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Evolution model of concrete failure surface under coupling effect of seawater freeze-thaw and erosion

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Abstract: In order to effectively assess the mechanical properties of concrete with freeze-thaw and seawater erosion, tests about basic mechanical properties of concrete after freeze-thaw and seawater erosion are conducted based on the large-scale static and dynamic stiffness servo test set. 50, 100, 200 and 300 cycles of freeze-thaw cycling are made on normal concrete, and the artificial seawater is produced. The reasonable wet and dry accelerate system is selected. 10, 20, 30, 40, 50 and 60 cycles of wet and dry cycling are made to concrete after freeze-thaw cycling. The degeneration law of the concrete elastic modulus and compressive strength is studied. The Ottosen tri-axial strength criterion considering cycles of freeze-thaw and wet and dry cycling is deduced based on uniaxial mechanical properties of concrete and damage theory. Experimental results show that with the increase in the number of wet and dry cycles and freeze-thaw cycles, the concrete axial compressive strength and the elastic modulus decline gradually. Tensile and compressive meridians of concrete shrink gradually. The research can be referenced for anti-crack design of actual structures eroded by seawater at cold regions.

Key words: concrete; freeze-thaw; wet and dry cycles; erosion; Ottosen strength criterion
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In 2001, after summarizing 59 years research progress of concrete durability, Professor Mehta[1] at the University of California found that the main deterioration factors that lead concrete structures to degenerate are reinforcement rust, seawater freeze-thaw and erosion. Evaluating the concrete coupling damage under seawater freeze-thaw and erosion has engineering application and theory value.

Freeze-thaw is one of the main factors that cause mechanical properties damage to concrete structures. The concrete eroded by the freeze-thaw cycles generally appears to be surface loose, spalling, exposed aggregate and exposed reinforcement and so on. Domestic and foreign scholars have done much research on concrete freeze-thaw damage [2-3]. Currently, one of the most popular theories is the hydrostatic hypothesis proposed by Powers[4-5]. At present, most studies on concrete structure performance after freeze-thaw cycles[6-7] involve the changes of material properties after freeze-thaw. The research concerning mechanical properties degradation rules is rare.

Any environments whose pH value is less than 12.5 can be theoretically classified into erosion conditions [1]. The pH value of natural seawater is between 7.9 and 8.4. Mu et al. [8-9] studied variation rules of the concrete dynamic elastic modulus under chemical corrosion and freeze-thaw damage.

It is found that the literature concerning concrete mechanical performance degradation after wet and dry cycles is rare[10-11]. The relevant literature about triaxial strength criterion of concrete considering the coupling effect of seawater freeze-thaw and erosion is not found.

1 Experimental Design

Concrete in marine environments is immerged and corroded by ions such as SO_4^{2-}, Mg^{2+}, and Cl^-. But the concrete corrosion is a long-term progress in low concentration sulfate solutions, especially in Na_2SO_4 corrosion solutions. So, the reasonable acceleration system is used to study the concrete mechanical properties in erosion solutions.

At present, most studies concerning concrete damage use the wet and dry acceleration system, but this system is not uniform[12-16]. Obviously, there is not a specific rule about the acceleration test system. Atkinson's acceleration test system is improved in this paper. The highest temperature is considered, and the highest temperature in the wet and dry cycle system is 80 ℃. For preventing the temperature stress, the specimen is immersed in solution after cooling 1 h naturally. The design wet and dry cycle system of concrete is as follows: the concrete specimen is baked 16 h in a furnace at 80℃, cooled down 1 h at room temperature and immersed 7 h in the corrosion solution.

The erosion ions concentration in the corrosion solution is five times that in seawater (see Tab. 1).

Tab. 1 Artificial seawater composition g/L

Chemical composition	Chemical contents in natural seawater	Chemical contents in artificial seawater
NaCl	21.00	105.00
$MgCl_2$	2.54	12.70
$MgSO_4 \cdot 7H_2O$	1.54	7.70
$CaSO_4 \cdot 2H_2O$	2.43	12.15
$CaCO_3$	0.10	0.50

First, freeze-thaw tests of 50, 100, 200 and 300 cycles are done to the concrete specimen. Secondly, the wet and dry cycle test is done to concrete specimens after freeze-thaw. Finally, the compressive strength test is done.

