A Multi-factors Model for Predicting the Resistance of Chloride Penetration of Concrete with Mineral Admixtures

Yaquin Zhu¹, Zheng Chen², Yuhao Tang³* and Yi Jiang

¹Key Laboratory of Disaster Prevention and Structural Safety of China Ministry of Education, School of Civil Engineering and Architecture, Guangxi University, Nanning 530004, China
Email: ¹894858815@qq.com, ²chenzheng@gxu.edu.cn, ³594320520@qq.com

Abstract. A high-order multi-factors model for predicting the resistance of chloride penetration of concrete with mineral admixtures was developed in this paper. The concrete specimens with different water-binder ratios, replacement of mineral admixtures, replacement of manufactured sand and replacement of coarse aggregates were prepared by orthogonal test design, whose 6h electric fluxes were tested after curing 28d. According to the influence of different factors on the electric flux of concrete, some multi-factors models for predicting the resistance of chloride penetration of concrete with mineral admixtures were proposed. The results show that the resistance of chloride penetration of concrete could be improved by increasing the replacement of fly ash and decreasing the replacement of GGBS, and the high-order multi-factors model proposed is better than the models without high-order terms in predicting the resistance of chloride penetration of concrete with mineral admixtures.

1. Introduction

Durability plays a decisive role in evaluating the quality of concrete. Under the chloride surrounding such as marine environment and the places where deicing salts are applied, chloride ions absorb and corrode the passivating film on the surface of reinforced concrete through erosion and penetration into the concrete, resulting in the pitting corrosion of the galvanic cells on the surface of the steel bars, and then the corrosion and expansion failure of the reinforced concrete [1]. The concrete compactness essentially determines the time for chlorine ions to migrate from the outside into the surface of the steel in the concrete, that is, the service life of the concrete [2]. The ASTM C1202 standard in US adopts 6h of concrete electric flux as its evaluation index of the chloride resistance of concrete. Chinese standard has also used concrete electric flux as a method to evaluate the resistance of chloride penetration of concrete with mineral admixtures.

The electrical flux of concrete is closely related to its mix ratio, it can evaluate and predict the resistance of chloride penetration of concrete with mineral admixtures. Yin Huiguang et al [3] proved that the effect of water-binder ratios on the the performance of the resistance of chloride penetration of concrete is obvious. Homas M, Bamforth P B et al [4] studied and established a chloride ion diffusion model for concrete considering fly ash and slag. Zhuqing Yu, Guang Ye et al [5] studied the chloride ion penetration and microstructure development of fly ash concrete. Shi Huisheng et al [6] showed that fly ash, GGBS and other mineral admixtures will affect the original linear relationship between concrete flux and water-binder ratio, so that the electrical flux and the ratio of the various parameters appear nonlinear relationship. In summary, there are many factors that affect the electric flux of concrete, but most studies mainly focus on one or two of them, and don’t consider the high-order effect between those factors.
In this paper, based on orthogonal design and ASTM C1202 method, we studied factors affecting the resistance of chloride penetration of concrete, and analyzed the influence of different levels of water-binder ratios, replacement of fly ash and GGBS, replacement of manufactured sand and replacement of coarse aggregates. According to the influence of different factors on the electric flux of concrete, to explore the high-order relationship between the various factors, some multi-factors models for predicting the resistance of chloride penetration of concrete with mineral admixtures were proposed.

2. Experimentation
Studies have shown that the permeability of concrete is closely related to its compactness, pore characteristics, material composition and hydration characteristics. Water-binder ratio is one of the important factors to affect the compactness. GGBS and fly ash have fine filling and secondary hydration, which can improve the pore structure and interface structure between cement stone and aggregate. To a certain extent, the type of aggregates will affect the permeability of concrete. The replacement of coarse aggregate is the volume fraction of the coarse aggregate in the concrete, and it will affect the volume of the paste and the volume fraction of the interfacial zone, thus affecting the degree of difficulty of chloride ion penetration in the concrete.

Therefore, this study selected water-binder ratio, replacement of fly ash, replacement of manufactured sand, and replacement of coarse aggregates as the main factors. Each factor took four levels for research.

3. Raw materials
The chemical composition ratio of PO 42.5 Portland cement produced by China Resources (Nanning) Cement Co., Ltd. is shown in Table 1. Mineral admixtures: Class II fly ash and S95 GGBS were used in this exhibition; Fine aggregate: The natural river sand and machined sand are medium sand. The basic properties are shown in Table 2. Coarse aggregates: gravel, apparent density 2720kg/m$^3$, particle size range 5~25mm, continuous grading; Chemical admixtures: Polycarboxylate water reducer which solids content is 8.6%, density is 1.027 g/cm$^3$, water reduction rate is 23.6%.

