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Study on Damage Failure Criterion of Concrete under Sulfate Attack and Drying-Wetting Cycles

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Abstract
In order to effectively assess mechanical property of concrete exposed to sulfate solution under drying-wetting cycles, the degradation rule of mechanical property of concrete was studied under sulfate attack and drying-wetting cycles. Based on the damage mechanics and Ottosen failure model, the damage failure model of concrete under sulfate attack and drying-wetting cycles was established. The experimental results show that the axial compressive strength and elastic modulus of concrete decrease with increase of drying-wetting cycles, and the tensile and compressive meridian of concrete move to the hydrostatics compressive axis. Concrete failure surface shrinks gradually with the increase of damage and the crack-resistant property of concrete reduces. At the early stage of the sulfate attack, the shrinkage degree of concrete failure surface is smaller. With corrosion time increases, the shrinkage degree of concrete failure surface is accelerated, and the degradation degree of concrete increases. The tensile and compressive meridian of concrete is significantly dependent on the types of sulfate solutions. Compared with concrete in sodium sulfate solution, the shrinkage degree of concrete failure surface under magnesium sulfate solution is more obvious, indicating that the concrete deterioration by magnesium sulfate covers more aggressive corrosion.
Keywords: CONCRETE, DRYING-WETTING CYCLES, SULFATE ATTACK, DAMAGE, OTTOSEN FAILURE MODEL

1. Introduction

Sulfate attack on cement materials is one of the most severe problems affecting the durability and service life of concrete structures in the natural climate. Sulfate iron exists widely in our country, such as in seawater, groundwater, salt lake and sulfate soil, and there are more than 1000 salt lakes scattering in the Northwest of China. The deterioration of concrete caused by sulfate attack is a process from outside to inside, which can take the form of expansion, cracking, loss of strength of concrete, and the damage layer of concrete is formed from the outside to the inside, eventually lead to damage of concrete [1]. In sulfate environment, the elements of concrete construction situated in water table fluctuation, tidal zone and splash zone will suffer from more complex attack because of the drying-wetting cycles, which can accelerate the deterioration of concrete.

The damage caused by sulfate attack on concrete structures caused the attention of the scholars both at home and abroad early. After a long period of exploration research, both the domestic and foreign researchers already have a certain understanding to the mechanism, influence factors, the evaluation methods and evaluation indexes of sulfate attack. A variety of prediction model of sulfate attack were also proposed [2-6]. In view of the durability of concrete under sulfate attack and drying-wetting cycles, Jin [7] discussed the damage rule of ordinary concrete and high strength concrete exposed to sulfate solution under drying-wetting cycles by the view of the dynamic modulus of elastically loss of concrete. Qiao [8] investigated the flexural strength, compressive strength and dynamic modulus of elastically of concrete under sulfate attack. Dong [9] investigated the deterioration regularity of double-K fracture parameters of concrete subjected to drying-wetting cycles in sulfate solution by three-point bending test. Yuan [10] established the probability model of compressive strength of high-performance concrete exposed to the sulfate environment. Niu [11] discussed the damage mechanism of concrete under sulfate environment is analyzed by the view of the damage layer of concrete.

These researches have focused on the dynamic modulus of elastically and uniaxial compression characteristics of concrete subjected to drying-wetting cycles in sulfate solutions. However, concrete structures in the actual engineering projects were used under complex stress state, few studies have been conducted concerning the triaxial strength criterion of concrete under drying-wetting cycles and sulfate attack. Multiaxial strength criterion of concrete considering the three-dimensional stress, which could study the evaluation of durability of concrete structures under complex stress state effectively. The Ottosen four parameters model could comprehensively consider the characteristics of concrete damage surface. Therefore, the damage failure model of concrete under sulfate attack and drying-wetting cycles was established based on the damage mechanics and Ottosen failure model. It could provide theoretical basis for the structural calculation of concrete in sulfate environment.

2. Methodology

2.1. Materials and Mix Proportions

A Chinese standard Ordinary Portland Cement (OPC) of PO 42.5R produced by the Cement Factory of Tongchuan was adopted. Grade II fly ash from the Weihe Power Station, river sand with a fineness modulus of 2.69 and coarse aggregate of crushed basalt stone with a diameter of 5-16 mm were used in the test. A naphthalene-type superplasticizer was used, and the dosage was adjusted to keep the slump of fresh mixed concrete in the range of 50-120 mm. The tap water was adopted as mix water. The chemical composition of cement and fly ash is shown in Table 1. The mixture proportion and the mechanical property of the concrete are given in Table 2.

