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Influence of freeze–thaw cycles and sulfate corrosion resistance on shotcrete with and without steel fiber

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HIGHLIGHTS

- Durability of frost and sulfate resistance of shotcrete with and without steel fiber was tested.
- Original performances include relative dynamic elastic modulus and weight loss rate, and relative mechanical properties were measured.
- Damage mechanisms of shotcrete by freeze–thaw and sulfate attack were analyzed.
- Shotcrete had better durability than ordinary concrete, whereas steel fiber reinforced shotcrete had the best durability.

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ABSTRACT

Shotcrete with low-alkali accelerator has short final setting time, high early strength, and various hydration products and microstructures because of different hydration processes of ordinary concrete without accelerator. In tunnel operation processes, a shotcrete single-layer lining structure is subjected to positive and negative temperature alternation and corrosion ions, particularly sulfate ion. The durability and service life of the lining structure are seriously threatened.

In this study, the performances, including relative dynamic elastic modulus, mass loss ratio, and mechanical properties after corrosion, were tested to investigate the shotcrete durability of frost and sulfate resistance. Then, mineral composition, thermal analysis, pore structure, and microscope analysis of the specimen before and after corrosion were characterized. To achieve this objective, ordinary concrete and accelerated shotcrete with and without steel fiber were fabricated. Results showed that ordinary shotcrete was more durable under the action of freeze–thaw cycles and sulfate ion attack than that of the ordinary concrete with the same mixture. Thus, steel fiber led to a considerably dense microstructure in the shotcrete matrix, and it could significantly improve the early-age compressive and splitting tensile strengths. Steel fiber reinforced shotcrete had the best durability performance in frost and sulfate resistance.

1. Introduction

Shotcrete is concrete which is conveyed under pressure through a pneumatic hose or pipe and projected into place at high velocity, which simultaneous compaction, condensation, and hardening [1,2]. Unlike ordinary concrete without accelerator, accelerated shotcrete has short final setting time and high early-age mechanical properties [3,4]. Since shotcrete was used as a material in lining structures on the municipal tunnel of Frankfurt and Munich in 1970, shotcrete 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].

Shotcrete single-layer lining structure has become a trend in the design and construction of modern tunnel lining structures [8,9]. In cold environments, particularly in North China and plateau region, a shotcrete single-layer lining structure is subjected to low temperature. Positive and negative temperatures change alternatively; thus, the lining structure freezes and melts repeatedly for nearly 130 times per year. During the cyclical process of freezing and thawing, free water and capillary pore water in shotcrete undergo alternating positive and negative temperatures; moreover, the lining structure is damaged, and the durability of the structure decreases [10]. Otherwise, shotcrete lining structures in mountainous and saline soil environments contact with sulfate mineral-rich ground water for a long time. The shotcrete lining structure is subjected to dry–wet cycles because the other side of the lining structure contacts with air in the tunnel that has high

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temperature and humidity. These dry–wet cycles lead to rapid diffusion of sulfate ions into shotcrete, which combines with hydration products to form ettringite and gypsum. The corrosion products can produce expansion stress that causes lining concrete cracking and spalling [11,12].

In summary, lining structure disease in a tunnel operation process appears in terms of cracking, physical and chemical damages, seepage, and shotcrete spalling under the action of freezing and thawing cycles and sulfate attacks. Moreover, the lining structure durability and service life are seriously threatened [13]. Therefore, the durability of shotcrete single-lining structure must be examined.

Thus far, frost and sulfate resistances of a normal concrete have been investigated extensively [14,15]. However, hydration processes of products with added accelerator into concrete are different from those of normal concrete. Compressed air exists in shotcrete and is not timely discharged; thus, the isolating micropores form in shotcrete with 2.5–5.3% air content [16]. Therefore, the damage process in shotcrete is also different from that in normal concrete. In recent years, only a few studies on shotcrete durability have been conducted. Chen [17] analyzed the frost resistance of a C25 shotcrete. After 400 freeze–thaw cycles, the weight loss rate, relative dynamic modulus of elasticity, and compressive strength of this shotcrete are 3.1%, 22.5%, and 36.5, respectively. Park [18], Won [19], and Park [20] reported that the loss rate of the relative dynamic modulus of elasticity of shotcrete after 300 freeze–thaw cycles is not more than 1%. Lee [21] investigated the sulfate corrosion durability of shotcrete. After immersion for 360 days, the loss rate of compressive strength is more than 50%.

