Interaction between compressive load and corrosive-ion attack on reinforced concrete with accelerated potentiostatic corrosion

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Abstract: The corrosive-cracking behavior of two types of reinforced concrete accelerated by a potentiostat and sustained compressive load was studied. The corrosion-rate function of steel bar in reinforced concrete based on electric-current evolution and the critical-cracking model of reinforced concrete considering the compressive load influence parameter were established. Subsequently, the interaction effects among compressive load, corrosion solutions, and materials on the corrosive cracking of reinforced concrete were proposed. The microstructures of corroded steel bar in seawater and compound solution were observed by SEM. Results showed that under the accelerated potentiostatic condition, there was interaction effect between compressive load and corrosive-ion attack on reinforced concrete. The compressive load had a threshold value for corrosion rate of steel bar and could increase the lateral tensile strength of reinforced concrete. Seawater and compound solution(1% NaCl+0.5% MgSO₄) could result in the increment of the critical compressive load, and decrease the lateral tensile strength of reinforced concrete.

Keywords: reinforced concrete; potentiostat; compressive load; interaction effect

1. INTRODUCTION

Reinforced-concrete corrosion has been widely studied for more than 100 years[1]. In the USA, the cost of corrosion accounts for 2% to 5% of the national GDP [2-3]. Given that reinforced concrete are used in marine and saline soils area, chloride and sulfate ions would penetrate into the concrete cover and induce the depassivation and corrosion of the steel bar [4-5], which could result in corrosive cracking and carrying capacity loss, and ultimately damage the concrete structures [6-7]. Practical concrete structures, such as concrete column and beam, are usually subjected to attack of load and multiple corrosive ions. Significant effect of flexural loading on the deterioration of concrete under combined actions of sulfate attack, drying-wetting cycles, especially when the flexural loading exceeds

40% of the maximum flexural load[8]. And the frost resistance performance deterioration in the concrete subjected to third point bending load was significantly accelerated[9]. Meanwhile, Stress corrosion is an interaction between the ammonium sulfate chemical and mechanical attacks, And the mechanical effect would be increased by reducing the concentration of the solutions or by increasing the load level[10]. Experimental results from 26-year-old corroded RC beam under attack of 80% of failure load shown that corrosion cracks were more developed in the tensile surface. And the corrosion of reinforcement changes the failure mode from yielding followed by concrete crushing for control beam to brittle failure of corroded tension bars which strongly reduced the ductility of the corroded beam[11]. Accelerated corrosion results from Hariche[12] shown that the deflections of beams increased with progressive corrosion of the reinforcement under simultaneous bending load and accelerated corrosion. An increase in the ratio of applied load to the ultimate load increased the drop in the flexural capacity. And experimental results from Du[13] also indicated that concrete beam would fail and collapse without significant warning of signs. Pre-loading induced cracks on concrete specimens, despite these surface cracks ranging between 0.02 and 0.06mm, the time to corrosion initiation tended to be shorter[14]. And the sustained flexural load could increase the corrosion rate of steel bar in ordinary performance concrete (OPC) specimens and reduce the time to corrosion-induced crack of concrete cover in short-term exposure. But the concrete materials would increase or decrease the effect of flexural load on the corrosion behavior of the steel bar[15].

When concrete subjected to the compressive load and corrosion, the application of loads up to 90% of the ultimate strength had little effect on the chloride permeability[16]. But a uniaxial compressive load at 90% of the ultimate strength can increase the axial permeability by about one order of magnitude after unloading[17]. When the compressive load is in excess of the threshold value (0.8–0.95 of the peak load), chloride ions would penetrate into concrete rapidly [18]. And the progress of sulfate attack on concrete was accelerated by high sustained compressive stress (0.65R) whereas it is retarded by the low one (0.275R) [19]. Feng [20-21] studied the degradation of passive film on carbon steel in concrete pore solution under tensile and compressive stresses indicated that compressive stress induces de-bonding of the interface between the passive film and the substrate. And compressive stress produces more severe degradation of the passive film than does the tensile stress. Further experiment about the corrosion behaviour of the rebar in mortars subjected to flexural stresses and be maintained in the solutions of 3.0% (wt.%) sodium chloride shown that the corrosion of the rebar increases with

increasing magnitude of the stress, and the rebar in the compressive stress region was more severely corroded than that in the tensile stress region due to de-bonding zones formed in the mortar/rebar interface subjected to compressive stresses. Obviously, the magnitude and course of uniaxial and triaxial compressive loading would also affect the immigration of water, gas, and ions into the concrete. Further research is needed to determine the quantitative influence of compressive loading on corrosion of steel bar in concrete.

