Corrosion Behavior and Evaluation of Modified Silicate Composite Grounding Material in Soil

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Abstract. In view of the problems of metal grounding material, including non-corrosion resistance, poor combination with soil, easy to steal and so on, a kind of composite grounding material with the modified silicate cladded carbon steel is developed, which takes the corrosion resistance of modified silicate material and the good conductivity of metal into account. By simulating the corrosion tests in the environments with different pH value, the results show that in the soil with different pH value, the modified silicate can protect the carbon steel well, and its anti-corrosion effect is better than that of the galvanized steel; in the soil with pH = 5, its anti-corrosion effect is better than that of copper; in the soil with pH = 9, its anti-corrosion effect is better than that of copper plated steel. The modified silicate composite grounding material has obvious corrosion resistance in both acid and alkaline soil.

1. Introduction
The grounding grid of transmission equipment usually adopts steel, copper, galvanized steel, copper-clad steel, stainless steel-clad steel and other metal grounding materials with electroplated metal layer. The biggest bottleneck problem of metal grounding materials is that they are easy to corrode. The actual operation experience shows that steel and galvanized steel grounding materials corrode quickly, and serious corrosion often occurs after 3-7 years of operation. Although the corrosion resistance of stainless steel and stainless steel-clad steel developed in recent years has been improved, the intermediate core is prone to spot corrosion, and with the increase of Cl⁻ in the soil, the corrosion will be aggravated. Therefore, their actual operation experience is less. The corrosion resistance of copper is 3-4 times of that of steel, but its high cost of materials is the main reason to limit the application in the grounding grid. The corrosion resistance of copper-clad steel grounding material is good, and generally the spot corrosion is prone to occur at the end of grounding body. When the copper-clad steel grounding body is twisted or bent due to natural factors, the surface copper cladding is easy to crack and accelerate the corrosion rate of internal steel material. Meanwhile, the corrosion test shows that the acid soil will aggravate the corrosion of copper. In addition, since the hardness of metal grounding material is much higher than that of soft soil colloid, the air gap is easy to form between these two due to the deformation caused by external force, which not only increases the contact resistance of the two, but also further affects the service life of the grounding device due to the formation of electrochemical corrosion caused by oxygen concentration difference.

In view of the long-term corrosion problems of metal grounding material, some non-metal grounding materials have emerged in the market, such as flexible graphite grounding body, conductive anti-corrosion coating, and grounding module. These materials all have their own defects in the actual use
on site. For example, due to the infiltration of water and air, the grounding module will suffer from internal metal corrosion; the construction of conductive and anti-corrosive coating is difficult, which is easy to be damaged; the reliability of flexible graphite ground has yet to be verified due to its short service time.

In order to solve the problems of metal grounding material, including non-corrosion resistance, poor combination with soil, easy to steal and so on, a new type of grounding body, modified silicate composite grounding body, is designed and prepared in this paper. The composite grounding body uses the metal material as the conductive core material, and the modified silicate material which is externally cladded plays the role of corrosion prevention and dissipation. The composite grounding body has good conductivity and corrosion resistance, which can play a good anti-corrosive and resistance reducing effect when used for the grounding of transmission line poles and towers.

2. Characteristics of Modified Silicate Material

The modified silicate materials are mainly composed of Portland cement, bentonite, fly ash, silicon powder, polyacrylonitrile-based carbon fibre, moisturizer and other raw materials. The carbon fibre is of good self-lubricity and electrical conductivity. The reinforced concrete made by mixing with some carbon fibre has high compressive strength and tensile strength. The carbon fibre is the key raw material for modifying the silicate materials. Generally speaking, the higher the content of carbon fibre, the better the conductivity of concrete; in the case of the same carbon fibre content, the better the dispersion of carbon fibre, the easier to form a complete conductive network.

The specific components of modified silicate materials prepared in this paper are expressed by weight percentage, including 25 ~ 30% Portland cement, 25 ~ 35% bentonite, 15 ~ 25% fly ash, 5 ~ 15% silicon powder, 1.5 ~ 3% PAN-based carbon fibre, and 1 ~ 5% moisturizer (polyacrylamide). The test block made of modified silicate material is as shown in Figure 1, and its measured resistivity is 0.07 $\Omega \cdot m$.

![Figure 1. Test block made of modified silicate material](image)

The modified silicate material has good corrosion protection for the metals, which mainly because it can resist the penetration of chloride ions. The modified Portland cement is a kind of hydraulic cementitious material made by grinding the active mineral materials (fly ash, silica fume, etc.). Through the pozzolanic effect and micro filling of fine grinding mineral materials (slag powder, fly ash, etc.), the hydration products and pore structure of cement are optimized, enhancing the chemical combination and physical adsorption of chloride ion, so as to achieve strong resistance to chloride ion penetration.

