Experimental Study on the Effect of Stray Currents on the Mechanical Properties of Concrete with Different Cementitious Systems and Rebar Corrosion

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Abstract. In order to study the effect of stray current on the compressive strengths of concrete and rebar corrosion under different cementitious systems, a set of test device is designed to simulate the migration of stray current in the concrete. The compressive strength of the concrete is tested in the 4th week and 7th week after electrification to evaluate the compressive strength ratio of the concrete with different cementitious materials under the influence of stray current. The polarization curve of the rebar is measured to evaluate the electrochemical properties of the rebar. The result shows that: The influence laws of stray currents on the strength of concrete with different cementitious materials and rebar corrosion are consistent. The reduction extent of the compressive strength of concrete and corrosion extent of rebars follows the sequence: pure cement > fly ash + mineral powder + fiber > fly ash > fly ash + mineral powder + swelling agent > fly ash + mineral powder. With the increase of current time, the longer the current time is, the more significant the reduction of compressive strength is, and the more serious the rebar corrosion is.

1. Introduction

In the running process of metro trains with DC power supply traction, some direct currents leak to the vicinity of tracks to form messy electricity flows, which are called stray currents. Stray currents are mainly direct currents [1]. Stray current can cause electrochemical corrosion of underground metal pipelines, sheath of communication cables, roadbeds and even rebars in the main structures of stations and running tunnels. Therefore, the service life of metal pipelines and rebars may be shortened and the strength and durability of the reinforced concrete main structure of the metro may be reduced due to the existence of stray current [2-3]. In order to mitigate the influence of stray current on reinforced concrete, in engineering circle, the protection against stray current is implemented according to the principles of “Putting prevention in the first place, taking drainage as supplement, combining prevention with drainage and strengthening monitoring”. Improving the erosion resistance of concrete against stray current is an important measure to prevent the harm from stray current.

Stray currents influence reinforced concrete in two ways: For one thing, it causes electrolytic
corrosion of rabars, which reduces the working section and produces rust whose volume expands. The concrete cracks eventually. For another, it causes Ca\(^{2+}\) and other ions in the concrete dissolve continuously, which increases the porosity and brings down the strength. The two aspects above can ultimately weaken the durability of the structure \[4\]. To improve the resistance of concrete against stray current, stray current simulation test is conducted to study the influence of stray current on the mechanical properties of concrete with different cementitious materials and rebar corrosion.

2. The test

2.1. Raw materials
Cement: PO42.5 cement produced (denoted as C) by Ningbo Conch Cement Company Limited, with a specific surface area of 380m\(^2\)/kg; Mineral admixtures: Grade II fly ash (denoted as FA) produced by Beilun Power Plant, with a fineness of 11.7%, S95 ground granulated blast furnace slag (GGBS) (denoted as SL) produced by Ningbo Iron & Steel Co., Ltd, with a specific surface area of 400m\(^2\)/kg; Additive: polycarboxylic acid high performance water reducer (denoted as PS) produced by CCCC Wuhan Harbor Engineering Design & Research Co., Ltd, with a water-reducing rate of 28%; functional components (denoted as F) are respectively the swelling agent produced by Tianjin BaoMing Co., Ltd and polypropylene fiber produced by Shanghai Tongji Ark Special Building Materials Co., Ltd, with a diameter of 18±2\(\mu\)m and a length of 6mm; Coarse and fine aggregates are respectively continuous graded crushed stones (5~25mm) collected from the Fujingling crushing plant in Ningbo and local river sand, with a fineness modulus of 2.7.

2.2. Mixing ratios
The mixing ratios adopted in the test are shown in Table 1. Each mixing ratio is used in 4 groups. The first group is electrified and embedded with rebars. The second group is electrified but not embedded with rebars. The third group, not electrified nor embedded with rebars, is put in distilled water for curing as with the first two groups. The forth group, not electrified but embedded with rebars, put in distilled water for curing as with the first three groups.

| No. | Amounts and proportions of the cementitious materials (C:FA:SL:F) | ratio of water to cementitious material | C | FA | SL | F | S | G | W | PS |
|-----|---------------------------------------------------------------|----------------------------------------|---|----|----|---|---|---|---|---|
| ZS-0 | 410 | 0.36 | 410 | 0 | / | / | 735 | 1103 | 147 | 4.10 |
| ZS-1 | 410 (70:30:0:0) | 0.36 | 287 | 123 | / | / | 735 | 1103 | 147 | 3.32 |
| ZS-2 | 410 (60:40:0:0) | 0.36 | 246 | 164 | / | / | 735 | 1103 | 147 | 3.32 |
| ZS-3 | 410 (50:50:0:0) | 0.36 | 205 | 123 | 82 | / | 736 | 1103 | 147 | 3.32 |
| ZS-4 | 410 (60:30:10:0) | 0.36 | 246 | 123 | / | 41* | 737 | 1106 | 147 | 3.69 |
| ZS-5 | 410 (60:40:0:15) | 0.36 | 246 | 164 | / | 0.6** | 735 | 1103 | 147 | 3.90 |

Note: ①F is the content of functional components; ②*is swelling agent, **is fiber.

