



Behavior of mortar exposed to different exposure conditions of sulfate attack

Xiao-tong Yu^a, Da Chen^{a,*}, Jia-rui Feng^a, Yan Zhang^b, Ying-di Liao^a

^a College of Harbour, Coastal and Offshore Engineering, Hohai University, Nanjing, 210098, China

^b College of Mechanics and Materials, Hohai University, Nanjing, 210098, China

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ABSTRACT

The sulfate deterioration of cement-based materials has become severe durability problems for the offshore structures. Considering the various service conditions such as splash and tidal zone with/without sulfate attack, the behavior of mortar samples under full immersion and dry-wetting cycles with 0% and 5% Na₂SO₄ solution, i.e., four exposure conditions, was investigated in this research. Compressive strength, elastic modulus, permeability (water permeability coefficient), expansion behavior and SEM images were tested and analyzed. The results showed that the behavior of mortar evolved in two stages, initial improvement followed by later degradation, determined by two competitive effects under each condition. Different deterioration mechanisms worked in the different exposure conditions. We proposed binomial formulas to describe the evolutions of the compressive strength and water permeability, and we further applied them in other researches well. Meanwhile, there was a linear relationship between elastic modulus and square root of compressive strength. Furthermore, the relation between water permeability and compressive strength was highly dependent on exposure types and time. Study showed that compressive strength and water permeability coefficient can be selected as controlling parameters in in-situ tests, and a possible approach to evaluate the sulfate deterioration level of concrete structures in-situ was represented.

1. Introduction

Cement-based materials have been widely applied in marine and offshore engineering (say piers, abutments and offshore turbines) due to their good performance and low cost. However, the aggressive marine environment causes serious durability problems on them, shortening the service life (Yu et al., 2017). The detrimental ions in seawater, like Cl⁻ (chloride ions), SO₄²⁻ (sulfate ions), Mg²⁺ (magnesium ions), induced reinforcement corrosion and concrete deterioration (Glasser et al., 2008). While the temperature and humidity changes in splash and tidal zones further aggravate the durability (de Medeiros-Junior et al., 2015). Compared with the indirect effect from chloride ions, sulfate ions deteriorate the concrete directly through reacting with cement hydration products (Yin et al., 2017). And it is an adverse environmental factor in the service of concrete structures, second to reinforcement corrosion (Ghafoori et al., 2015). According to the deterioration features in different exposure conditions, there are chemical attack and physical attack. In chemical sulfate attack, sulfate ions penetrate into internal pores and react with cement hydration products to form expansive products (ettringite, gypsum or thaumasite), leading expansion,

cracking, softening and degradation of concrete (Whittaker and Black, 2015). In physical sulfate attack (PSA), also termed as salt weathering, humidity and temperature changes induce sulfate salt crystalline and pressures against pore wall, causing surface scaling and flaking of concrete (Haynes et al., 2008). In marine environment, both attacks might happen simultaneously to concrete structures. For instance, the structure foundations sited in sulfate-bearing ground and seawater suffer from the chemical sulfate attack under the water level. Whereas parts of them undergo physical sulfate attack from dry-wetting cycles in splash and tidal zone (Yoshida et al., 2010). Thus, it is essential to investigate the behavior of cement-based material under different exposure conditions of sulfate attack, for the sulfate deterioration assessment of structures serving in marine environment.

So far, chemical sulfate attack, in form of full-immersion in sulfate solutions, on cement-based materials has been paid much attention. Experimental results reveal the expansion and degradation mechanism (Whittaker and Black, 2015; Lothenbach et al., 2010; Rozière et al., 2009). Various affecting factors, e.g., water-cement ratio, cement type, sulfate types, temperature, pH, on the deterioration process have been investigated (Santhanam et al., 2002; Wee et al., 2000; Monteiro and

* Corresponding author.

E-mail address: chenda@hhu.edu.cn (D. Chen).

Kurtis, 2003). Further, diffusion - chemo - mechanical models considering sulfate ions diffusion, chemical reactions and mechanical damages are established (Bary, 2008; Tixier and Mobasher, 2003). PSA on concrete was often overlooked and received little attention until recent years (Haynes et al., 1996). Many long-term field tests showed that the concrete foundation parts exposed to air were severely deteriorated, and various efflorescence salts remained on the evaporating surface (Stark, 1989; Li et al., 1995). In laboratory tests, two exposure regimes are often applied, one is partial immersion in sulfate solution with cyclic temperature and humidity condition (Haynes et al., 2008; Bassuoni and Rahman, 2016; Nehdi et al., 2014; Aye and Oguchi, 2011), the other is full-immersion in sulfate solution under dry-wetting cycles (Sahmaran et al., 2007; Yuan et al., 2016).

