on the chloride diffusion coefficient. Based on the orthogonal experimental data, a multi-factor coupling model of chloride diffusion coefficient of 180d cured concrete was established and could be verified by full range experimental data.

**EXPERIMENTATION**

The performance of resistance to chloride ion penetration can be represented by the chloride diffusion coefficient, and the major factors having effect on the coefficient are the curing time, the water/binder ratio and the mineral admixture content. Thus, in order to study the impact of various factors on the chloride diffusion coefficient of high-volume mineral admixture concrete, this paper lays emphasis on the 180d cured concrete. Based on orthogonal and the full range design, the water/binder ratio, the total content of mineral admixture and the different combination of FA and GGBS are chose and analyzed as the major factors in this experiment. The 9 groups of mixtures proportions with 3 factors-3 levels are designed in orthogonal way. With the water/binder ratio of 0.35, 2 factors-3 levels of 9 groups are designed based on full range. There are 3 sets of mixtures proportions based on orthogonal design coincides with the sets in full range. Finally, there are 15 groups of concrete mixtures proportions in total.

The specific surface areas of PII 42.5 Portland cement produced by Huarun (Nanning) Cement Co., Ltd. and S95 grade GGBS produced by Guangxi Yuansheng Co., Ltd are 379 m\(^2\)•kg\(^{-1}\) and 432 m\(^2\)•kg\(^{-1}\) respectively. The 45μm sieving residue of FA (grade II) produced by Guangxi Laibin power plant is 10.2%. A kind of sand with apparent density of 2514 kg•m\(^{-3}\) and fineness modulus of 2.42 was a river-sand produced by Guangxi Qinzhou. The continuously graded gravel with a grain size of 5~25 mm, apparent density of 2709 kg•m\(^{-3}\) was used as coarse aggregate. Polycarboxylate superplasticizer with a solid content of 10.32% was used.

The testing concrete was molded into cylindrical concrete specimens (\(\Phi 100\)mm × 200mm), and demolded after 1 day, then they were placed in the standard curing room (temperature 20 ± 2 ℃ and RH above 95%) for 180 days. After 180d, the original specimens were incised into three cylindrical specimens (\(\Phi 100\)mm × 50mm) for RCM test.

RCM is a method about non-steady-state chloride rapid electro migration, which accelerates the migration of chloride inside the concrete through applying electric field at both ends of the concrete specimens. The chloride diffusion coefficient analyzers used in the tests were RCM-NTB, which produced by Beijing Nile Composites. The main indicator is that plus electric field voltage achieved 30±0.2V, and the rapid electro migration experiments can be performed on six concrete specimens simultaneously in six different channels.
The specific steps of the test are: First, keep the testing concrete blocks in vacuum water for 24 hours, and then install the testing blocks on the chloride diffusion coefficient tester. Inject 5% (mass fraction) of NaCl and 0.2mol/L concentration of potassium hydroxide solution (cathode) in the solution tank, then inject 0.2mol/L KOH solution (anode) into the rubber tube. Finally, connect the solution tank of the specimens with the corresponding interface of the chloride diffusion coefficient testers, and turn on the power to start the experiment. After the specify testing time, remove blocks and record the power time and average temperature. Split the specimens in the axial block, and spray 0.1mol/L AgNO3 indicator in the split after the cross-section. The depth of chloride penetration can be measured following the boundary of color on surface, and finally the chloride diffusion coefficient of concrete can be calculated based on the Nernst-Plank relationship. The represented index of this experiment is the average values of the coefficient measured from the three concrete specimens.

Results And Analysis

The results are presented in TABLE I. The chloride diffusion coefficient increases when the water/binder ratio in high-volume mineral admixture concrete for 180d is increased, and decreases with increasing the total content of mineral admixture, which is presented in Figure 1. The coefficient decreases at first and then increases as relative content of fly ash in the total content of mineral admixture increases, which shows the concrete has a good chloride ion erosion resistance when the content of FA is close to GGBS. The factors level of the concrete with the best resistance to chloride ion erosion are as followed: the water/binder ratio is 0.3, the total content of mineral admixture is 70%, and the proportion of FA content and GGBS content is 1:1.

In the orthogonal experiment, the range analysis is based on the average difference of each factor to reflect the impact on the corresponding factor. Within the range of the experiment, the range, R, for size of fluctuation is positive. Thus, the factor having maximum value of R in the orthogonal test is regarded as the dominant factor having a noticeable effect on the experimental result, the range analysis could be shown in Figure 1.

TABLE I. MIX PROPORTIONS AND DIFFUSION COEFFICIENTS OF CONCRETE.

