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Chloride diffusivity and service life prediction of RC columns with sustained load under chloride environment

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HIGHLIGHTS

- Synthetic effects of crack width and tension strain are experimentally studied.
- Service life prediction model of one and two dimensional states are proposed.
- Crack has more adverse effect than tension strain when width is more than 0.07 mm.

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ABSTRACT

The synthetic effects of crack width and environment actions on chloride diffusivity of reinforced concrete (RC) columns were experimentally studied after the alternative action of 300 cycles of freeze-thaw and 75 times of seawater immersion. Cracks and tension strain of concrete were induced by eccentric compression load which was sustained till the alternative action finished. The experimental results show that, when the crack width was less than 0.07 mm, the effect of cracks on chloride diffusivity was slight and it could be neglected. When the crack width was more than 0.07 mm, cracks accelerated the chloride diffusivity and the synthetic effects of crack and environment on chloride diffusivity was bigger than tension strain. Furthermore, chloride diffusion in one-dimensional and two-dimensional state was respectively considered. And the corresponding service life of RC columns were predicted by Monte-Carlo Method. It was concluded that crack width significantly expedited chloride diffusivity and shortened the service life of RC structures in cold coastal regions or deicing condition.

1. Introduction

Chloride ion ingress significantly affects the durability of RC structures in coastal environment or deicing conditions [1], and concrete structures in these environments normally work with cracks and tension strain in actual service condition.

Existing studies have proved that cracks accelerate chloride penetration in coastal environment or dicing conditions. Şahmaran [2] experimentally studied the effect of flexural crack widths on chloride diffusivity. The cracked RC beams were immersed in NaCl solution for 30d. Results showed that, when crack width was between 0.0294 mm to 0.1029 mm, effective chloride diffusion coefficient was almost the same. And when crack width was larger than 0.135 mm, the chloride diffusion coefficient increased sharply. Li [3] simulated tidal and splash zones by spraying NaCl solution (3.5% by weight) to the specimens with initial crack widths of 0.05, 0.1 and 0.2 mm, respectively and these cracks were induced by loading. It was found that when crack width was less than 0.1 mm, cracks had few effect on chloride penetration and when crack width was larger than 0.1 mm, chloride penetration was significantly accelerated. Wang et al. [4] investigated the influence of crack density, orientation, tortuosity and width on chloride penetration. Nine different levels of uniaxial compressive loads (0%, 30%, 40%, 50%, 60%, 70%, 75%, 80% and 85% of the compressive strength of the concrete) were applied to generate cracks and an external electrical potential of 30 ± 0.2 V was applied across the specimen to force the chloride ions from the 10% NaCl solution to penetrate into the concrete. The results of chloride penetration showed that, when the crack width was between 0.1 mm and 0.4 mm, the chloride diffusivity through concrete cracks increased rapidly and the chloride penetration in concrete increased apparently with the crack tortuosity when the crack width was between 0.15 mm and 0.37 mm.

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Alkam [5] developed a transient, two-dimensional simulation of chloride diffusion into a concrete column and predicted the service life of a reinforced concrete column exposed to severe chloride environment. It was concluded that regions closed to the corners of the column cross section were more susceptible to chloride ion penetration than regions far from the corners. However, the effect of loadings and strain on chloride diffusion coefficient were not taken into account in their study.

Under the action of service load, tension strain also exists in concrete, which accelerate the chloride diffusion. Wang et al. [6] immersed fatigue loading damaged beams in 3%NaCl + 0.34% $MgSO_4$ solution for 8 h, and then these specimens were dried in atmosphere for 16 h. After 100 cycles, the chloride diffusivity in tension and compression concrete was investigated. It was clearly observed that apparent chloride diffusion coefficient of tension concrete was higher than that of compression concrete when the upper limit of fatigue load was 0.2 Pu (Pu is the static ultimate capacity of reinforced concrete beam specimens at the age of 90 days). Poupard et al. [7] put the RC beam specimens in tidal zone for 40 years and investigated the steel corrosion in RC beams. Results showed that diameter loss of steel bar was about 30% in tension zone (equivalent to approximately 50% loss of steel bar cross-sectional area) while it was no more than 2% in compression zone, which illustrated that micro-cracking generated by tensile stress aggravated chloride and oxygen penetration causing the steel corrosion. According to these studies, both cracks and tension stress expedite chloride diffusivity and subsequently accelerate corrosion initiation.

