



Effect of surface treatment on durability of concrete exposed to physical sulfate attack



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HIGHLIGHTS

- The resistance of concrete to physical sulfate attack was explored.
- Reducing the w/c ratio improved the resistance of concrete to physical sulfate attack.
- Epoxy and silane surface treatments protected concrete against physical sulfate attack.
- Bitumen surface treatment was adequate when concrete has been properly cured.
- Water-based solid acrylic resin did not provide adequate protection of concrete.

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ABSTRACT

Concrete exposed to sulfates in hot and arid regions can severely suffer from salt weathering. The resulting damage is typically localized at the above ground portion of concrete members. This process highly depends on the pore structure of the concrete surface through which salty water rises by capillary action. When water evaporates, salt crystals grow in the concrete surface pores leading to concrete damage. Thus, protecting the concrete surface can potentially enhance its durability to salt weathering. However, the vast variety of surface treatment compounds available makes the selection of an adequate material challenging. This is particularly true for concrete exposed to physical sulfate attack due to the lack of pertinent data in the open literature. Therefore, this study focuses primarily on assessing the effectiveness of different commercially available surface treatment materials in mitigating physical sulfate attack on concrete.

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1. Introduction

Damage of concrete due to salt crystallization has been described as a physical salt attack [1,18]. This type of attack can manifest itself in the form of surface deterioration of the above ground portion of concrete that is partially immersed in sulfate rich soil [1]. Several previous field investigations have reported concrete damage due to physical sulfate attack. For instance, in southern California, Novak and Colville [30] investigated the cause of damage in concrete floor slabs of 20–30 year-old homes located on sulfate rich soil. They insinuated that the cause of damage was mainly due to salt crystallization since none of the chemical sulfate products such as ettringite and gypsum were identified, yet salt minerals such as thenardite (Na_2SO_4) and mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) were found within cracks.

Another field study by Stark [37] showed extensive damage that was limited to the upper portions of concrete beam specimens half

embedded in sulfate rich soil, whereas the embedded portion was found in intact condition. In addition, damage escalated in the beam specimens made with higher w/c and when pozzolanic additives were included in the concrete mixtures. It was concluded that salt crystallization was responsible for the observed damage. Similar cases of deterioration were reported elsewhere including in the Arabian Gulf region, Japan, and Australia [2,21,43].

However, only limited studies have so far focused on physical sulfate attack. Indeed, the chemical form of sulfate attack was the main interest of previous research [10,17]. Moreover, cases of concrete damaged by physical sulfate attack were misidentified as chemical sulfate attack [25]. There have been several lawsuit cases in California related to sulfate attack on residential concrete foundations [16]. The main claim of the plaintiffs was that higher water-cement ratio (w/c) than what ACI 318 permits was used in the deteriorated foundations. Nevertheless, the analysis of hundreds of cores extracted from the deteriorated concrete did not show signs of chemical sulfate attack. Instead, signs of physical sulfate attack were found.

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Several researchers supported the separation of physical sulfate attack from chemical attack (e.g. Skalny et al. [36]) since their consequences are different. For instance, Haynes et al. [15]; Mehta [25]; Mehta and Monteiro [26] argued that salt weathering is a purely physical phenomenon, which has similar appearance to that of surface scaling caused by cycles of freezing and thawing. According to Mehta [25], physical sulfate attack mainly induces surface scaling in concrete above the ground level, while chemical sulfate attack consists of chemical reactions between sulfate ions and the cement paste components, leading to the formation of ettringite and gypsum.

Conversely, Skalny [35,36] suggested that the complete separation of physical and chemical sulfate attack is probably a wrong assumption and causes more confusion. They criticized characterizing the repeated expansion and contraction of sulfate minerals by the term physical. They suggested that the main process is the hydration and dehydration of sulfate minerals, which is similar to ettringite or gypsum formation.

However, the conversion of sulfate minerals from the hydrated to dehydrated form is not a necessary condition to cause damage since salt crystals can grow from a supersaturated solution and cause extensive damage [39]. Folliard and Sandberg [12] reported that concrete samples were extensively damaged when exposed to rapid crystallization of mirabilite through cooling, without transition to thenardite. Moreover, mirabilite crystals can also cause destructive damage when they grow from a supersaturated condition that results from thenardite dissolution rather than from the thenardite hydration Tsui [33,40]. Navarro and Doehne [28] observed this phenomenon using environmental scanning electron microscopy (ESEM). They reported dissolution of thenardite followed by mirabilite precipitation rather than thenardite hydration to form mirabilite. Thus, super-saturation appears to be an essential condition for crystal growth to apply destructive pressure [39].

Several factors can lead to super-saturation including evaporation, the rate of solution supply, and the type of salt. Previous study by Scherer [34] showed that damage of stone specimens occurred at the evaporation surface where the super-saturation was exceeded, which resulted in crystals precipitation in the sub-florescence zone. In this zone, crystals can grow below the external surface of a porous material when the evaporation rate is higher than the rate of water supply by capillary action, leading to salt crystallization and damage [34]. This was also observed by Haynes et al. [17] and Hartell et al. [14] in concrete partially immersed in sodium sulfate where damage was confined to the drying surface. Therefore, protecting the evaporation surface using surface treatment materials may mitigate the damage due to physical sulfate attack.

