INFLUENCE OF DIFFERENT CORROSION SOLUTIONS ON REINFORCED CONCRETE BY DIC AND TRADITIONAL STRAIN TEST

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Abstract

When the corrosion expansion stress of the steel reinforcement exceeds the ultimate tensile strength of the concrete, the concrete will crack and eventually cause structural damage. Therefore, direct characterization methods of steel corrosion expansion stress can help predict the concrete cracking time, prevent corrosion expansion and repair the reinforcement concrete in advance. In this paper, by using the digital image correlation technology (DIC) to monitor the surface strain of concrete, and using the hollow steel bar to catch the strain of the steel bar under the condition of constant potential acceleration, the experiment and theory are established to characterized the relationship between the corrosion expansion stress and the concrete surface deformation. Besides, different corrosion solutions were applied to the specimens to investigate the effect of the corrosion solution on the corrosion rate of the steel bars in the concrete. The results show that the corrosion rate is seawater > 3% NaCl solution > 3% NaCl + 5% Na_2SO_4 composite solution. Among them, sulfate ions inhibited the promotion of chloride ions corroding on steel bars to a certain extent.
Keywords: Reinforced concrete, Corrosion, Corrosion expansion stress, DIC

1. INTRODUCTION

Since the appearance of Portland cement in 1824 and the patent for reinforced concrete in France in 1867, reinforced concrete structures, as a composite material, has fully exerted to the compressive properties of concrete materials and the tensile properties of reinforcement, forming the complementary synergy. Because of its low cost performance, easy access to raw materials, it has become the most mainstream materials used in various types of construction facilities. American researchers have said the "five-fold law" to vividly describe the durability of reinforced concrete structures [1]. Obviously, it can be seen that the decline in the durability of reinforced concrete structures and the premature attenuation of service life have become important scientific and engineering problems that need to be solved nowadays, which has attracted close attention from the scientific and engineering community in the domestic and overseas[2-3].

Under the action of corrosion ions, Steel bars in concrete have de-passived and gradually be corroded, and the volume of corrosion products is 2~4 times of the corresponding steel bars [4]. With the increase of the corrosion degree of reinforcement, the corrosion expansion stress will augment. Accordingly, when the corrosion expansion stress exceeds the concrete tensile strength, the concrete protective layer will crack [5]. Apparently, it is significant to accurately investigate the corrosion degree of steel bars and obtain the change of corrosion expansion stress stage of steel bars to predict the cracking caused by corrosion expansion stress and durability issues of reinforced concrete [6-7].

At present, the detection of the reinforcement corrosion in concrete mainly uses electrochemical methods, such as semi-battery potential method, linear polarization method, constant voltage method, resistance probe method, etc. [8]. Based on these methods, we can see that the reflection of the averaging corrosion state of the whole steel bar by measuring the electrochemical characteristic information. It is unable to reflect the local pitting phenomenon of the reinforcement. The methods for detecting cracks in reinforced concrete structures include manual observation method, ultrasonic inspection method, sensor detection method, strain gauge, and extensometer [9-10]. The artificial observation method is subjective, and the results produced vary from person to person. In addition, the observation of micro-cracks by human eyes cannot reach the accuracy of industrial cameras. Ultrasonic testing cannot carry out long-term continuous monitoring of the whole process of steel corrosion. The sensor detection method cannot monitor the stress-strain on the surface of the specimen in real time, and it is easy to be damaged by the corrosion ions because it is placed inside the specimens. And strain gauges, extension gauges cannot detect cracks in the specimen (cracks caused by the reinforcement corrosion expansion stress) [9-10]. Therefore, how to accurately monitor the corrosion expansion stress of reinforcement and the crack growth caused by corrosion expansion, then establish the quantitative relationship between them is a major difficulty in the monitoring system of reinforced concrete structures. These problems can be solved by the digital image correlation technology (DIC) method, which can monitor the crack propagation process of reinforced concrete specimens in real time. DIC is a non-destructive, non-contact optical measurement method. Yamaguchi[10] and Peters[11] first introduced this method, and it has gradually been used by researchers to measure the displacement and surface deformation characteristics of objects in three-dimensional space.The method has high precision, low requirements on environmental conditions, less economic investment of the equipment, and can continuously monitor the whole process of the specimens in real time. Thus, DIC is easy to implement and cost-effective, and is widely used to monitor mechanical damage and structural health of materials [12-13].

In this paper, the combination of DIC method and traditional strain collection method is used to continuously track the deformation and cracking effect of reinforced concrete specimens under constant potential acceleration conditions. Based on this method, the corrosion stages of reinforced concrete specimens are monitored in real time. The process provides a new method for the study of corrosion of reinforcement concrete cracking.