Given that reinforced concrete columns in marine and saline soil environments are subjected to attack of compressive load coupled with corrosive ions, this study assessed the corrosion behavior of two series of reinforced concretes under simultaneous compressive load and corrosion environments, including seawater, compound solution, and tap water. The interaction influence between compressive load and corrosive ions on the corrosion behavior of steel bar, which could induce the crack of reinforced concrete, was elaborated systematically. Given that the natural process of ions entering into concrete and inducing rebar corrosion is long [22-23], the constant potentiostatic accelerated method was employed to obtain the damage process of reinforced concrete quickly[24]. This work is significant for corrosion control and durability design of reinforced concrete columns in saline soil environment and coastal areas.

2. EXPERIMENTATION

2.1. Materials and specimen preparation

P.I.52.5 Portland cement in accordance with Chinese standard GB175-2007, with a compressive strength of 59.8 MPa at an age of 28 days, was used in this study. Class I fly ash (as per Chinese standard GB1596-2005) and S95 GGBS (Chinese standard GB/T18046-2008) were employed to replace Portland cement. The chemical composition of cement, fly ash, and GGBS is shown in Table 1.

Crushed granite with a maximum size of 25 mm was used as coarse aggregate, whereas river sand with fineness modulus of 2.6 was used as fine aggregate. A polycarboxylic super plasticizer was used, and its dosage was adjusted to keep the slump of fresh concrete in the range of 140 mm to 180 mm. The concrete mixtures were prepared with an effective water-to-cement ratio (w/c) of 0.34 and total binder content of 450 kg/m³. Based on considerable trials and durability tests, high content mineral admixtures including GGBS and Fly ash could improve the workability of fresh concrete, chloride bound capacity and crack resistance capacity of harden concrete. Therefore, the optimized mixture proportion C50FS mixed with about 31% GGBS and 18% fly ash and with w/c=0.33 was

identified and had used in lining concrete structure of Qingdao Underground. The influence of high content mineral admixture on corrosion of steel bar in concrete may be occurred, the comparative concrete C50 with the same w/c and total cement content as C50FS was prepared. Considering the corrosion of reinforced concrete in marine environment and saline soil in the Northwest of China was mainly induced by sea water, and compound solution, respectively. The mixing water included tap water, sea water, and compound solution (1% NaCl+0.5% MgSO₄ by weight of mixing water) was used to simulated corrosion environment. The composition of sea water from Qingdao was shown in Table 2, and the mixture proportions of the concretes are given in Table 3. Twenty-seven reinforced concrete specimens for each mix proportion were cast as a square section prisms section (100 mm×100 mm×300 mm). The longitudinal reinforcements were made of two bars (10 mm diameter round carbon-steel bars at the left with an effective cover of 25 mm and 8mm diameter stainless steel bar at the right with an effective cover of 20 mm). The carbon-steel bar was cleaned and coated with cement paste, followed by epoxy coating at the concrete-air interface. The surface of the round carbon-steel bar was polished with 200# sand paper. The steel bars were degreased with acetone prior to being placed in the mold; the effective exposure length of the steel bar was 250 mm. Reinforced concrete samples were cast and placed at room temperature in the mold, which were removed after 48 h. All specimens were cured at 20±3 °C and 95% relative humidity for 28 days.

