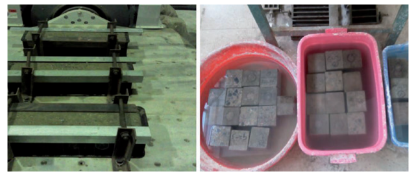
Damage evolution model of early disturbed concrete under sulfate attack and its experimental verification



Modelo de evolución del daño sobre hormigón, afectado tempranamente por ataque de sulfato y su verificación experimental

Huimin Pan*, Xiuyong Si and Qingxin Zhao
School of Civil Engineering and Mechanics, Yanshan University, Qinhuangdao, 066004, China, hmpan2005@163.com

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RESUMEN

- Perturbaciones durante una edad temprana de la fase de fraguado y endurecimiento del hormigón suelen crear microfisuras en la matriz del hormigón y, por lo tanto, disminuyen su resistencia y durabilidad. Entre los factores que afectan a la durabilidad del hormigón, el ataque por sulfato es uno de los factores importantes que causan daños. Para analizar el desarrollo de deterioro del hormigón alterado prematuramente bajo el entorno de ataque de sulfato, se ensayó el coeficiente residual de resistencia a la flexión del hormigón mediante la perturbación en una mesa vibratoria horizontal. Utilizando el factor de daño por erosión para caracterizar el grado de deterioro de la erosión del hormigón, se llevaron a cabo las pruebas de ataque de sulfato sobre el hormigón perturbado. Partiendo de la condición de iniciación de grietas por ataque de sulfato, y en base a la teoría de la nucleación de microfisuras y el crecimiento en el proceso de erosión, se obtuvo la ecuación de evolución estadística del daño por corrosión del sulfato en el hormigón utilizando la propagación de microfisuras para caracterizar el comportamiento mecánico del hormigón tras el daño por corrosión. Considerando la influencia de las perturbaciones tempranas en la tensión crítica de la nucleación de microfisuras del hormigón, se estableció el modelo de evolución de daños del hormigón con diferentes condiciones perturbadas bajo ataque de sulfato, y se predijo el grado de corrosión del hormigón perturbado con diferentes tiempos de erosión. Basándose en los datos experimentales de los factores de daño, se ajustó la ecuación de evolución del daño y se validó el modelo. Los resultados demuestran que la curva del modelo de daño encaja bien con la curva de ensayo del factor de daño, y que los coeficientes de correlación están por encima de 0.98, lo que puede reflejar la ley de evolución del daño del hormigón perturbado por ataque de sulfato. Este método proporciona una buena referencia para evaluar el efecto de las alteraciones tempranas en la resistencia al sulfato del hormigón.
- **Palabras clave:** Hormigón, Perturbación, Ataque de sulfato, Nucleación de microgrietas, Evolución del daño.

ABSTRACT

The disturbance during the early age of the setting and hardening stage of concrete usually creates microcracks in the concrete matrix and thus decreases its strength and durability. Among the factors that affect the durability of concrete, sulfate attack is one of the important factors that cause damage. To analyze the damage development of early disturbed concrete under sulfate attack environment, the residual coefficient of flexural strength of concrete was tested by the perturbation of horizontal vibrating table. Using erosion damage factor to characterize the degree of erosion deterioration of concrete, the sulfate attack tests were carried out on the disturbed concrete. Starting from the crack initiation condition of sulfate attack, and based on the theory of microcrack nucleation and growth in the process of erosion, the statistical evolution equation of sulfate corrosion damage of concrete was obtained by using micro crack propagation to characterize the mechanical behavior of concrete after corrosion damage. Considering the influence of early disturbance on the critical stress of concrete microcrack nucleation, the damage evolution model of concrete with different disturbed conditions under sulfate attack was established, and the corrosion degree of disturbed concrete at different erosion ages was predicted. Based on the experimental data of damage factors, the damage evolution equation was fitted and the model was validated. Results demonstrate that the damage model curve fits well with the test curve of damage factor, and the correlation coefficients are above 0.98, which can reflect the damage evolution law of disturbed concrete sulfate attack. This method provides a good reference for evaluating the effect of early disturbance on the sulfate resistance of concrete.

Keywords: Concrete, Disturbance, Sulfate attack, Microcrack nucleation, Damage evolution.

