

Effect of temperatures on TSA in cement mortars under electrical field

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HIGHLIGHTS

- The deterioration of mortars exposed to different temperatures was studied.
- The damage of mortars under electrical field was more severe than immersed specimens.
- Electrical field accelerated the thaumasite form of sulfate attack (TSA).
- Thaumasite was detected after 120 d under electrical field at low temperatures.

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ABSTRACT

This study was aimed to investigate the effect of temperatures on thaumasite form of sulfate attack (TSA) in cement mortars under electrical field. The mortars were preserved at -5°C , 5°C , 20°C , $5^{\circ}\text{C}-20^{\circ}\text{C}$ cycles, respectively. The damages were visually observed and compressive strengths of specimens were tested on a regular basis. X-ray diffraction (XRD) and Fourier Transform Infrared Spectroscopy (FTIR) were carried out to analyze deteriorated products. The results indicated that the specimens at 20°C under both full-immersion and electrical field after 150 days were rarely damaged and thaumasite could not be detected. The failure of specimens at -5°C was mainly due to freezing-thawing and salt scaling, resulting superficial damage. Moreover, an electrical field accelerated the damage induced by sulfate attack in the mortars and the deterioration of specimens at 5°C was mostly due to the formation of TSA.

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1. Introduction

The thaumasite occurrence in deteriorated concrete was first described and reported by Stark and Erlin [1], since it has been recognised by concrete researchers as an unusual form of sulfate attack [2]. The TSA is potentially more serious than the traditional sulfate attack. Because the TSA is directly corroding the calcium silicate hydrates (C-S-H) in the hardened Portland cements, resulting in a loss of compressive strength and transformation of the cement paste into a mushy, incohesive mass [3,4].

The formation of thaumasite requires a source of calcium silicate, sulfate and carbonate ions, excess humidity and low temperature [5]. Thaumasite was preferentially formed and more stable at lower temperatures which were usually less than 15°C in some literatures [6–9]. It can also form at temperatures around 20°C , but the rate is much slower. Hartshorn et al. [10] suggested that the mortars stored in magnesium sulfate solution at 20°C

after a year eventually showed a mixture of gypsum and thaumasite to be products of sulfate attack. Gao et al. [11] found that thaumasite was formed in the mortars containing limestone filler after a year exposure to magnesium sulfate solutions at both 5°C and 20°C . Moreover, Pipilikaki et al. [12] studied the effect of temperature on thaumasite formation. The results indicated that thaumasite formation was related inversely to the stored temperature of the mortars. Nonetheless, thaumasite was not identified in the mortars immersed in a solution of 5% Na_2SO_4 at 20°C for a year.

In the recent years, the deterioration of concretes induced by TSA combined with other factors have been researched increasingly. Hill et al. [13] investigated the role of sulfuric acid in the thaumasite form of sulfate attack (TSA) of concrete at $4.5 \pm 0.5^{\circ}\text{C}$ and the results suggested that the presence of acid did not seem to promote the formation of thaumasite. Nehdi et al. [14] found that the deterioration of self-consolidating concrete (SCC) to sulfate attack coupled with frost action was more serious due to the formation of TSA. Moreover, Abdalkader et al. [15] confirmed that the deterioration of specimens preserved at 5°C was owing to thaumasite or thaumasite-ettringite formation, and the

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Table 1

Chemical components of clinker, gypsum, and limestone powder (wt%).

Materials	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	LOI
Clinker	19.99	2.98	4.80	61.22	3.27	0.18	0.88	0.23	3.52
Gypsum	4.47	0.36	0.99	34.05	1.84	0.08	0.23	40.61	16.87
Limestone powder	0.23	0.21	–	55.46	–	–	–	–	41.75

Table 2

The mix proportion of mortar.

Cementitious materials/g		Sand/g	Water/cementitious materials ratio
Cement	CaCO ₃ powder		
315	135	1350	0.5

concentration of chloride affected thaumasite degradation, accelerating the damage at 0.5% and mitigating it at 2% in the experiment. In particular, as the urban rail transit systems are developing rapidly in many countries worldwide, some surveys showed that more than ten cities in China have rail transit operation at present and about 40 cities will have subway by 2020, the total planning mileage will be 7000 kms which was 4.3 times of the current total mileage. Moreover, there were a large number of sulfate ions in groundwater and soil in western China and coastal areas (For example, the concentration of sulfate ions in groundwater of Chongqing was up to 2800 mg/L). The deterioration of reinforced concretes by chloride ions combined with stray currents (electrical field) have been researched and reported [16–18]. Therefore, it is necessary to research the failure of concrete subjected to stray current (electrical field) as well as coupled with sulfate attack. Luo et al. [19] studied the effect of electrical field on TSA failure of cement-based materials and confirmed that an electrical field can accelerate TSA failure in cement-based materials at 5 °C. However, there is a lack of the effect of temperatures on TSA failure of cement-based materials under electrical field.