2.3. Testing device of stray current simulation
Compared with normal current, the stray currents of metro trains are “lost”, but it is directional for earth, an objective cathode. Therefore, the running rail can be taken as an anode, the earth as a cathode, and the void solution in the roadbed concrete and water solution in the construction joint as electrolyte solution to simulate the stray currents. Figure 1 shows the device to simulate the effect of stray currents on concrete.
When 150mm×150mm×150mm concrete specimens are kept for curing in the 28th days, the two ends of the specimens are wrapped with inert titanium mesh to work as cathode and anode. Insert rebars in the specimens to simulate rebars inside the concrete under the effect of stray currents. HRB400 rebars (Φ8 mm ×140 mm) are adopted. The rebars are placed in the middle of the cathode and anode, with copper conductors drawn out for electrochemical testing. Distilled water is fed into the testing device, with the liquid level 5-10mm lower than the concrete specimens. A thermometer is placed to measure the temperature of distilled water in the tank. When the liquid level is lower than the required height, distilled water is supplemented in time.

As for the choice of electric current, the investigation into the leakage of stray currents of metro trains in Beijing, Shanghai and other cities shows that the intensity of stray currents leaking into rebars of the main concrete structure is about 20~100 mA/m²[5]. So, the current density through the concrete is controlled at 10~100 mA A/m² by adjusting the applied voltage.

2.4. Test method

Specimens in the second group and third group are respectively taken out in the 4th week and 7th week after electrification to test the compressive strength of concrete and evaluate the compressive strength ratios of concrete with different mixing ratios under the influence of stray currents. Specimens in the first group and forth group are taken out to measure the polarization curve of the rebars and evaluate the electrochemical properties of the rebars.

\[
i_{\text{corr}} = \frac{1}{R_p} \frac{b_a b_e}{2.303(b_a + b_e)}
\]

In which, \(i_{\text{corr}}\) is the corrosion current density; \(R_p\) is the polarization resistance; and \(b_a\) and \(b_e\) are respectively the Tafel slope of anodic polarization curve and cathodic polarization curve.
3. Test results and discussion

3.1. Effect of stray currents on the compressive strength of concrete

The compressive strength ratios of concrete are tested in the 4th week and 7th week after electrification and the results are presented in Table 2.

Table 2. The effect of stray currents on the compressive strength of concrete

| No. | Amounts and proportions of the cementitious materials (C:FA:SL:F) | 28th day after electrification | 49th day after electrification |
|-----|---------------------------------------------------------------|--------------------------------|--------------------------------|
|     |                                                               | Standard current | Applied current | Reduction of compressive strength/% | Standard current | Applied current | Reduction of compressive strength/% |
| ZS-0 | 410(100/0/0/0) | 58.4              | 52.2             | 10.6       | 57.2              | 50.2             | 12.2       |
| ZS-1 | 410 (70:30:0:0) | 48.0              | 44.8             | 6.7        | 50.6              | 47.0             | 7.1        |
| ZS-2 | 410 (60:40:0:0) | 44.1              | 41.1             | 6.8        | 47.5              | 43.8             | 7.8        |
| ZS-3 | 410 (50:50:20:0) | 45.5              | 44.2             | 2.9        | 48.6              | 46.8             | 3.7        |
| ZS-4 | 410 (60:30:10:0) | 43.9              | 41.6             | 5.2        | 45.9              | 43.0             | 6.3        |
| ZS-5 | 410 (60:40:0:15) | 41.5              | 37.4             | 9.9        | 43.8              | 39.2             | 10.5       |

Note: ①F is the content of functional components; ②*is swelling agent, **is fiber.

As is seen from Table 2, in a certain period of current load, electrical current affects the compressive strength of concrete by reducing it, but the reductions of the compressive strengths of concrete with different cementitious materials vary greatly. The reduction extents of the compressive strengths of concrete with different cementitious materials follow the sequence: pure cement > fly ash+mineral powder+fiber > fly ash ≥ fly ash+mineral powder+swelling agent ≥ fly ash+mineral powder. For concrete with the same mixing ratio, the compressive strength decreases more significantly with the increase of the time of current load.

After the concrete is electrified, under the same conditions, the closer to the center of the concrete, the higher porosity is and the larger the pore size is. Therefore, the structure becomes more and more loose. The reason is that under the effect of electric field, the directional migration of ions in the pore solution of concrete leads to the increase of porosity and the formation of interconnected pores, which brings down the strength. Microscopic tests have shown that the Ca/Si ratio of calcium silicate hydrate products drop slightly with the increase of loose degree of cementitious products in the concrete mortar near the cathode.

The differences in the compressive strength reduction of concrete with different mixing ratios lie in that: Under the action of electric current, the ions in the internal pores of wet concrete migrate directionally, causing differences in hydration process. For concrete with different mixing ratios but the same ratio of water to cementitious material, the differences of cementitious systems result in the difference of pores in the concrete. In contrast, the concrete mixed with fly ash and mineral powder is more compact, so it is less influenced. This proves that choosing appropriate cementitious materials can lower the influence of stray currents on the performance of concrete to some extent.