2.2 Accelerated corrosion of reinforced concrete under sustained compressive load

For reinforced concrete molding, the mixing water containing tap water, sea water, and compound solution (1% NaCl+0.5% MgSO₄ by weight of mixing water) was used to accelerate corrosion of steel bar in reinforced concrete. The compressive strength of concrete mixed with different solutions was tested. The value of C50 mixing with tap water, sea water and composite solution was 59.8, 61.4 and 63.5MPa. And the compressive strength of C50FS mixing with sea water and composite solution was 62.5 and 68.8MPa, respectively. According to the load level, the compressive stress was determined. Then the reinforced concrete was placed under the reaction frame, the sustained compressive stress was applied through a jack, onto the steel plate placed on the top of the reinforced concrete specimens Two sets of nut on the threaded rods that passed through a movable plate were tightened when the magnitude of the load was achieved, and then the jack was removed, as shown in Fig.1(a).The load level (as a fraction of ultimate compressive load) [25] was 0, 40%, and 85%.

Each series of three beams were prepared for test. The reinforced concrete under sustained compressive load was subjected to accelerated corrosion current supplied by potentiostatic through carbon-steel bar (connected to the positive electrode) and stainless steel bar (connected to the negative electrode)[24]. The electric potential was kept constant at 30 V. The current was continuing determined every 1 to 2 h during day time, and every 8 h to 10 h at night. Concrete surface was observed constantly by video camera. When the initial crack on the surface of concrete specimens was observed, the crack width was tested by crack width measuring instrument every four hours until the width was near 0.2mm. The entire duration of accelerated corrosion test was conducted from 100 to 400 hours according to different series. A diagram of the test is shown in Fig. 1.

2.3 Surface characterization

The surface morphologies of the steel bar were visually observed, and its microstructure was analyzed by scanning electron microscopy (SEM, KYKY-2800B).

3. RESULTS AND DISCUSSION

3.1 Electric current

Concrete specimens under sustained compressive load were polarized by a constant voltage of 30 V, and the current change with time is shown in Figs. 2 and 3. The electric current decreased fast at the early stage, but slowed as the concrete cracked. There were two reasons for this, the first was that the water transportation from inner to the outer under electric field would reduce the concrete humidity, the second was that the rust layer on the surface of steel bar fulfilled the concrete matrix, which in turn increased the electric resistance. Additionally, high concentration of corrosive ions in seawater caused the value of electric current was the highest, and that of concrete mixed with compound solution was the second.

Given that the voltage between carbon-steel bar and stainless steel bar was 30 V, the electric resistance could be calculated based on the current evolution. The initial resistance of reinforced concrete under sustained compressive load is shown in Fig. 4. The initial resistance of reinforced concrete mixed with seawater was less than that with other solutions. This result could be attributed to two aspects. The first was that the concentration of Cl^- in seawater was 17533.33mg/L, and that in compound solution was 6173.91mg/L, the chloride content in sea water was 2.4 times of that in compound solution, which resulted in the increment of the conductivity of concrete mixed with seawater. The second was that MgSO_4 could react with hydrated cement and produce ettringite, brucite

and thaumasite and induce the decalcification of C-S-H [26]. Due the curing and testing period was only 33-48d, expansive corrosion products would compact the microstructure of concrete and the degeneracy effect induced by decalcification of CSH could be ignored in short term. Only 2176 mg/L SO_4^{2-} was observed in seawater, whereas 4000 mg/L for the compound solution; hence, the compactness of the concrete mixed with seawater was lower than that with compound solution.

When concrete was mixed with tap water and seawater, the influence of compressive load on the initial resistance of concrete was that the resistance increased when the load level was 40% and decreased when the load level was 85%. These findings may be attributed to the fact that the concrete was at the compactness state if subjected to lower compressive load, whereas micro cracks appeared inside the concrete when the compressive load exceeded the critical stress value [18].

However, when concrete was mixed with compound solution, the initial resistance still increased when the compressive load level was 85%, indicating that the compound solution could improve the threshold value of the compressive load. The compounds produced by MgSO_4 with hydrated cement, such as ettringite, brucite and thaumasite, could self-heal the concrete micro cracks produced by compressive load in early stage to improve the compactness of the concrete, and then result in constant increment of the resistance.

