Comparison of corrosion characteristics of conductive concrete

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Abstract. Conductive concrete has great application potential in grounding and electromagnetic shielding. To verify the effect of conductive concrete on the corrosion of grounded metals, several conductive concrete with different conductive phase, such as Q235 carbon steel, galvanized steel and stainless steel, were prepared. The conductive concrete test specimens are immersed in red soil leachate, their open circuit potential, potentiodynamic polarization and electrochemical impedance spectroscopy were measured by electrochemical method. Corrosion behaviour of different grounding metals in conductive clays with different conductive phase are compared based on the pre-mentioned three indicators. The results show that conductive concrete can reduce the corrosion of grounded metal effectively compared with ordinary concrete, galvanized steel has better corrosion resistance than Q235 carbon steel, graphite-based conductive concrete can protect the grounding metal better than stainless steel-based conductive concrete, and high conductive phase content can make a low metal corrosion.

1. Introduction
With the power grid expansion, the construction of grounding grids under harsh environmental has become more and more common [1-2], the grounding metal faces more and more corrosion threat. The corrosion will break the grounding conductors, which will cause the ground potential rise and threaten the safety of workers and equipment. The corrosion of grounded metals has become one of the important reasons affecting the stability and safety of power systems [3-5].

Conductive concrete has lower soil resistivity and better gelation performance [6-8]. When applied to the grounding of the tower for power system, the grounding resistance can be effectively reduced. At the same time, because the conductive cement is weakly alkaline, it will form a certain protective effect on the grounding metal. However, the corrosion characteristics of the grounded metal in conductive concrete environment are still less analyzed, and the anti-corrosion effect is still unclear. Therefore, from the perspective of electrochemical corrosion, the electrochemical corrosion test of grounded metal in conductive cement was designed by the principle analysis of open circuit potential, dynamic potential polarization curve and electrochemical impedance spectroscopy. Corrosion behavior and regularity of both Q235 carbon steel and zinc in different graphite and stainless steel proportion conductive concrete

2. Corrosion principle of grounding electrode
The grounding metal is affected by various complicated factors such as humidity, temperature, pH value, soil quality and microorganisms in the soil. The corrosion of the surface is inevitable, which can be roughly divided into micro-cell corrosion and electrolytic corrosion.

A large amount of electrolytes such as acid-base salts are generally dissolved in the soil moisture, and the grounded metal is buried therein, which causes microbattery reaction, thereby leading to the corrosion on metal surface [9]. Taking the galvanized steel commonly used in the tower grounding as an example, the metal zinc on the surface loses electrons in the electrolyte solution to form soluble zinc ions:

\[ \text{Zn} - 2e \rightarrow \text{Zn}^{2+} \]  

(1)

When electron enters the solution, if the solution is acidic, the electron will combine with the hydrogen ion in the solution to generate hydrogen and escape on the impurity. If the solution is neutral or alkaline, the electron will combine with the oxygen in the solution to produce hydrogen and oxygen. And then root ions, oxygen corrosion occurs.

\[ 2\text{H}^+ + 2e \rightarrow \text{H}_2 \uparrow \]  

(2)

\[ \text{O}_2 + 2\text{H}_2\text{O} + 4e \rightarrow 4\text{OH}^- \]  

(3)

Throughout the process, due to the movement of electrons, a string of current is generated between the impurities and the metal zinc to form a battery effect.

Red soil is usually dark red, mostly acidic, with a surface and center pH between 5.0 and 5.5. In this environment, the grounded metal is prone to corrosion and the corrosion rate is fast, and certain improvement measures are needed.

3. Evaluation index and testing method for grounding metal corrosion

In order to evaluate the corrosion behavior of metals, the corrosion characteristics of metals were evaluated by three indicators: open circuit potential, dynamic potential polarization curve and electrochemical impedance spectroscopy.

Open Circuit Potential Method (OCP) refers to the electrode potential when the current density is zero, which is essentially the potential difference between the working electrode and the reference electrode without load [10]. It can measure the total potential difference between the corrosion micro-potential of the grounded metal material and the reference electrode without the applied current. The greater the potential difference, the tendency of corrosion occurs. The measurement of the open circuit potential is relatively simple.

The potentiodynamic polarization method is to set the scan rate by determining the initial potential and the termination potential, and then electrochemically measure the constituent three-electrode system. The corrosion rate of the grounding metal in the conductive cement is obtained by analyzing the data of the current and the potential [11], therefore, it can reflect the speed of metal corrosion.