1. INTRODUCTION

In civil engineering construction, it is necessary to ensure the progress and continuity of the construction of the structure, and the construction process cannot be interrupted most of the time. Therefore, the concrete structure usually suffers the disturbance such as blasting excavation, piling, train vibration, shock and other forms of earthquake at this stage prior to the full hardening of the casting. The internal microstructure of cement-based materials is formed mainly in the early period of hydration. In this stage, the cement paste in the concrete is gradually hardened, resulting in the initial shear stress of the skeleton structure, but the bond strength of the interface transition zone is not yet fully formed, and the influence of the external disturbance is very sensitive [1]. The disturbing force can easily destroys the weak bond strength of the interface transition zone and thus create microcracks in the matrix, which will affect the strength growth of concrete and decrease its durability [2, 3].

The raise of influence of disturbance on the early age concrete was originally aimed at the possibility of repeated vibration of concrete after initial setting [4]. After that, many scholars had carried out experimental research, and the influence of perturbation time, perturbation parameters on concrete strength and crack width was studied by simulation engineering perturbation [5-7]. Previous studies have shown that the early disturbance reduces the compressive strength and flexural strength of concrete, and deteriorates the mechanical properties of concrete. Moreover, the micro cracks and micro cracks caused by the disturbance can cause the initial damage of the concrete structure, and the existence of these initial defects also buries the hidden danger for the safety and durability of the concrete in service. At present, the research on the durability of disturbed concrete has not been reported yet.

Among the factors that affect the durability of concrete, sulfate attack is one of the important factors [8]. Concrete structures always work in the sulfate environment, but what is the effect of the early disturbance on the resistance of concrete to sulfate attack is unclear. Based on the above analysis, this paper focuses a central problem in the damage development of concrete under sulfate attack by considering the influence of early disturbance on concrete. Using the micro crack growth to characterize the mechanical properties of concrete after corrosion damage, the statistical evolution equation of sulfate attack damage of concrete is derived base on statistical evolution of nucleation and growth of microcracks during sulfate attack and the equilibrium equation of microcrack density evolution. At the same time, the damage model is verified according to the test results.

2. STATE OF THE ART

In practical engineering, because of the interaction of multiple damage factors, the concrete problems become more complex, and the macro mechanical behaviors of concrete sulfate corrosion caused by degradation has become a focus problem. In the aspect of corrosion damage mechanism of sulfate on concrete, scholars at home and abroad had carried on the relevant experimental research. However, due to sulfate attack of concrete is a complex physical and chemical - mechanical coupling process, and the evolution of material properties is also affected by the environment, so it is difficult to accurately evaluate the performance of the material under sulfate attack only through indoor accelerated test method. Therefore, scholars have established a variety of theoretical models of damage deterioration in the whole process of erosion by combining experimental research and numerical analysis at present. The representative models are empirical models and theoretical models.

For empirical model, researchers obtained the relationship between macro mechanical degradation and external sulfate based on sulfate erosion tests. By changing the cement quality, the erosion solution concentration and the water cement ratio, Marchand and Kurtis et al. carried out rapid erosion and long-term natural immersion tests on concrete and studied the influence of various factors on erosion performance. In their study, the STADIUM model and the empirical formula of material expansion rate and erosion time were proposed respectively [9, 10]. Zhou et al. also took the test method of sulfate attack on concrete under cyclic wetting and drying conditions. But it is different from the above research that this study suggested that the erosion process of concrete sulfate is the gradual process including the crystallization process of solid-liquid interface adsorption, diffusion process and sulfate sulfate solution in the concrete chemistry and physical chemistry. Considering the chemical mechanical coupling effect of concrete under sulfate attack, the influence of concrete diffusion depth on sulfate attack was systematically studied in the experiment. And a sulfate ion diffusion reaction coupling model was established based on Fick's second law in their study [11-13]. In order to study the corrosion of gypsum rock to tunnel lining structure, Ren et al. studied the variation law of the corrosion coefficient of concrete by sulfate through orthogonal test. And the mechanism and influencing factors of sulfate attack on concrete were analyzed. Based on BP neural network, the prediction model of strength change after concrete corrosion was established, and the model was successfully applied to the lining design of tunnel [14].