The electric resistance evolution of reinforced concrete under the potentiostatic accelerated corrosion was obtained, as shown in Figs. 5 and 6. The relationship between ' $R(t)$ ' and corrosion time ' t ' can be regressed by the exponential function as follows:

$$R(t) = R(0) \times \exp(at) \quad (1)$$

Where $R(t)$ is the electric resistance of reinforced concrete at t time, $R(0)$ is the electric resistance of reinforced concrete at the initial time, t is the corrosion time, and a is the regression coefficient.

The electric resistance between carbon-steel bar and stainless steel bar increased with the aggravation of corrosion process as shown in Figs. 5 and 6. This increase may be attributed two reasons: first, the water transportation from the inner to the outer parts along the carbon-steel bar reduced the concrete humidity; second, the rust layer on the steel-bar surface fulfilled the concrete matrix[27], which in turn increased the electric resistance.

3.2 Corrosion rate of steel bar in reinforced concrete

The amount of corrosion products is related to the electrical energy consumed, which is a function

of voltage, amperage, and corrosion time interval [28]. The quantity of charge applied for any given electrolysis is given by the product of time (s) and current (A). For the corrosion process, for each mol of iron that oxidizes, 2 mol of electrons are given out, consuming a charge of 2×96.487 coulomb. The mass loss is then calculated by multiplying the applied charge by the molar mass (55.847 g/mol for iron) and dividing by the charge needed per mole. The amount of corrosion products can be estimated from Eq. (2).

$$\Delta w = \frac{t \times i \times 55.847}{2 \times 96.487} \quad (2)$$

The relationship between electrical current and corrosion time in Figs. 2 and 3 can be regressed by the exponential function as follows:

$$i_t = i_0 \times \exp(at) \quad (3)$$

Where, $\Delta w(g)$ is the mass loss, t (s) is the corrosion time, i_t (A) is the electric current of the reinforced concrete at t time, i_0 is the electric current of reinforced concrete at the initial time, and a is the regression coefficient.

Based on the experimental results, the electric current fitting functions of reinforced concretes under sustained compressive load are shown in Table 4, all the corresponding correlation coefficients of the fitting equations are larger than 0.95.

According to Eqs. (2) and (3), weight loss of steel corrosion in concrete was calculated by integration, the amount of corrosion products can be estimated as follows:

$$\Delta w = \int_0^t \frac{i_0 \times \exp(-at) \times 10^{-3} \times 3600 \times 55.847}{2 \times 96487} dt = \int_0^t 0.001042 \times i_0 \times \exp(-at) dt = \frac{0.00142 i_0}{a} (1 - \exp(-at)) \quad (4)$$

The corrosion rate of steel bar in reinforced concrete can be calculated as follows:

$$\rho = \frac{\Delta w}{w_0} = \frac{\Delta w}{\pi \times r^2 \times l \times \rho} = \frac{0.00142 i_0 \times (1 - \exp(-at))}{a \times 3.14 \times 5^2 \times 250 \times 7.8 \times 10^{-3}} \times 100\% \quad (5)$$

where ρ (%) is the corrosion rate of the steel bar, w_0 (g) is the initial mass of the steel bar. The initial mass of the steel bar w_0 is the product of its own density and exposed volume. The steel bar has a diameter of 10 mm, with an exposure length of 250 mm. The density of steel bar is 7.8×10^{-3} g/mm³.

When the reinforced concrete was subjected to accelerated corrosion for 30 h, the corrosion rate

(ρ_{load}) of the steel bar subjected to sustained compressive load could be calculated by Eq. (5), and the impact parameter of load level on the corrosion rate (ρ_{load} / ρ_0) could also be obtained; the results are listed in Table 5.

For the same load level, the corrosion rate of steel bar in reinforced concrete mixed with different solutions had the following order: seawater > compound solution > tap water. The influence of compressive load on the corrosion rate of steel bar was that the corrosion rate of steel bar in concrete decreased when the load level is small. Meanwhile, the corrosion rate of steel bar increased when the load level exceeded threshold value. For the threshold value of the compressive load level, the corrosion rate of steel bar in concrete subjected to compressive load was equal to that of the unloaded control specimens [25]. For example, when the C50 reinforced concrete was mixed with tap water, the load level changed from 40% to 85% and the corrosion rate of steel bar increased by 65%. The increment of corrosion rate for seawater was 38%, whereas that for compound solution decreased by 10%.