The electrode potential and the applied polarization current density generally satisfy the Tafel equation:

\[ |\Delta E| = -b_1 \log i_{\text{corr}} + b_2 \log i_{\text{at}} \]  

(4)

\[ |\Delta E| = -b_1 \log i_{\text{corr}} + b_2 \log i_{\text{ct}} \]  

(5)

The polarization curve of the strong polarization region on \( E - \log i \) the semi-logarithmic coordinate is linear. According to this, the Tafel straight line can be obtained, and the straight line is extrapolated to \( E_{\text{corr}} \), and in the horizontal axis, the corrosion current \( i_{\text{corr}} \) can be calculated from the value \( \log i_{\text{corr}} \) corresponding to the upper point.

In addition to the open circuit potential and the polarization curve, the impedance spectroscopy can also describe the corrosion of the metal. It refers to the sinusoidal variation of the current (or potential)
flowing through the electrochemical system over time under small amplitude conditions. Simultaneously measure the change of the corresponding system potential (or current), or directly measure the AC impedance (or admittance) of the system, analyze the reaction mechanism of the electrochemical system and the relevant parameters of the calculation system [12]. The polarization resistance can be measured by the impedance spectrum method, and the larger the polarization resistance, the better the corrosion resistance [13]. Besides, the process and principle of corrosion can also be judged by the shape of the electrochemical impedance spectrum.

4. Corrosion test and comparison for grounded metal in conductive concrete

Based on ordinary Portland cement and fine sand, graphite (500 mesh, carbon content 99% or more), stainless steel fiber (316L, diameter 0.035 mm, length 8-12 mm) were added as a conductive phase material. Conductive concrete with different conductive phase content were prepared by changing the mass ratio of the conductive phase to the Portland cement, the contents are shown in Table 1.

| Table 1. Conductive phase material proportion. |
|-----------------------------------------------|
| Stainless fiber (%) | Graphite (%) |
|----------------------|-------------|
| 0                    | 0           |
| 1                    | 30          |
| 1.5                  | 35          |
| 2                    | 40          |
| 2.5                  | 50          |
| 3                    | 55          |

The conductive phase material was mixed according to the ratio of Table 1 and vibrated, the grounded metal was vertically inserted into the center of the test piece. The samples were placed in a curing box for 24 hours, and maintained for 28 days before demolded, thus the 100mm*100mm*100mm test sample were made.

Q235 carbon steel and galvanized steel are used to test, their open circuit potential, polarization curve and impedance spectrum are measured by using the electrochemical workstation. The results are shown in figure 1 to figure 3.

(a) Q235 carbon steel sample OCP results
(b) Galvanized steel sample OCP results

Figure 1. OCP testing results.

(a) Q235 carbon steel sample dynamic potential polarization curves
4.1. Corrosion behavior comparison under different soil environments

It can be seen that the metal electrode has lower open circuit potential in the red soil leaching solution than in the concrete. It shows that conductive concrete can greatly reduce the corrosion sensitivity of metal to the environment. Taking polarization curves into consideration, we can find that the corrosion potential of the red soil leaching solution is the lowest and the corrosion current is the largest. From chemical impedance spectroscopy observation, we can see that the chemical arc impedance radius of the red soil leaching solution is very small compared with that of the concrete, indicating that the corrosion resistance of the grounded metal in the red soil environment is relatively poor.
Taken together, red soil has the strongest corrosive ability in four different soil environments, followed by ordinary concrete, while graphite-based conductive concrete has the weakest corrosion ability.

4.2. Comparison of corrosion characteristics of different metals

It can be seen from figure 1(a) that the performance of the ‘pregnancy period’ of each group is consistent with the open circuit potential. The performance of the graphite group is superior to that of the stainless steel fiber group.

Under the conditions of red soil leachate, the test results of the potentiostatic polarization curves of the test pieces of each group are shown in figure 2(a). The corrosion potential of the Q235 carbon steel specimens coated with conductive cement is higher than that of the control group. It can be seen from figure 2(a) that as the content of the conductive phase increases, the passivation region of the polarization curve also gradually increases, which is consistent with the monitoring result of the open circuit potential. So the Q235 carbon steel has a slower corrosion rate in the graphite-based conductive cement.

The part of the figure 3(a) clearly constitutes the semicircular inductive arc is a result of the high frequency region. It can be seen that as the graphite content increases, the radius of the inductive arc gradually decreases. It is worth noting that the conductive cement group with stainless steel fiber is not as good as the ordinary concrete group in corrosion durability, which is probably because the chemical properties of stainless steel fiber are more active than ordinary concrete aggregates, when experimental current increases or there is an increase in time, corrosion does happen. It can be concluded that the application of conductive cement can improve the corrosion resistance of Q235 carbon steel in red soil environment and improve its anti-corrosion ability. However, unlike the two indicators of open circuit potential and polarization curve, there is no change in the corrosion resistance of the metal in the conductive cement. As the amount increases, the corrosion durability will decrease.

