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Deterioration of concrete fracture toughness and elastic modulus under simulated acid-sulfate environment

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HIGHLIGHTS

- Three-point bending tests were conducted by using laboratory corroded concrete specimens.
- Subcritical propagation took place during the propagation from severe corroded layer to mild corroded layer.
- Under simulated acid-sulphate attack, fracture toughness and elastic modulus of concrete were deteriorated.

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ABSTRACT

In order to investigate the deterioration of the elastic modulus and fracture toughness of corroded concrete, three-point bending (TPB) tests were conducted by using corroded concrete specimens. The initiation load, the maximum load, the *P-CMOD* (loads versus crack mouth opening displacements) curves and the stress-strain curves were measured. Meanwhile, the deterioration near crack tips of the corroded specimens was observed with the aid of scanning electronic microscopy (SEM). Under the simulated acid solutions, the corrosion depth near crack tips gradually grows with the increase of corrosion time, and finally the concrete microstructures are porous and loose and microcracks are developed, which will deteriorate concrete material parameters, such as elastic modulus and fracture toughness. The test results show that subcritical propagation occurs during the loading progress from the initiation load to the maximum load, and the initiation toughness is about 80%–85% of the fracture toughness of the corroded concrete. For the specimens immersed in pH 2.5 and 3.5 solutions, both the fracture toughness and the elastic modulus increase in the early stage and then decrease with the increase of corrosion time, whereas for the specimens immersed in pH 1.5 solutions, both the elastic modulus and fracture toughness decrease almost linearly with immersion time. H^+ and SO_4^{2-} are two main factors in the deterioration of concrete in the simulated acid solutions.

1. Introduction

Concrete has been applied widely in civil engineering due to its low price, high strength and long durability, etc. However, it also has many drawbacks, such as poor tensile capacity, easy cracking, and alkaline property [1]. As one engineering material, concrete is inevitably exposed to acidic substances [2]. Environmental water and atmospheric precipitation may be two main sources of acid corrosion that many concrete structures are suffered. Under such acid environment, the concrete strength as well as the corresponding structural stability will be impaired. With the development of the industry, the acid rain attack has become a more serious problem in the whole world. The rainwater of most parts of Europe, the eastern parts of the United States, the southwest parts of China and parts of Japan has been strongly acidified. Currently, acid rain has covered more than one third of Chinese territory. Many famous structures have been attacked by acid rain, such as Acropolis monument in Greece, the Statue of Liberty in America. Therefore, it is essential to investigate the mechanism of acid attack on concrete structures so as to minimize its attacks.

Recently, many scholars have carried out numerous researches on the durability of concrete under acid rain attacks. Chen et al. [3] revealed the chemical reaction process and the deterioration mechanism of concrete under acid rain by laboratory-accelerated corrosion tests. They also pointed out that the deterioration of concrete is mainly caused by the coupling of H^+ and SO_4^{2-}. Tsutomu [4] studied the relationship of corrosion depth versus rainfall of acid rain by long-term exposure experiment, and he indicated that the

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corrosion depth is linearly related with rainfall. Siad et al. [5] studied the effects of glass powder content on the sulfuric acid resistance of mortars and the results showed that the sulfuric acid resistance of mortars could be improved with the increase of glass powder content. Fan et al. [6] defined the related three-parameter damage indexes of mass loss, compressive strength and elastic modulus for concrete under acid corrosion by experimental research and theoretical calculation. Mahdikhani et al. [7] studied the deterioration trend of compressive strength for concrete in sulfuric acid rain condition. Araghi et al. [8] investigated the erosion resistance of concrete containing various PET particles percentages against sulfuric acid attack, and Nematzadeh et al. [9] investigated erosion resistance of high-strength concrete containing forta-ferro fibers against sulfuric acid attack with an optimum design. Li et al. [10] studied the degradation mechanism of sulphoaluminate cement sea sand concrete eroded by biological sulfuric acid. Although many scholars have conducted a plenty of researches on the deterioration of the mechanical properties of concrete under acid rain attack, for the fracture toughness of concrete under acid rain attacks, less attention has been paid. Wang et al. [11] investigated deterioration of fracture toughness of concrete under acid rain environment by means of laboratory accelerated corrosion tests, but the corrosion period was only for 60 days, which is not long enough. After 60 days, the corrosion layer of concrete is fluffy and porous, and the crack structures change significantly and the pore size increases largely. The test results of the fracture toughness and elastic modulus for the 60 day corrosion concrete can only present mild acid corrosion impacts, whereas the results for the 90 day corrosion concrete can provide severe acid corrosion impacts, which exists widely for those concrete structures exposed in acid environment for a long period. In this paper, we will perform more detail study on the deterioration of the parameters of corroded concrete, and the corrosion time will be expanded to 90 days.