Supposed that the steel bar in reinforced concrete was subjected to 100% compressive load, the corrosion rate was 2 times that of the unloaded control specimens. The quadratic function could be used to fit the experiment results as follows:

$$\rho_{load} / \rho_0 = 1 + a * S + b * S^2 \quad (6)$$

Where ρ_{load} and ρ_0 are the corrosion rate of the steel bar in concrete subjected to compressive load and unload, respectively; S is load level, a and b are the regression parameters.

Definition was that the critical load value of the corrosion of steel bar in concrete was the corresponding load as the corrosion rate of loaded concrete was equal to the unloaded one. Based on Eq.(6), the critical load could be obtained as the compressive load ratio was zero and the corrosion rate of steel was equal. The threshold values of compressive load level for C50 concrete mixed with tap water, seawater, and compound solution are 0.59, 0.72, and 0.82, respectively. But experiment results from C.C. Lim[18] shown that the threshold value of the compressive load was 0.8-0.95 of the peak strength in terms of chloride diffusivity. For natural exposed concrete, the influence factors of steel bar corrosion in reinforced concrete was mainly determined by corrosive ions, water and oxygen. But in this test, the corrosive ions were introduced through the concrete forming

process mixed with salt solution, so, the penetration rate of oxygen was the determinants of corrosion of steel bar in concrete.

The results of Teggner[28] indicated that compressive load at 30%fc to 60%fc, the bond cracks increase in length, width and number as the load increases. For loads above 60%fc, the maximal strain $\epsilon_{\max}$ and residual strain $\epsilon_{\text{rés}}$ increase with increasing load. The relative gas permeability $k_{v(d)}/k_{v0}$ increases with the damage coefficient. And the $k_{v(d)}/k_{v0}$ tended to increase slightly beyond the damage coefficient of 0.03 corresponds to the load level be 70% for both concretes. Meanwhile, the gas permeability changes very significantly with the increase of damage level, while chloride penetration is much less affected by cracks. Therefore, the threshold values of compressive load level for concrete mixed corrosive solutions were lower than that reported by C.C.Lim. Moreover, the gas permeability and chloride diffusion of concrete all used the unloading concrete specimens; the parts of micro cracks would be closed after unloading. In this corrosion test, the reinforced concrete under sustained compressive load was subjected to accelerated corrosion, the micro cracks induced by compressive load couldn't closed. So, the critical compressive load level would be lower that reported by Teggner.

These results indicated that seawater and compound solution increased the threshold value of compressive load compared with tap water. That is, the critical load leading to the penetration of chloride ions is higher than that of the accelerated gas penetration. In this paper, the corrosive ions was introduced by added salt and cured for 28 days. Comparing to the concrete mixed water, MgSO_4 in compound salt solution would compact the concrete structure at an early stage. a small amount of sulfate ion in seawater will also improve the density of the concrete. Therefore, the external air penetrated the most easily into the concrete mixing with tap water, the second is into the concrete with seawater, the most difficult is the concrete with compound salt solution. Therefore, the order of the critical load of concrete was tap water < seawater < compound salt solution. To illustrate the problem, the detail explained was added in the article. Therefore, both seawater and compound solution reduced the influence degree induced by compressive load on the corrosion rate of steel bar.

3.3 Crack of reinforced concrete

According to Jin's report [30], the expansion pressure induced by uniform corrosion of steel bar can be calculated as follows:

$$q = \frac{\left(\left[\sqrt{(n-1) \times \rho + 1} - 1 \right] \times R \right)^{-0.049n^2 + 0.4n + 0.9546}}{\frac{(1+u_1) \times R \times C^2 + (1-u_1) \times R^3}{E_1 \times (C^2 - R^2)} + \frac{n \times \rho \times R}{140 \times \exp(-0.33n) \times (1.924n\rho + 2 - 2\rho)}} \quad (7)$$

where n is the ratio between the volumes of corrosion products and its basic steel, ρ is corrosion rate of steel bar, u_1 is Poisson's ratio of concrete, E_1 is elastic modulus of concrete (MPa), C is the thickness of concrete cover (mm), R is the radius of steel bar (mm).

