Corrosion Research and XCT Investigation of RC under Different Artificial Environment Simulation

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Abstract. In this experiment, the common electric accelerated corrosion and drying-wetting cyclic corrosion test are compared, and the influencing factors (diameter of steel and thickness of protective layer) of the two corrosion methods are analyzed. When the constant current density was 100μA/cm², the cracking time of the protective layer of the wetting-drying test samples was about 4 times that of the electrified test samples. For the two kinds of acceleration experiments, the cracking time of the protective layer increases with the increase of the diameter of the reinforcement and the thickness of the protective layer. Under the condition of accelerated corrosion by electrification, the diameter of reinforcement has a great influence on the cracking time of the protective layer, while the thickness of the protective layer has a relatively small influence. Under the condition of accelerated drying-wetting cyclic corrosion, the thickness of the protective layer has a great influence on the cracking time. The influence of the diameter of reinforcement is not obvious. In addition, we further explored the specimen with XCT. The rust patterns of the two samples are different.

Keywords. Corrosion cracking, μCT technology, wetting-drying test, current acceleration, cracking time.

1. Introduction
Reinforced concrete structure (RCS) is one of the most widely used building structure forms in construction engineering. Its durability has gradually become a prominent issue which has been highly concerned by a large number of experts and scholars at home and abroad [1]. The durability problem caused by the corrosion of steel bars leads to considerable economic losses. Therefore, steel corrosion is a very serious and urgent problem to be solved.

The effect of reinforcement corrosion on the durability of reinforced concrete is primarily reflected in two aspects: at the macro-scale, first, corrosion of steel bar reduces the effective cross-section of steel, thus reducing the load bearing capacity of components [2]; secondly, corrosion affects the bonding properties interface between reinforcement and concrete, which significantly reduces the bond strength [3]; at the micro-scale, due to the corrosion of reinforcement, the expansion of corrosion products produces enough stress in the concrete, which eventually leads to the concrete cover cracking [4]. The cracks can make a large amount of aggressive ions (such as chloride ions) quickly penetrate into the structure from the outside, accelerating the rust rate of steel bars, resulting in faster structural failure [5].
Although the test results in the natural environment are one of the critical factors to determine the parameters of the artificial accelerated corrosion test, the data of the existing natural environment tests are not much. This is owing to the fact that in the natural environment, the steel corrosion needs to go through decades or even longer [6], so the natural corrosion method is seriously limited in the study of reinforcement corrosion. In addition, the natural corrosion test requires numerous human and material resources, and it is not realistic to carry out a large number of natural corrosion tests. For this reason, many scholars have tried a variety of simulation test methods.

Simulation test methods include accelerated corrosion impressed current method, immersion drying method, electro-migration corrosion method, internal penetration method, immersion method, artificial climate simulation method, etc. However, due to the differences in the principles of different test methods, contradictory conclusions are likely to be drawn eventually, thus affecting the reliability of the results. Most of the existing studies only use one method for testing, because the selection of test methods needs to consider the operability of the test. We lack a horizontal comparison of the obtained critical cracking time and other degradation parameters. Therefore, it is of great value to study the differences between them for the application of the research results of the simulated experiment method in the practical engineering [7].

The experiments of electrification accelerated corrosion and drying-wetting cycling corrosion were carried out in this paper. The cracking time and the corrosion morphology were compared. We further scanned the corresponding samples with XCT, which has become a new trend in concrete research [1], extracted and analyzed the internal quantitative information such as the internal volume expansion rate and the corrosion rate of reinforcement.

2. Experimental Details

2.1. Materials
The HRB335 steel bars with a diameter of 6mm, 8mm, and 10mm respectively were used in this study. The ordinary Portland cement of type P.O.42.5 was used and concrete specimens with a water-cement ratio of 0.44 were cast. The mix design for concrete composition is given in table 1, and coarse aggregate used is crushed stone with a particle diameter of range from 2.5 to 4.75 mm.

Table 1. Mix proportion of concrete.

| W/C | Water | Cement | Sand | Crushed stone | Sand ratio |
|-----|-------|--------|------|---------------|------------|
| 0.44| 275   | 624    | 500  | 1011          | 0.33       |

2.2. Samples Preparation
The sample treatment method is shown in figure 1. The first letter represents the rust environment (A-Electrification, B- wetting-drying); The second letter represents the diameter of the reinforcement (A-6, B-8, C-12); The third letter represents the sample diameter (A-25, B-32, C-40); The last digit represents the sample number. For the Electrified sample, the exposed reinforcement and wire are wound together before the two ends are wrapped with epoxy resin, and the constant current density is 100 μA/cm². Following the 28 days standard curing process, the test specimens were divided into 2 groups according to the various corrosion conditions, and then the artificial corrosion experiment was carried out.
2.3. Testing Process under Three Corrosion Conditions

2.3.1. Electrification Accelerated Corrosion Experiment. In the present experiment, 5% NaCl solution was prepared as electrolyte solution, and different currents were applied to samples of different diameters, respectively. Observed samples every 12 h interval and adjusted the electrolyte solution concentration and current in time. When the first visible crack appeared on the concrete cover, stopped electricity and recorded the cracking time, location, crack length and width. The crack width is measured by a crack width meter, as shown in figure 1. It is specified when the crack width is 0.1 mm, determining that concrete cover has cracked. At the time, the experiment was finished.