2. EXPERIMENT

2.1 Raw materials and mix proportion

PI.52.5 Portland cement is used according to Chinese standard GB 175-2007. The chemical composition of the cement is shown in Table 1. Class I FA, specific surface area is 380~400 m^2/kg, S95 GGBS, specific surface area is 430~450 m^2/kg, coarse aggregate is granite, continuous grading of 5~20 mm, crushing value is 13.8%. The fine aggregate is river medium sand, the fineness modulus is 2.7. The polycarboxylate based superplasticizer is JM-PCA(I) type with a water reduction rate is about 30%, the dosage is 5.58kg/m^3, air-entraining agent content is 0.22kg/m^3, adopting H700 type super absorbent resin (SAP), which is pre-absorbed and mixed into the concrete. The water absorption ratio is taken as SAP: water=1: 30 by mass (SAP water consumption is a part of the total water consumption in the concrete mix ratio), and the water is tap water. Q235 carbon steel bar is used and their specific chemical compositions is shown in Table 2. The mixture ratio of concrete is prepared with the effective water cement ratio (w/c) of 0.33. The mixture proportions for the reinforced concrete is shown in Table 2-3. The compressive strength of concrete is 30.03Mpa and 37.14Mpa after standard curing for 7d and 28d respectively.

Table 1: Chemical compositions of P.I 52.5 cement

Constituent	SiO_2	LOI	Fe_2O_3	Al_2O_3	MgO	CaO	K_2O	SO_3	Na_2O
Wt%	20.87	0.77	3.59	4.87	2.13	64.49	0.65	2.52	0.11

Table 2: Chemical compositions of Q235 carbon steel bar

Fe	C	Si	Mn	P	S	V	Cr	Ni	Al	Mo
Bal.	0.22	0.35	1.4	0.04	0.05	-	-	-	-	-

Table 3: Concrete mix ratio (kg/m^3)

Name	Cement	GGBS	FA	Sand	Aggregate	Water	SAP
LF50SP1	250	145	75	730	1095	130	1

2.2 Preparation of reinforced concrete specimens

The size of reinforced concrete specimens are 100*100*250 mm^3, and the size of upper prepared corrosion solution tank is 15*20*150 mm^3. After curing for 24h in mould, the reinforced concrete specimens are placed in a standard curing room (temperature (20±3) ℃, relative humidity RH⩾95%) for curing to 28 days. In order to ensure that the strain gauge is not affected by external corrosion ions, the Q235 carbon steel bar with a diameter of 20 mm is split into two halves, internal processing diameter of 15 mm grooves, decorated in the steel bar inside groove section 7 points, points as shown in Figure 1. Among them, the leftmost point is the strain gauge compensation point, and the remaining points are strain collection points. The formed reinforced concrete specimen is shown in Figure 2. The thickness of concrete protective layer designed in this experiment is 25 mm.

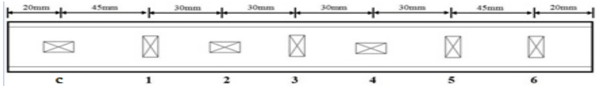


Figure 1: Position of resistance strain gauges

Figure 2: Reinforced concrete specimen

2.3 Principle of DIC method

The DIC method, also known as the digital speckle method (DSCM), is a non-contact deformation measurement method that uses the randomly distributed spots on the surface of the object to give the deformation field [9]. In this method, the deformation information is obtained by correlation processing of two speckle images on the object surface before and after deformation. The basic idea of the DIC method is to compare the images before and after the deformation of the object, and identify the specific sub-regions to "track" the deformed position of the points on the surface of the object, and then obtain the displacement and strain values.

3. RESULT AND DISCUSSION

3.1 Micro-strain of reinforcement

Figure 3 shows the variation of the micro-strain value of point 3 on the inner surface of reinforcement under electrical acceleration of three different corrosion solutions, the micro-strain values of the three specimens gradually increase with time at first, especially for the specimen under the action of 3% NaCl solution, which indicate a very obvious strain growth trend. This phenomenon indicates that chloride ions promote the corrosion reaction of reinforcement and accelerate the process of the corrosion reaction. At the later stage of the corrosion reaction, the micro-strain values of the specimens gradually decreases under the action of 3%NaCl solution and 3%NaCl+5%Na_2SO_4 composite solution, while the concrete specimen under the seawater solution still showed an increasing trend. It is indicated that high concentration of chloride ions causes pitting corrosion phenomenon, then the corrosion products only appeared in the area of point 3. After reaching the ultimate tensile strength of the concrete, then micro-cracks are generated, the stress unloading occur. As sulfate ions can inhibit the corrosion of steel bars, the change of micro-strain values from beginning to end is not obvious, and it is consistent with the phenomenon described in previous literature [14]. As a composite solution of various ions, seawater causes extensive corrosion of steel bars, and its micro-strain continue to increase and causes concrete corrosion and cracking.