4.3. Corrosion behavior comparison under different conductive phase contents

Different graphite content (30%, 35%, 40%, 50%, 55%) and different stainless steel fiber content (1%, 1.5%, 2%, 2.5%, 3%) (galvanized steel / carbon steel, according to the analysis in session 4.2), the results of the open circuit potential, polarization curve and chemical impedance spectrum can help understand the influence of the conductive phase content on the corrosion of the metal. With the increase of the amount of graphite or stainless steel fiber, the open circuit potential is gradually positive, and the open circuit potential is more obvious when the graphite content is 50%. In the stainless steel fiber group, the open circuit potential is more significantly improved when the stainless steel fiber content is 2.5%. This shows that the addition of two conductive phase materials reduces the possibility of corrosion of the coated Q235 carbon steel.

5. Conclusions

(1) In general, the degree of corrosion of grounded metals in ordinary concrete, soil leachate and conductive cement can be arranged as: soil leachate > ordinary concrete > conductive cement.

(2) Open-circuit potential monitoring and other three types of tests show that compared with Q235 carbon steel, galvanized steel has lower corrosion tendency, less corrosion rate and stronger corrosion resistance in conductive cement.

(3) With the increase of the content of conductive phase, the corrosion tendency of grounded metal in conductive cement is getting lower and lower, the corrosion rate is getting smaller and smaller, but the corrosion resistance is getting worse. The above three indicators are obviously stronger than the performance of grounding metals in ordinary concrete or soil leaching solution. The test results show that the conductive cement has the best protection effect on the grounded metal when the graphite content is 50% or the stainless steel fiber content is 2.5%. Compared with stainless steel fiber, graphite as a conductive phase material to prepare conductive cement is more conducive in protecting the grounding metal.
6. References

[1] Zhou L J, He Z J, Chen Y, et al. Impact of grounding conductor corrosion on grounding resistance of grounding mesh and improvement method[J]. Journal of the China railway society, 2018, 40(2):39-44.

[2] Wei W, Wu X Q, Ke W, et al. Research progress on corrosion and protection of grounding grid materials[J]. Corrosion science and protection technology, 2015, 27(3):273-277.

[3] Liu S N, Wang C, Deng J L, et al. Epoxy based conductive anti-corrosion coatings for grounding grid[J]. Journal of Chinese society for corrosion and protection, 2015, 35(6):510-518.

[4] Hua G R, Li W H, Guo Y Y. Corrosion rate prediction of Q235 steel in Hainan substation grounding grid based on neural network models[J]. Corrosion and protection, 2017, 38(8):573-577.

[5] Meng X M, Wang L M, Chen S M, et al. Research status and prospect of grounding material in power engineering[J]. New chemical materials, 2016(9):10-12.

[6] Li T F, Luo R C, Pan J W, et al. Analysis of influence of resistance reducing material on electrical performance parameters of vertical DC ground electrode[J]. Insulators and surge arresters, 2018(1):132-136.

[7] Niu J G, Xian R C, Sun X F, et al. Influence of grounding material and structure on the resistance of tower grounding grid in urban distribution overhead lines[J]. Science technology and engineering, 2018, v. 18; No.453(20):121-127.

[8] Gao Z Q, Cao X B, Du J L, et al. Study on the effect of vertical rod on reducing tower’s impulse grounding resistance[J]. High voltage apparatus, 2018(4):182-187.

[9] Li J, Su H, Yan A J, et al. Research of acid soil corrosion resistant new steels for grounding grid[J]. Corrosion science and protection technology, 2015, 27(2):116-122.

[10] Wen D J, Zhao Y H, Tang L L, et al. Effect of high-pressure torsion on corrosion behavior of GW83K magnesium alloy[J]. Materials review, 2017, 38(5):6-12.

[11] Zou S Y, Zhou X L, Cui X, et al. Effect of electroless copper plating on surface of SiCp on corrosion resistance of Si Cp/Al composites[J]. Transactions of materials and heat treatment, 2017, 358(5):6-12.

[12] Wang J, Jia M Y, Yang C H, et al. On completeness of EIS equivalent circuit analysis for electrochemical corrosion process[J]. Journal of Chinese society for corrosion and protection, 2017, 37(06):479-486.

[13] Qiao H X, Lu C G, L Q, et al. Experimental study on corrosion resistance of erinforced concrete based on different cementitious materials[J]. Bulletin of the Chinese ceramic society, 2018, 37(1):25-34.