The self-healing effect of cracks was observed in some research. Liu et al. [8] exposed the fatigue loading damaged reinforced concrete beams to seawater wet-dry cycles as well as freeze-thaw cycles. The results revealed that three fatigue cracks (initial maximum widths of 0.07 mm, 0.09 mm and 0.10 mm) had been observed before the seawater wet-dry cycles. However, only two cracks could be observed after 100 cycles of seawater wet-dry. This could be attributed to self-healing effect. Şahmaran [2] proved the cause of self-healing was the formation of calcite ($CaCO_3$) by X-ray diffractogram of crack surface.

Based on chloride diffusivity, Monte Carlo Simulation was utilized to evaluate the effect of crack on durability of RC structures. Kwon et al. [9] obtained chloride diffusion coefficient in cracked concrete of wharf from field investigation. Based on the relationship between diffusion coefficients and crack width, service life was predicted in probabilistic framework of Monte Carlo Simulation. The results showed that the service life calculated from probabilistic method ($P_{f\ max}$ = 7% and 10%, and $P_{f\ max}$ is the intended maximum probability of durability failure) are evaluated to be shorter than those obtained from deterministic method. Lu et al. [10] developed a model to predict the diffusion coefficient of chloride ingress into load-induced cracked concrete. Two dimensional chloride diffusion were considered and Monte Carlo Simulation was used to calculate the probability of corrosion initiation. Results demonstrated the importance of considering the effect of the load-induced cracks for prediction service life of RC bridge exposed to chlorides.

For RC structures in cold coastal environment, service load usually generated both cracks and tension strain. But the study of the effect of cracks and tension strain on chloride diffusivity of RC column is lacking in existing literature and consideration of the effect of cracks and tension strain on the service life is fewer. Furthermore, for better simulation of the cold coastal environment, the combined effect of freeze-thaw cycles, seawater immersion and service load need to be considered.

The combined effects of crack width, freeze-thaw cycles, and seawater immersion on RC column specimens were experimentally studied. The alternative action of 300 cycles of freeze-thaw and 75 times seawater immersion were adopted to stimulate cold coastal environment or deicing conditions, and sustained eccentric compression load was applied to induce different crack widths and tension strains on RC columns. The evolution of cracks and tension strains were monitored during the corrosion period (freeze-thaw cycles and seawater immersion). After alternative action of 300 cycles of freeze-thaw and 75 times seawater immersion, the chloride content test was conducted and chloride profile of samples were obtained. The apparent chloride diffusion coefficient was determined by the best curve fit of chloride profile according to the Fick's second law. The effects of cracks and tension strain on chloride diffusivity was analyzed. Furthermore, the Monte-Carlo Method was utilized to predict the service life, based on chloride diffusion under one-dimensional and two-dimensional state. A comparative study of the effect of crack width and tension strain on service life of RC structures was conducted.

2. Experimental details

2.1. Specimens

Five RC column specimens, named as COL-0 to COL-4, with same sizes and same reinforcements were made, where COL-0 was placed in an atmospheric environment as reference and COL-1–COL-4 were exposed to alternative action of 300 cycles of freeze-thaw and 75 times seawater immersion. The reinforcement arrangements and dimensions of RC column specimens are shown in Fig. 1. The rectangular cross-section was 100 mm × 200 mm, and the length of the column specimen was 700 mm. Concrete cover was 30 mm and four plain steel bars with 10 mm diameter were symmetrically placed as longitudinal bars with yield and ultimate strengths of 510 MPa and 825 MPa respectively.

The proportion of concrete mixtures is listed in Table 1. The air content in concrete mixtures was measured with the pressure method in Standard test method for air content of freshly mixed concrete (ASTM C231/C231M). The amount of air content was 5.7%. The curing method adopted in this study was consistent with that in an earlier experiment of Diao et al. [11]. The compression strength of concrete used for RC column specimens was 41 MPa at the concrete age of 28 d.

2.2. Producing cracks on RC column specimens

At the age of 28 d, eccentric compression load was performed on RC column specimens COL-2, COL-3 and COL-4 respectively to induce flexural cracks. The bolts attached to the spiral rebar passing through the brackets at two ends of the column were tightened to apply eccentric compression load on column specimens, as shown in Fig. 2. The loading eccentricity was 130 mm.

The desired widths of flexural cracks of column specimens COL-2 to COL-4 were controlled by eccentric compression load. And for each column specimen, the maximum crack width was measured and recorded with a Crack Width Measuring Instrument. The maximum crack widths of column specimen COL-2–COL-4 were 0.06, 0.11 and 0.15 mm, respectively.

In order to investigate the impact of concrete strain on chloride penetration. The concrete strains in mid-segment of column specimens were tested. As shown in Fig. 3, four fixed measuring points along the section height were arranged. Each measuring point included two fixed stainless steel targets with a spacing of 250 mm. The Demec strain gauge was utilized to measure longitudinal strain of RC columns.