3. Experimental Method

The materials used for accelerated corrosion test include stainless steel, copper, copper plated steel, carbon steel, galvanized steel and new modified silicate composite grounding material (cladding the carbon steel). Among them, for new modified silicate composite grounding material, the test block is made of modified silicate material (110mm × 90mm × 70mm), which clads a carbon steel test piece (50mm × 25mm × 2.5mm); for other metal materials, the specifications of test piece is 50mm × 25mm × 2.5mm. The grounding material is cut, milled, punched (numbered), pickled, degreased and dried. In order to reduce the influence of surface state on the corrosion test process, the surface of the test piece will be uniformly polished with 1000# sandpaper.

DC interference accelerated corrosion test: select the soil with different pH value as the corrosion medium (the water content is 25%), and control the corrosion temperature to be 60$^\circ$C. Set two corrosion test pieces for each grounding material as parallel ones, insert them vertically into the soil, and arrange them side by side at the same depth (the distance between the test pieces shall not be less than 15 cm).
In addition, the return electrode is set, and 6V direct current is loaded. The corrosion period is one month. After the end of the corrosion period, the test piece will be taken out for analysis.

Non-DC interference accelerated corrosion test: no loop electrode is set, and no direct current is loaded; other test settings are the same as above.

After the end of corrosion period[1-3], the corrosion products on the surface of test piece shall be removed according to the standard. The micro morphology before and after the removal of these products shall be observed and recorded by SLR camera, and the corrosion rate shall be calculated by using weight-loss method.

4. Comparison of Corrosion Resistance

4.1. Corrosion test under non-electrified condition in the environment with different pH value

After 720h accelerated corrosion under non-electrified condition in the environment with different pH value, the results of corrosion rate are as shown in Table 1 and Figure 2. By comparing carbon steel with composite material, the results show that no matter in the soil with what pH value, the corrosion rate of carbon steel is the highest; in the soil with pH=5, the corrosion rate of carbon steel is the maximum one (0.28773g/m²•h), while the corrosion rate of composite material is only 0.11977 g/m²•h, that is to say, the corrosion rate of carbon steel is 24.2 times of that of composite material; in the soil with pH = 9, the difference between the corrosion rate of carbon steel and composite material is the large (the corrosion rate of carbon steel is 35.2 times of that of composite material). In the soil with pH = 7, the corrosion rate of carbon steel is 10.9 times of that of composite material.

Moreover, it can be seen from Table 1 that the composite material ranks the fourth in comprehensive ranking; its anti-corrosion effect is better than that of copper in the soil with pH = 5, and better than that of copper plated steel in the soil with pH = 9, its corrosion rate is lower than that of galvanized steel in 3 environments with different pH value.

| Test piece          | pH=5  | pH=7  | pH=9  | Comprehensive ranking |
|---------------------|-------|-------|-------|-----------------------|
|                     | Corrosion rate | Score | Corrosion rate | Score | Corrosion rate | Score | Score |
| Stainless steel     | 0.00021 | 1     | 0.00028 | 1     | 0.00052 | 1     | 1 (3)   |
| Cooper              | 0.01267 | 4     | 0.00555 | 3     | 0.00562 | 2     | 3 (9)   |
| Copper plated steel | 0.00451 | 2     | 0.00469 | 2     | 0.00809 | 4     | 2 (8)   |
| Galvanized steel    | 0.23838 | 5     | 0.07890 | 5     | 0.09788 | 5     | 5 (15)  |
| Carbon steel        | 0.28773 | 6     | 0.11977 | 6     | 0.20787 | 6     | 6 (18)  |
| Modified silicate composite material | 0.01188 | 3     | 0.01095 | 4     | 0.00591 | 3     | 4 (10)  |

Table 1. 720h non-DC interference corrosion rate in the soil with different pH value (g/m²•h)

Note: 1. The smaller the corrosion rate, the lower the score, that is, the better the corrosion resistance. 2. The lower the comprehensive ranking, the better the corrosion resistance. The number in the bracket of this ranking is the sum of the scores in 3 environments with different pH value.
Figure 2. Comparison of 720h non-D C interference corrosion rate in the soil with different pH value

| pH | Material                  | Corrosion Rate (g/m²·h) |
|----|---------------------------|--------------------------|
|    | Stainless steel           |                          |
| 5  | (a) Macro morphologies    | 0.35                     |
|    | of stainless steel        |                          |
| 7  | (b) Macro morphologies    | 0.25                     |
|    | of copper                 |                          |
| 9  | (c) Macro morphologies    | 0.15                     |
|    | of copper plated steel    |                          |
|    | (d) Macro morphologies    | 0.10                     |
|    | of galvanized steel       |                          |
|    | (e) Macro morphologies    | 0.05                     |
|    | of Q235 steel             |                          |
|    | (f) Macro morphologies    | 0.00                     |
|    | of modified silicate      |                          |
|    | composite material        |                          |
4.2. Corrosion test under electrified condition in the environment with different pH value

After 720h accelerated corrosion under electrified condition in the environment with different pH value, the results of corrosion rate are as shown in Table 2 and Figure 3. No matter in the soil with what pH value, the corrosion rate of stainless steel is the highest; in the soil with pH=5, the corrosion rate of stainless steel is the maximum one(6.94811g/m²*h), while the corrosion rate of composite material is 2.47050g/m²*h, that is to say, the corrosion rate of stainless steel is 2.1 times of that of composite material; in the soil with pH = 7, the difference between the corrosion rate of carbon steel and composite material is the largest (the corrosion rate of carbon steel is 29.5 times of that of composite material); In the soil with pH = 9, the corrosion rate of carbon steel is 14 times of that of composite material.

