Construction and Building Materials 141 (2017) 453–460

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Study on the micro-crack evolution of concrete subjected to stress corrosion and magnesium sulfate

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HIGHLIGHTS

- The damage behaviors of concrete under the combined actions of $MgSO_4$ attack and flexural or tensile loads were studied.
- A crack density model was proposed to evaluate the damage degree of the concrete.
- The deterioration mechanisms of two types of concrete under various corrosion conditions were analyzed.

ARTICLE INFO

Article history:
Received 6 November 2016
Received in revised form 1 February 2017
Accepted 22 February 2017

Keywords:
Concrete
Durability
Stress corrosion
Sulfate attack
Crack density

ABSTRACT

The deterioration processes of two types of concrete under chemical corrosion ($MgSO_4$), tensile loading coupled with chemical corrosion or flexural loading coupled with chemical corrosion were investigated in this study. Tensile stress and flexural stress loading devices that were designed by the authors were used. A relative dynamic elastic modulus test using the ultrasonic method was utilized, and through the derivation of empirical equations, a crack density model was obtained to describe the concrete damage process. Furthermore, scanning electron microscopy (SEM) was used to investigate the microstructure changes inside the concrete. The results indicated that the flexural and tensile loads significantly affected the deterioration of concrete when combined with magnesium sulfate. Exposure to magnesium sulfate coupled with tensile loading is a harsh environment for concrete. The rate of concrete deterioration under different stress conditions at the same loading level is ranked as follows: tensile stress coupled with chemical corrosion > flexural stress coupled with chemical corrosion > chemical corrosion.

1. Introduction

Generally, concrete structures are simultaneously subjected to chemical attacks and loads during the service life of actual engineering projects. Therefore, there has been increasing concern regarding the durability of concrete under the combination of stress corrosion and chemical attack. Research on the concrete corrosion process under both chemical attack and loading has important implications for concrete design and service life predictions.

Several studies have attained significant achievements in this field. Saito et al. [1] studied the stress corrosion of concrete under both static and cyclic loading. The results indicated that there was no significant increase in the permeation of corrosion ions into concrete under static loading. However, when the cyclic loading increased to 60%, the permeation of corrosion ions into the concrete increased significantly. By studying the stress corrosion of various strength grades of concrete, Konin et al. [2,3] determined the relationship between the strength and loading level as well as the relationships among the diffusion coefficient of the corrosion ions, loading level and concrete strength. Schneider et al. [4] investigated the deterioration damage process of high strength concrete, ordinary concrete and cement under a 30% flexural stress coupled with a 5% or 10% $(NH_4)_2SO_4$ solution. The results indicated that flexural stress accelerated concrete corrosion and that chemical corrosion was a dominant factor for high strength concrete. However, stress corrosion became a dominant factor with decreasing concentration of the $(NH_4)_2SO_4$ solution and increasing flexural stress ratio. Mu [5] determined that a steel fiber could inhibit the flexural stress corrosion of concrete immersed in a Na_2SO_4 solution. The research results indicated that the corrosion properties improved significantly when the concrete was mixed with an activated admixture [6,7]. However, Liu [8] stated that the improvement in the resistance to stress corrosion due to the mineral

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http://dx.doi.org/10.1016/j.conbuildmat.2017.02.127
0950-0618/

admixture was insignificant when the concrete was subjected to high flexural stress. The research results from Yu et al. [9] indicated that with higher concrete strength, the role of stress corrosion was more apparent. Chen's research results indicated that stress corrosion was significantly greater than chemical corrosion; the strength loss in the concrete increased with increasing flexural stress and corrosion time. The rate of corrosion damage for high performance concrete (HPC) in four corrosion mediums was ranked as follows: $MgSO_4 > H_2O > Na_2SO_4 > MgCl_2$ [10]. Gao et al. [11] determined that flexural loading increased the degree of damage to concrete under the combined actions of a sulfate attack and drying-wetting cycles, especially when the flexural loading exceeded 40% of the maximum flexural load. The accelerated corrosion results from Jin et al. [12] indicated that a seawater and compound solution increased the critical compressive load level for the corrosion rate of a steel bar in reinforced concrete but also increased the negative effect generated by the compressive load on the tensile strength of reinforced concrete.

Exposure to sulfate is well known to affect the durability of concrete materials and thus concrete structures. Several studies have researched concrete expansion and cracking due to sulfate exposure [13–19]. Moreover, a theoretical expansion model was proposed for predicting the volume expansion during the sulfate attack process [20]. However, few reports have investigated the micro-crack evolution process of concrete exposed to magnesium sulfate under various stress corrosions. This study investigated the damage processes of fly ash concrete (FAC) and HPC subjected to magnesium sulfate, magnesium sulfate combined with tensile loading and magnesium sulfate combined with flexural loading. The relative dynamic elastic modulus (E_{rd}), crack density and microstructure were used to investigate the damage processes for the two types of concrete.