<table>
<thead>
<tr>
<th>Group</th>
<th>W/B</th>
<th>FA content</th>
<th>GGBS content</th>
<th>Diffusion coefficient</th>
<th>Group</th>
<th>W/B</th>
<th>FA content</th>
<th>GGBS content</th>
<th>Diffusion coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3</td>
<td>15</td>
<td>35</td>
<td>1.313 × 10⁻¹² m²/s</td>
<td>9</td>
<td>0.35</td>
<td>45</td>
<td>15</td>
<td>2.472 × 10⁻¹² m²/s</td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
<td>30</td>
<td>30</td>
<td>1.189</td>
<td>10</td>
<td>0.35</td>
<td>15</td>
<td>55</td>
<td>2.198</td>
</tr>
<tr>
<td>3</td>
<td>0.3</td>
<td>55</td>
<td>15</td>
<td>1.232</td>
<td>11</td>
<td>0.35</td>
<td>35</td>
<td>35</td>
<td>0.704</td>
</tr>
<tr>
<td>4</td>
<td>0.35</td>
<td>15</td>
<td>35</td>
<td>2.357</td>
<td>12</td>
<td>0.35</td>
<td>55</td>
<td>15</td>
<td>1.284</td>
</tr>
<tr>
<td>5</td>
<td>0.35</td>
<td>25</td>
<td>25</td>
<td>2.495</td>
<td>13</td>
<td>0.45</td>
<td>35</td>
<td>15</td>
<td>2.607</td>
</tr>
<tr>
<td>6</td>
<td>0.35</td>
<td>35</td>
<td>15</td>
<td>2.692</td>
<td>14</td>
<td>0.45</td>
<td>45</td>
<td>45</td>
<td>2.516</td>
</tr>
<tr>
<td>7</td>
<td>0.35</td>
<td>15</td>
<td>45</td>
<td>2.234</td>
<td>15</td>
<td>0.45</td>
<td>35</td>
<td>35</td>
<td>1.276</td>
</tr>
<tr>
<td>8</td>
<td>0.35</td>
<td>30</td>
<td>30</td>
<td>2.120</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The range analysis in Figure 1 shows the order: RA>RB>RC. Therefore, factor A (water/binder ratio) contributes the biggest range and is the dominant factor determining the chloride diffusion coefficient of high-volume mineral admixture concrete cured for 180d; factor B (the total content of mineral admixture) is the secondary influencing factor, and the influence of factor B is higher than that of factor C. The preferred scheme is A1B3C2 by selected the optimum durability performance of concrete from each factor.

**Multi-factor Model For Diffusion Coefficient**

Some studies [10] show that the chloride diffusion coefficient has a linear relationship with the water/binder ratio, the content of FA and the GGBS. However, the results of the study [8] show that the incorporation of mineral admixtures such as FA and GGBS in concrete will have impact on the linear relationship between the chloride diffusion coefficient and the water/binder ratio. Thus, considering the coupling relationship between water/binder ratio and the contents of mineral admixtures, a coupling regression equation may be written as:

$$D_{180} = \left(\frac{W}{B}\right) + a_1(R_{FA} + a_2R_{SG} + a_4) + a_5R_{FA} + a_6$$

Where $D_{180}$ is the chloride diffusion coefficient of 180d cured concrete, $\times 10^{-12} \text{m}^2\text{s}^{-1}$; $R_{FA}$ is the FA content, %; $R_{SG}$ is the GGBS content, %; $W/B$ is the water/binder ratio; $a_0, a_1, \ldots, a_6$ are the regression coefficients to be determined.

Using the method of MLR (Multiple Linear Regression), a multi-factor model of chloride diffusion coefficient could be established. Based on the method of Minimum Square, the Eq. (1) can be written as:
Based on the orthogonal experiment and the concrete mixtures proportions of other six groups, compassion between the predicted values from multi-factor coupling model and experimental data is shown in Figure 2. The points of experimental values and the contour line is close, which shows the predicted values from multi-factor coupling model of chloride diffusion coefficient is in good agreement with the experimental data.

Note in Figure 2 that the values from the predictive model are in good agreement with the values from orthogonal experiment. It also shows that the points of experimental values in other six groups are distributed in the neighbor of the contour line. And it shows that the model has well credibility and accuracy.

**CONCLUSIONS**

Based on measured values of chloride diffusion coefficient of 15 specimens with different mixtures proportions designed by orthogonal test method and full range test method, a multi-factor model of chloride diffusion coefficient of long-age (180d)
cured concrete with high-volume mineral admixture is developed. Based on the results presented in this paper, the following conclusions can be drawn:

1) The W/B, content of FA and GGBS have a certain effect on the chloride diffusion coefficient, within the range of the experimental factors, better durability of the concrete is observed, with smaller water/binder ratio and a higher total content of mineral admixture.

2) The order of influence of the factors is deduced by comparing ranges as: the water/binder ratio > the total content of mineral admixture > different combination of FA and GGBS.

3) The predicted values from multi-factor coupling model of chloride diffusion coefficient of 180d cured concrete is in good agreement with the experimental data, which can be used for predicting chloride permeability in practical engineering.

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