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

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HIGHLIGHTS

- Corrosive cracking of reinforced concrete subjected to coupled effects was studied.
- The critical compressive load level for the corrosion rate of steel bar was given.
- The coupled effect of corrosion solution and compressive load was analyzed.
- The order of corrosive action induced by corrosion solutions was obtained.

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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% $MgSO_4$) could result in the increment of the critical compressive load, and decrease the lateral tensile strength of reinforced concrete.

1. Introduction

Reinforced-concrete corrosion has been widely studied for more than 100 years [1]. In the USA, the cost of corrosion accounts for 2–5% 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

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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 0.06 mm, 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 tresses 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 behavior 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 140–180 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/m^3. 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 been 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% $MgSO_4$ 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 8 mm 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% $MgSO_4$ 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 63.5 MPa. And the compressive strength of C50FS mixing with sea water and composite solution was 62.5 and 68.8 MPa, 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 1–2 h during day time, and every 8–10 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 4 h until the width was near 0.2 mm. The entire duration of accelerated corrosion test was conducted from 100 to 400 h 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