Application of the Resistivity in Quality Control of Concrete Durability for the Hong Kong–Zhuhai–Macao Bridge

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ABSTRACT

Engineering uses the chloride ion diffusion coefficient as the durability of concrete quality control indicators under the marine environment, due to the chloride ion diffusion coefficient and the electrical resistivity of concrete parameters are reflected in the concrete pore structure, and resistivity testing is convenient, fast advantages, the resistivity alternative chloride ion diffusion coefficient for the durability of concrete quality control has practical significance. In this paper, using concrete mix of the immersed tube tunnel in Hong Kong–Zhuhai–Macao Bridge as research object, Under the standard curing conditions (temperature $20\pm 2^{\circ}\text{C}$, 95% RH or more), Through the different ages of the specimen tested, Wenner method resistivity test results are more stable than the RCM chloride diffusion coefficient of the test results. Building the relationships between resistivity and chloride diffusion coefficient, and resistivity tests the specimen which is the entire structure of retention, compared with the result of the actual measured RCM method of chloride diffusion coefficient, average value of the diffusion coefficient what is concluded by resistivity is higher than real one, using the resistivity for the durability of control indicators is conservative, more demanding of the quality of concrete materials. Therefore, using resistivity as index to monitor changes of the materials is possible.

1. INTRODUCTION

Hong Kong–Zhuhai–Macao bridge acrossing the Pearl River Estuary and Lingdingyang Sea, connecting Hong Kong, Zhuhai, and Macao large sea—channel, is part of the Pearl River Delta Region link and key projects that span the Lingdingyang Sea, is the most complex technology in the world today—The Island Harbour Crossing the Bridge integration of clusters of projects, the main structures life requires 120 years of engineering structures. Because of its dominate the durability of concrete structure in the entire process of service ‘health’ and ‘life’ very serious consequences caused by the lack of durability. Therefore, the quality of the concrete for the entire project has a significant impact on the quality. For example, the Hong Kong–Zhuhai–Macao Bridge to the immersed tube tunnel, a total of 242 segments of about 7,86,500 m³ concrete, so such a large amount of concrete and the raw materials used in the performance of uncertainty, the durability of concrete quality control is very difficult. the durability of quality control is the use of RCM chloride ion diffusion coefficient under standard curing conditions as a control indicator. RCM methods, its process is complex includes $\text{Ca}(\text{OH})_2$ soak in the vacuum for 24 h before the test, Cl^- migration for 24 h, measuring the Cl^- penetration depth, etc., each process has an impact on the experimental results;

the accuracy of the instrument and personnel quality test have a greater additional impact too.

The resistivity of concrete can characterize the permeability of related ions, which is related to the concrete pore structure, porosity, pore size distribution. According to this principle using the electrical resistivity of concrete as durability quality indicators is feasible. Resistivity testing process is simple, quick, simple calibration of the instrument before the test, and the resistivity of concrete using different raw materials have some sensitivity. In this paper, Wenner concrete resistivity test is the main object of study, and resistivity alternative RCM chloride diffusion coefficient of as a new concrete durability quality control method is researched.

2. TEST METHODS AND MATERIALS

Wenner four electrode method is currently the most widely used concrete resistivity test method. It consists of two low frequency alternating current electrodes and two AC voltage electrodes, and the use of digital equipment directly resistivity data. This article uses the Swiss PROCEQ concrete resistivity tester as test equipment, the tester's four electrodes apart 50 mm, 72Hz frequency AC power to the power supply, the resistance between the electrodes is 10 M Ω , the

resistivity of the test range from 0 to 99 ± 1 k Ω .cm. The equations for calculating the resistivity is the formula 1.

$$\rho = 2\pi aUI \quad (1)$$

Where ρ is the resistivity (Ω .m), a is the width of the electrode, U is the voltage (V), I is the current (A).

