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Study on the mechanical properties of the mortars exposed to the sulfate attack of different concentrations under the triaxial compression with constant confining pressure

Da Chen *, Xiaotong Yu, Mengyuan Guo, Yingdi Liao, Feng Ouyang

College of Harbor, Coastal and Offshore Engineering, Hohai University, Nanjing, Jiangsu 210098, China

HIGHLIGHTS

- Failure mode, crack angle of the sample stored in Na_2SO_4 solution has no difference.
- Mechanical properties in high sulfate concentration increased, then rapidly reduce.
- Sample under the confining pressure exhibited the better mechanical properties.
- Cohesion in Mohr-Coulomb criterion related with the exposure day and concentration.
- Functional parameters in Willam-Warnke criterion largely depended on the immersion period.

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ABSTRACT

The ingress of sulfate ion and mechanical load are two main reasons to induce the degradation of the properties in the marine structures. In this study, the mechanical properties of the samples exposed to sodium sulfate (Na_2SO_4) solution under the triaxial compression with three confining pressures were tested. Mohr-Coulomb, Willam-Warnke criteria were used to calibrate the mechanical properties of the sample. The concentration of Na_2SO_4 solution had no significant effect on the failure mode and the angle of the crack. The sample immersed in Na_2SO_4 solution of high concentration had a larger stress, a low strain, a fast increase rate in the mechanical properties and a short time to reach the ultimate mechanical properties at initial stage. Beyond an immersion time, sulfate attack of high concentration caused a rapid reduction in the stress, a low mechanical properties and strain. The increase of the confining pressure changed the failure mode, increased the angle of the crack. The sample in the high confining pressure had larger stress and mechanical properties, low strain. The cohesion in Mohr-Coulomb criterion had the relationships with the day of exposure and the concentration of Na_2SO_4 solution. The parameters in Willam-Warnke criterion were dependent on the immersion period.

1. Introduction

In recent years, with the increase of the marine sense in many countries around the world, more and more cement-based materials were used in the marine engineering structure. The durability of the cement-based materials in the marine environment has become a major concerned problem in the development of the sustainable engineering [1].

It is well known that the marine environment contains a large number of sulfate ions. Sulfate ions from seawater had been recognized as one of the major causes to induce the degradation in the properties of the cement-based materials [2–4].

A number of previous studies had shown that sulfate attack on the cement-based materials is a complicated chemical process [5]. Many factors, i.e. the concentration of sulfate solution, the temperature of exposure, the pH of the solution, may affect the evolution of the properties of the cement-based materials [6]. Biczok found that, for the cement-based materials by sulfate attack, with the change in the concentration of the sulfate solution, the corrosion products had obvious difference. At the low and the intermediate concentration of sulfate solution, the primary product was ettringite, gypsum and ettringite. While at the high concentration of sulfate attack, gypsum and magnesium corrosion were the main corrosion products [7], the sulfate solution of the high concentration

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

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also accelerated the reaction between sulfate ions and cement hydration products [8–10]. Moreover, the high temperature of exposure could improve the resistance of the concrete to sulfate attack [11–13]. Besides, the increase in the pH of the solution resulted in a low rate of expansion for the mortar bar [14]. It is noteworthy that, for the cement-based materials under the natural field condition, in addition to sulfate attack by surrounding environments, the cement- based materials also bear the function of the multiaxial load. The evolution in the properties of the cement-based material not only had relationship with sulfate attack, but also depended on subjected to mechanical load [15]. The further study on the evolution of the properties in the cement-based materials under sulfate attack and mechanical load will provide a valuable help for the marine structure designs.