Moreover, it can be seen from Table 2 that the composite material ranks the first in comprehensive ranking; its anti-corrosion effect is better than that of copper in the soil with pH = 5, and better than that of stainless steel in the soil with pH = 9; its corrosion rate is lower than that of copper, copper plated steel and galvanized steel in 3 environments with different pH value.

Table 2. 720h DC interference corrosion rate in the soil with different pH value (g/m²*h)

| Test piece       | pH=5           | pH=7           | pH=9           | Comprehensive ranking |
|------------------|----------------|----------------|----------------|-----------------------|
|                  | Corrosion rate | Score          | Corrosion rate | Score          | Corrosion rate | Score          |               |
| Stainless steel  | 0.00229        | 1              | 0.24899        | 2              | 0.10414        | 2              | 2              | (5)         |
| Cooper           | 4.70333        | 3              | 0.74986        | 3              | 0.28662        | 3              | 3              | (9)         |
| Copper plated    | 6.09722        | 5              | 0.85769        | 5              | 0.72546        | 5              | 5              | (15)        |
| Galvanized steel | 6.94811        | 6              | 3.33691        | 6              | 3.12395        | 6              | 6              | (18)        |
| Carbon steel     | 5.23034        | 4              | 0.84775        | 4              | 0.38870        | 4              | 4              | (12)        |
| Modified silicate composite material | 2.47050        | 2              | 0.02873        | 1              | 0.02778        | 1              | 1              | (4)         |

| Ratio of corrosion rate (carbon steel / composite material) | 2.1 | 29.5 | 14.0 |
Figure 4. Comparison of 720h DC interference corrosion rate in the soil with different pH value

| pH Value | Material                  | Macro Morphologies          |
|----------|---------------------------|-----------------------------|
| pH=5     | Stainless steel           | (a) Macro morphologies      |
|          | Cooper                    | (b) Macro morphologies      |
|          | Copper plated steel       | (c) Macro morphologies      |
|          | Galvanized steel          | (d) Macro morphologies      |
|          | Carbon steel              | (e) Macro morphologies      |
|          | Modified silicate         | (f) Macro morphologies      |
|          | composite material        |                             |
| pH=7     | Stainless steel           | (g) Macro morphologies      |
|          | Cooper                    | (h) Macro morphologies      |
|          | Copper plated steel       | (i) Macro morphologies      |
|          | Galvanized steel          | (j) Macro morphologies      |
|          | Carbon steel              | (k) Macro morphologies      |
|          | Modified silicate         | (l) Macro morphologies      |
|          | composite material        |                             |
| pH=9     | Stainless steel           | (m) Macro morphologies      |
|          | Cooper                    | (n) Macro morphologies      |
|          | Copper plated steel       | (o) Macro morphologies      |
|          | Galvanized steel          |                             |
|          | Carbon steel              |                             |
|          | Modified silicate         |                             |
|          | composite material        |                             |
Macro morphologies of Q235 steel (p)
Macro morphologies of galvanized steel (q)
Macro morphologies of modified silicate grounding material (r)

Figure 5. Macro morphology of corrosion test specimens under electrified condition

The above comparison results of corrosion rate show that as the protective layer of carbon steel, the modified silicate material can protect the carbon steel well in the soil with different pH value.

5. Conclusions
Based on some existing problems of grounding material in power system, a modified silicate composite grounding body was designed and prepared by using modified silicate and carbon steel, and the structure and performance characteristics were described. The main conclusions are as follows:

1. The specific components of modified silicate materials prepared in this paper are expressed by weight percentage, including 25 ~ 30% Portland cement, 25 ~ 35% bentonite, 15 ~ 25% fly ash, 5 ~ 15% silicon powder, 1.5 ~ 3% PAN-based carbon fibre, and 1 ~ 5% moisturizer (polyacrylamide); and its measured resistivity is 0.07 Ω•m.

2. The results of corrosion test with different pH value show that as the protective layer of carbon steel, the modified silicate material can protect the carbon steel well in the soil with different pH value. For the prepared composite material, when no direct current is loaded, its anti-corrosion effect is better than that of copper in the soil with pH = 5, and better than that of copper plated steel in the soil with pH = 9; its corrosion rate is lower than that of galvanized steel in 3 environments with different pH value; when a direct current is loaded, its corrosion rate is lower than that of copper, copper plated steel and galvanized steel in 3 environments with different pH value. The modified silicate composite grounding material has obvious corrosion resistance in both acid and alkaline soil.

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