

Durability performance of brine-exposed shotcrete in salt lake environment

Jiabin Wang^{a,*}, Ditao Niu^{b,d}, Yan Wang^c, Bin Wang^a

^a School of Civil & Architecture Engineering, Xi'an Technological University, 710021 No.2 Xuefuzhong Rd., Xi'an, Shaanxi, PR China

^b College of Civil Engineering, Xi'an University of Architecture and Technology, 710055 No.13 Yanta Rd., Xi'an, Shaanxi, PR China

^c College of Materials and Mineral Resources, Xi'an University of Architecture and Technology, 710055 No.13 Yanta Rd., Xi'an, Shaanxi, PR China

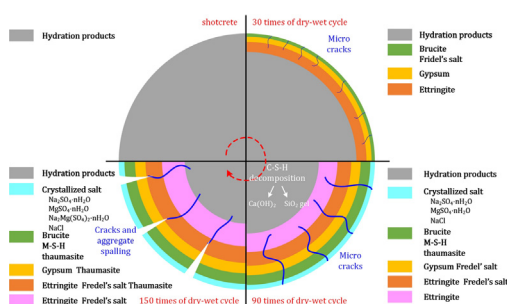
^d National Key Laboratory of Green Building in West China, Xi'an University of Architecture and Technology, 710055 No.13 Yanta Rd., Xi'an, Shaanxi, PR China



HIGHLIGHTS

- Durability performance degradation rules and damage depth of shotcrete under brine attack was tested.
- Microstructure of brine-exposed shotcrete was characterized.
- Air-void structure parameters and high-resolution surface scanning images of brine-exposed shotcrete were measured.
- Ions diffusion in shotcrete pore solution were researched include sodium, calcium, chloride, sulfate and pH of pore solution.

GRAPHICAL ABSTRACT



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ABSTRACT

Salt lake is widely distributed in Western China. The high concentrations of chlorine salt, sulfate, and magnesium salt in soil and underground water are the leading causes to the deteriorated performance of lining shotcrete and corrosion of reinforcement. This study aims to investigate the durability performance and deteriorated rules and mechanism of shotcrete lining in salt lake corrosion environment by using dry-wet (D&W) alternate method for simulating the corrosion mode of tunnel lining. A shotcrete durability experiment is performed in 5% Na₂SO₄ + 5% MgSO₄ + 3.5% NaCl solution. Relative dynamic elastic modulus, mass change, and relative compressive strength are measured. Thereafter, the mineral composition and microscopy of corrosion products and the air-void structure parameter and ion content of water-soluble sodium, chloride, and calcium ions; acid-soluble sulfate ion; and pH value of pore solution are tested using X-ray diffraction, thermogravimetric-differential scanning calorimetry, scanning electron microscopy, energy-dispersive X-ray spectroscopy, RapidAir 457, and electrochemical method.

Acid solubility sulfate content clearly increased with the D&W cycle, and water-soluble chloride and sodium content slowly increased. Meanwhile, water-soluble calcium and concrete pH value decreased. The combination of the expansion stress and crystallization pressure from thaumasite, brucite, gypsum, ettringite, and crystallized salt enlarged the air-void number and air content in shotcrete. Moreover, web crack formation caused deterioration of the physical and mechanical properties of shotcrete. Meanwhile, normal concrete was damaged by macrocracks connected with air void and microcracks, thereby creating crystallization pressure. Drawing stress between steel fiber and shotcrete could evidently absorb the expansion stress and crystallization pressure. Consequently, steel fiber could improve shotcrete corrosion resistance.

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* Corresponding author.

E-mail address: wangjiabin@xatu.edu.cn (J. Wang).

1. Introduction

Shotcrete is a type of concrete that is transported under pressure through a pneumatic hose or pipe and projected into place at high velocity with simultaneous compaction [1,2]. In comparison with ordinary concrete without an accelerator, accelerated shotcrete has a short final setting time and high early-age mechanical properties [3,4]. Shotcrete was first used as part of the lining structures in the municipal tunnel of Frankfurt and Munich in 1970; since then, it has been widely used in different fields, such as tunnel support, rapid repair, slope support, gas and oil wells, and other underground structures [5–7].

Salt lake and saline soil are widely distributed in Western China. High concentration of chlorine salt, sulfate magnesium salt, carbonate, and other corrosive salts in lake water, soil, and underground water is the leading cause to the deteriorated performance of concrete and corrosion of reinforcement [8]. Portlandite, calcium aluminate hydrate (CAH), and calcium–silicate–hydrate (C–S–H) gel, which are mainly the mineral phase of concrete hydration products, react with sulfate and magnesium to form ettringite, gypsum, and brucite. Furthermore, sodium and magnesium are combined with sulfate and chloride to form crystal salts, such as $\text{NaSO}_4 \cdot 10\text{H}_2\text{O}$, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, and NaCl, which produce high crystallization pressure [9]. Micropores and microcracks appear in interfacial transition zone (ITZ) and around aggregates. These effects pose a considerable threat to the safety and durability of concrete structures.