In the establishment of theoretical damage models, researchers usually predict the performance of concrete subjected to sulfate attack on the basis of some assumptions. Assuming ettringite was the only product that causes the expansion of concrete, Krajcinovic et al. established the coupling model of concrete and concrete subjected to sulfate attack and obtained the relation between microstructure change and macro mechanical properties of the material based on microscopic damage mechanics [15]. Supposing the swelling process of sulfate corrosion can be divided into two stages, Gouder et al. proposed governing equations for the combined problem of steady-state diffusion and reaction of sulfates with concrete by using the framework of mixture theory to model the changes that occur in concrete exposed to sodium sulfate [16,17]. For the volumetrical expansion of cement-based materials caused by sulfate attack, Yin et al. studied the influence of sulfate concentration, water binder ratio, mineral admixture and admixture on compressive strength of concrete by grey relational theory. The research established the mechanical model of the representative volume element (RVE) reflecting the interaction between cement matrix and ettringite crystal in capillary pores based on the microporous mechanics and the crystallization theory. By the homogenization method, the equivalent RVE location of the stress changes with the concentration of ettringite was analyzed on a macroscopic scale in the study. And the strength degradation law and service life of concrete under sulfate attack environment were analyzed by establishing the grey prediction model [18,19]. Different from the assumption of the above scholars, Bao et al. obtained the damage deterioration model of concrete by getting the crack initiation conditions according to the tensile strength of concrete through the volume integral of microcracks [20].

These existing methods have successfully provided theoretical basis for the establishment of damage evolution model of concrete under sulfate action. While a few studies have established erosion model based on the theory of the formation and propagation of internal cracks in concrete. Moreover, the model established by considering the effect of early disturbance on the erosion process of concrete has not been reported. For concrete which is disturbed at the early stage of setting and hardening, the damage deterioration of concrete under sulfate attack is different from that of ordinary concrete. The damage after deterioration of sulfate attack should be estimated to better understand the damage variation of concrete in early service environment. This study proposes a new corrosion damage model for the concrete that be disturbed in early age by starting from the initiation conditions of micro cracks produced by sulfate attack. The model is based on the theory of nucleation and growth of microcracks in the erosion process and considers the effect of early perturbation on the critical stress of microcrack nucleation.

The remainder of this paper is organized as follows. Section 3 establishes damage evolution model of disturbed concrete under sulfate attack by using micro crack propagation to characterize the mechanical behavior of concrete after corrosion damage. In the 4th section, the model is verified by curve fitting according to the test results of early disturbed concrete by sulfate attack and the research results are discussed. Section 5 summarizes the conclusions.

3. METHODOLOGY

3.1. MODEL ESTABLISHMENT

3.1.1. Mathematical characterization of sulfate attack damage

The process of corrosion of concrete under the action of sulfate is a process of expansion reaction, which is the damage process of its own structure [21]. When the swelling stress produced by sulfate attack exceeds the tensile strength of concrete material, micro structure defects gradually accumulate and develop, and the material deteriorates gradually. This process is called damage. For the scale of micro-defects inside the materials is much smaller than the size of matter micro-elements inside the continuum mechanics, the damage of materials could be described by introducing the internal variable of damage which represents the micro-defects of materials [22]. The damage of concrete is usually composed of many micro-holes or micro-crack under the action of external loads [23]. The existence of microcracks in the early disturbed concrete provides a convenient condition for the entry of harmful ions, so that the damage evolution process of concrete may be studied by the statistical evolution of micro-crack [24, 25]. When the tensile stress produced by the combined action of external load and erosion expansion force exceeds the tensile strength of concrete, which would lead to micro-crack initiation.

Assumed n is be the number of microcracks in the interior of the concrete working at t moment, and n can be calculated according to the following Eq. (1):

$$n = n(t, l, x, q) \tag{1}$$

where n is the number density of micro-cracks. Then the number of micro-crack within unit volume length $[l, l+dl]$ is ndl, x is the lagrange coordinate of the crack location and q is the orientation of micro-cracks.

Under the combined action of external load and erosion, it is assumed that the density of micro-crack is independent of orientation q. So Eq. (1) can be rewritten as Eq. (2):

$$n = n(t, l, x) \tag{2}$$

The decay of concrete is caused by the damage of its own structure, and the decay is the amount of damage. The sum of all the crack volumes per unit volume of concrete is defined as the amount of damage D, which is also called damage factor. D is calculated according to the following Eq. (3):

$$D = D(t, x) = \int_0^\infty n(t, l, x)\beta_l l^3 dl \tag{3}$$

where β_l is the dimensionless parameter relating to the material.