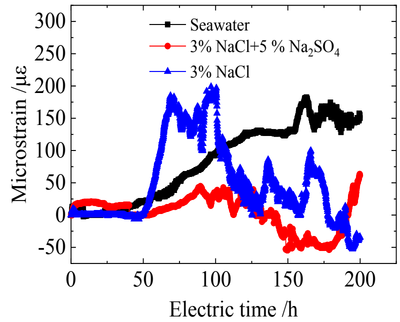
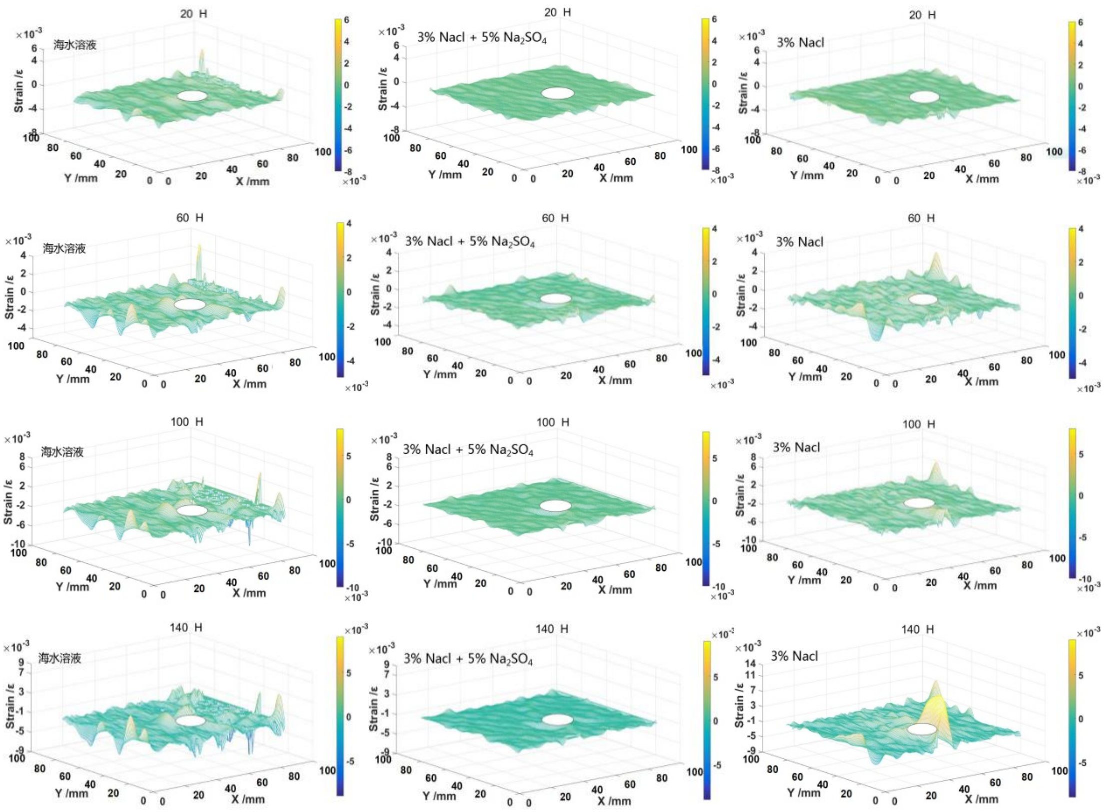


Figure 3: The internal micro-strain value of reinforcement in concrete varies with time

3.2 Strain evolution analysis based on DIC test

The square section of the reinforced concrete side is as 100×100 mm^2. The calibration result of this section is 0.076 mm/pixel, and the area size is 122×166 pixels. The evolution process of the strain field is shown in Figure 4.This figure shows that the change of strain field with time is consistent with the information in Figure 3. In the early stage of the experiment, the degree of corrosion reaction is: seawater > 3%NaCl solution > 3%NaCl+5%Na_2SO_4 solution, and in the middle and late stage of the experiment, the degree of corrosion reaction is: 3%NaCl solution > seawater > 3%NaCl+5%Na_2SO_4 composite solution.