### Table 1. Chemical composition of cement clinker.

| Composition | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | SO$_3$ | R$_2$O | K$_2$O | Na$_2$O |
|-------------|--------|------------|------------|-----|-----|-------|-------|-------|--------|
| Content /%  | 22.09  | 6.7        | 4.43       | 58.13 | 0.87 | 2.22  | 0.54  | 0.37  | 0.3    |

### Table 2. Fine aggregate basis performance.

| Performance  | Apparent density /kg.m$^3$ | Bulk density /kg.m$^3$ | Porosity | Stone powder content /% | MB value | Fineness modulus | Crush index | Mud content /% | Graded section |
|--------------|---------------------------|------------------------|----------|-------------------------|----------|------------------|-------------|----------------|----------------|
| River sand   | 2750                      | 1898                   | 42       | 0                       | 0.1      | 2.9              | 16          | 0              | II             |
| Mechanism sand | 2700                    | 1580                   | 41       | 1.5                     | 0.4      | 2.7              | 17          | 0.2            | II             |

4. Sample preparation and test methods

4.1. Specimen preparation and curing period
We determine the orthogonal test scheme and prepare 16 groups of concrete according to the orthogonal test design table shown in Table 3. With a hard 100mm PVC tube molding, 1D after release, and then into the standard curing room (temperature 20±2°C, humidity above 90%), respectively cured for 28d. Finally, three cylindrical specimens were cut out from the middle of the original test block on 7 days before the test.
4.2. Rapid chloride penetration test
The American standard ASTM C1202 is used to evaluate the permeability of concrete, the test principle was to determine the resistance of chloride penetration of concrete by the DC electricity method. The instrument used in this test is the concrete electric flux detector produced by Beijing Nilde Company, the specific operating procedures and procedures are referred to the specifications. The electric flux of concrete 6h in all groups of this test was characterized by the average electric flux of 3 blocks of concrete.

Table 3. Orthogonal test program and test results of the resistance of chloride penetration of concrete.

| Groups | Water-binder ratio | Fly ash /% | Replacement of manufactured sand /% | Replacement of coarse aggregates/ % | 28d Electric flux |
|--------|------------------|-----------|----------------------------------------|-------------------------------|------------------|
| 1#     | 0.5              | 45+0      | 0                                      | 20                            | 4032.29          |
| 2#     | 0.5              | 30+15     | 33.3                                   | 30                            | 2876.54          |
| 3#     | 0.5              | 15+30     | 66.7                                   | 40                            | 1394.08          |
| 4#     | 0.5              | 0+45      | 100                                    | 50                            | 859.37           |
| 5#     | 0.45             | 45+0      | 33.3                                   | 40                            | 2789.16          |
| 6#     | 0.45             | 30+15     | 0                                      | 50                            | 1836.02          |
| 7#     | 0.45             | 15+30     | 100                                    | 20                            | 1628.99          |
| 8#     | 0.45             | 0+45      | 66.7                                   | 30                            | 1596.36          |
| 9#     | 0.4              | 45+0      | 66.7                                   | 50                            | 1588.07          |
| 10#    | 0.4              | 30+15     | 100                                    | 40                            | 2659.6           |
| 11#    | 0.4              | 15+30     | 0                                      | 30                            | 1496.27          |
| 12#    | 0.4              | 0+45      | 33.3                                   | 20                            | 1247.74          |
| 13#    | 0.35             | 45+0      | 100                                    | 30                            | 1858.95          |
| 14#    | 0.35             | 30+15     | 66.7                                   | 20                            | 2274.88          |
| 15#    | 0.35             | 15+30     | 33.3                                   | 50                            | 1009.5           |
| 16#    | 0.35             | 0+45      | 0                                      | 40                            | 728.39           |

5. Results and analysis

5.1. Results and permeability analysis
The average value of the 6h electric flux test results for the concrete blocks with various mix ratios is shown in Table 3. It can be seen from the table that the 6h electric flux at the 28th in the 16#concrete block of all concrete is the lowest (728.39C). The level of each factor is taken as the abscissa, and the mean 6h electric flux of the concrete is taken as the ordinate to draw the trend diagram of electric flux, as shown in Figure 1. As can be seen from the figure, at the age of curing about 28d, the concrete mix proportion parameter with the best resistance to chloride ion permeation was: the water-binder ratio A was 0.35; the replacement of fly ash and GGBS was 0+45%; the replacement of manufactured sand is 0%; the replacement of coarse aggregates is 50%.

From Figure 1, it can be seen that the electric flux of concrete decreases as the ratio of water to cement decreases; When the total amount is the same, the amount of GGBS increases and the amount of fly ash decreases, the electric flux of the concrete decreases. For 28d age concrete, the influence of replacement of manufactured sand on electric flux is small, the electric flux of concrete decreases with the increase of coarse aggregate content.
5.2. Multi-factors model and verification of the resistance of chloride penetration of concrete

The literature shows that the concrete electrical flux and water-binder ratio have a good linear relationship; however, the amount of mineral admixtures such as fly ash and GGBS will influence the linear relationship between the flux and the water-binder ratio, the high-order relationship is exhibited. In view of this, this paper will study the high-order model of electric flux on different factors, we compare the correlation coefficient $R^2$ between the predicted values of each model and the measured values of concrete flux, establish the best prediction model for the resistance of chloride penetration of concrete, and regression coefficient and significance test of the model.