2 Concrete Damage Variable

From an injury phenomenological perspective, material

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inner injury can be described entirely by macro-parameters such as the elastic modulus and Poisson's ratio. The four-order isotropic tensor $\boldsymbol{D}$ is used to describe concrete injury.

$$\boldsymbol{D}_{ijkl} = D_1 \boldsymbol{\delta}_{ij} \boldsymbol{\delta}_{kl} + D_2 \boldsymbol{\delta}_{ik} \boldsymbol{\delta}_{jl} \tag{1}$$

$$D_1 = \frac{\bar{E}(\nu - \bar{\nu})}{E(1+\bar{\nu})(1-2\bar{\nu})},\ D_2 = 1 - \frac{\bar{E}(1+\nu)}{E(1+\bar{\nu})} \tag{2}$$

where E and ν are the non-destructive concrete elastic modulus and Poisson's ratio, respectively; $\bar{E}$ and $\bar{\nu}$ are the destructive concrete elastic modulus and Poisson's ratio, respectively; D_1 and D_2 describe volume injury and distortion injury, respectively.

The expression of the concrete destructive elastic modulus is simplified as follows:

$$\bar{E} = E[1 - pN]^k \tag{3}$$

The equation of the concrete Poisson's ratio with the number of wet and dry cycles can be written as

$$\bar{\nu} = \frac{1}{2} - \frac{1-2\nu}{2}[1 - qN]^h \tag{4}$$

where N is the number of the concrete indoor wet and dry cycles; p, q, k and h are material micro-parameters. They can be determined by tests.

3 Concrete Wet and Dry Cycles Damage Criteria

The strength criterion of concrete after wet and dry cycles of seawater can be established according to existing tests combined with the classic injury and plasticity theory. The concrete after wet and dry cycles is assumed to have characteristics of a non-destructive concrete failure surface. The stress invariants of concrete after wet and dry cycles can be written as

$$\bar{I} = \alpha I_1,\ \bar{J}_2 = \beta^2 J_2,\ \bar{J}_3 = \beta^3 J_3,\ \bar{\theta} = \theta \tag{5}$$

where

$$\alpha = \frac{1}{1 - 3D_1 - D_2},\ \beta = \frac{1}{1 - D_2}$$

and $\bar{I}$, $\bar{J}_2$, $\bar{J}_3$ are concrete invariants after wet and dry cycles; I_1, J_2, J_3 are non-destructive concrete invariants; α, β are pending parameters; $\bar{\theta}$, θ are Lode angles after wet and dry cycles and before wet and dry cycles, respectively.

Substituting D_1 and D_2 in Eq. (2) into Eq. (5), α, β can be expressed as

$$\alpha = \frac{E(1+\bar{\nu})(1-2\bar{\nu})}{\bar{E}[(1+\nu)(1-2\bar{\nu}) + 3(\nu - \bar{\nu})]},\ \beta = \frac{E(1+\bar{\nu})}{\bar{E}(1+\nu)} \tag{6}$$

The equation of the concrete failure surface in the Cauchy stress space can be expressed as

$$f(I_1, J_2, J_3; \bar{\alpha}_i(D), i = 1, 2, \ldots) = 0 \tag{7}$$

The Ottosen four parameters model can reflect the main characteristics of the concrete failure surface, so the Ottosen model is adopted to establish the triaxial strength criteria of concrete after suffering from seawater erosion. The four parameters model can be expressed as

$$\left.\begin{aligned} & f(\bar{I}_1, \bar{J}_2, \cos 3\bar{\theta}) = a\frac{\bar{J}_2}{f_c'^2} + \lambda\frac{\sqrt{\bar{J}_2}}{f_c'} + b\frac{\bar{I}_1}{f_c'} - 1 = 0 \\ & \bar{\lambda} = \bar{\lambda}(\cos 3\bar{\theta}) > 0 \end{aligned}\right\} \tag{8}$$

where a and b are used to determine the meridian curve; $\bar{\lambda}$ is used to determine the partial plane destruction graphics; f_c' is the concrete uniaxial compressive strength.

According to the assumption of membrane analogy, $\bar{\lambda}$ can be expressed as

$$\left.\begin{aligned} & \bar{\lambda} = \frac{1}{\rho} = k_1 \cos\left[\frac{1}{3}\arccos(k_2 \cos 3\theta)\right] && \cos 3\theta \geqslant 0 \\ & \bar{\lambda} = \frac{1}{\rho} = k_1 \cos\left[\frac{\pi}{3} - \frac{1}{3}\arccos(-k_2 \cos 3\theta)\right] && \cos 3\theta < 0 \end{aligned}\right\} \tag{9}$$

where k_1 is the size coefficient, and k_2 is the type coefficient.

