Effects of alternating stray current on chloride transport in cement-based materials

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Abstract: A series of tests were conducted to investigate the effects of alternating stray current on chloride transport in cement-based materials (mortar). The chloride distributions in the mortar after the conditioning of immersion in 35 g/L NaCl solution or coupled with direct/alternating stray current within 14 days were gained. Test results show that: (1) The distribution of chloride ions along the depth in mortar shows an exponential shape, after the conditioning of immersion in 35 g/L NaCl solution or coupled with direct or alternating stray current within 14 days; (2) Comparing with the immersion in the NaCl solution without stray current, the transport of chloride in the mortar under DC electric field is significantly accelerated. The maximum chloride content in the mortar under this environment was almost seven times higher than that in the condition without current; (3) The chloride contents at different depths of the mortar in the AC electric field are slightly less than those in the solution without electric field and are much less than that with direct stray current.

1. Introduction
Durability deterioration of concrete structures occurs when they are exposed to corrosive environments, such as wet-dry cycling, freeze-thaw cycling, wet environments combined with chloride and sulfate. The economic loss induced by the deterioration is huge[1]. Many developed countries spent more money on repairing buildings than on building new ones. With the development of constructions all over the world, the durability issue of concrete structures is attracting more and more attentions.

Different from the overground structures, the urban underground structures are in a more complex environment, and the durability of them faces great challenges[2]. The concrete structures of urban metro system are subjected to corrosive underground water, in which there may be multiple aggressive ions, with great probability. Besides, subway trains often use direct current to create tractive forces. Due to the difficulty in achieving complete insulation between steel rails and ground, stray currents could leak into the steel bars of the concrete structures of metro tunnels as well as the buried metal components. When the current goes through the concrete, the way of chloride ions invading the concrete is different from that in general erosion environments. Because chloride ions participate in the ionic conduction process in the pore solution, there is not only diffusion movement caused by the concentration gradient, but also forced diffusion movement caused by the electric field. In this case,
the transport process of chloride ions into concrete is accelerated, which badly threatens the service performances of tunnel structures.

Chloride ion combined with stray current could lead to corrosion of reinforcement and directly affect the durability of concrete [3], so in recent years, many research concerning the effects of stray current on the transport of chloride in concrete was carried out. Corrosion tests on C55 concrete in chloride solution under four different stray current intensities were conducted by Zhang et al.[4]. It was found in the study that the migration mechanism of chloride ion changed from the diffusion under general conditions to the electromigration in electric field formed by direct current. With the increasing of current intensity, larger chloride content could be found in a certain depth of concrete. Hu et al. [5] studied the behaviors of chloride binding in cement under stray current, and found that the current had adverse effects on the stability of the bound chlorides. Study of Zhu et al.[6] showed that the average diffusion depth under potential difference of 20 volts was 7~8 times that in general diffusion condition. Similarly, Geng et al.[7] revealed that with the increase of direct current intensity and exposure time, the acceleration effect of the current on transport of chloride ions became more obvious.

At present, most of the concerns focused on the corrosion of direct stray current. However, due to the harmonics of the current output by the traction converter and the load changes during the train start-stop process, stray current is no longer a complete direct current, but a dynamic alternating-direct mixed current[8]. Therefore, the study of chloride transport in concrete under stray current should not only consider the corrosion of direct current, but also increase the understanding of alternating stray current. At the meso level, concrete can be regarded as a composite material composed of cement mortar, coarse aggregate and the interface between them. Since chloride ions basically do not go through the densely structured coarse aggregate, they mainly migrate in the cement mortar and the mortar-coarse aggregate interface. Therefore, a series of experiments were conducted and the primary objective of this work to investigate the effects of alternating stray current on chloride transport in cement-based materials (mortar).

2. Experimental Program

2.1. Materials and specimens

Ten mortar specimens were made in this study. The mix ratio of the mortar was based on a high-strength (C50) concrete used for a metro tunnel construction, which consisted of PO 42.5 Portland cement (according to GB 175-2007[9]), II fly ash, S95 blast furnace slag, granite gravel with the size of 5~20 mm (coarse aggregate) and river sand with a fineness modulus of 2.8 (fine aggregate). In this study, the mix proportion of the mortar is the concrete mixture without the coarse aggregate. The detailed mix proportions are tabulated in Table 1.

| Type  | Water (kg/m³) | Cement (kg/m³) | Sand (kg/m³) | Fly ash (kg/m³) | Slag (kg/m³) | Water reducer (kg/m³) |
|-------|---------------|----------------|--------------|----------------|-------------|-----------------------|
| Mortar| 133           | 342            | 632          | 69             | 103         | 4.11                  |

The specimen is a 100 mm mortar cube with a graphite sheet (100 mm long×50 mm wide×3 mm thick) partially embedded in it, and the details of the specimen are shown in figure 1. The graphite sheets were chosen to be electrodes since the material is inert and would not react with the composition of the mortar, so to prevent its internal environment from interference of unconcerned ions. One of the two surfaces, which were parallel to the graphite sheet, was chosen to be the exposed surface, through which the chloride in the solution could migrate into the mortar. Except for the exposed side, the other five surfaces were all sealed with paraffin wax, to make sure it could be a one-dimensional chloride penetration. The photo of the specimen could be seen in figure 2.
2.2. Test methods

The specimens for the test were divided into four groups: (1) one control specimen was placed in the air; (2) three specimens were immersed in NaCl solution for 3, 7 and 14 days; (3) three specimens were immersed in NaCl solution, and DC electric field was applied simultaneously with the conditioning time were 3, 7 and 14 days, respectively; (4) the rest three specimens were also immersed in the solution and was loaded with AC electric field, the conditioning duration was the same as above.

