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Degradation progress of concrete subject to combined sulfate-chloride attack under drying-wetting cycles and flexural loading

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HIGHLIGHTS

- Durability of concrete under sulfate-chloride, dry-wet cycle and flexural load was investigated.
- Compared to long-term loading, short-term loading accelerated the damage of concrete slightly.
- Load accelerated the damage of concrete in tensile region, while retarded it in compressive zone.

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ABSTRACT

This paper presents an experimental study on the damage progress of concrete subject to combined sulfate-chloride attack under drying-wetting cycles and flexural loading. Two different loading regimes (long-term loading and short-term loading), which contain three different stress levels and both tensile and compressive regions, are applied in this test. The research results indicate that flexural loading accelerates the deterioration of concrete subject to sulfate and chloride attack under dry-wetting cycles. The damage of concrete was increased with the increasing stress level under both long-term loading and short-term loading. Compare to long-term loading, concrete under short-term loading shows slight damage. In the tensile region, loading accelerate the sulfate and chloride attack of the concrete, while in the compressive region, loading improve resistance of concrete against sulfate and chloride attack and this effect is more obvious with the increase of stress levels. It was also found that mineral admixtures, such as fly ash and ground granulated blast slag can improve the resistance of concrete under combined sulfate-chloride attack, with drying-wetting cycles and flexural loading.

1. Introduction

Concrete structures in marine environments are destroyed early in practical applications and cannot reach their predetermined service lives, since sea water contains high concentration of sulfate and chloride. For concrete in splash and tidal zone, drying-wetting cycles accelerate the sulfate and chloride attack against concrete caused by splash and tide. Furthermore, concrete structures in practical applications bear multiple mechanical loading all the time and also due to the fast damage of structures. A large numbers of researches have investigate the durability of concrete under chemical and physical effect of sulfate [1–5], coupling attack of sulfate and drying-wetting cycles [5–9] or combine chloride and sulfate attack [10–13] and flexural loading [14–17].

Researches of coupling function of mechanical loading and salt attack are limited in the literature. Gao [15] and Yang [18] investigated the coupling effect of salt solution attack and long-term loading, which is main due to the self-weight of marine structures or these structures have to bear loading for a long time, such as the pillars of bridges, baseplates of dams and railway bridges. Their research shows that long-term loading can accelerate the sulfate and chloride attack. Yu [14] researched the coupling function of sulfate attack and dynamic flexural loading and research indicated that solution concentration and stress levels are two important factors that affect durability of concrete and dynamic flexural loading make cracking occur early and promote sulfate ion diffusing rate. However, to some infrastructures, such as high-speed railway sleeper, bridge decks, airfield runways and structures under earthquake, they are bearing short-term loading when trains, cars and planes passed or under suffer earthquakes. These previous reporters did not consider the coupling function of short-term loading and combined sulfate and chloride attack of concrete.

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Moreover, the influence of flexural loading on durability of concrete structures exposed to salt attack is a complicated question. The force regions of concrete structures under flexural loading should be divided into compressive region and tensile region, which is result from the different types of loading. In compressive region, concrete is under compressive stress, whilst in tensile region is under tensile stress and different types of stress have different effect on damage progress of concrete exposed to salt attack. However, even to date, there are still few researches relating to this issue.

In this paper, the deterioration process of concrete beams subjected to sulfate and chloride attack under drying-wetting cycles and flexural loading is investigated. Two different loading regimes (long-term loading and short-term loading), which contain three different stress levels and both tensile and compressive regions, are applied in this test. Ultrasonic method is used to analyze the evolution of relative dynamic elastic modulus (E_{rd}). The chloride ion content is determined by chemical titration. The microtopography, corrosion products and pores distribution of interior concrete are investigated by scanning electron microscopy (SEM), X-ray diffraction (XRD) and Nitrogen Adsorption (BET), respectively.

2. Materials and methods

2.1. Materials and mixture proportion

Chinese standard P II 52.5 Portland cement produced by Jiangnan-Onoda Cement Co. Ltd was used. Chinese standard class-I fly ash(FA) and Chinese standard S95 ground granulated blast slag (GGBS) were used. The physical properties and chemical compositions of Portland cement, FA, and GGBS are shown in Table 1. The fine aggregate was normal river sand (<5 mm) and the coarse aggregate was limestone, which had a continuous gradation (5–20 mm). A polycarboxylate-type superplasticizer with a water reducing rate of 30% was used. The slumps of the concrete were about 200–220 mm. The mixture proportions of concrete are summarized in Table 2. C50K50 represents 50% replacement of Portland cement with GGBS and C50F30 means 30% replacement of Portland cement with FA.

2.2. Fabrication and curing of specimens

The concrete specimens with molds were placed in lab with a temperature of 20 ± 5 °C for 24 h after the concrete specimens were cast in molds of 70 × 70 × 280 mm, specimens were then cured for 56 days at a temperature of 20 ± 2 °C and 95% of relative humidity. The compressive and flexural strength of concrete under different curing time were showed in Table. 3. Following standard curing, two loading regimes were applied. Long-term loading was applied by four-point bending loading equipment (see Fig. 1) and continue to the end of this experiment, in which three stress levels were used, such as 0%, 35% and 50%. Short-term loading removed after applied on specimens for 5 min by universal testing machine and stress level was 35%, 50% and 70%. Then specimens were submerged in a complex solution of 5% by mass of NaCl and 5% by mass of Na_2SO_4 for 21 h and then drying for 3 h at the environment temperature of 20 °C. Following that, the specimens were placed in an oven at a temperature of about 60 °C for 45 h, then cooled at the environment temperature for 3 h. After this drying process the specimens were immersed in the solution again. This wetting and drying cycle was repeated for specific period.