In this study, the electrical resistivity testing is done indoors, concrete specimens' size is 150 mm $\times$ 150 mm $\times$ 150 mm cube, and six face were tested using Wenner resistivity. The concrete is preparation using the mix of the immersed tube tunnel in Hong Kong–Zhuhai–Macao Bridge, which is used as an object for the durability quality control. Under the standard curing conditions (temperature $20 \pm 2^\circ\text{C}$, 95% RH or more), researching the relationship between the resistivity and RCM chloride diffusion coefficient about the 7, 14, 28, 56, and 90 days different curing period. We have a large number of the resistivity and the RCM test for the concrete of the immersed tube tunnel using the same batch of raw materials and conducted the statistical analysis. We compared the statistical characteristics what is the real test 28 days RCM data and others data obtained based on the relationship between the resistivity and the RCM.

The concrete using the same concrete mix was formulated resistivity testing, research resistivity sensitivity under the different raw materials for concrete. The concrete mix for precast immersed tube (cementitious materials 420 kg/m³, cement, fly ash, granulated blast furnace slag cementitious materials accounted for 45, 25, 30%) as shown Table 1, its properties as shown in Table 2.

Table 1. Precast immersed tube concrete mix.

w/b	Sand ratio (%)	Water (kg/m ³)	Cement (kg/m ³)
0.35	43	147	189
Fly ash (kg/m ³)	Slag (kg/m ³)	10–20 mm stone (kg/m ³)	5–10 mm stone (kg/m ³)
105	126	733	314
Sand (kg/m ³)	Admixture (kg/m ³)	Slurry rate (%)	
775	4.2	32.2	

Table 2. Concrete performance.

Slump (mm)	Air content (%)	Bulk density (kg/m ³)	28 days chloride ion diffusion coefficient (10^{-12} m ² /s)	28 days compressive strength (MPa)
210	2	2410	4.5	62.5

According to the durability design quality control values requirements at a temperature $20 \pm 2^\circ\text{C}$, relative humidity above 95%, 28 days max RCM chloride diffusion coefficient of concrete is 6.5×10^{-12} m²/s, the concrete as shown in Table 1 achieve durable design.

3. TEST RESULTS AND DISCUSSION

3.1 The relationship between resistivity, RCM chloride ion diffusion coefficient and age

Forming 150 mm $\times$ 150 mm $\times$ 150 mm cube standard specimens and Φ 100 mm $\times$ 200 mm cylindrical specimens and for curing under the conditions of the temperature $20 \pm 2^\circ\text{C}$ and relative humidity of 95% or more. For Wenner resistivity and RCM chloride diffusion coefficient of 7, 14, 28, 56, and 90 days were tested. Which the resistivity of each age has 10 specimens obtained 60 data, RCM chloride diffusion coefficient for each age of 5 specimens obtained 15 data. Through statistical analysis, the mean, standard deviation, and percentage error of both statistical characteristic values as shown in Table 3.

Table 3. Statistics characteristic values of resistivity and RCM in different age.

Performance and age (days)	Resistivity (k Ω .cm)	Resistivity error percentage	RCM chloride diffusion coefficient (10^{-12} m ² /s)	RCM error percentage
7	16.0, 1.5	9.4	8.17, 0.33	4.0
14	9.0, 1.6	8.4	6.31, 0.81	12.8
28	22.0, 1.9	8.6	4.39, 0.34	7.7
56	47.0, 3.5	7.4	2.70, 0.59	21.8
90	75.0, 6.5	8.7	2.05, 0.33	16.1

As can be seen from Table 3, the error percentage of Wenner resistivity in different age is maintained at less than 10%, we can see that the test results are relatively stable; the error percentage of RCM chloride diffusion coefficient in different age is maintained at less than 10%, the test results are unstable.

As shown in Table 3, we obtained the relationship between resistivity and age, the relationship between RCM chloride diffusion coefficient and age, and the relationship between resistivity and RCM chloride diffusion coefficient, as shown in Figures 1–3. From Figure 1, with the growth of curing period, the average resistivity continue to grow, while Figure 2 shows with the growth of curing period the average chloride diffusion coefficient are declining. This is because the concrete with the growth of age, and continue to occur hydration, hydration products continue to fill the pore inside the concrete, the concrete internal structure continuously dense. The relationship between the age and RCM, resistivity is index and the correlation is very good, with correlation coefficients above 0.9.

Since the resistivity and chloride diffusion coefficient can characterize compacting properties of the internal structure for concrete, and therefore, established relationship between the two, shown in Figure 3, the relationship between them is exponential, the correlation coefficient was 0.8614, the relevant very good.

