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Review

Does concrete suffer sulfate salt weathering?

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HIGHLIGHTS

- Sulfate salt weathering of concrete is questioned in this review paper.
- The contradictions between test results and classic theory are extensively discussed.
- A viewpoint that chemical sulfate attack should still be the mechanism for concrete is deduced.
- Several issues needing further research are proposed to prove the above viewpoint.

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ABSTRACT

Due to several similarities in deterioration behavior between concrete and other porous materials, *sulfate salt weathering* is regularly considered to be the degradation mechanism causing the concrete deterioration in evaporation zone of partially buried concrete elements in the sulfate environment. This issue has received increasing attention in recent years.

However, according to an extensive literatures review on long term field and laboratory tests in this paper, the experimental results are clearly illogical and contradict with the classic theory of salt weathering of porous materials, such as (1) the sulfate crystals cannot be identified by means of micro-analysis methods in the damaged concrete as direct evidences for sulfate crystallization in concrete; (2) concrete is susceptible to deterioration in a high RH environment; (3) a mere change of cement compositions shows significant influence on concrete damage, however concrete damage is immune to pore structure change; and (4) the damaged concrete part does not contain the highest salt content, and so on. Instead, the experimental results support that the chemical sulfate attack should be still the mechanism causing the concrete deterioration.

Therefore, an adequate understanding of deterioration mechanism of concrete in the evaporation zone of partially buried concrete elements is quite urgent. In this paper, several issues aimed at the contradictions deduced from field and laboratory tests are proposed to attempt to seek the truth of *sulfate salt weathering of concrete*.

Contents

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1. Introduction

Concrete damage caused by sulfate attack is categorised into chemical or physical attacks in numerous literature sources [1]. The identified harmful sulfate salts are sodium, calcium, magnesium, potassium and ammonia sulfate. Sulfate attack has been considered the culprit of concrete damage for over 100 years [2]. However, this process is not adequately understood [3].

Chemical sulfate attack is considered a complex physicochemical process that consists of the formation of harmful products (such as ettringite, gypsum and thaumasite) via chemical reactions, which is accompanied by the physical crystal growth of these products [1]. The so-called physical sulfate attack, also called sulfate salt crystallisation or sulfate salt weathering, refers to the crystallisation of sulfates in the pores of concrete without chemical reactions. In 1996, Haynes et al. [4] stated that physical attack due to salt crystallisation in the pores has received little attention because the problem is often misidentified as sulfate attack. Only a few reports were available on this topic at that time [5,6]. Currently, physical sulfate attack on concrete is receiving increasing attention, and an increasing number of reports can be found in the literatures [7–20]. To enhance and intensify the research of this topic, the American Concrete Institute (ACI) created a new subcommittee named ACI 201-E: Salt Weathering/Physical Salt Attack in 2009. A new Chapter 8, "Physical Salt Attack" [21], was also separated from Chapter 6 "sulfate attack" of the 201.2R-08: Guide to Durable Concrete of the ACI 201 committee in 2010.

According to the definition cited in Chapter 8 [21], "physical salt attack is a deterioration mechanism caused by crystallisation of salts in pores near concrete evaporative surfaces. The mechanism is called physical salt attack because chemical reactions between concrete and crystallising salt are not involved. The most common salts linked to physical salt attack include sodium sulfate, sodium carbonate, and sodium chloride, in order of decreasing aggressiveness".

The physical effects of sodium carbonate and sodium chloride are well understood. However, Young found that the physical process of sodium sulfate does not take place without chemical changes. Furthermore, sulfate salt crystallisation – especially in cases where a portion of the relevant concrete structure is exposed to frequent temperature and humidity changes – is the result of a superposition of an upward flux of sulfate driven by capillary effects on regular sulfate attack [22]. According to Hime, this physical type of deterioration worsens as the concrete permeability decreases [23]. Numerous papers on stone deterioration due to sodium sulfate report that the presence of finer pores usually results in more deterioration. All of these findings suggest that a higher water-to-cement ratio (W/C) concrete should be used to prevent this type of attack. However, according to the results of long-term field experiments, the W/C ratio is the primary factor that affects the durability performance of concrete in contact with sulfate-containing soils. Applying a low W/C ratio increases the resistance to sulfate attack (see Section 2.1). Conversely, a micro-analysis of concrete damaged by so-called physical sulfate attack characterised by pure Na_2SO_4 efflorescence on its surface revealed clear signs of chemical and micro-structural changes, including low levels of calcium hydroxide, the presence of gypsum and magnesium silicate, and excessive amounts of ettringite [5,6,13,14,17,18].

Therefore, sulfate salt weathering may not be the cause of concrete damage. The contradictory observations obtained from the experimental research on the sulfate salt weathering of concrete are presented and discussed in Section 2 to provide an omni-faceted review. Section 3 presents the issues that require further research and the key factors to understand the actual mechanism of sulfate salt weathering.

2. Disputations of sulfate salt weathering of concrete

Thaulow and Sahu [11] categorised the mechanisms of physical sulfate attack on concrete into three groups according to previous papers:

- solid volume change during transformation of anhydrous salt into its hydrous form,
- salt hydration pressure,
- salt crystallization pressure.

However, based on the results of a theoretical analysis and experimental micro-analysis [24–28], salt crystallisation pressure is considered to be the relevant mechanism.

Salt scaling on concrete is also a type of physical attack, but salt scaling is identified as superficial damage caused by the freezing of a saline solution on the concrete surface. Scaling does not occur when the pool of solution is missing from the concrete surface [29,30]. Salt scaling clearly differs from salt crystallisation.

Generally, salt crystallisation has been extensively studied in the geology community, but instead of "salt crystallisation" the term "salt weathering" is commonly used by geologists [31] to describe the natural degradation of a porous stone near the Earth's surface [32]. The porous materials show deterioration, as indicated by the severe deterioration of parts of the porous materials in contact with relatively dry air near the Earth's surface, while the parts buried in the salt environment appear intact [32]. Because deterioration performances of concrete and stone are similar [21], the term "salt weathering" is also used in this paper.

2.1. Long term field tests

As already mentioned, Haynes et al. [4] indicated in 1996 that the so-called physical attack on concrete by sulfate crystallisation has not received due attention. However, a number of long-term field tests have been performed by the Portland Cement Associa-