The critical expansion pressure resulted in crack of reinforced concrete can be expressed by Eq.(8)

$$f_{crack} = 0.3 + 0.6 \times \frac{C}{2R} \times f_{tk} \quad (8)$$

where f_{crack} is the critical expansion pressure (MPa), f_{tk} is the tensile strength of the concrete (MPa), C is the thickness of concrete cover (mm), and R is the radius of the steel bar (mm).

The influence of corrosion solution and compressive load on corrosion expansion pressure can be reflected by 'n' and ' ρ ' parameters. In addition, When the concrete column was pressed, the transverse deformation was produced, which would cause the tensile stress at the concrete side, and the micro cracks appeared. The micro cracks would not be closed if the axial compressive load of concrete existed for a long time, which could lead to the decrease of the lateral tensile strength of concrete. Herein, a damage variable D_{load} is defined to characterize the effect of axial load on the lateral tensile strength of concrete. That is

$$f_{tk} = f_{tk0} \times (1 - D_{load}) \quad (9)$$

Where, f_{tk} is the lateral tensile strength under the influence of axial compressive load, f_{tk0} is the initial tensile strength of concrete, and D_{load} is the damage variable caused by axial load.

Therefore, Eq.(9) was introduced into Eq. (8), the critical crack press of concrete under axial compress load was proposed as follows:

$$f_{crack} = 0.3 + 0.6 \times \frac{C}{2R} \times f_{tk0} \times (1 - D_{load}) \quad (10)$$

Thus, the critical crack model of reinforced concrete under compressive load can be expressed as

Eq.11.

$$q = \frac{\left(\left(\sqrt{(n-1) \times \rho + 1} - 1 \right) \times R \right)^{-0.049n^2 + 0.4n + 0.9546}}{\frac{(1+u_1) \times R \times C^2 + (1-u_1) \times R^3}{E_1 \times (C^2 - R^2)} + \frac{n \times \rho \times R}{140 \times \exp(-0.33n) \times (1.924n\rho + 2 - 2\rho)}} = 0.3 + 0.6 \times \frac{C}{2R} \times f_{tk0} \times (1 - D_{load}) \quad (11)$$

The time of crack initiation and achieving maximum crack width of 0.2 mm was tested and plotted in Figs. 7 and 8. The initial cracking time of reinforced concrete mixed with seawater was the shortest under all compressive load levels.

According to properties of reinforced concrete, the values of variables in Eq. (10) are taken as: $C=25$ mm and $d=10$ mm. And the mechanical properties of C50 reinforced concrete were tested and shown as following: $u_1=0.25$, $E_1=30\ 000$ MPa, and $f_{tk}=2.5$ MPa. And that of C50FS reinforced concrete was also tested and listed as follows: $u_1=0.2$, $E_1=25\ 000$ MPa, and $f_{tk}=1.8$ MPa. The initial crack time of reinforced concrete was introduced into Eq. (10), where ‘ n ’ can be calculated. The calculated values of ‘ n ’ were 2.1, 5.75–5.85, and 4.2–5.4 for reinforced concrete mixed with tap water, seawater and compound solution, respectively. These results indicated that the expansion rate of rusts growing in concrete mixed with seawater was the maximum, while with tap water, it was the minimum.

D_{load} was calculated and plotted in Fig. 9. Obviously, the value of ‘ D_{load} ’ increased with increment of compressive load level. This result can be attributed to the fact that compressive load imposed on vertical plate (100×300 mm²) of specimens would result in deformation of lateral plate (100×100 mm²), which would lead to tensile pressure imposed on the lateral plate of concrete specimens. Therefore, the tensile strength of reinforced concrete in lateral plate would be decreased, and result in the increment of D_{load} with compressive load level.