Figure 1. Relationship between resistivity and age.

Figure 2. Relationship between RCM chloride diffusion coefficient and age.

Figure 3. Relationship between RCM chloride diffusion coefficient and resistivity.

3.2 The sample specimen resistivity and RCM chloride diffusion coefficient statistical analysis

Resistivity and RCM chloride diffusion coefficients test the sample specimens which use the same batch of cementitious raw materials for precast immersed tube tunnel under a temperature $20 \pm 2^\circ \text{C}$, relative humidity of 95% conditions curing more than 28

days to test, and get 120 resistivity data, 45 chloride diffusion coefficient data, statistical analysis shown in Figures 4 and 5.

Figure 4. Resistivity statistics.

Figure 5. RCM chloride diffusion coefficient.

Figure 6. RCM statistics based on resistivity relationship with RCM.

From the resulting graph, average value of 120 sets of resistivity data is 21.9 kΩ.cm, the standard deviation

is 2.0 k Ω .cm; average value of 45 sets of chloride ion diffusion coefficient data is 4.53×10^{-12} m²/s, a standard deviation of 0.60×10^{-12} m²/s. Based on the relationship under Section 3.1 resistivity and chloride diffusion coefficient, transforming the resistivity to chloride diffusion coefficient, and statistical analysis, its average value is 5.67×10^{-12} m²/s, the standard deviation is 0.24×10^{-12} m²/s.

By comparing the real measured chloride diffusion coefficient and chloride diffusion coefficient, according to the resistivity relationship with RCM, its average is larger than the real test. But its value is also controlled within the range of the design quality control value for immersed tunnel, and the use of the resistivity for the durability of control indicators is conservative, more demanding of the quality of concrete materials.

3.3 Analysis of concrete resistivity using different raw

Quality control of raw materials is the most important part of the durability of quality control concrete. Under the same conditions concrete mix, molding, curing environment, it is compared 120 sets of resistivity data using different batches of cement, resistivity data using different batches of slag and resistivity of Section 3.2 described statistical analysis chart as shown in Figures 4, 7, and 8, the statistical characteristic values as shown in Table 4.

Figure 7. Concrete resistivity using different cement for statistical analysis chart.

In this paper all tests are ignored resistivity temperature, humidity, and construction (molding) process on them. Cementitious materials for concrete pore structure, distribution, and hydration process has important implications. In Table 4, prepared using different batches of raw resistivity of concrete is a difference, it is shown that resistivity of the concrete what change the raw materials have a certain sensitivity.

Figure 8. Concrete resistivity using different slag for statistical analysis chart.

Table 4. Concrete resistivity using different batches of raw material.

Concrete ID	Resistivity (k Ω .cm)
C1S1F1	(21.9, 2.0)
C2S1F1	(23.5, 3.1)
C1S2F1	(20.1, 2.2)

In this paper all tests are ignored resistivity temperature, humidity, and construction (molding) process on them. Cementitious materials for concrete pore structure, distribution and hydration process has important implications. In Table 4, prepared using different batches of raw resistivity of concrete is a difference, it is shown that resistivity of the concrete what change the raw materials have a certain sensitivity. In determining the durability quality of concrete, which is prepared as a batch of raw materials as a datum, using resistivity as indicators to monitor change in raw materials is feasible.

4. CONCLUSIONS

Under the same conditions concrete mix, molding, curing environment, this paper studies the feasibility of resistivity alternative RCM chloride diffusion coefficient as a new methods for concrete durability quality control. By comparing the test results of resistivity and RCM chloride diffusion coefficient, Wenner resistivity test method is convenient, fast, and stable test results than RCM. Establishing relationship between resistivity and chloride diffusion coefficient, if using the resistivity as the durability quality control indicators, it is conservative, and demand high quality material for compounding concrete. By resistivity testing for the concrete prepared with different materials, the resistivity have some sensitivity when materials is change, so using resistivity as index to monitor changes of the materials is possible.

Raw materials of the concrete, curing environment, pouring the concrete conditions which affect the resistivity, these three areas are the necessary control

process for the durability quality control of concrete, it implemented the use of electrical resistivity as an indicator to monitor the curing environment, pouring condition, which needs more work.

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