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Deterioration of fracture toughness of concrete under acid rain environment

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ABSTRACT

Deterioration of fracture toughness of concrete caused by acid rain attack was investigated through laboratory-accelerated corrosion tests. Fracture toughness of the corroded concrete with different corrosion period was obtained by three point bending tests, and meanwhile the *P-COMD* curves and elastic modulus E of the corroded specimens with different corrosion degrees were also obtained. The experimental results showed that the deterioration of concrete surface is large and the corrosion depth increases with corrosion duration. The observation by scanning electron microscopy showed that the microstructures of crack tip are porous and loose due to acid corrosion, and many crisscross cracks appear at corrosion layer. Based on the experimental results, equivalent crack length in the fracture process zone and the effective fracture toughness K_{IC} were also obtained by theoretical analysis. Under the impact of acid corrosion, the concrete material physical and chemical properties changed significantly, which made the corresponding resistance stresses to crack propagation decrease. The curves of fracture toughness versus corrosion depth were obtained in this study.

1. Introduction

Concrete has been used widely as one of predominant building materials since last century because of its low price, high strength and durability, etc. However, it also has many shortcomings; the principal demerits of concrete are poor tensile capacity, easy cracking, and alkaline property [1]. The pore solution in concrete typically has a pH value ranging from 12 to 13.5 [2], which could result in physical and chemical reactions as concrete structures contact with acid environment, and as the reaction continued to proceed, the concrete structures could gradually lose its mechanical strength and eventually lead to structural failure.

As an engineering material, concrete could be directly exposed to all kinds of acid environments. The source of acid media is broad [3], and they may be produced from industrial processes and some urban activities. Soils may contain huminous acids. Several organic and inorganic acids may occur in sea-water as a consequence of bacteriological activity. Significant quantities of free acids in plants and factories may be found. Air pollution by gaseous carbon dioxide, sulfur dioxide and nitrogen oxides exist widely [4]. 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 minimized [5]. Currently, with industrial and urban development, the worldwide acid rain problems have become more and more serious, for example, it was reported that acid rain falls cover at least one third of Chinese territory. Therefore, it is necessary to study the mechanism of acid rain attack on concrete structures so as to minimize its impact.

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Recently, many scholars have devoted to the study on the impacts of acid corrosion. The experimental results by Chen et al. [2] showed that the deterioration of cementitious material specimens under acid rain attack was mainly caused by the coupling of H^+ and SO_4^{2-}, and the deterioration began from the exterior to the interior and continuously accumulated until the specimens were fully degraded. Experimental study on concrete corrosion depth, mass loss, compressive strength and elastic modulus under acid rain environment was implemented by Fan et al. [6–7], and three damage indices corresponding to relative mass loss, compressive strength, and elastic modulus were defined and calculated. Zhang et al. [8–11] revealed the deterioration trend of elastic modulus, tensile property and flexural behavior of concrete structure by acid rain attack through a series of experiments. Through laboratory tests by using mortar specimens, Kanazu et al. [12] pointed out that the eroded depth of the specimen subjected to simulated acid rain attack has a good linear relation to the total rainfall. Although for the problems of acid corrosion impact have been studied by many researchers, but for the impact on the fracture toughness of concrete materials, less attention has been paid.

Fracture mechanics has been widely applied to brittle materials [13–15]. Concrete, as a kind of quasi-brittle material, is prone to generating crack, and such cracks usually play a dominant role in the stability of concrete structures since many destructions of concrete structures were induced by crack expansion. In order to predict and prevent engineering disasters induced by such cracking, theoretical and experimental studies on the fractures of concrete materials under acid rain environment are essential. Since Kaplan applied the concept of fracture mechanics to concrete material in 1961, many fracture problems of concrete structures have been studied by using fracture mechanics [16–18].

A large number of studies showed that a fracture process zone exists at the crack tip of concrete [16–17]. As cracked concrete exposed in acid rain circumstances, the cementitious material near crack tip will fail gradually, the fracture behavior will be different with those without the impact of acid corrosion, and accordingly the effective parameters, such as elastic modulus and fracture toughness will change.

In this study, the impact of acid rain on concrete fracture behavior is investigated using accelerated acid tests established in our laboratory, and scanning electron microscopy (SEM) experiments and three point bending tests are conducted.

2. Concrete specimen and experimental procedure

In order to investigate the crack behavior of concrete under the impact of acid rain environment, three – point-bend (TPB) specimens were used to implement experimental study.

2.1. Concrete TPB specimen

In this study, Portland cement with a strength grade of 42.5 MPa was used to make TPB specimens. The specimens were square beams with a dimension of 100 mm × 100 mm × 400 mm, as shown in Fig. 1, and an penetrated crack which measure 30 mm in length was cut by using a very thin 0.1 mm film which was imbedded the specimens during the process of casting in a mold until they were loaded. It was found that after the specimens have been stored in a heating apparatus with a temperature 130 °C for 2 h, the films can be easily pulled out from the specimens. The material is cement mortar, and the ratio of cement, sand, and water is 1:3.5:0.5 by weight. The crack propagation can be blocked by coarse aggregate [18–19], which will increase the dispersion of the test results, thus in this study, no coarse aggregate was added.

2.2. Experiment procedure

Soaking method is suitable to perform a fast test on acid rain corrosion of concrete [20], and therefore, it was adopted in this study. Laboratory-accelerated corrosion tests based on the equivalent value of acid rain attacking strength per year can simulate long period corrosion in natural condition and can be completed in a short time [21]. Wang et al. [22] pointed out that acid rain is mostly caused by sulfuric acid, and therefore, only the impact of sulfuric acid rain is considered in this study, which was achieved by mixing ammonia sulfate and nitric acid solution. Three groups of experiments were designed in this study, and the lowest pH value of simulated acid rain solution was 1.5, 2.5, 3.5 respectively, and the initial concentration of sulfate ion was 0.1 mol/L.

All the specimens were kept in the casting room for 1 day and then they were demolded and cured in water for 28 days. After the 28-day curing period, all specimens were removed and dried in the air, and then, one-quarter of the specimens were cured again in water, while the rest were immersed in the simulated acid rain solutions until they were tested. In order to ensure that all surfaces of the specimen can be uniformly exposed to the solution, the distance from the upper surface of the specimens to the surface of the liquid was greater than 5 cm and the adjacent specimens were separated with batten as shown in Fig. 2. Since the

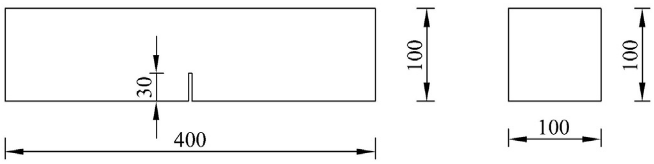

Fig. 1. Sketch of a three-point-bend specimen.