4 Calculation of Concrete Elastic Modulus

The values of the concrete initial elastic modulus after freeze-thaw cycles are obtained by dealing with measured data, The results are presented in Tab. 2.

Tab. 2 Test values of concrete mechanical properties after freeze-thaw

Cycle	Number	f_c/MPa	Peak strain $\varepsilon/10^{-3}$	E/GPa
0	1	60.22	1.24	96.82
	2	53.95	1.15	93.50
	3	44.43	1.14	78.22
50	1	43.97	1.33	66.17
	2	44.82	1.22	73.71
	3	45.27	1.12	81.14
	4	54.27	1.26	86.14
	5	63.75	1.81	70.63
100	1	34.00	1.75	38.86
	2	38.00	1.73	43.93
	3	39.90	1.75	45.60
	4	40.00	1.10	72.73
	5	52.00	1.40	74.29
	6	62.00	1.60	77.50
200	1	36.30	1.73	41.92
	2	37.56	1.51	49.85
300	1	26.73	1.71	31.27
	2	29.73	2.09	28.45
	3	31.90	1.91	33.40
	4	27.33	2.03	26.93

Multiple linear regression is conducted to the experimental data presented in Tab. 2, and parameters p, k are calculated. The concrete elastic modulus degradation model is expressed as

$$\bar{E} = E_0(1 + 0.001N)^{-3.892} \tag{10}$$

where E_0 is the initial elastic modulus of non-destructive concrete.

Another group of test cubes undergo coupling effect of seawater freeze-thaw and erosion. Their mechanical properties are shown in Tab. 3.

Tab. 3 Concrete compressive strength test values MPa

Cycles	Cube 1	Cube 2	Cube 3
Ordinary test cube	55.44	48.73	56.48
100 freeze-thaw cycles	47.53	45.28	40.52
100 freeze-thaw cycles + 10 wet and dry cycles	48.37	45.65	40.67
100 freeze-thaw cycles + 20 wet and dry cycles	43.24	37.75	39.26
100 freeze-thaw cycles + 30 wet and dry cycles	38.24	33.75	36.26
100 freeze-thaw cycles + 40 wet and dry cycles	34.24	32.75	30.26
100 freeze-thaw cycles + 50 wet and dry cycles	30.24	27.75	31.26
100 freeze-thaw cycles + 60 wet and dry cycles	28.24	26.75	22.26

The Poisson ratio considering the number of freeze-thaw cycles N_1 is expressed as

$$\bar{\nu}=\frac{1}{2}-\frac{1-2\times 0.2}{2}(1+0.001N_1) \tag{11}$$

The concrete elastic modulus after different freeze-thaw cycles N_1 and different wet-dry cycles N_2 is assumed to be

$$\bar{E}=E_0(1+0.001N_1)^{-3.892}(1+AN_2)^{B} \tag{12}$$

where N_1 is the number of indoor rapid freeze-thaw cycles; N_2 is the number of wet and dry cycles where concrete is in water whose concentration is five times than in natural seawater.

Parameters $A=1.359$ and $B=-0.111$ are obtained by the use of multiple linear regression modeling of the experimental data in Tab. 2 and Tab. 3. The concrete elastic modulus under the coupling effect of freeze-thaw and erosion is

$$\bar{E}=E_0(1+0.001N)^{-3.892}(1+1.359N_2)^{-0.111} \tag{13}$$

5 Parameters Determination of Ottosen Strength Model

The concrete uniaxial compressive strength is 52.863 MPa and the uniaxial tensile strength is 3.81 MPa according to the test results. The nonlinear equations of the Ottosen strength criteria are written as

Uniaxial compression

$$\frac{a}{3}+\frac{k_1\cos\left(\frac{\pi}{3}-\frac{1}{3}\arccos(k_2)\right)}{\sqrt{3}}-b-1=0 \tag{14a}$$

Uniaxial tension

$$\frac{af_t^2}{3f_c^2}+\frac{k_1\cos\left(\frac{1}{3}\arccos(k_2)\right)f_t}{\sqrt{3}f_c}+\frac{bf_t}{f_c}-1=0 \tag{14b}$$