Table 1. Chemical composition of OPC and fly ash

Constituent (wt.%)	SiO_2	Al_2O_3	CaO	MgO	SO_3	Fe_2O_3
OPC	21.66	5.13	64.37	1.06	2.03	5.25
Fly ash	49.02	31.56	4.88	0.83	1.20	6.97

Table 2. Mixture proportion and mechanical property of concrete

	Fly ash content%	cementitious materials ($kg \cdot m^{-3}$)	Sand ($kg \cdot m^{-3}$)	Aggregate ($kg \cdot m^{-3}$)	Water ($kg \cdot m^{-3}$)	Superplas -ticizer %	Compressive strength/Mpa	splitting tensile strength /Mpa
							90d	90d
0.45	20	355	585	1300	160	0.5	61.6	6.34

2.2. Experiment Methods

The components of concrete mixture were batched by weigh, cement were premixed with fly ash, sand and coarse aggregate before adding the water and the admixtures for 1 min. Then, the entire amount of mixing water with the dissolved superplasticizer were added and mixed for 3 min. Finally, concrete mixture was mixed for an additional 2 min. The concrete specimens were cast in steel moulds and compacted on a vibration table. All specimens were demolded after 24 h of casting and cured in a condition of 20 ± 3℃ and 95% relative humidity until the age of testing.

At the age of 90 days curing, the concrete specimens exposed to drying-wetting cycles. Most researches have focused on raising the temperature of sulfate solution in the drying state to accelerate the damage process of concrete under sulfate attack. But the high temperature has a great influence on the quantity of corrosion products in concrete, probably altering the mechanism of sulfate attack. In this work, the drying state was natural drying in the air, which was more relevant to in-service conditions. One dry-wet cycle lasted 15 days. First, the specimens were continuously immersed in the test solution for 7 days, and then were moved into the air to dry naturally for another 8 days. Sodium sulfate and magnesium sulfate solution were chosen as attack solution, and the mass fraction was 10%. Specimens of 100mm×100mm×100mm cubes were used for the study of the compressive strength and the splitting tensile strength of concrete. Specimens of 100mm×100mm×300mm prisms were used for the uniaxial compression experiments.

3. Results and Discussion

3.1. Ottosen Failure Criteria of Concrete under Sulfate Attack

When concrete exposed to sulfate attack under drying-wetting cycles, the function relationship between the uniaxial strength and corrosion time is simple, and it is relatively easy to establish the strength damage condition. But in complex stress (biaxial and triaxial) conditions, the strength is more complex, including sulfate attack and multiaxial strength test. Therefore, it is difficult to build the strength damage condition. On the basis of existing test and classic failure criteria, the damage failure model of concrete under sulfate attack and drying-wetting cycles could be established.

So, the effective stress tensor $\bar{\sigma}$ described by Cauchy stress tensor σ and damage tensor $\boldsymbol{D}$**,** which can be written as

$$\bar{\sigma} = \sigma(I - D)^{-1} \quad (1)$$

where, I is the fourth-order tenstor;

$$D_{ijkl} = D_1\delta_{ij}\delta_{kl} + D_2\delta_{ik}\delta_{jl}$$

In the Canchy stress space, the damage surface equation of non-destructive concrete could be described by the first invariant stress tensor I_1, the second and third invariant deviatoric stress tensor J_2, J_3 can be expressed as [12]

$$f\left(I_1, J_2, J_3; a_i, i = 1,2,...\right) = 0 \quad (2)$$

Therefore, the equation of the concrete failure surface under sulfate attack and drying-wetting cycles in the Cauchy stress space can be expressed as

$$f\left(\overline{I_1}, \overline{J_2}, \overline{J_3}; a_i, i = 1,2,...\right) = 0 \quad (3)$$

Through the derivation, the stress invariants of the damaged concrete exposed to sulfate attack can be written as

$$\overline{I_1} = \alpha I_1,\ \overline{J_2} = \beta^2 J_2,\ \overline{J_3} = \beta^3 J_3,\ \bar{\theta} = \theta \quad (4)$$

where, $\alpha = \frac{1}{1-3D_1-D_2}$, $\beta = \frac{1}{1-D_2}$, which are damage parameters of concrete; D_1 and D_2 describe the volume injury and distortion injury of concrete, respectively.

The expression of D_1 and D_2 refer to the literature [12]

$$D_1 = \frac{\overline{E}(\nu - \overline{\nu})}{E(1+\overline{\nu})(1-2\overline{\nu})},\ D_2 = 1 - \frac{\overline{E}(1+\nu)}{E(1+\overline{\nu})} \quad (5)$$

where E and ν are the elastic modulus and Poisson's ratio of the non-destructive concrete, respectively; $\overline{E}$, $\overline{\nu}$ are the elastic modulus and Poisson's ratio of the damaged concrete under sulfate attack, respectively.