Table 1
Physical properties and chemical compositions of cement, FA and GGBS.

Chemical Composition/%	Cement	FA	GGBS
CaO	62.6	5.75	36.35
SiO_2	21.35	51.07	33.48
Al_2O_3	4.67	30.86	12.21
Fe_2O_3	3.31	5.26	1.40
MgO	1.11	2.72	10.60
SO_3	2.25	1.48	0.66
K_2O	0.54	1.13	0.56
Na_2O	0.21	0.79	1.27
Loss on ignition	3.26	2.8	0.36
Physical properties			
Specific gravity/(g/cm^3)	3.112	2.346	2.82
Blaine fineness/(cm^2/g)	3680	4000	4600

To determine the penetration of chloride ions into concrete, expected for two opposite surfaces (70 × 280 mm), other four surfaces were covered by epoxy resin before exposure tests. The ion content of specimens will be measured after exposure for 30, 90 and 150 days. To measure the damage progress of concrete exposed to combine sulfate and chloride attack under drying-wetting cycles and flexural loading, the specimens were submerged in salt solution directly after loading. The relative dynamic elastic modulus (E_{rd}) was determined by using the ultrasonic method every three cycles. The microstructure, corrosion products and porosity of specimens would be measured by SEM, XRD and BET after exposure for 150 days.

2.3. Testing scheme

2.3.1. Dynamic modulus of elasticity(E_d)

The NM-4A nonmetal ultrasonic detector was used to investigate the ultrasonic times of concrete exposed to combined attack of chloride and sulfate solutions under drying-wetting cycles and flexural loading. Furthermore the E_{rd} of the compressive region was measured by the upper part of specimens, while E_{rd} of tensile region was measured by the lower part. Since the sensor frequency of this instrument was 50 kHz, the test length needed to be greater than 100 mm, so the largest length (280 mm) of specimens was examined. Before exposed to drying-wetting cycles, the dynamic modulus of elasticity(E_d) of the specimens was determined by Eq. (1). The Ed changes of specimens were then monitored at every dying-wetting cycle during the first month, tested every two cycles during the middle two months, and detected every four cycles during the last two months. The relative dynamic modulus of elasticity (E_{rd}) was determined by Eq. (2), which is the ratio of the E_d value to the initial E_d value after a certain exposure age.

$$E_d = \frac{(1+\upsilon)(1-2\upsilon)\rho V^2}{1-\upsilon} \tag{1}$$

$$E_{rd} = \frac{E_{dn}}{E_{do}} = \frac{V_n^2}{V_o^2} = \frac{t_o^2}{t_n^2} \tag{2}$$

where E_d is Dynamic modulus of elasticity, V is ultrasonic speed (m/s), ρ is density of specimen (kg/m^3), υ is Poisson's ratio, t_0 is initial ultrasonic time of specimen before corrosion (μs), and t_n is ultrasonic time of specimen exposing to N_{th} dying-wetting cycles (μs).

2.3.2. Free chloride content

Powder was collected from samples by drilling at some different depths of concrete, then passed the 0.15 mm sieve. Following that, powder was dried in an oven at a temperature of 105 °C for 2 h. Weigh about 2 g powder (m) was taking by using the electronic scale (capacity of 200 g, with a precision of 0.0001 g) after the powder cooled down to room temperature and the weight m was recorded accurately. Mixing the powder weighed by electronic scale with 50 ml (V_1) distilled water measured by pipette in conical flask, then the conical flask was put aside for 1 day after 1 min shake. 10 ml (V_2) supernatant measured by pipette and 2 drops phenolphthalein solution was put into another conical flask, then slowly added dilute sulphuric acid until the mixed solution turned colorless. The solution was titrated by silver nitrate solution until it turn to brick red after added 10 drops potassium chromate indicator. The consumed volume of titrant volume was denoted by V_3. Free chloride content was calculated using Eq. (3).

$$P = \frac{C_{AgNO_3} \cdot V_3 \cdot 0.03545}{m \cdot \frac{V_2}{V_1}} \times 100\% \tag{3}$$

2.3.3. SEM/XRD/BET tests

Sirion 200 field emission scanning electron microscope with energy dispersive X-ray analysis (EDX) was used to investigate the microstructure of specimens. Samples for SEM analysis were coated with gold before testing. X-ray diffraction (Bruker D8 diffractometer) was carried out to investigate the changing of hydration products and corrosion products in concrete. All samples were dried and grounded to pass the 75 μm sieve before testing. Samples were measured in θ/2θ geometry over an angular range of 5–70° 2θ (Cu Kα radiation) using a 0.02°2θ step size and 0.15 s/step counting time. The power used in XRD test was also applied in BET test. Autosorb-IQ2 Nitrogen Adsorption equipment was used for BET test and the specific surface area and pore size of this equipment were more than 0.0005 m^2/g and 0.35 nm, respectively.

3. Results and discussion

3.1. The relative dynamic elastic modulus (E_{rd})

Fig. 2 shows the variation of E_{rd} at tensile region for C50 concrete exposed to 5%NaCl + 5% Na_2SO_4 attack under different levels of flexural loading and drying-wetting cycles. It is clear that the E_{rd} of specimens under 35% and 50% flexural loading are much lower