The concentration of the NaCl solution used in the study was 35 g/L. The DC and AC electric field were provided by DC and AC power supply, respectively. For the tests in groups (3) and (4), there was one other graphite sheet, which was exposed to the NaCl solution directly, to act as the other electrode in the electric circuit. The potential difference between the two electrodes was set 20 V for both DC and AC electric field. In the test concerning direct stray current, the graphite sheet embedded in the cube was always connected to the positive of the power supply to make the migration direction of chloride ions was towards the mortar. The schematic diagram of the experimental setup and its photo were shown in figure 3 and 4, respectively.

At the end of each conditioning time (such as 3, 7 or 14 days), the specimens were removed from the solution and dried in the air for 14 days. Then the mortar cube specimen was ground into powder every 2 mm depth in the direction perpendicular to the exposed surface (from depth 0 mm to 30 mm, totally 15 layers). Potentiometric titration was used to determine the mass percentage of chloride in the powder of each layer, refer to the test method for the water-soluble chloride ion content in hardened concrete in the specification JGJ/T 322-2013[10], so to investigate the transport behavior of chloride in the mortar under the effect of direct or alternating stray current.

![Figure 1. Details of the specimen (Unit: mm)](image1)

![Figure 2. The photo of the specimen](image2)

![Figure 3. Schematic diagram of the experimental setup (top view)](image3)
3. Results and discussions
Chloride distributions in mortar after the immersion in the NaCl solution, or coupled with direct/alternating stray current could be seen in figure 5, 6 and 7, respectively. The data of “0 days” in these figures is those of the control specimen, giving the inherent chloride content in the specimen without any conditioning. In terms of mass percentage of mortar powder, the initial chloride contents at different depths of the specimen are basically identical, being about 0.01%. It is noting that, for all the testing specimens, when the distance from the exposed surface exceeded 10 mm, the chloride content always kept constant at its initial value, meaning chloride did not migrate to a deeper place under the environments studied in this paper. So the data of chloride content at the depth from 10 to 30 mm were not adopted for easy processing. It could be seen from these figures that:

(a) Under the three different environments, the distribution of chloride ions along the depth in mortar shows an exponential shape, indicating that the chloride is easier to accumulate near the surface of the mortar than to penetrate into it. Chloride ion could gather in the pores which directly connect to the solution in a unimpeded manner, and the deeper the chloride goes, the weaker the driving force of diffusion determined by the concentration gradient would be. The content of chloride ion decreases obviously with the increase of depth. As shown in “14 days” curve of figure 5, the chloride contents at depth of 2~4 mm and 4~6 mm are 59% and 34% of that at depth of 0~2 mm, respectively. The values in “14 days” curve of figure 6 are 43% and 22%. For figure 7, the values are 57% and 37%, which are similar as that in figure 5. It could be seen that the decrease rate of chloride content along the depth in the specimen under direct stray current is relatively higher than those in other two conditions.

(b) Comparing with the immersion without stray current, the transport of chloride in the mortar under DC electric field was significantly accelerated. After 14 days of immersion coupled with direct current, the chloride content at depth 0–2 mm reached to 0.3%, which was almost seven times higher than that in the condition without current. For the cases of “7 days” and “3 days”, the chloride contents at the depth 0~2 mm of the mortar specimens in DC electric field combined with NaCl solution are, respectively, three and one point five times higher than those of the specimens underwent just immersion. These results indicate that the existence of direct stray current changes the dominant factor of mechanism of chloride ion transport. In this one-way DC electric field, the concentration gradient-dominated diffusion process coexists with the electric field force-driven electromigration process, make the chloride ion move in the same direction towards the internal of mortar, so the chloride content in the mortar was greatly increased.

(c) In general, as to the case of immersion in NaCl solution coupled with the AC electric field, for a certain conditioning time, the chloride contents at different depths of the mortar are slightly less than those of the specimens immersed in the solution without electric field. Certainly they are much less than that in the DC electric field. Take the contents of chloride at depth 0~2 mm of the mortar specimens as example. After 7 and 14 days’ conditioning in the AC electric field, the chloride contents at this depth are 85% and 82% of the corresponding values of the specimens merely immersed in NaCl.
solution, and they are only 12% and 27% comparing with the specimens under the coupled effects of immersion and direct stray current. The reason for the results may be as follows. The DC power supply creates a unidirectional electric field, and negative chloride ions in the NaCl solution could transport along the field lines, with the driving force always directing at the electrodes in the cube. However, the magnitude and direction of alternating stray current varies in accordance with sine wave, meaning that the electric driving force in this field will vary accordingly. So the chloride ions in the solution might reciprocate between the two electrodes, therefore the chloride migration into the mortar would not be accelerated in the AC electric field. Besides, the alternating current may have some inhibition to the concentration gradient-dominated diffusion process, and there need to be further study on this issue.

4. Conclusions
This experimental study aimed at shedding light on the effect of stray current on chloride transport behaviour in mortar. The work has led to the following conclusions:

(1) The distribution of chloride ions along the depth in mortar shows an exponential shape, after the conditioning of immersion in 35 g/L NaCl solution or coupled with direct or alternating stray current within 14 days.

(2) Comparing with the immersion in the NaCl solution without stray current, the transport of chloride in the mortar under DC electric field is significantly accelerated. The maximum chloride content in the mortar under this environment was almost seven times higher than that in the condition without current.
(3) The chloride contents at different depths of the mortar in the AC electric field are slightly less than those in the solution without electric field and are much less than that with direct stray current.

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