However, research on freeze–thaw cycles and sulfate corrosion on accelerated shotcrete was limited and unsystematic. The performances of a shotcrete after corrosion, including relative dynamic elastic modulus, mass loss rate, relative compressive and splitting tensile strengths, and damage layer thickness (only for sulfate attack), were tested to analyze the durability of the shotcrete single-layer lining structure. The aggressive mechanism of the shotcrete was also investigated through mineral composition measurement and thermal analysis, pore structure (only for freeze–thaw cycles), and microscope analysis of concrete specimens after corrosion.

2. Materials and experiments

2.1. Raw materials

Ordinary Portland cement PO. 42.5 and class II fly ash were used in this experiment. Their chemical composition and physical properties are listed in Table 1. The fine aggregate used in this study was natural river sand with fineness modulus of 3.4. Crushed limestone with continuous grading from 5 mm to 10 mm was used as course aggregate. Both aggregates complied with the GB50086-2001 requirement [22]. An accelerator and polycarboxylate-based superplasticizer were necessary to achieve shortened setting time and workability. Wave-shaped steel fiber with length, width, and aspect ratio of 30 mm, 2 mm, and 24.3, respectively, was adopted.

2.2. Specimen preparation

Three mix designs with a water-to-binder ratio (w/b) of 0.43, fly ash-to-cementitious material (cement and fly ash) ratio of 0.1, and sand-to-total aggregate ratio of 0.5 were used in this study. Mix C43F10 was ordinary concrete without accelerator, and mix S43F10 and S43F10SF50 were shotcrete with and without steel fiber of 50 kg/m^3. Table 2 lists the mix proportion details. In all mixtures, the mixing amount of superplasticizer and accelerator was 1% and 4%, respectively, of the cementitious material. The compressive and splitting tensile strengths of the concrete specimens with curing age are listed in Table 3.

Table 1
Chemical composition and physical properties of cement, fly ash, and accelerator.

	Cement	Fly ash	Accelerator
Chemical composition			
SiO_2	19.50	43.64	14.74
Al_2O_3	6.45	25.39	18.83
Fe_2O_3	3.08	4.19	4.17
CaO	57.57	5.62	32.72
MgO	1.21	0.84	0.64
SO_3	2.01	0.28	0.29
Alkali	1.14	1.80	10.47
f-CaO	0.81	0.46	–
Loss on ignition	4.12	3.0	–
Mineral composition			
C_3S	52.70	–	–
C_2S	23.04	–	–
C_3A	6.37	–	–
C_4AF	11.76	–	–
Physical properties			
Density/g·cm^{-3}	3.08	2.09	–
Blaine fineness/cm^2·g^{-1}	3340	4040	–

The concrete was first sprayed as large slabs with dimensions of 1 m × 0.5 m × 0.15 m using dry method (Fig. 1). The slab molds were oriented 75° to the ground, and the nozzle was oriented 90° relative to the bottom plate of the mold. The distance between the nozzle and the bottom of the mold ranged from 0.85 m to 1.2 m. After 3 h, the slabs that had formed were removed and placed into a tunnel for 7 d of curing. The large slabs were subsequently cut into standard cube specimens measuring 400 mm × 100 mm × 100 mm by using an automatic rock cutting machine. Then, prism specimens were cut into three cube specimens with lengths of 100 mm. Finally, the specimens were moisture-cured at 20 °C ± 2 °C and 95% relative humidity for 21 d and then dry-cured until testing.

2.3. Testing method

2.3.1. Freeze–thaw cycles

The freeze–thaw cycles of concrete was performed to evaluate frost resistance in accordance with ASTM C666-03 (2008) [23]. In the experiment, two sizes of specimen, that is, 400 × 100 × 100 m^3 and 100 × 100 × 100 m^3, were used. The temperature range in the examination was from 5 °C to −17 °C. After every 25 freezing and thawing cycles, the dynamic elasticity modulus, weight, and compressive and splitting tensile strengths were tested. The experiment was terminated when 300 freeze–thaw cycles were completed, and the result showed that 60% loss rate of relative dynamic elasticity modulus was reached, or 5% weight loss ratio was obtained.

2.3.2. Sulfate corrosion

An accelerated durability test was performed using a dry–wet cycle method to study the sulfate attack of shotcrete. The experiment was performed as follows. One dry–wet cycle included two steps. The specimens were initially immersed in 10% Na_2SO_4 solution for 16 h and then dried at 60 °C for 8 h. The experiment was subjected to five accelerated ages, including 15, 30, 60, 90, 120, and 150 cycles. At the end of each accelerated aging, relative dynamic elasticity modulus, weight loss rate, cubic compressive and splitting tensile strengths, and damage layer thickness were examined.