Concrete surface generally includes macro-pores and micro-cracks that provide paths for the ingress of harmful substances into the concrete, often leading to deterioration [1,38]. Thus, concrete protection can be provided using surface treatment materials, such as hydrophobic and film-forming coating materials that act as a barrier to isolate the concrete from its surrounding environment [1]. However, choosing an effective type of surface treatment material is a challenge since different types and formulations are commercially available [19]. In particular, only limited studies have focused on concrete exposed to physical sulfate attack [10,17,29]. Therefore, the main focus of this study is to assess the ability of different types of surface treatment materials to enhance the durability of concrete to physical sulfate attack.

2. Research significance

Protecting the surface of concrete can be essential for improving its durability under certain exposure conditions. However, different types of surface treatment materials are commercially

available, which makes it difficult to identify the appropriate type, especially in the case of concrete exposed to physical sulfate attack. Therefore, this study focuses on evaluating the effects of coating the surface of concrete with different types of commercially available surface treatment materials on its resistance to physical sulfate attack. The results could provide guidance to avoiding many law suits related to physical sulfate attack damage of concrete.

3. Experimental program

Sixty concrete cylinders 100 mm (4 in.) diameter and 200 mm height (8 in.) in size were cast according to [4]. Super-plasticizer was used to control the slump (14 cm). Table 1 summarizes the concrete mixture compositions. Physical and chemical properties of the used cement and fly ash are illustrated in Tables 2. The coarse aggregate was river gravel, with 19 mm (0.7 in.) maximum particle size.

Generally, sulfate attack on concrete structures exposed to sulfate rich-soil can start at early-age. In addition, most cast in-situ concrete structures are not cured for 28 days and are usually surface coated at early-age to accelerate the construction process. Therefore, in this study, concrete cylinders were de-molded after 24 h from casting and divided into two groups. The first group was kept at ambient laboratory temperature (20 °C [68 °F]–23 °C [73 °F]) for 72 h before coating, while the other group was cured for 28 days before coating and exposure to the sulfate environment. The curing was carried out according to [5].

Two application layers of four different types of surface treatment materials were tested, namely (a) silane, which is a hydrophobic penetrating sealer (water-repellent), (b) epoxy, which acts as a membrane coating, (c) bitumen modified polyurethane, which is a waterproof membrane, and (d) water-based solid acrylic polymer resin, which is a curing and surface sealer compound.

Fig. 1 illustrates a schematic of concrete surface pore structure and the proposed protection mechanism provided by each of the four surface treatment materials. After coatings have dried, cylinders were partially immersed (40% of the sample submerged) in a 5% sodium sulfate solution and placed inside a walk-in environmental chamber with cycling temperature and relative humidity. Previous study by Haynes et al. [17] found that the surface scaling escalated drastically when the concrete was exposed to cyclic temperature and RH consisting of two weeks at temperature = 20 °C [68 °F] and RH = 82% followed by two weeks at temperature = 40 °C [104 °F] and RH = 31%. Therefore, to accelerate the experiment, cycles were reduced to one week at temperature = 20 °C [68 °F] and RH = 82% followed by one week at temperature = 40 °C [104 °F] and RH = 31%.

Table 1
Proportions of tested concrete mixtures.

Ingredient	Mixture 1	Mixture 2
Cement (kg)	300	263
Fly ash (kg)	100	87
Coarse aggregate (kg)	1110	1110
Fine aggregate (kg)	705	754
w/c	0.45	0.60
Superplasticizer (ml/m ³)	900	–

Table 2
Physical and chemical properties of cement and fly ash.

Components/property	Type (10) cement	Fly ash
Silicon oxide (SiO ₂) (%)	19.60	43.39
Aluminum oxide (Al ₂ O ₃) (%)	4.80	22.08
Ferric oxide (Fe ₂ O ₃) (%)	3.30	7.74
Calcium oxide (CaO) (%)	61.50	15.63
Magnesium oxide (MgO) (%)	3.00	–
Sulfur trioxide (SO ₃) (%)	3.50	1.72
Loss on ignition (%)	1.90	1.17
Insoluble residue (%)	0.44	–
Equivalent alkalis (%)	0.70	–
Tricalcium silicate (C ₃ S) (%)	55.00	–
Dicalcium silicate (C ₂ S) (%)	15.00	–
Tricalcium aluminate (C ₃ A) (%)	7.00	–
Tetracalcium aluminoferrite (C ₄ AF) (%)	10.00	–
Blaine Fineness (m ² /kg)	371.00	–
Autoclave expansion (%)	0.09	–
Compressive strength 28 days (MPa)	40.90	–
Specific gravity	3.15	2.50
Initial time of setting (min) by Vicat needle	104	–

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