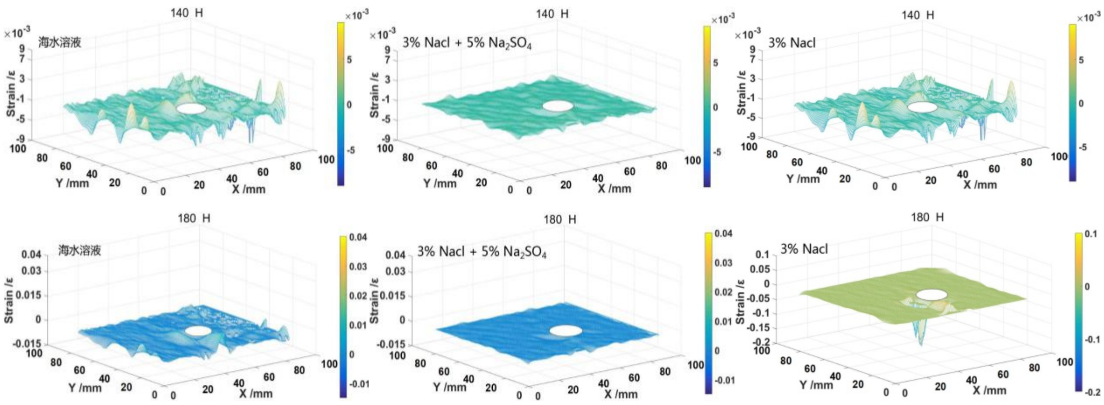
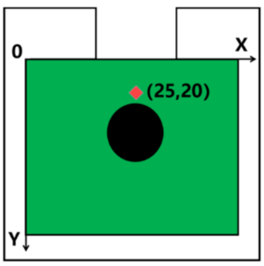
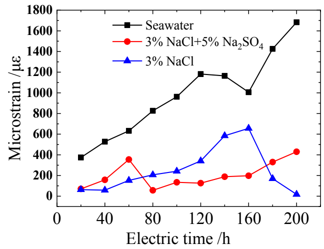


Figure 4: The strain field on the side of reinforced concrete changes with time

According to Figure 5, the strain variation of upper side reinforcement (x=25 mm, y= 20 mm) of the three specimens is shown in Figure 5. Figure 5(b) shows that the reinforced concrete specimens under the action of seawater and 3% NaCl solution gradually increase the lateral strain at first stage due to the corrosion expansion stress. At 120 h, the specimen subjected to seawater show a small degree of stress unloading phenomenon, indicating that the cracks spread to the concrete surface, so the corrosion products overflow with the corrosive solution, and a significant sudden increasing occurs at 160h. After that the strain show increases till the end of the experiment, indicating that the corrosion effect of seawater on steel bars is continuous, and the incremental volume of corrosion products are much larger than the volume of overflow, resulting in more and more obvious cracks on the concrete surface and increasing the crack width. For the specimen under the action of 3% NaCl solution, although the growth trend of the strain curve is consistent with that of seawater at first, the micro-strain value is much smaller than that of the seawater, which further confirms that the influence of seawater on steel corrosion is more serious. At 160 h, the specimen also appears obvious stress unloading phenomenon due to the pitting corrosion of chloride ions, which indicates that the volume of corrosion products is much smaller than the volume of corrosion products under seawater. For the specimen corroded by 3%NaCl+5%Na_2SO_4 composite solution, during the whole experimental time, although there is a certain trend of micro-strain variation, the micro-strain value is relatively small, and the maximum micro-strain value is 300 με, which cannot reach the ultimate tensile strength of concrete. The above results further illustrate that seawater has the greatest effect on the corrosion of steel bars in concrete, while sulfate ions can inhibit the corrosion of steel bars by chloride ions.





(a) Schematic diagram **(b) Micro-strain contrast diagram**

Fig. 5 Comparison of the points on the side of reinforced concrete

4. CONCLUSIONS

(1) The strain gauge inside the steel bar can effectively monitor the variation of the steel corrosion expansion stress with time. Besides, the DIC technology can realize the real-time monitoring of the reinforced concrete surface strain field and the cracking process.
(2) Through the method of full-field strain monitoring combining DIC technology and hollow steel bar strain gauges, the real-time monitoring of the internal and external reinforced concrete specimens can be effectively carried out to estimate the corrosion expansion stress caused by reinforcement corrosion of concrete specimens. In addition, it can also catch the damage form and evolution process of cracking.
(3) The effect of different types of corrosive solutions on the corrosion rate of steel in concrete is seawater > 3% NaCl solution > 3%NaCl+5%Na_2SO_4 composite solution. Moreover, the single chloride salt solution causes obvious pitting corrosion phenomenon of the steel bars. The seawater containing multiple ions causes the large-area continuous corrosion reaction of the steel bars, and the presence of sulfate ions can mitigate the corrosion of the steel bars caused by the chloride salts to some extent.

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