2. Materials and experiments

2.1. Materials

Chinese standard 525# ordinary Portland cement (OPC), which was supplied by Nanjing Jiaxin Jingyang Cement Corporation in China, was used in the experiments. ASTM C618 class F fly ash (FA), slag (SG) and silica fume (SF) were used. The chemical compositions of the above binders are listed in Table 1. The fine aggregate was natural river sand with a fineness modulus of 2.72, and crushed basalt was used as the coarse aggregate with a continuous grade of 5–10 mm. The high-range water reducer used in the experiments was a naphthalene-type super-plasticizer (J-MB) with a water reduction of greater than 20%; the content of Na_2SO_4 was less than 2%, and the content of Cl^- was less than 0.01%.

2.2. Mixture proportions and properties

Two types of concrete were tested in this experiment, and the details of the mixture proportions are listed in Table 2.

Four groups of prism specimens with dimensions of 40 mm × 40 mm × 160 mm and 40 mm × 40 mm × 120 mm that were pre-embedded with a thread pull bar were cast and cured under sealed conditions for 24 h. Then, the prism specimens were demolded and cured in saturated limewater from 20 °C to 23 °C for 28 d. One group of specimens was used to measure the 28-day axial tensile strength and flexural strength. The corresponding mechanical properties of the sample materials are summarized in Table 3.

2.3. Test method

The other three groups were used to experimentally study the damage processes under the combined effect of magnesium sulfate attack and stress load. The specimens underwent one of three types of tests: (1) transferred into a solution of 5% magnesium sulfate by weight (MS); (2) immersed in 5% magnesium sulfate after being subjected to a tensile load (with a tensile ratio of 35%) (MS + TL); or (3) immersed in 5% magnesium sulfate after being subjected to a flexural load (with a flexural ratio of 35%) (MS + FL).

A load device designed by the authors was used for the tensile and flexural stress conditions. The setup for the load test is illustrated in Fig. 1. After the specimens were cured for a certain number of days, they were subjected to bending loads. The bending stress level was maintained by monitoring the displacements of the disc springs. The flexural load values were determined using the displacement of the upper steel plate, which was determined by a digital caliper, and the tensile load values were obtained from the testing machine. The stress level λ can be defined as follows:

$$\lambda = \sigma/\mathrm{f} \times 100\% \tag{1}$$

where σ is the applied stress and f is the measured flexural or tensile strength of the concrete specimen. In this study, λ was 35%.

A non-metal ultrasonic detection analyzer (NM-4B Type) was used to detect and analyze the sonic time during different exposure times in the two types of concrete. A schematic diagram of the measurement is depicted in Fig. 2. The ultrasound measurement method was used to detect the sonic time through the length of the concrete, which was generally 160 mm.

The relative dynamic elastic modulus (E_{rd}) of concrete can be calculated using Eq. (2) [21,22] as follows:

$$E_{rd} = \frac{E_{dn}}{E_{d0}} = \frac{v_n^2}{v_0^2} = \frac{t_0^2}{t_n^2} \times 100\% \tag{2}$$

where E_{rd} is the relative dynamic elastic modulus of the concrete after corrosion, E_{d0} and v_0 are the initial dynamic elastic modulus of the concrete and the initial velocity before corrosion, respectively, E_{dn} and v_n are the dynamic elastic modulus and the velocity of the concrete after corrosion, respectively, and t_0 and t_n are the ultrasonic travel time before corrosion and the ultrasonic travel time after corrosion, respectively.

According to the *Standard for test methods of long-term performance and durability of ordinary concrete* (GB/T 50082-2009), if the relative dynamic elastic modulus (E_{rd}) of concrete drops below 60%, the concrete is considered to have failed.

The microstructures of the samples were observed using scanning electron microscopy (SEM, JSM-5610LV, Japan) on the fracture surface coated with gold.

Table 1
Chemical compositions of the raw materials (wt%).

Materials	SiO_2	Al_2O_3	CaO	MgO	SO_3	Fe_2O_3	Na_2O	K_2O	I.L
Cement	20.30	5.03	65.06	0.55	2.24	4.38	–	–	1.30
FA	52.37	32.13	2.16	0.47	0.33	4.13	0.25	0.61	1.30
SG	32.86	13.21	40.34	2.72	5.59	1.90	1.22	–	0.94
SF	93.1	0.61	0.52	–	–	0.22	–	–	–