2.3.2. Wetting-Drying Test. In the present experiment, wetting-drying was set as a cycle of 8 h drying and 16 h wetting. Preparing 5% NaCl solution, 36 samples were immersed in the solution for 16 h, and then removed and placed them in a drying oven (as shown in figure 2). The temperature was set at 40 °C. Wetting-drying test was finished until a crack width of 0.1 mm appears on the concrete surface.

2.4. XCT Test and Microscopic Verification Test of Samples
The one of the samples with same specifications (same size and maximum crack width) in the two different corrosive environments mentioned above, both wetting-drying environments and galvanostatic electrochemical corrosion were selected for XCT scanning test (table 2). The sample specifications are shown in table 3.

| Table 2. XCT Device information. |
|----------------------------------|
| **Equipment type** | X-CT (Y.CT Precision S,YXLON) |
| **Pixel size** | 200 μm |
| **Reconstruction algorithm** | Filter back projection algorithm |

| Table 3. Sample parameters. |
|-----------------------------|
| **Specimen number** | **Specimen type** | **Maximum crack width (mm)** |
| ACC2 | Electrification corrosion | 1.37 |
| BCC4 | Wetting-drying test | 1.34 |
3. Result and Discussion

3.1. Analysis of Cracking Time and Influencing Factors

3.1.1. Effect of Cover Thickness on Cracking Time. Figure 3 shows that the effect of the thickness of the cover on the cracking time when the diameter of the steel bar is definite under two different experimental methods. As shown in figure 3, it can be seen that under a certain diameter of the reinforcing bar but different cover thicknesses, the difference in cracking time of the accelerated corrosion specimens with current is relatively small, and the cracking time differs by about 200h. While under the drying-wetting cycle, the difference in cracking time of cover is larger of electrification accelerated samples. The above results show that under the two corrosion modes of the same sample, the cracking time of the sample increases with the thickness of the concrete cover. Among them, the average growth rate of the cracking time under the accelerated corrosion is 65.6% (The thickness of protective layer increases by 7.5 mm), and the change rate of drying-wetting cracking time is 46.2%, indicating that the thickness of the cover has a significant effect on the cracking time of the accelerated sample. This is due to the increase in the thickness of the cover, which prolongs the penetration path of corrosive media such as chloride ions, thus prolonging the corrosion time of the steel bars, and ultimately delaying the cracking time; moreover, because the life cycle of the electrified specimen is shorter than that of the drying-wetting specimen, it is easier to enlarge the influence of the thickness of cover on the cracking time. At the same time, due to the increase of the thickness of the cover, more expansion force is needed to expand the concrete cover, that is to say, the cracking time is extended [8].

![Figure 3](image_url)

**Figure 3.** The influence of protective layer thickness of electrified sample(left), drying-wetting sample(right) on cracking time.

3.1.2. Effect of Steel Diameter on Cracking Time. It can be seen from figure 4 that under different corrosion methods, when the thickness of the cover is similar, the larger the diameter of the steel bar, the longer the cracking time. When the diameter of reinforcement is increased from 6mm to 12 mm, the growth rates of cracking time in 9.5/10 mm cover group and 13/14 mm cover group were 208.6% and 133.9%, respectively. The growth rates of cracking time of 9.5/10 mm group and 13/14 mm cover group was 23% and 11.1% under drying-wetting conditions, respectively. The reason may be that the larger the diameter of the reinforcement, the greater the contact area between the reinforcement and the protective layer. The more the area, the amount and the thickness of the corrosion, the longer the cracking time is.
Figure 4. The influence of steel bar diameter of electrified sample (left), drying-wetting sample (right) on cracking time.

3.2. Three-Dimensional XCT on Rust Expansion and Cracking of Reinforced Concrete under Accelerated Corrosion and Drying-Wetting Conditions

According to the analysis of the XCT scanning results of the samples, the three-dimensional spatial distribution and interrelation of the corrosion products and cracks, as well as the quantitative analysis results of the corrosion rate and the volume expansion rate of the reinforcement under the real situation are obtained, as shown in figure 5.