Biaxial compression

$$\frac{1.16^2\times a}{3}+\frac{k_1\cos\left(\frac{1}{3}\arccos(k_2)\right)\times 1.16}{\sqrt{3}}-b\times 2\times 1.16-1=0 \tag{14c}$$

Triaxial compression

$$8a+2\sqrt{2}\cos\left(\frac{\pi}{3}-\frac{1}{3}\arccos(k_2)\right)-5\sqrt{3}b-1=0 \tag{14d}$$

Four parameters are obtained by solving the above nonlinear equations (14). The surface of the Ottosen strength criteria is written as

$$f(I_1,J_2,\cos3\theta)=1.2735\frac{\beta^2J_2}{f'^2_c}+\lambda\frac{\beta\sqrt{J_2}}{f'_c}+3.1924\frac{\alpha I_1}{f'_c}-1=0 \tag{15}$$

When $\cos3\theta\geqslant 0$,

$$\lambda=\frac{1}{\rho}=11.725\cos\left[\frac{1}{3}\arccos(0.98\cos3\theta)\right]$$

When $\cos3\theta<0$,

$$\lambda=\frac{1}{\rho}=11.725\cos\left[\frac{\pi}{3}-\frac{1}{3}\arccos(-0.98\cos3\theta)\right]$$

6 Determining Tensile Meridian and Compressive Meridian

The concrete elastic modulus degradation model (Eq. (12)) and the Poisson ratio degradation model (Eq. (11)) are substituted into Eq. (2), and D_1, D_2 are written as

$$D_1=\frac{(1+0.001N_1)^{-3.892}\times(1+1.359N_2)^{-0.111}\times 0.002N_1}{(1.2+0.0002N_1)(0.6-0.0004N_1)}$$

$$D_2=1-\frac{(1+0.001N_1)^{-3.892}\times(1+1.359N_2)^{-0.111}\times 1.2}{(1.2+0.0002N_1)}$$

The Haigh-Westergard coordinate (ρ,ξ,θ) is used to describe the surface of the Ottosen strength criteria, and the coordinate relationships are written as

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

The tensile meridians and compressive meridians of different freeze-thaw cycles and wet-dry cycles are drawn in Fig. 1.

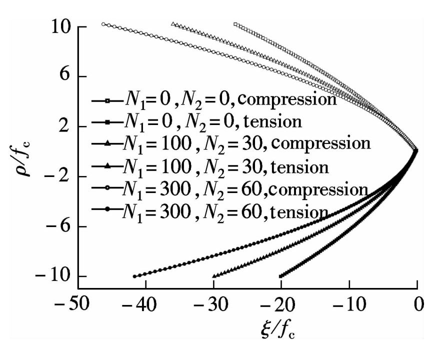

Fig. 1 Tensile and compressive meridians of concrete coupling injury failure surface

7 Conclusions

1) The triaxial strength criterion of concrete considering

the number of wet-dry cycles and freeze-thaw cycles is established based on the continuum of damage mechanics and classical failure criterion models.

2) The numbers of both wet-dry cycles and seawater freeze-thaw cycles in this paper are indoor numbers, and the numbers under natural conditions are useful for evaluating the service performance of structures in marine environments. It is necessary to study the effective indoor and outdoor correlation models. We will do such research in the future.

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海水冻融和侵蚀耦合作用下混凝土破坏面演化模型

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摘要:为了有效评估海水冻融与侵蚀后混凝土的力学性能,基于大型静态和动态刚度伺服压力机进行了混凝土冻融和海水侵蚀后的力学性能试验. 对混凝土进行了 50, 100, 200 和 300 次冻融循环,并配置了人工海水;选择了合理的干湿循环机制,对冻融后的混凝土试块进行了 10,20,30,40,50 和 60 次干湿循环. 对混凝土弹性模量和抗压强度退化规律进行了研究. 基于混凝土单轴力学性能和损伤理论,推导了考虑干湿循环次数和冻融循环次数的 Ottosen 三轴强度. 试验研究表明:随着干湿循环和冻融循环次数增加,混凝土轴心抗压强度和弹性模量逐渐下降,强度准则的拉、压子午线逐渐收缩. 该研究可为受海水侵蚀在寒冷地区的实际结构抗裂设计提供参考.

关键词:混凝土;冻融循环;干湿循环;侵蚀; Ottosen 强度准则

中图分类号:U311.2