Currently, the performance of concrete subjected different sulfate environments is receiving increasingly attention. Also, the concrete resistances have been modified using fly ash, silica fume, blast furnace slag, nanoparticles for those exposure conditions (Bassuoni and Rahman, 2016; Nehdi et al., 2014; Nehdi and Hayek, 2005). Jiang et al. (2014); Jiang and Niu, (2016) explored the effect of solution concentrations and sulfate types on the deterioration process of concrete subjected to dry-wetting cycles in different sulfate solutions. Haynes et al. (2008) submerged concrete samples partially in 5% Na₂SO₄ solutions with temperature and humidity cycles simulating 5 ambient exposures. Aye and Oguchi (2011) investigated the resistance of cement mortar blended with pozzolans in 10% Na₂SO₄/MgSO₄ solutions under four exposure conditions, including full-immersion and partial-immersion at constant temperature/dry-wetting cycles. However, the mentioned exposure conditions are always the coupled actions between sulfate immersion and dry-wetting cycles, the comparisons between individual effect of immersion and dry-wetting cycling on the behavior of concrete is limited in literature. In dry-wetting process, drying removes water in concrete and leads shrinkage and microcracks (Hansen, 2010). Though re-wetting regains water, some microstructural changes and microcracks in the previous drying are irreversible (Wu et al., 2017). Such effect should not be ignored in the coupled action. In addition, establishing the real sulfate deterioration level in-site is a hot topic for scientists. However, few researches above concern the damage evaluation of concrete structures on spot. It is essential to extend those experimental and modelling results to the practical assessment for deteriorated concrete.

The permeability of concrete controls the transport of aggressive ions/water, primarily affecting the structure durability in severe environments. Permeability has been suggested to be taken into account for mix design and quality control of concrete (Aldea et al., 1999). Nevertheless, the evolutions of water permeability of concrete subjected to sulfate exposures are rarely reported (Hadjasadok et al., 2012). In our study, besides the mechanical properties (compressive strength, static elastic modulus), expansion behavior and SEM images, the permeability (water permeability coefficient) of the deteriorated mortar (susceptible matrix of concrete) was tested and analyzed. The samples were prepared under 4 different exposure conditions, i.e., full-immersion and dry-wetting cycles in 0% and 5% Na₂SO₄ solutions up to 270 days. The deterioration mechanisms and property evolutions were then discussed and described by binomial functions. Finally, we proposed a possible solution to establish real sulfate deterioration level in-situ.

Table 1
Chemical compositions and mineral compositions of the OPC.

Chemical compositions (%)									Mineral compositions (%)			
SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	SO ₃	K ₂ O	Na ₂ O	TiO ₂	C ₃ S	C ₂ S	C ₃ A	C ₄ AF
21.35	4.94	60.16	2.71	0.46	1.96	0.48	1.00	0.15	60.74	16.18	6.66	14.17

Table 2
Particle size distribution and the physical properties of the fine aggregate.

Sieve size (mm)	Cumulative pass amount (%)
5	100
4.75	100
2.36	100
1.18	75.7
0.6	46.2
0.3	36.1
0.15	9.0
Fineness modulus	2.33
Physical properties	
Specific gravity (kg/m ³)	2590
Apparent density (kg/m ³)	2608
Bulk density (kg/m ³)	1438
Water absorption (%)	0.64

2. Experimental procedure

2.1. Materials and samples preparation

The Ordinary Portland cement (P.O. 42.5) supplied by Anhui Conch Cement Company, China was used in this study. The chemical compositions and the mineral compositions are presented in Table 1. The ISO standard sand complying with GB 178-1977 (SAC, 2006) was used as fine aggregate. Its particle size distribution and physical properties are given in Table 2. The mortar mixture was prepared with the water/cement ratio of 1:2 and cement/sand ratio of 1:3. The mixture proportion is shown in Table 3.

Cylinders (Φ 50 mm \times 100 mm) and prismatic bars (25 mm \times 25 mm \times 285 mm) were prepared. The mortar was prepared in cement mixer as follows:

- (1) The cement and fine aggregates were premixed for 0.5 min.
- (2) The entire amount of water was added and mixed for 1 min.
- (3) After a pause for 1 min, the mortar mixture was mixed against for 2 min.
- (4) The fresh mortar was filled into the mold by three times.
- (5) The fresh samples were compacted by a mechanical vibrating table for 2–3 min at a frequency of 50 Hz and the vibration amplitude of 0.5 mm.
- (6) After compacting, the samples were cured at 23 °C for 24 h in molds covered with polyethylene film to prevent moisture loss.
- (7) After 1 day, the samples were demolded and transferred to a standard curing box (20 \pm 2 °C and 95 \pm 3% RH) for 28 days according to ASTM C192 (ASTM, 2007).

2.2. Exposure conditions

After the standard curing of 28 days, the mortar samples were divided into 4 groups and subjected to 4 different exposure (list in Table 4) conditions up to 270 days. The solutions were refreshed every 2 months.

There were various dry-wetting cycles in the literature (Nehdi et al., 2014; Sahmaran et al., 2007; Wu et al., 2017). The dry-wetting cycles of this study were referred to GB/T 50082-2009 (SAC, 2010), A CABR-LSB/ldry-wetting machine designed in accordance with this code

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