Over the last three decades, much attention had been paid to the evolution of the properties of the cement-based materials subjected to sulfate attack and mechanical load. The researches made by Xiong and Yu, Liu et al. [16,17] showed that, under uniaxial compression test, the compressive strength of the mortar with high water/cement ratio was more sensitive to the strain peak value than that with lower high water/cement ratio. The sensitivity degree of the strain and the compressive strength peak value of the mortar increased under sulfate attack. Liao et al. [18] studied the mechanical behavior of the mortar subjected to wet-dry cycles under sulfate solution and uniaxial compression, it found that the mortar subjected to wet-dry cycles and sulfate attack had more severely damaged than that only stored in the sulfate solution. The increase in the time of the wet-dry cycles resulted in an increase in the ultimate compressive strength, the static elastic modulus and the mass of the sample, a decrease in the corresponding strain peak value. Also, with the further increase in the days of wet-dry cycles, a reduction in the mechanical properties and a high strain peak value could be found on the mortar sample. Chen et al. [19] found that the uniaxial compression controlled the micro-cracks on the surface void of the sample, the use of uniaxial compression load in the mortar promoted the nucleation of micro-cracks on the surface void of the mortar. Except for the compression load, the flexural load was also used to study the evolution of the properties of the cement-based materials under sulfate attack. Yu et al. and Zhu et al. [20,21] results showed that the level of the flexural load was an important factor for the evolution of the properties of the concrete, the presence of the dynamic flexural load in the concrete increased the diffusion rate, the penetration depth of sulfate ion and the amounts of sulfate corrosion products. As a result, the dynamic flexural load made the crack and the strength loss occurred earlier, especially at the high level of the dynamic flexural load. Gao et al. [22] assessed the deterioration behavior of the concrete exposed to sulfate attack under the flexural load and the wet-dry cycles, the test report showed that the deterioration of the concrete got aggravated as the flexural load level on the concrete increased, which was characterized by the fast reduction in the strength of the concrete. Schneider and Piasta [23] proposed that, under the sulfate attack, the time-dependent deformations, deformation recovery, residual strength of the concrete had a direct relationship with the level of flexural load, the sulfate corrosion for the concrete was accelerated by the high flexural load.

Up to now, although some research results about the effect of the sulfate attack and mechanical load on the mechanical properties of the cement-based materials had been established. However, these studies mainly focused on the mechanical behaviors of the cement-based materials acting in sulfate attack and uniaxial compression load or flexural load. There are few studies considering the mechanical properties of cement-based materials in the synergistic function of sulfate attack and multiaxial load, which is the working condition of the marine structures in theirs service life. Therefore, more studies need to carry out in these aspects. The study on the mechanical properties of the cement-based materials subjected to sulfate attack and multiaxial load will help us to better predict the ultimate state of stress in the marine structure. Moreover, these research results are very useful for us to establish the failure criterion of the cement-based materials, the incorporation of these failure criteria into the constitutive model can help us to provide more valuable information in the design of the marine structure.

In this study, the mortar samples with a water-to-cement ratio of 0.50 were prepared. After the samples cured at a standard curing box for 28 days, the samples were full-immersed in the tanks with Na_2SO_4 solutions of 0%, 5%, 15% up to 270 days. At a certain immersion period, the triaxial compression test was carried out on the samples with three confining pressures (0 MPa, 5 MPa, 15 MPa). The stress-strain curves of the samples were obtained. The failure modes, the static elastic modulus and the ultimate compressive strength of the mortar sample under sulfate attack and confining pressure were analyzed. Based on the experimental data, Mohr-Coulomb and Willam-Warnke failure criteria were used to calibrate the mechanical properties of the sample under sulfate attack and triaxial compression. The functional parameters in Mohr-Coulomb and Willam-Warnke failure criteria were obtained. A more comprehensive understanding about the mechanical behavior of the mortar under sulfate attack and multiaxial load was presented.

2. Experimental procedures

2.1. Materials

2.1.1. Cement

Ordinary Portland cement (OPC) complying with ASTM Type I was used as the cementing material in this study. The chemical compositions determined according to BS EN 197 [24] and the mineral compositions are presented in Table 1.

2.1.2. Fine aggregate

The ISO standard sand sourced from China was used as fine aggregate. The particle size distribution and the physical properties are given in Table 2.

2.2. Mix proportions

In this study, a total of eighty-four mortar mixtures were used. The mortar samples were prepared with a fixed cement content of 450 kg/m^3.The water-to-cement ratio (W/C) by weight is 0.5.The weight ratio of fine aggregates to-cement (F/C) was kept at 3. The mix proportion of the mortar mixture was shown in Table 3.

Table 1
The chemical compositions and the mineral compositions of the OPC.

Chemical compositions (%)									Mineral compositions (%)				
SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	TiO_2	C_3S	C_2S	C_3A	C_4AF	Loss
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	2.25