The ability of materials to resist cracking is reflected by its fracture toughness which has been considered as a threshold value and has been applied widely in the prediction of engineering structure stabilities [12–14]. Since the concept of fracture mechanics was introduced to concrete material in 1961, a plenty of fracture problems of concrete structures has been investigated by using fracture mechanics [15–17]. Concrete, as a kind of quasi-brittle material, is very prone to generate cracks or microcracks, and for long service concrete structures, they inevitably have defective cracks. In some unfavorable acid circumstances, concrete material will be corroded and the ability to resist cracking will be reduced, which will directly minimize the service life of concrete structures. The existing experimental results show that environmental factors have great influence on the fracture behavior of concrete [18–21]. Therefore, it is necessary to study fracture toughness of concrete attacked by acid rain through experimental research, which is of great significance for life prediction and evaluation of concrete structures in acid rain zone. In this paper, laboratory-accelerated corrosion tests are performed and the concrete specimens under different corrosion degree are applied in the three-point bending (TPB) tests. The material parameters of fracture toughness and elastic modulus of corroded concrete are measured, and crack surfaces are scanned by using electronic microscopy.

2. Experimentation

In order to study the effect of acid environment on concrete fracture, the three-point bending (TPB) specimens were made by using concrete with small size coarse aggregate, and the specimens were immersed in acid solutions, and then these specimens were applied in fracture experiments.

2.1. TPB specimens

Ordinary Portland cement (OPC) of strength grade 42.5 MPa and fine size river sand were applied in this experimental study. Because of the distribution heterogeneity of large size coarse aggregate, the dispersion of test results could increase considerably [16,17,21,22], thus coarse aggregates are not applied. The chemical compositions and the loss on ignition (LOI) of OPC are given in Table 1. Additionally, the mineral compositions of OPC are given in Table 2. The physical and mechanical properties of OPC are shown in Table 3. The TPB specimens were made of cement, sand and water, and the mass proportion was 1:3.5:0.5. The TPB specimens measure 400 mm in length, 100 mm in width and 100 mm in height, as shown in Fig. 1. A stalloy of 1 mm thickness was buried inside the specimens before curing to prefabricate a crack. The crack length is 30 mm and its width is 1 mm. In order to easily remove the stalloy from the specimen, lubricating oil was evenly coated on the stalloy. Cuboid plastic mould with a dimension of 100 mm × 100 mm × 400 mm was used to make the concrete specimens. The mould was removed after 24 h, and then the specimens were placed in a standard curing room for 28 days, whose temperature and air humidity were set to 20 °C and 95% respectively. In this study, the specimens, which were conditioned in water and acid solutions, were placed in a thermostatic chamber, and the constant temperature of 20 °C was regulated by an air conditioner.

2.2. Laboratory-accelerated corrosion

Laboratory-accelerated corrosion is a useful and applicable approach, and it has been applied by several researchers [8,11,18,23,24]. In this study, concentrated nitric acid and ammonium sulfate were used to make the corrosion solutions. Four *pH* levels of corrosion solutions with the *pH* value 1.5, 2.5, 3.5, 7, respectively, were prepared. The pH values of most parts of Europe, the eastern parts of the United States, the southwest parts of China and parts of Japan are below 4.5, whose rainwater has been strongly acidified. The minimum pH value of the severe acid rain area in China has reached about 2.85, and there is still a tendency to decrease gradually. Actually the pH 7 solutions were tap water without any other chemical reagents. The analytical reagents of dilute nitric acid and ammonium sulfate were used to adjust the pH value and the concentration of sulfate ion of the acid solutions, respectively. The initial concentration of sulfate ion was set as 0.1 mol/L. The simulated solutions were replaced every five days to try to keep the concentrations of all the ions as constants, and the concentrations of all the ions are presented in Table 4.

The concrete specimens were divided into 4 groups, and they were soaked in the 4 *pH* levels of solutions, respectively. The specimens were immersed in acid solutions and the top of the specimens was more than 5.0 cm below the solution surface since there was evaporation loss of the solutions. The hydration product and calcium hydroxide of Portland cement is pretty alkaline, which would consume huge amounts of hydrogen ions. A portable acidometer was used to monitor the *pH* values of the solutions, and the *pH* value was kept as a constant. After the specimens were taken out from the corrosion solutions, they were naturally dried for 24 h, and then placed into the 80 °C air circulation oven for 48 h.

2.3. Three-point bending tests

The three-point bending (TPB) tests of the corroded specimens were carried out by means of a 300 kN electronic universal testing machine which was controlled by a computer. Loading rate was controlled by displacement 0.01 mm/min which could make crack propagation slowly. The distance between two supports of the concrete specimen was 300 mm in the TPB tests, and the loading