Figure 5. From left to right, there are reconstruction images of concrete, reinforcement, corrosion products and cracks.

It can be seen from table 4 that when the crack widths are similar, the corrosion rate of the steel bar under the condition of accelerated corrosion with low current is higher than that under drying-wetting conditions. This is because under the electrification condition, the samples are more inclined to uniformly rust, the rust products are more uniformly distributed, and stress concentration is more difficult to occur. Therefore, so more rust is required to achieve the cracking requirements, so the corrosion rate is high. Because the sample contains a lot of rusted holes, these holes will spread a large number of rust products, which delays the overall rust expansion and cracking process, and makes the development of large cracks run through the sample slow. Under the parameters of this present experiment, when the crack develops to about 1.35 mm, the actual corrosion rate of the steel bar is approximately 35%-40%. In addition, according to Faraday's law, the calculated corrosion rate of the electrified sample is 37.4%, which is slightly less than the 40.1% corrosion rate calculated by the software, and the error is small.
Table 4. Corrosion rate of steel bar under two corrosive environments.

| The experimental method       | Remaining steel bar volume Vs(mm³) | The volume of steel bars before corrosion V(mm³) | The corrosion rate of steel bar calculated |
|-------------------------------|-----------------------------------|-----------------------------------------------|-------------------------------------------|
| (Electrification acceleration) | 2049                              | 3418                                          | 40.1%                                     |
| (Wetting-drying)              | 2170                              | 3418                                          | 36.5%                                     |

It can be seen from the data in Table 5 that under the condition of similar crack widths, the volume expansion rate under the condition of small current accelerated corrosion is higher than that under drying-wetting conditions. This is because when the samples are under the drying-wetting cycling conditions, the reinforcement is more prone to non-uniform corrosion and the rust swelling stress is more easily concentrated, and the cracking can be realized at a low expansion rate. Besides, it can be obtained that when the crack develops to about 1.35 mm under the parameters of this present experiment, the volume expansion rate of the steel is about 20%-25%.

Table 5. The volume expansion rate of samples under two corrosive environments.

| The experimental method       | Remaining steel bar volume Vs(mm³) | The volume of corrosion products and interfacial pores VC(mm³) | The volume of steel bars before corrosion V(mm³) | Volume inflation rate N |
|-------------------------------|-----------------------------------|---------------------------------------------------------------|-----------------------------------------------|------------------------|
| (Electrification acceleration)| 2049                              | 2268                                                          | 3418                                          | 26.3%                  |
| (Wetting-drying)              | 2170                              | 1993                                                          | 3418                                          | 21.8%                  |

Figure 6 and figure 7 show the three-dimensional spatial location relationship between cracks and corrosion products in two corrosion environments. It can be observed that the cracks of the electrification accelerated sample are more uniform and orderly than that of the drying-wetting samples, while the cracks of the drying-wetting samples are more disorderly. Furthermore, there are many disordered pores around the crevice. This is due to the different accumulation forms caused by different accumulation rate of rust products. In the early stage of drying-wetting corrosion, there is less excessive rust, and rust products accumulate and expand in the sample, thus forming a large number of not through holes and cracks inside the cover.

Figure 6. From left to right, corrosion products, corrosion products and cracks are shown in front view and top view (electrification accelerated sample).
Figure 7. From left to right, corrosion products, corrosion products and cracks are shown in front view and top view (drying-wetting cycle accelerated sample).

4. Conclusion
In the present study, based on the small current accelerated corrosion experiment and drying-wetting cyclic experiment, which accords with the characteristics of coastal chloride-induced corrosion, the critical point of the rust expansion cracking time of concrete cover is obtained, and the cracking time under different corrosion environment is analyzed to determine the influence of corrosion environment, cover thickness, the diameter of reinforcement and cracking time. Finally, the relevant rules and main conclusions are summarized as follows:

1. Under this present experimental condition, the cracking time of the cover under the drying-wetting cycle condition is about twice of that of the electrification accelerated sample; under two types of corrosion environments with the same specifications, with the increase of the thickness of the concrete cover, the longer the cracking time of the sample is; when the thickness of the cover is constant, the larger the diameter of the reinforcement is, the longer the cracking time is.

2. The results of three-dimensional reconstruction show that the cracks of the electrification accelerated samples are even, and the cracks of the drying-wetting samples are disordered. This is caused by the different accumulation rate of corrosion products. The longer the corrosion time is, the more likely the corrosion products tend to fill the internal pores, thus forming a large number of non-through holes and cracks inside the cover, resulting in non-uniformly surface of the rust layer of drying-wetting samples, and more formation of disordered cracks.

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