Construction and Building Materials 123 (2016) 346–356

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Damage layer thickness and formation mechanism of shotcrete with and without steel fiber under sulfate corrosion of dry–wet cycles by ultrasound plane testing method

Jiabin Wang [a], Ditao Niu [a,b,*], Zhanping Song [a]

[a] College of Civil Engineering, Xi'an University of Architecture and Technology, 710055 No. 13 Yanta Rd., Xi'an, Shaanxi, China
[b] Key Laboratory for Structural Engineering and Seismic Resistance of Ministry of Education, Xi'an University of Architecture and Technology, 710055, No. 13 Yanta Rd., Xi'an, Shaanxi, China

HIGHLIGHTS

- The damage layer thickness of shotcrete after sulfate attack was measured using ultrasound NDT.
- The relationship between damage layer thickness and ordinary performance of the corrosion specimen was calculated.
- The formation procedure of the damage layer was discussed by dividing it into three stages.
- The sulfate attack mechanism of shotcrete was researched using SEM-EDS, XRD, and TG-DSC.
- Steel fiber-reinforced shotcrete had improved sulfate resistance.

ARTICLE INFO

Article history:
Received 8 March 2016
Received in revised form 17 June 2016
Accepted 29 June 2016

Keywords:
Damage layer thickness
Sulfate attack
Dry–wet cycle
Shotcrete
Steel fiber
Ultrasound plan testing method

ABSTRACT

In recent years, nondestructive testing, especially ultrasound testing method, has been increasingly used to detect concrete strength, compactness, cracks, and other aspects. In this work, the damage layer, thickness measured by ultrasound plane testing method and the formation mechanism of the damage layer were studied. Simultaneously, the damage process and microstructure of shotcrete under multiple coupling effects of sulfate attack and cyclic drying and wetting were also investigated. The results indicated that ultrasound plane testing accurately characterizes the damage layer thickness of shotcrete with and without steel fiber. The variation in performance of the original specimen was significant with increased thickness. An exponential distribution existed between the damage layer thickness and the original performances expected weight loss ratio. In the corrosion process, sulfate ions were transported into micropores and microcracks layer by layer, and velocity was slowly diffused from a distance from the surface. For ordinary shotcrete, sulfate attack is divided into three stages: ettringite action, combined ettringite and gypsum action, and gypsum action. However, for steel fiber-reinforced shotcrete, sulfate attack only occurred at the combined ettringite and gypsum action.

1. Introduction

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

In the realm of design and construction of modern tunnel lining structures, shotcrete single-layer lining structure is regarded as the trend of future development [8,9]. In mountain and saline soil environments, shotcrete lining structures are in contact with rock interstitial water and groundwater, which is rich with sulfate minerals, for long periods [10,11]. At the same time, because the other side of the lining structure is in contact with air in the tunnel, which has high temperature and humidity, the shotcrete lining

* Corresponding author at: College of Civil Engineering, Xi'an University of Architecture and Technology, 710055 No. 13 Yanta Rd., Xi'an, Shaanxi, China.
E-mail address: niuditao@163.com (N. Ditao).

http://dx.doi.org/10.1016/j.conbuildmat.2016.06.146
0950-0618/

structure is subjected to dry–wet cycles that cause sulfate ions to rapidly diffuse into shotcrete and react with hydration products to form ettringite, thaumasite, and/or gypsum [12]. Corrosion products produce expansion stress, which cause lining concrete cracks and spalling [13–15].

The damage layer is a horizontal layer formed when concrete is exposed to an aggressive environment, such as fire, freezing and thawing cycle, sulfate attack, and other physical damage or chemical corrosion. The horizontal layer has different physical properties (e.g., high porosity, low strength, etc.) or chemistry performance (e.g., mineral composition, microscope, etc.). The thickness of the damage layer characterizes the level of specimen damage/corrosion. Usually, applying Huygen's principle, the thickness of the damage layer is measured and calculated using nondestructive methods of ultrasonic pulse velocity methods. The damage degree of concrete is easily obtained by this method, which detects the existing structure [16].

In recent years, nondestructive testing, especially ultrasound testing method, has been increasingly used to detect concrete strength, compactness, cracks, and other aspects [17]. Currently, the main evaluation indices that characterize the original performance of concrete under sulfate attack includes relative dynamic elastic modulus, weight loss ratio, and mechanical properties, such as compressive strength, splitting tensile or tensile strength, and flexural strength [18,19]. Compared with destructive testing, ultrasonic testing, which is a common type of nondestructive testing method, is the first choice for damage layer testing owing to portability of the instrument and its simple detection method [20]. In recent years, only a few investigations had been carried out on the damage layer of concrete after frost damage and/or sulfate attack [21–24]. However, research on damage layer and its shotcrete thickness under sulfate attack with cyclic drying and wetting cycles are confined and not a system.

The current study aims to identify the formation process of the damage layer; compare the thickness of damage layer in ordinary concrete, ordinary shotcrete, and steel fiber-reinforced shotcrete (SFRS); and determine the relationship between original performances and damage layer thickness. The experiment is assessed by altered depths, and the mineralogical and relative content are analyzed by X-ray diffraction and thermogravimetric (TG)–differential scanning calorimetry (DSC). The microscopic evolution of the damage layer is characterized by scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS).