The D_{load} of reinforced concrete mixing with seawater and compound solution was higher than that mixing with tap water. The reason could be explained as following, reinforced concrete mixing with seawater and compound solution would generate larger corrosion rate of the steel bar than tap water. The expansion pressure induced by corrosion of steel bar in concrete mixed with seawater and compound solution was larger than that with tap water. Thus, the damage of lateral direction of reinforced concrete mixing with sea water and compound solution was more serious than that with tap water, which resulted to different value of D_{load} of reinforced concrete mixing with different solution.

In addition, the D_{load} of C50FS mixed with compound solution was lower than that of C50, indicating that the effect of compressive load on tensile strength of C50FS was less than that of C50.

3.4 Surface morphologies

The images of the corroded steel bar were obtained from reinforced concretes; their surface corrosion area rate was calculated and shown in Fig. 10. The rust spots of corroded steel bar from reinforced concretes mixed with seawater and composite water were recorded on parchment paper, and the area was counted. The surface corrosion area rate of the steel bar in 250 mm length range from the top to the bottom of concrete specimens could be gained as follows:

$$\gamma = \frac{S_{rust}}{S_0} * 100\% \quad (12)$$

where γ is the surface corrosion area rate of the steel bar (%), S_{rust} is the surface corrosion area in 250 mm length range (mm^2), and S_0 is the surface area in 250 mm length range (mm^2).

As shown in Fig.10, the corrosion products were thin and uniform as the reinforced concrete mixed with tap water. SEM images and EDS of the corroded steel bar with rusts obtained from the reinforced concrete mixed with seawater and compound solution are shown in Figs. 11 and 12. The corrosion products were compact and massive as the concrete mixed with seawater; corrosion induced cracks can be observed on the steel bar. Meanwhile, the corrosion products became soft, uniform, and small as concrete mixed with the compound solution. The rusts induced by seawater were thicker than that by compound solution. Moreover, the amount of rust spots at the top and the bottom of steel bar were fewer than that in the middle of the steel bar. The results proved that the existence of MgSO_4 could lighten the expansion pressure caused by corrosion products.

4. CONCLUSIONS

The corrosion process of steel bar and it induced crack of concretes mixing with tap water, sea water and compound solution under sustained compressive load was tested and presented in the current study. By comparing the corrosion rate of steel bar and initial crack time of concrete, it became evident that corrosive cracking behavior of reinforced concrete influenced by compressive load level, corrosion solution and materials. To quantitative analyze these results, the quadratic function relationship between compressive load level and corrosion rate of steel bar, and the critical crack model of reinforced concrete under sustained compressive load were proposed. To further clarify the influence of

corrosion solutions on corrosive cracking behavior of reinforced concrete, microstructure of corroded steel bar was observed by SEM. Overall, based on the experimental results and research findings as it was described in this paper, it can be concluded that:

- When reinforced concrete was subjected to potentiostatic accelerated corrosion, the electric current decreased fast at the early stage, but slowed as the concrete cracked.

- The initial electric resistance and initial cracking time of reinforced concrete mixed with seawater was the minimum, whereas that with tap water was the maximum.

- Compressive load could simultaneously affect the corrosion rate of steel bar and the lateral tensile strength of concrete.

- Seawater and compound solution increase the critical compressive load level for corrosion rate of steel bar in reinforced concrete, but increase the negative effect generated by compressive load on the reduction of tensile strength of reinforced concrete.

- The corrosion products were thin and uniform when concrete was mixed with tap water. The rusts were compact and massive for the concrete mixed with seawater and compound solution. C50FS concrete containing larger amount of GGBS and fly ash would lead to reduction of the negative effect of compressive load and corrosion solution on corrosion of reinforced concrete.

