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Experiment study on the failure mechanism of dry-mix shotcrete under the combined actions of sulfate attack and drying–wetting cycles

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HIGHLIGHTS

- Carried out sulfate immersion and drying–wetting cycle test on the shotcrete coupons.
- Studied the corrosion products and the microstructure during the damage process.
- Proposed the failure mechanism of shotcrete under sulfate attack.

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ABSTRACT

The damage process and failure mechanism of shotcrete under the combined actions of sulfate attack and drying–wetting cycle were investigated. The results indicated that shotcrete was inherently more inhomogeneous, the compact area and defect region exhibited different erosion mechanisms and failure forms. The connected and loose defects could accelerate the intrusion of external sulfate ions and the growth of corrosion products. The localization and directivity of defects would lead to the localized distribution of expansive stress. Hence, the crack in defect region developed significantly faster and was the key factor that limited the durability of shotcrete under sulfate attack.

1. Introduction

Shotcrete is well known to have fast development of strength, simple constructional process, limitless shape possibility and low economic cost [1,2], therefore is extensively applied in underground engineering and other fields [3,4]. However, the properties or advantages mentioned above mean that the service environment of shotcrete often combines some complex or abominable hydrogeological conditions such as sulfate-rich soils or groundwater. Sulfate attack as one of the most aggressive environmental deteriorations that adversely affect the long-term durability of underground structures has been found to widely distribute in marine environments, industrial sulfate environments, and saline-alkali soil of Western China [5–7]. More seriously, drying–wetting cycle or water evaporation can make sulfate accumulated and crystallized in concrete by cycled moisture gradient and capillarity absorption and therefore can accelerate the deterioration of concrete structures, especially near the phreatic line of groundwater and the splash zone of salt lakes [6,8].

Despite structural failures due to sulfate erosion are rare [9], the underground structures may still suffer from softening, spalling, integrity degradation and strength reduction after long-term service, which will cause many hidden problems affecting normal operations [10–13]. In 2009, Ma [14] and Long [15] investigated the service conditions of more than ten existing tunnels built in the 1960s in Chengdu-Kunming railway of China. Among them, the lining of Fala Tunnel was built with shotcrete. The surveys revealed that the windward-side of concrete lining was damaged seriously due to the water evaporation, but the waterward-side of concrete lining was still in good condition.[1] Various types of damages such as swelling and spalling (see Fig. 1) appeared in Fala Tunnel, although a great deal of repair works had been carried out in 1982, 1987 and 2000, respectively. With the wide application of shotcrete in underground engineering, we can foresee that an

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[1] The side contacting with sulfate-rich groundwater is called waterward-side, and the other side contacting with air is called windward-side [14].

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increasing number of shotcrete structures will face durability problems induced by sulfate attack in the near future.

In the past few decades, many outstanding achievements about the sulfate attack phenomenon and deterioration mechanism of ordinary concrete have been obtained. Sulfate attack against concrete is generally recognized as a complex expansive reaction between penetrating sulfate and hardened cement pastes [16], accompanied with the formation of ettringite and, at high sulfate concentrations, gypsum [17–19]. Several hypotheses [20–23] have been proposed to explain the mechanism of expansion. Chen [24] investigated the damage evolution of cement mortar due to sulfate erosion and concluded that the formation of gypsum and ettringite can not only reduce the porosity of concrete but also cause damage. Sarkar [25] drew the same conclusion and proposed a two-stage failure mechanism to demonstrate the progression of sulfate damage in space and time.

However, up till now, almost no literature can be found on aspect of sulfate-resistance performance of shotcrete. The studies in [26] have shown that shotcrete could be produced with as good durability characteristics as a similar conventionally cast concrete in the laboratory environment. However, the spraying technology and in particular dry-mix sprayed concrete is susceptible to the various external factors such as workmanship, nozzle design, and spraying angle [27]. The air and rebounds wrapped into the cement slurry will inevitably change the internal structure of concrete, accompanied with a lot of macro- and micro- defects [26]. The heterogeneity and the internal defects, as the greatest differences between shotcrete and ordinary concrete, can lead to the change of sulfate-resistance performance. Thus, whether the erosion mechanism and assumptions for ordinary concrete are suitable for shotcrete, is also a question worthy of further study.

The present study is undertaken as a first step toward investigating the sulfate-resistance performance of shotcrete. The major objectives of this paper are to (1) obtain the damage process of shotcrete in the laboratory environment, (2) propose the failure mechanism of shotcrete, and (3) attempt to explain the failure mechanism of shotcrete by means of microscopic test methods. In this work, the sulfate solution immersion and drying–wetting cycle were conducted on the shotcrete specimens to simulate the evaporation action in actual service environment and subsequently obtain the damage process of shotcrete. The microstructure and corrosion products were characterized by scanning electron microscopy (SEM), X-ray diffraction (XRD) and thermal analysis method (TAM) to further investigate the corrosion mechanism and explain the damage process of shotcrete. Through this research, the authors hope to make more researchers to realize the serious damage of sulfate attack on the durability of shotcrete, and pay more attention to this issue.