2. Materials and experiments

2.1. Raw materials

PO 42.5 Ordinary Portland cement (OPC) and class II fly ash (F) complying with Chinese standard GB175-2007 [25] and GB/T 1596-2005 [26] were used in this experiment. The fine aggregate used in this study was from natural river sand with a fineness modulus of 3.5. The coarse aggregate used was gravel with continuous grading from 5 mm to 10 mm. Both aggregates complied with the GB 50086-2001 requirement [27]. The accelerator (A) used contained $NaAlO_2$ and Ca_2SiO_4 (C_2S) as major substances. The chemical characteristics of cement, fly ash, and accelerator are listed in Table 1. The physical properties of cementitious materials are listed in Table 2.

Table 2
Physical properties of cementitious materials.

Cementitious materials	Density (g/cm^3)	Blaine fineness (cm^2/g)	Compressive strength/MPa		Flexural strength/MPa	
			3 days	28 days	3 days	28 days
OPC	3.08	3340	29.8	56.0	6.21	8.20
F	2.09	4040	/	/	/	/

2.2. Specimen preparation

Experiment specimens were prepared with three mix proportions: (a) ordinary concrete without accelerator, (b) ordinary shotcrete, and (c) SFRS with 50 kg/m^3 steel fiber. The three mixtures are illustrated in Table 3. In all mixtures, the water-to-cementitious materials (cement and fly ash) ratio and dosage of fly ash were 0.43% and 10% respectively. The sand-to-total aggregate ratio of 0.50 and the mixing amount of water reducing and accelerator was 1% and 4% [3] of the cementitious material respectively. Compressive and splitting tensile strengths of the specimen for curing age are listed in Table 4.

The concrete was first sprayed as large slabs with dimensions of 1 m × 0.5 m × 0.15 m using the dry method. 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 (Fig. 1). After 3 h, slabs that had formed were removed and placed into a tunnel (17 °C and 75% relative humidity) for 7 d of curing. The large slabs were subsequently cut into standard cube specimens measuring 400 mm × 100 mm × 100 mm using an automatic rock-cutting machine. Afterwards, prism specimens were cut into three cube specimens with lengths of 100 mm. Finally, specimens were moisture cured at 20 ± 2 °C and 95% relative humidity for 21 days and then dry-cured until testing.

2.3. Testing method

2.3.1. Sulfate corrosion

An accelerated durability test was performed using a dry–wet cycle method to analyze the sulfate corrosion of shotcrete. The experiment was performed as follows: (a) one dry–wet cycle included two steps. The specimens were initially dried at 60 °C for 8 h and then immersed in 10% Na_2SO_4 solution for 16 h. (b) The experiment was subjected to five accelerated ages, including 15, 30, 60, 90, 120, and 150 cycles of drying and immersing. A temperature of 60 °C was preferred over 110 °C to stabilize ettringite in the samples, and 10% Na_2SO_4 concentration accelerated damage to the samples.

At the end of each accelerated aging, relative dynamic elasticity modulus, weight loss rate, cubic compressive, and splitting tensile strengths were examined. Dynamic elasticity modulus was characterized by using ultrasonic transit time. The testing method was accorded with reference [28]. The test procedures and calculation method of weight loss and strengths were according to the Chinese National Standard GB/T 50082-2009 [29] and GB/T 50081-2002 [30], respectively.

2.3.2. Damage layer thickness [16]

The transmitter sends the pules and, according to Huygen's principle, each point on a wavefront behaves as a point source for generating secondary spherical waves and creating a series of wavefronts. If the materials are uniform, a unique straight line is obtained in a time versus distance plot. If large heterogeneities are present, the plot deviates from this unique straight line as indicated in Fig. 2.

A series of receivers is placed on the specimen surface as shown in Fig. 3a. Owing to high porosity and other defects in the damage layer, wave velocity V_1 is lower than velocity V_2. At first, receivers close to the transmitter only sense the top layer, and the time versus distance plot is a straight line similar to Fig. 3(b) with slope $k_1 = 1/V_1$. However, as the distance increases, the influence from the lower layer is felt. Fig. 3(a) shows the case where the wave hits the interface at the critical incidence angle θ_{ic} and the refracted angle is parallel to the interface between the two materials. Applying Huygen's principle, the refracted wave generates secondary waves that reach the receiver before the direct arrival.

Table 1
Chemical composition of cementitious materials and accelerator (/%).

Raw materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	TiO_2	P_2O_5	f-CaO	Alkali	Cl^-	LI
OPC	19.50	6.45	3.08	57.57	1.21	2.01	0.34	0.43	0.81	1.14	0.007	4.12
F	43.64	25.39	4.19	5.62	0.84	0.28	1.15	0.20	0.46	1.80	0.011	3.0
A	14.74	18.83	4.17	32.72	0.64	0.29	1.48	0.30	/	10.47	0.30	/

Alkali content is the sum of $Na_2O + 0.658K_2O$.
OPC: ordinary Portland cement; F: fly ash; A: accelerator; LI: Loss ignition.