Hence, the aim of this paper was to investigate the effect of temperatures on TSA in cement mortars under electrical field and analyzed the mechanism of TSA failure combined with electrical field at different temperatures.

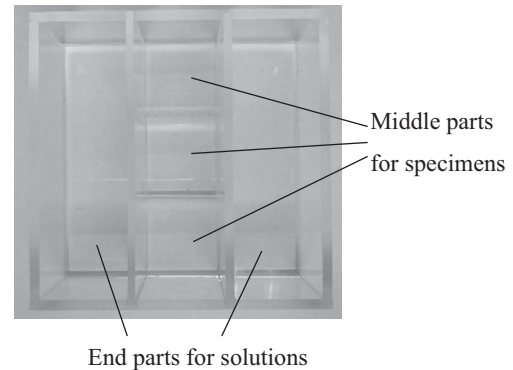
2. Materials and methods

2.1. Raw materials

The Portland cement (PC) used in this investigation was consisted of 95% of clinker and 5% of dihydrate gypsum by weight. Limestone powder with CaCO₃ ≥ 98 wt% was obtained from Bao Xing Company, Sichuan province China. The chemical components of the clinker, gypsum and limestone powder are listed in Table 1. Siliceous sand with the fineness modulus of 2.70 were used. Sodium sulfate (Na₂SO₄) and magnesium sulfate (MgSO₄) solutions with sulfate concentration of 33.8 g/L were used. Sodium sulfate (Na₂SO₄) and magnesium sulfate (MgSO₄) solutions were 50 g/L and 44.2 g/L respectively.

2.2. Experimental procedures

The mortars were produced with a cementitious materials-sand ratio of 1:3. The mix proportions are given in Table 2. Mortar mixtures were cast into the middle part of special molds (as shown in Fig. 1), which consist of three cube with dimensions of 40 mm × 4 mm × 40 mm. 1 d later, the specimens along with molds were cured in a moist room at a temperature of (20 ± 2) °C and with a relative humidity of above 95%. After additional 27 days of curing,

**Fig. 1.** Special mold.

all specimens were taken respectively at −5 °C, 5 °C, 20 °C, 5 °C–20 °C cycles for testing, the experiments of 5 °C–20 °C cycles meant that the specimens were tested circularly for a week at 5 °C environment and then a week at 20 °C environment. Then, the specimens at the temperatures were divided into two groups respectively. The control group was fully immersed in MgSO₄ solution, the other group was carried out for electrical field test in which that the cathode and anode solutions were Na₂SO₄ and MgSO₄ solutions, respectively [20]. The sulfate solutions were replaced every two weeks and the cracked molds were sealed with the supplementary Vaseline. The combined action test of sulfate attack and electrical field is shown schematically in Fig. 2. The electrical pulse field used in this paper was more similar to the stray current than direct current. The results from the previous study [21] indicated that the deterioration degrees were in inverse correlation with the period between 20 s and 40 s. Moreover, the deteriorations were more severe with the voltage values increasing, however, there was a report [22] showed that the maximum voltage drop of the stray current on the 1 km line is about 30 V. Therefore, the electrical voltage was 30 V, and the period was 20 s during which both the circulation and interruption periods were 10 s. The waveform of electrical pulses is shown in Fig. 3. The cryogenic equipment was used as shown in Fig. 4, which can adjust the temperature at 5 °C and −5 °C to reach the requirement in the experiment.

2.3. Test methods

A visual inspection of the specimens was implemented on a regular basis of 30 days to assess any visible changes and the damage grades were judged according to Table 3 [19,23]. Compressive strengths of the specimens were also evaluated in accordance with GB/T17671-1999 [24] by the test machine BC-300 produced by Beijing constant compressive technology Co. Ltd. Afterward, the attacked specimens from damaged surface of the cathodic mortars were taken for Fourier Transform Infrared Spectroscopy (FTIR) and X-ray diffraction (XRD) tests. Infrared Spectroscopy instrument with a resolution of 4 was used. The X-ray diffractometer used was from Ricoh Company with D/MAX-IIIC and CoKα radiation (0.2 Å).

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