2. Materials and methods

2.1. Materials and experiment

The shotcrete specimens used here were produced at the construction site of a tunnel in Western China by using the dry-mix method according to [28]. The physical properties of materials are indicated in Table 1, and the mix proportion is shown in Table 2. The materials were first sprayed into the molds (1200 mm × 500 mm × 120 mm) and cured for 8 days in the tunnel. Then the shotcrete panels were transported to a laboratory, where the cube specimens (100 mm × 100 mm × 100 mm) were cut out from the panels. All specimens were cured in a standard curing room with a temperature of 20 ± 2 °C and a relative humidity of 95% for 28 days. In view of the mandatory provisions [28–30] that shotcrete should be produced without quality problems such as large voids, and macro-laminations, the specimens having macro-defects were eliminated by visual inspection before conducting the test of sulfate attack. Since the studies [14,15,31–33] on sulfate damage in tunnels have confirmed the presence and importance of water evaporation, the test condition of drying–wetting cycle was employed here to simulate the water evaporation and shorten the test time. The test procedures were as follows [34]: (1) the samples were immersed in the sodium-sulfate solution (10% by weight) for 16 h; (2) then the specimens were dried in an oven at a temperature of 60 °C for 6 h, and underwent a natural cooling for 2 h. These two steps (24 h in total) represented one drying–wetting cycle. When the drying–wetting cycle reached the specified time: 30 d, 60 d, 90 d, and 140 d, respectively, three corresponding specimens were removed out.

2.2. Characterization

The microstructures of shotcrete before and after being corroded were characterized by SEM. The corrosion products formed in the shotcrete were characterized by XRD and TAM. Energy-dispersive X-ray (EDX) microanalysis of the corrosion products was also performed during the SEM measurements.

3. Results and discussion

The damage process is shown in Fig. 2. At the early stage of corrosion (30 d), a thin macro-crack perpendicular to the spraying direction could be observed on the surface of shotcrete specimen. With increasing the drying–wetting cycles, the skin of shotcrete began to fall and the thin macro-crack gradually expanded. After 140 d of corrosion, the macro-crack had extended to the whole cross section and ultimately resulted in the fracture of specimen. Simultaneously, white crystalline powders could be observed on the fracture (Fig. 2e). The damage process of shotcrete indicated that the macro-crack resulting from sulfate attack was the predominate factor that would significantly degrade the sulfate-resistance performance of shotcrete, despite the synchronous appearance of other damage forms such as the exfoliation corrosion. Fig. 2f also shows the macro corrosion morphology of ordinary concrete specimens after they were exposed to the same corrosion environment for 140 d by our research team [35]. It can be seen that the ordinary concrete specimen was covered all over with exfoliation damage, however, they generally did not suffer a fracture. Obviously, the distinctive failure form of shotcrete was attributed to the construction method, i.e., the spraying technology. To further explain the damage process of shotcrete, the corrosion products and the microstructure of shotcrete need to be further analyzed.

3.1. Microstructure of shotcrete (Fig. 3)

Although we had chosen the shotcrete specimens without quality problems, many bubbles and micro-defects (represented by the darker color region, hereafter termed "defect") resulting from spraying technology can still be observed in Fig. 3a. From Fig. 3c and d, it can be seen that various degree of structural defects interspersed in the shotcrete matrix, and the structure of these defects was generally connected and relatively loose. Moreover, owing to the effect of spraying technology, the internal defects distributed intensively on a layer (Fig. 3a and c) which was perpendicular to the spraying direction, therefore were extremely conducive for the formation of weak areas under sulfate attack. Fig. 3e also shows the microstructure of ordinary concrete obtained from [35]. A lot of pores could be observed in the matrix of ordinary concrete, but the distribution of pores was relatively uniform and independent. The inset of Fig. 3 further indicates that shotcrete was inherently more inhomogeneous due to the localized distribution of pores and defects, and this was also a prime factor that would lead to the distinctive failure form of shotcrete. To facilitate further understanding the sulfate-resistance performance of shotcrete, the shotcrete matrix could be divided into the defect region and the compact area, as shown in Fig. 3c and d.

3.2. XRD patterns of corrosion products (Fig. 4)

In Fig. 4, high diffraction peaks of portlandite could be observed in non-corroded shotcrete. With the passage of erosion time, high-