Through the derivation, α and β can be expressed as

$$\alpha = \frac{E(1+\overline{\nu})(1-2\overline{\nu})}{\overline{E}\left[(1+\nu)(1-2\overline{\nu})+3(\nu-\overline{\nu})\right]},\ \beta = \frac{E(1+\overline{\nu})}{\overline{E}(1+\nu)} \quad (6)$$

Therefore, the equation of the concrete failure surface under sulfate attack and drying-wetting cycles in the Cauchy stress space can be expressed as

$$\left(I_1, J_2, J_3; \overline{a}_i(D), i = 1,2,...\right) = 0 \quad (7)$$

In the four parameters of concrete damage criterion, the Ottosen criterion is proposed based on the triangle function, which can reflect the main characteristics of the concrete failure surface. Therefore, the Ottosen four parameters model is adopted to establish the triaxial strength criteria of concrete after suffering from sulfate corrosion under drying-wetting cycles. The Ottosen four parameters model including I_1, J_2 and $\cos 3\theta$, which can be expressed as [13]

$$f\left(I_1, J_2, \cos 3\theta\right) = a\frac{J_2}{f_c^2} + \lambda\frac{\sqrt{J_2}}{f_c} + b\frac{I_1}{f_c} - 1 = 0 \quad (8)$$

According to the assumption of membrane analogy, λ can be expressed as

$$\begin{cases} \lambda = k_1 \cos\left[\frac{1}{3}\arccos(k_2 \cos 3\theta)\right], & \cos 3\theta \geq 0 \\ \lambda = k_1 \cos\left[\frac{\pi}{3} - \frac{1}{3}\arccos(-k_2 \cos 3\theta)\right], & \cos 3\theta < 0 \end{cases}$$

where k_1 is the size coefficient; k_2 is the type coefficient; θ is the lode angle; λ function is used to determine the partial plane destruction graphics; f_c is the uniaxial compressive strength of concrete. Parameters a, b, k_1 and k_2 are calculated and determined by the test.

According to Eq. (7), the Ottosen parameters model after sulfate corrosion can be expressed as

$$f\left(\overline{I_1}, \overline{J_2}, \cos 3\overline{\theta}\right) = a\frac{\overline{J_2}}{f_c^2} + \overline{\lambda}\frac{\sqrt{\overline{J_2}}}{f_c} + b\frac{\overline{I_1}}{f_c} - 1 = 0 \quad (9)$$

After the above derivation, the Ottosen four parameters damage failure model of concrete under sulfate attack and drying-wetting cycles can be expressed as

$$f\left(I_1, J_2, \cos 3\theta; D_1, D_2\right) = a\frac{\beta^2 J_2}{f_c^2} + \lambda\frac{\beta\sqrt{J_2}}{f_c} + b\frac{\alpha I_1}{f_c} - 1 = 0 \quad (10)$$

By using large electro-hydraulic servo universal testing machine (as shown in Fig.1), the uniaxial compression behavior of concrete subjected to 0, 8, 16, 20, 24 drying-wetting cycles in 10%Na_2SO_4 solution and 10%$MgSO_4$ solution were studied. The peak stress, peak strain and elastic modulus of concrete under sulfate attack and drying-wetting cycles were obtained, which were shown in Table 3. The elasticity modulus value is the secant elastic modulus, which is calculated according to 50% of the peak stress and corresponding strain [14]. The experimental results show that the peak stress and elastic modulus of concrete decrease, the peak strain increases gradually with increase of drying-wetting cycles. This phenomenon is more obvious in magnesium sulfate solution, and the sulfate resistance of concrete is the worst.

Based on the regression of experimental data in table 3, the quantitative fitting equation of the concrete elastic modulus with the drying-wetting cycles number N is obtained.