3.1.2. Statistical evolution equation of erosion damage

Under the condition of sulfate attack, the evolution of micro-damage of concrete mainly includes nucleation, growth and coalescence of micro-crack. To the crack confluence stage, the concrete has been formed within the macro-cracks, indicating that the structure comes to the repair stage. Therefore, the statistical evolution in the micro-damage of concrete caused by erosion in this experiment, only the nucleation and growth of micro-cracks are considered in this study.

Bai et al. [23] suggested that the nucleation rate n_N of micro-crack was related to the local stress σ and the crack length l and can be expressed as:

$$n_N = k_{th}\left(\sigma_t/\sigma_{th} - 1\right)\left(l/l_{th}\right)\exp\left[-\left(l/l_{th}\right)^m\right] \tag{4}$$

where k_{th} and m are the constants associated with the material, l_{th} is reference length, σ_{th} represent critical stress of micro-crack nucleation, and σ_t is a combination of external load and erosion factors.

Sulfate attack causes expansion of concrete and induces internal expansion stresses. Therefore, the erosion factor can be converted to internal expansion force F. So, σ_t can be expressed as the superposition of the external load and the internal expansion force and σ_t is calculated according to the following Eq. (5):

$$\sigma_t = \sigma_0 + \beta_F F \tag{5}$$

where β_F is proportionality coefficient and σ_0 is stress caused by external loads.

The second item in Eq. (5) represents the swelling force caused by the erosion product produced during erosion according to reference [26]. It is approximately represented by a linear function of erosion time:

$$\beta_F F = F_0^*\left(t/t_0\right) \tag{6}$$

where t_0 is reference time.

If concrete is only subjected to sulfate attack without external load, the value of σ_0 can be taken as 0. Substituting Eq. (6) into Eq. (5), it can be obtained as Eq. (7):

$$\sigma_t = F_0^*\left(t/t_0\right) \tag{7}$$

Refer to Seaman et al. [27] and other research results, the micro-crack propagation equation L could be expressed as following Eq. (8):

$$L = g(t, x)l, g(t, x) = (\sigma_t - \sigma_{th})4\eta \tag{8}$$

where η is viscosity coefficient.

According to the conservation properties of micro-crack in the literature [23] in phase space, the number of micro-crack between $[l, l+dl]$ could be obtained as following Eq. (9):

$$\frac{\partial n}{\partial t} + \frac{\partial(Ln)}{\partial l} = n_N \tag{9}$$

Substituting Eq. (8) into Eq. (9), it can be obtained as following Eq. (10):

$$\frac{\partial n}{\partial t} + \frac{\partial n}{\partial l}L + g(t, x) = n_N \tag{10}$$

Eq. (10) can be transformed into a first order ordinary differential equation on the characteristic line, then the evolution equation of the micro-crack density can be obtained as Eq. (11):

$$\frac{dn}{dt}+g\left(t,x\right)n=n_N \tag{11}$$

By multiplying $\beta_l l^3$ in both sides of the Eq. (11) and integral with respect to l, it can be obtained as following Eq. (12):

$$\int_0^\infty \beta_l l^3\frac{dn}{dt}dl+\int_0^\infty g\left(t\right)n\beta_l l^3dl=\int_0^\infty n_N\beta_l l^3dl \tag{12}$$

Substituting Eq. (3) into Eq. (12), the following formula can be obtained: $\frac{dD}{dt}+g\left(t\right)D=\int_0^\infty n_N\beta_l l^3dl$. Let the right side of Eq. (12) be Q (t, l, x), then we can get Eqs. (13) and (14):

$$\frac{dD}{dt}+g\left(t\right)D=Q\left(t,l,x\right) \tag{13}$$

$$Q\left(t,l,x\right)=\int_0^\infty n_N\beta_l l^3dl \tag{14}$$

The initial condition of concrete without corrosion is t=0, D=0, substituting this initial condition into the Eq. (13), the differential equation can be solved:

$$D=\exp\left[-\int g\left(t\right)dt\right]\int_0^t Q\left(t,l,x\right)\cdot\exp\left[\int g\left(t\right)dt\right]dt \tag{15}$$

Eq. (15) represents the damage evolution model under the action of erosion.

3.1.3. Evolution model of concrete erosion damage

Eq. (15) shows that when Q (t, l, x) and g (t) are known, the specific damage model of concrete under the action of sulfate erosion can be obtained.