3.2. Effect of stray currents on rebars

The potentiodynamic polarization curves of rebars samples in the 49th day of electrification are shown in figure 3.
Figure 3. Potentiodynamic scanning of rebars with different mixing ratios 7 weeks after electrification

Table 3. The effect of stray currents on the polarization performance of rebars

| No. | Amounts and proportions of the cementitious materials (C:F:SL:F) | Before electrification | 49 days after electrification |
|-----|-----------------------------------------------------------------|------------------------|------------------------------|
|     |                                                                  | $I_o$ ($\mu A/cm^2$)  | $E_o$ (mV)                  |
| ZS-0| 410                                                             | 0.051                  | -150                         | 0.058                         | -276                  |
| ZS-1| 410 (70:30:/:/)                                                  | 0.057                  | -270                         | 0.061                         | -281                  |
| ZS-2| 410 (60:40:/:/)                                                  | 0.070                  | -125                         | 0.075                         | -132                  |
| ZS-3| 410 (50:30:20:/)                                               | 0.041                  | -74                          | 0.041                         | -75                   |
As is shown in Table 3, for concrete with different mixing ratios, the self-corrosion potentials of rebars before electrification and 49 days after electrification are all above -250 mV, and the corrosion current density is less than 0.1 μA/cm², indicating that the rebars in the concrete are in passivation without corrosion.

Compared with concrete applied with concrete, the self-corrosion potentials (E0) of rebars’ electrodes in the concrete gradually move negatively and the corrosion current density (I0) increase gradually after 49 days of electrification. The reason is that after electrification, the electric field imposes stronger effect on ions in the pore solution of the concrete, and the number of migrating ions per unit time becomes larger, and the corrosion of rebars becomes more serious. Meanwhile, the self-corrosion potentials and corrosion currents of the rebars’ electrodes show different change laws under different cementitious systems. The extent of change follows the sequence: pure cement > fly ash+mineral powder+swelling agent ≥ fly ash+mineral powder+fiber > fly ash ≥ fly ash+mineral powder. The sequence is consistent with the sequence of change extent of the compressive strength of concrete, indicating that stray currents’ corrosion effect on rebars greatly influenced by the deterioration of concrete performance, and the impact imposed by the mixing ratio of fly ash and mineral powder is lesser.

The reason for the changes above is that: The conduction of stray currents in concrete needs carriers. As concrete is an ionic conductor, the carriers of its stray currents are ions [6-7]. Compared with electrons, ions have greater mass and volume. When they move in the medium, the denser the medium is, the higher the resistivity is, and the more unfavorable it is to its movement. Therefore, improving the compactness and reducing the porosity of concrete will help to restrain the negative effect of stray currents on the durability of concrete. The addition of mineral substance can markedly improve the pore structure of concrete, improve the compactness and increase the resistivity of concrete, so mineral admixture can effectively inhibit the conduction of stray currents in concrete and reduce the current intensity. The composite cementitious system of fly ash and mineral power improves the compactness of concrete. Besides, the natural interfaces between fiber and powder constitute current carrying channels, which is adverse to the resistance of concrete against stray currents. In this test, maybe due to their own properties, swelling agents also impose some adverse but minor influence.

4. Conclusions

(1) The influence laws of stray currents on the strength of concrete with different cementitious materials and rebar corrosion are consistent. The reduction extent of the compressive strength of concrete and corrosion extent of rebars follows the sequence: pure cement > fly ash+mineral powder+fiber > fly ash ≥ fly ash+mineral powder+swelling agent ≥ fly ash+mineral powder. With the extension of electrification time, the more significant the reduction of compressive strength is, the more serious the corrosion of rebars is.

(2) As concrete is an ionic conductor, the carriers of its stray currents are ions. Compared with electrons, ions have greater mass and volume. When they move in the medium, the denser the medium is, the higher the resistivity is, and the more unfavorable it is to its movement. Therefore, improving the compactness and reducing the porosity of concrete will help to restrain the negative effect of stray currents on the concrete.

(3) The differences of cementitious materials lead to different porosities of concrete. Under the action of electric current, the ions in the internal pores of wet concrete migrate directionally, causing differences in hydration process. In contrast, the addition of mineral substance can markedly improve the pore structure of concrete, improve the compactness and increase the resistivity of concrete, so, cementitious material of this kind can effectively inhibit the conduction of stray currents in concrete, reduce the current intensity and alleviate the corrosion of concrete and rebars. Besides, the natural differences in hydration process. In contrast, the addition of mineral substance can markedly improve the pore structure of concrete, improve the compactness and reduce the porosity of concrete, so, cementitious material of this kind can effectively inhibit the conduction of stray currents in concrete, reduce the current intensity and alleviate the corrosion of concrete and rebars. Besides, the natural
interfaces between fiber and powder constitute current carrying channels, which is adverse to the resistance of concrete against stray currents.

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