Figure 1. Uniaxial compression test

in Na_2SO_4 solution

$$\overline{E} = E_0(1 + 0.0256N - 0.0016N^2) \quad (11)$$

in $MgSO_4$ solution

$$\overline{E} = E_0(1+0.0195N - 0.00153N^2) \quad (12)$$

The initial poisson's ratio of concrete is 0.20, and the Poisson's ratio considering the number of drying-wetting cycles N is expressed as [15]

$$\overline{\nu} = \frac{1}{2} - \frac{1-2\times 0.2}{2}[1+0.001N] \quad (13)$$

Table 3. Uniaxial compression test results of concrete under sulfate attack and drying-wetting cycles

Series	$10\%Na_2SO_4$					$10\%MgSO_4$			
Drying-wetting cycles	0	8	16	20	24	8	16	20	24
Peak stress/MPa	46.913	47.153	46.019	43.971	40.406	46.692	45.315	42.059	39.226
Peak strain/10^{-3}	1.64	1.67	1.73	1.8	1.91	1.69	1.77	1.85	2.01
Elasticity modulus /10^4MPa	4.72	5.255	4.625	4.171	3.257	5.04	4.33	3.635	2.811

3.2. Parameters Determination of Ottosen Failure Criteria

According to the test, the uniaxial compressive strength and the splitting tensile strength of concrete are 61.6 MPa and 6.34 MPa, respectively. The uniaxial tensile strength of concrete could be calculated by the equation $f_t = f_{sp} \times 1.369 \times f_c^{-0.0833}$ [14], which is 6.158 Mpa. Therefore, the nonlinear equations of the Ottosen strength criteria are written as

Uniaixal compression θ=60°

$$\frac{a}{3}+\frac{k_1\cos[\frac{\pi}{3}-\frac{1}{3}\arccos(k_2)]}{\sqrt{3}}-b-1=0 \quad (14)$$

Uniaixal tension θ=0°

$$\frac{a\times f_t^2}{3\times f_c^2}+\frac{k_1\cos[\frac{1}{3}\arccos(k_2)]\times f_t}{\sqrt{3}f_c}+\frac{b\times f_t}{f_c}-1=0 \quad (15)$$

Biaxial compression θ=0°

$$\frac{a\times 1.16^2}{3}+\frac{k_1\cos[\frac{1}{3}\arccos(k_2)]\times 1.16}{\sqrt{3}}-b\times 2\times 1.16-1=0 \quad (16)$$

Triaxial compression θ=60°

$$8a+2\sqrt{2}k_1\cos[\frac{\pi}{3}-\frac{1}{3}\arccos(k_2)]-5\sqrt{3}\times b-1=0 \quad (17)$$

Four parameters are obtained by solving the above nonlinear equations.

a=1.2783, b=3.2015, k_1=11.7486, k_2=0.9803

Therefore, the Ottosen failure criteria is written as

$$f\left(I_1,J_2,\cos 3\theta\right)=1.2783\times\frac{\beta^2 J_2}{f_c'^2}+\lambda\frac{\beta\sqrt{J_2}}{f_c'}+3.2015\times\frac{\alpha I_1}{f_c'}-1=0 \quad (18)$$

When $\cos 3\theta \geq 0$, $\lambda = 11.7486\times\cos\left[\frac{1}{3}\arccos(0.9803\times\cos 3\theta)\right]$

When $\cos 3\theta < 0$, $\lambda = 11.7486\times\cos\left[\frac{\pi}{3}-\frac{1}{3}\arccos(-0.9803\times\cos 3\theta)\right]$

3.3. Determining Tensile and Compressive Meridian

It is not easy to draw or understand the three dimentional stereogram of failure envelope surface. Therefore, the tensile and compressive meridian of concrete are commonly used in meridian plane. In order to describe the concrete failure surface under sulfate attack and drying-wetting cycles directly, the Haigh-Westergard coordinate (ρ, ξ, θ)is used to describe the envelope surface of the failure state of concrete, and the coordinate relationships are written as

$$\rho=\sqrt{2J_2}, \xi=\frac{I_1}{\sqrt{3}}, \cos 3\theta=\frac{\frac{3\sqrt{3}J_3}{3}}{2J_2^2}$$

The above coordinate relationships substituted into Eq. (18), and the tensile meridian and compressive meridian equation are written as

when θ=0°, λ=11.7228, the tensile meridian equation is written as

$$\frac{1.2783\beta^2}{2}\times(\frac{\rho}{f_c'})^2+\frac{11.7228\beta}{\sqrt{2}}\times\frac{\rho}{f_c'}+3.2015\times\sqrt{3}\times\alpha\times\frac{\xi}{f_c'}-1=0 \quad (19)$$

when θ=60°, λ=6.5352, the compressive meridian equation is written as

$$\frac{1.2783\beta^2}{2}\times(\frac{\rho}{f_c'})^2+\frac{6.5352\beta}{\sqrt{2}}\times\frac{\rho}{f_c'}+3.2015\times\sqrt{3}\times\alpha\times\frac{\xi}{f_c'}-1=0 \quad (20)$$