In the realm of design and construction of modern tunnel lining structures, the single-layer lining structure of shotcrete is the trend for future development [10,11]. In salt lake environment, shotcrete lining structures are in contact with rock interstitial water and groundwater, which is rich in chloride, sulfate, and magnesium, for long periods of time [12,13]. Moreover, pore solution moves directionally along the connected micropores because the other side of the lining structure is in contact with air in the tunnel, which has low humidity. Therefore, shotcrete lining structure is subjected to dry–wet (D&W) alternate method, which causes corrosion ions to diffuse into shotcrete rapidly and react with hydration products to form multiple types of corrosion products that produce expansion stress and cause cracks and spalling in the lining concrete [14–16].

Chloride diffusion, sulfate attack, and magnesium attack on normal concrete have received considerable attention. Tang [17,18] investigated the diffusion and migration of chloride ion based on diffusion kinetics and Fick's second law. The counter-electrical potential had a great influence on chloride diffusion, whereas the effect of activity coefficient was unimportant for sodium chloride and potassium chloride. The friction coefficient influenced chloride diffusion and migration. David et al. [19] established the comprehensive modeling of chloride and CO_2 diffusion considering the transfer of thermal, vapor, and liquid water. Goñi [20] studied the compressive strength and microstructure of concrete with chloride attack; the compressive strength of concrete increased due to ettringite and Friedel's salt that filled in the micropores, thereby decreasing the porosity.

In view of the aforementioned studies, concrete chloride attack is mainly achieved by chloride diffusion in concrete. However, as concrete is exposed to sulfate and magnesium attack, hydration products of portlandite, C–S–H gel, and calcium monosulfaluminate react with sulfate and magnesium to form ettringite and brucite [9]. In addition, thaumasite is also formed in carbonate concrete with sulfate attack. Zhang [21] established a numerical model to predict the degradation process of concrete subjected to sulfate attack and loading. The elastic modulus variation of concrete with sulfate attack included two stages, namely, the

enhancement stage of ettringite and weakening stage due to expansion. Similarly, Chen [22] proposed a chemo-mechanical model of damage in concrete under sulfate attack.

Yuan [23] analyzed the damage mechanism of concrete exposed to sodium sulfate and magnesium sulfate. The author demonstrated that the damage of concrete with sulfate sodium was more serious than that with magnesium sulfate. Meanwhile, Kunther [24] and Park [25] proposed that magnesium sulfate caused more surface damage than sodium sulfate due to magnesium silicate hydrate (M–S–H) formed under the reaction between C–S–H gel and magnesium. Magnesium sulfate also had a considerable effect on the reduction in compressive strength.

Regarding the durability influence of concrete on sulfate attack and chloride, the presence of sulfate in the composite solution with sulfate and chloride defers the ingress of chloride into concrete in the early exposure stage but accelerates it in the latter exposure stage [26–28]. The presence of chloride in the composite solution results in the retardation of concrete deterioration caused by sulfate. Chloride ion precedes sulfate ion that reacts with C_3A to form Friedel's salt because the diffusion velocity of chloride ion is faster than that of sulfate. In addition, chemical binding can occur between C_4AF and chloride.

In recent years, several researchers have investigated the sulfate attack of shotcrete. Wang [29] investigated the mechanical strength, damage depth, and the corrosion mechanism of shotcrete exposed to 10% Na_2SO_4 solution. The author found that shotcrete had excellent sulfate resistance due to a large amount of micropores in concrete formed by compressed air in spraying process. Ettringite and gypsum filled in micropores, and the density of shotcrete surface layer increased, which slowed down the corrosion reaction. Romer [30,31] surveyed some Swiss tunnel structures damaged by sulfate. Under the combined effect of ground water, sulfur from steam locomotive soot and automobile exhaust, and carbonate from rock fractured water, thaumasite was formed and exhibited a more notable damage than ettringite. Macro and microcracks appeared in shotcrete lining caused by rebar corrosion.

This study aims to investigate the durability performance and mechanism deterioration of shotcrete lining in a salt lake corrosion environment by using D&W alternate method for simulating the corrosion mode of tunnel lining; the shotcrete durability experiment is performed in composite solution of 5% Na_2SO_4 (in mass), 5% MgSO_4 , and 3.5% NaCl. Relative dynamic elastic modulus, mass change, and relative compressive strength and damage depth are measured. Thereafter, the mineral composition and microscopy of corrosion products are characterized using X-ray diffraction (XRD), thermogravimetric-differential scanning calorimetry (TG–DSC), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy. The air-void structure of hardened concrete has substantial effects on the mechanical properties and durability of concrete. Therefore, a high-resolution image analyzer that captures elaborate graphical layouts of air-void structure using the linear transverse method is employed. Finally, ion diffusion (including water-soluble sodium, chloride, and calcium ions, acid-soluble sulfate ion, and pH value of pore solution) in shotcrete is analyzed using electrochemical method.

2. Materials and experiments

2.1. Raw materials

The materials used to produce the shotcrete were as follows:

- Ordinary Portland cement P.O. 42.5 supplied by Baoji Conch Cement Co. Ltd. in compliance with Chinese Standard GB 175-2007 [32] (equivalent CEM II/A of EN 197-1 [33]);

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