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Table 1 Chemical composition of cement, fly ash and GGBS

Constituent	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	TiO ₂	Na ₂ O	K ₂ O	SO ₃	Cl
(wt%)										
Cement	21.8	5.42	3.44	66.01	1.26	0.36	0.57	0.33	0.66	0.00
GGBS	0.37	32.87	13.40	1.34	41.06	5.64	0.45	0.54	2.68	0.01
Fly ash	2.04	51.28	32	4.23	3.76	0.75	1.02	0.38	2.5	0.02

Table 2 Composition of sea water

Constituent	mg/l							pH
	NO ₃ ⁻	HCO ₃ ⁻	SO ₄ ²⁻	Cl ⁻	NH ₄ ⁺	Ca ²⁺	Mg ²⁺	6.90
Sea water	12.76	161.29	2176.12	17533.33	<0.04	407.83	1177.38	6.98

Table 3 Mix proportions of concretes

No.	kg • m ⁻³					
	Cement	GGBS	Fly ash	Sand	Aggregate	Water
C50	450	0	0	711	1067	155
C50FS	230	140	80	711	1067	155

Table 4 Electric current fitting functions of two types of reinforced concretes mixed with different solutions

Load level	0	40%	85%
C50/Tap water	$i_t = 54 \times \exp(-0.0012t)$	$i_t = 42 \times \exp(-0.0061t)$	$i_t = 82 \times \exp(-0.013t)$
C50/Sea water	$i_t = 117 \times \exp(-0.017t)$	$i_t = 84 \times \exp(-0.014t)$	$i_t = 146 \times \exp(-0.026t)$
C50/Compound solution	$i_t = 118 \times \exp(-0.022t)$	$i_t = 80 \times \exp(-0.015t)$	$i_t = 69 \times \exp(-0.013t)$
C50FS /Sea water	$i_t = 22 \times \exp(-0.0058t)$	$i_t = 10 \times \exp(-0.0037t)$	$i_t = 13 \times \exp(-0.0034t)$
C50FS/Compound solution	$i_t = 13 \times \exp(-0.0046t)$	$i_t = 10 \times \exp(-0.0049t)$	$i_t = 9 \times \exp(-0.0044t)$

Table 5 ρ_{load} and ρ_{load} / ρ_0 of reinforced concrete subjected to accelerated corrosion for 30 hours

Type of concretes	C50			C50FS	
Load level	Tap water	Sea water	Compound solution	Sea water	Compound solution
ρ_{load}	0	0.93	1.86	1.78	0.42
	40%	0.78	1.31	1.27	0.18
	85%	1.38	2.02	1.13	0.24
ρ_{load} / ρ_0	0	1	1	1	1
	40%	0.84	0.70	0.70	0.43
	85%	1.48	1.09	0.61	0.57

Fig. 1 Potentiostatic accelerated corrosion of reinforced concrete under sustained compressive load

Fig. 2 Electric current evolution of C50 concrete at different stress rate.

(a) tap water, (b) seawater, (c) compound solution.

Fig. 3 Electric current evolution of C50FS concrete by accelerated corrosion.

(a)seawater, (b)compound solution.

Fig. 4 Initial electric resistance of different reinforced concretes. (a)C50, (b) C50FS

Fig. 5 Electric resistance evolution of C50 reinforced concrete under compressive load.

(a) tap water, (b) compound solution

Fig. 6 Electric resistance evolution of C50FS reinforced concrete under compressive load.

(a) seawater, (b) compound solution

Fig. 7 Time of crack initiation and reaching the maximum crack width of 0.2 mm of C50 reinforced

concrete.(a) tap water, (b) seawater, (c) compound solution.

Fig. 8 Time of crack initiation and reaching the maximum crack width of 0.2 mm of C50FS concrete.

(a) seawater, (b) compound solution

Fig. 9 Calculated load effect coefficient ' D_{load} '. (a) C50; (b) C50FS

(a) Rusts on the steel bar

(b) Surface corrosion rate of the steel bar

Fig. 10 Surface rust spot rate of the steel bar subjected to accelerated corrosion.

(a) (300×)

(b) (600×)

Fig.11 Corrosion of steel bar in concrete mixed with seawater

(a) (300×)

(b) (600×)

Fig. 12 Corrosion of steel bar in concrete mixed with compound solution