As can be seen from Figure 1, compared with other factors, manufactured sand has less influence on the electrical flux of concrete, thus, this factor is ignored in this model, and then a multi-factors model of the chloride resistance of different orders of concrete is established:

In the formula, $R_{WB}$ is the water-binder ratio, $R_{FA}$ is the fly ash content (When the amount of admixture is 15%, $R_{FA}$=0.15), and $R_{SG}$ is the amount of GGBS (When the amount of admixture is 30%, $R_{SG}$ = 0.3). The undetermined coefficients of all models will be solved by using the least squares method. The resulting model expression is shown as follows.

Model (1-order):  
\[
Q = 5365.206R_{WB} + 884.671R_{FA} + 2720.001R_{SG}
\]

Model (2-order):  
\[
Q = 11555.342R_{WB} - 9646R_{FA} + 8325.843R_{FA}^2 + 27511.453R_{WB} - 308.948R_{WB}R_{SG} - 308.948
\]

Model (3-order):  
\[
Q = 9602.249R_{WB} + 3018.99R_{SG} + 9888.103R_{WB} - 34081.619R_{WB}R_{SG} + 175169.096R_{WB}R_{SG} + 94184.349R_{FA}R_{SG} - 139615.754R_{WB}R_{FA} - 2312.302
\]

From the experimental data of each group, the fitting value, regression value and residual of the model at 28d concrete were calculated, and the regression variance analysis was shown in Table 4. For 28d concrete, the significance of the 1-order and 2-order models is greater than 99.5%, and the significance of the 3-order models is greater than 98%. Therefore, the three models all have higher significance, which proves that the established model is reliable.
| Source of difference | SS          | df | MS          | F        | Significant | R² |
|---------------------|-------------|----|-------------|----------|-------------|----|
| Regress             | 7286449.447 | 2  | 3643224.724 | 11.647   |             |    |
| Residual            | 4066516.644 | 13 | 312808.973  | -        | >99.5%      | 0.642|
| Sum                 | 11352966.09 | 15 | -           | -        |             |    |
| Regress             | 8364946.275 | 4  | 2091236.569 | 7.699    |             |    |
| Residual            | 2988019.816 | 11 | 271638.165  | -        | >99.5%      | 0.737|
| Sum                 | 11352966.09 | 15 | -           | -        |             |    |
| Regress             | 9506057.725 | 7  | 1358008.246 | 5.882    | >98%        | 0.837|
| Residual            | 1846908.366 | 8  | 230863.546  | -        |             |    |
| Sum                 | 11352966.09 | 15 | -           | -        |             |    |

From Table 4, the correlation coefficient R² of the 1-order and 2-order models is lower than the correlation coefficient R² of the 3-order model, which proves that the 3-order model can more accurately predict the resistance of chloride penetration of concrete with mineral admixtures.

Combining the various mix ratio parameters of this orthogonal experiment and using each predicting model, the electric flux model fitting values of all groups of concrete can be calculated and compared with the measured values, as shown in Figure 2. In the Figure 2, the abscissa represents the 6h electrical flux test value of the concrete obtained by the orthogonal test, and the ordinate represents the 6h electrical flux value of the concrete obtained from different prediction models. Each shape point is the experimental value of 16 groups of concrete. Fit the data points of the data, and the straight line is the reference straight line when the test value and the fitting value are equal. The closer the data point is to the reference line, the more consistent the measured value with the model fit value. As can be seen from in Figure 2, compared with other models, the fitted value of the 3-order multi-factors model of the resistance of chloride penetration of concrete is in good agreement with the measured value, which proves the accuracy and universality of the 3-order model.

![Figure 2](image-url). Comparison and analysis of the fitted value and experimental value of each model's electric flux of 28d.

6. Conclusions
In this paper, based on orthogonal test design and ASTM C1202 test method, we tested and analyzed the resistance of chloride penetration of concrete. The effects of water-binder ratios, replacement of...
mineral admixtures, replacement of manufactured sand and replacement of coarse aggregates on the electric flux of 28d age concrete were studied, then high-order multi-factors model for predicting the resistance of chloride penetration of concrete were proposed, and we compared the accuracy and universality of all the models. The following conclusions can be drawn:

(1) The combination of fly ash and GGBS is the most important factor affecting the resistance of chloride penetration of concrete. When the total amount is the same, the amount of GGBS increases and the amount of fly ash decreases, the electric flux of concrete decreases; for 28d age concrete, the effect of manufactured sand content on electric flux is small, the electric flux of concrete would decreases with the increase of coarse aggregate content.

(2) Regression analysis shows that the effect of coarse aggregate content should be considered in the multi-factors model of the resistance of chloride penetration of concrete with mineral admixtures. The proposed high-order multi-factors model for chloride resistance of concrete has better accuracy and universality, and can be used for predicting the resistance of chloride penetration of 28d concrete in practical engineering.

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8. References
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