The elastic modulus degradation model (Eq. (11)-Eq. (12)) and the Poisson ratio degradation model (Eq. (13)) of concrete are substituted into Eq. (18), and D_1, D_2 are written as

in Na_2SO_4 solution

$$D_1=\frac{(1+0.0256N-0.0016N^2)\times 0.0003N}{(1.2-0.0003N)\times(0.6+0.0006N)}$$
$$D_2=1-\frac{(1+0.0256N-0.0016N^2)\times 1.2}{(1.2-0.0003N)} \qquad (21)$$

in $MgSO_4$ solution

$$D_1=\frac{(1+0.0195N-0.00153N^2)\times 0.0003N}{(1.2-0.0003N)\times(0.6+0.0006N)}$$
$$D_2=1-\frac{(1+0.0195N-0.00153N^2)\times 1.2}{(1.2-0.0003N)} \qquad (22)$$

According to the Eq. (19)-Eq. (20) and the expression of α and β. The tensile meridian and compressive meridian of concrete exposed to sulfate solutions under different drying-wetting cycles are drawn in Fig.2.

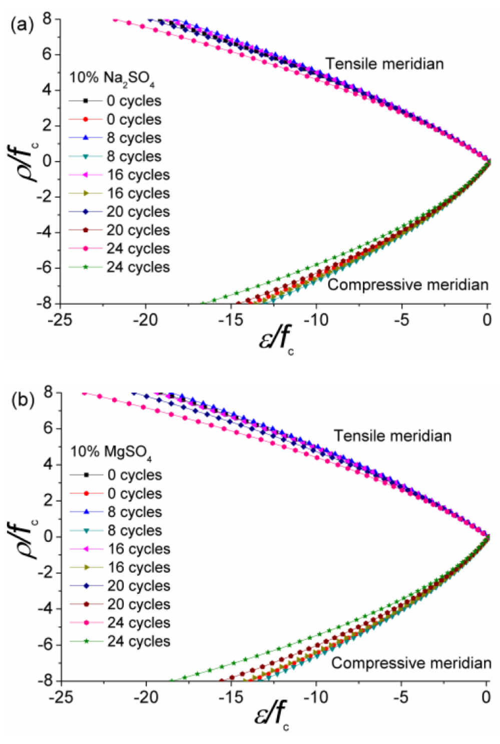

Figure 2. The tensile and compressive meridian of concrete under sulfate attack and drying-wetting cycles

It is clearly observed from Fig.2 that the tensile and compressive meridian of concrete move to the hydrostatics compressive axis with increase of drying-wetting cycles. Concrete failure surface shrinks gradually with the increase of damage and the crack-resistant property of concrete reduces. The tensile and compressive meridian of concrete is significantly dependent on the types of sulfate solutions. In the first 16 drying-wetting cycles, the shrinkage degree of concrete failure surface is smaller. This phenomenon is more obvious in magnesium sulfate solution, indicating that the damage deterioration of concrete is not obvious in the early stage of the corrosion time. With corrosion time increases, the shrinkage degree of concrete failure surface is accelerated, and the degradation degree of concrete increases. Compared with concrete in sodium sulfate solution, the shrinkage degree of concrete failure surface under magnesium sulfate solution is more obvious, indicating that the concrete deterioration by magnesium sulfate covers more aggressive corrosion. The reason is that magnesium sulfate reacts on all cement compounds, including calcium silicate hydrate (C-S-H). There occurs not only expansion due to the formation of gypsum and ettringite, but also intensive dissolution of cement hydrates, so the overall corrosive action of magnesium sulfate is greater.

Conclusions

1. Based on the damage mechanics and Ottosen failure model, the damage failure model of concrete under sulfate attack and drying-wetting cycles was established. This study could provide some reference for the study of the mechanical properties and durability evaluation of concrete structure in sulfate environment.

2. The axial compressive strength and elastic modulus of concrete decrease with increase of drying-wetting cycles, and the tensile and compressive meridian of concrete move to the hydrostatics compressive axis. Concrete failure surface shrinks gradually with the increase of damage and the crack-resistant property of concrete reduces. The damage deterioration of concrete is not obvious at the early stage of the sulfate attack. With corrosion time increases, the shrinkage degree of concrete failure surface is accelerated, and the degradation degree of concrete increases. The tensile and compressive meridian of concrete is significantly dependent on the types of sulfate solutions. Compared with concrete in sodium sulfate solution, the shrinkage degree of concrete failure surface under magnesium sulfate solution is more obvious, indicating that the concrete deterioration by magnesium sulfate covers more aggressive corrosion.

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