In this study, the reference length (l_{th}) is valued 1μm and m equals 1. Substituting Eq. (1) into Eq. (14), it can be obtained that:

$$Q\left(t,l,x\right)=\int_0^\infty n_N\beta_l l^3dl=\int_0^\infty k_{th}\beta_l\left(\frac{\sigma_t}{\sigma_{th}}-1\right)\left(\frac{l}{l_{th}}\right)\cdot\exp\left[-\left(\frac{l}{l_{th}}\right)\right]l^3dl=24k_{th}\beta_l\left(\frac{\sigma_t}{\sigma_{th}}-1\right) \tag{16}$$

The following expressions can be derived by substituting Eq. (7) into Eq. (14):

$$g\left(t,x\right)=\frac{F_0^*\left(t/t_0\right)-\sigma_{th}}{4\eta} \tag{17}$$

$$Q\left(t,l,x\right)=24k_{th}\beta_l\left[\frac{F_0^*\left(t/t_0\right)}{\sigma_{th}}-1\right] \tag{18}$$

Integrating the two sides of the Eq. (17), we can get:

$$\int g\left(t\right)dt=\frac{\sigma_{th}}{4\eta}t+\frac{F_0^*t^2}{8\eta t_0} \tag{19}$$

Substituting Eq. (18) and Eq. (19) into Eq. (15), then:

$$D=\frac{96k_{th}\beta_l\eta}{\sigma_{th}}\left[1-\exp\left(\frac{\sigma_{th}}{4\eta}t-\frac{F_0^*t^2}{8\eta t_0}\right)\right] \tag{20}$$

Taking k=$k_{th}\beta_l$, the damage evolution model of concrete under sulfate attack can be obtained as following Eq. (21):

$$D=\frac{96k\eta}{\sigma_{th}}\left[1-\exp\left(\frac{\sigma_{th}}{4\eta}t-\frac{F_0^*t^2}{8\eta t_0}\right)\right] \tag{21}$$

3.2. EXPERIMENTAL VERIFICATION

3.2.1. Materials

Portland cement is used as the cementitious material to make concrete in the experiment. Its parameters are listed in Table I.

Fine aggregate is natural river sand with the fineness modulus 2.9 and the apparent density of 2650 kg/m^3. Coarse aggregate is crushed limestone with the size of 5-25 mm and the apparent density of 2780 kg/m^3. A naphthalene water reducer with a water-reducing rate of 21 % is employed to achieve a target work-ability. Mixing water is tap water.

The adopted concrete mixture is designed to achieve a C40 class concrete. Table II lists mix proportions of concrete. The slump of each mixture is controlled within (100 ± 10) mm by adjusting the dosage of super plasticizer.

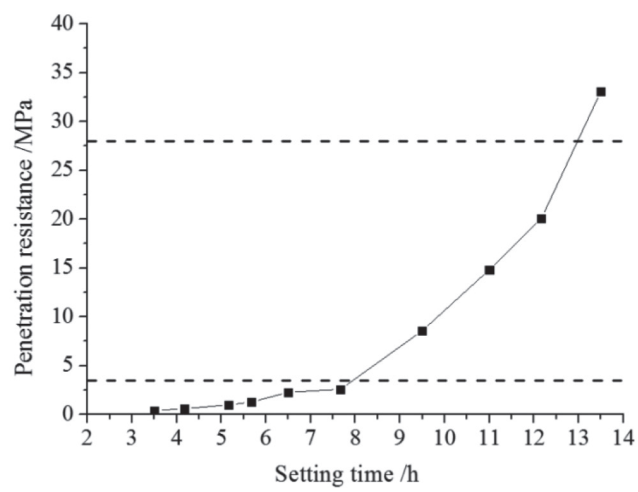


Fig. 1: Relationship between penetration resistance and setting time

80 μm remaining rate /%	Standard consistency /%	Initial setting time /min	Final setting time /min	28d compressive strength /MPa	28d flexural strength /MPa	Volume soundness
1.6	28.2	170	270	49.2	7.1	up to standard

Table I: Physical and mechanical properties of cement

Strength grade	Cement / kg/m^3	Fine aggregate / kg/m^3	Coarse aggregate / kg/m^3	Water /kg/m^3	Water cement ratio	Sand rate
C40	420	760	1040	176	0.42	0.42

Table II: The mix proportion of concrete

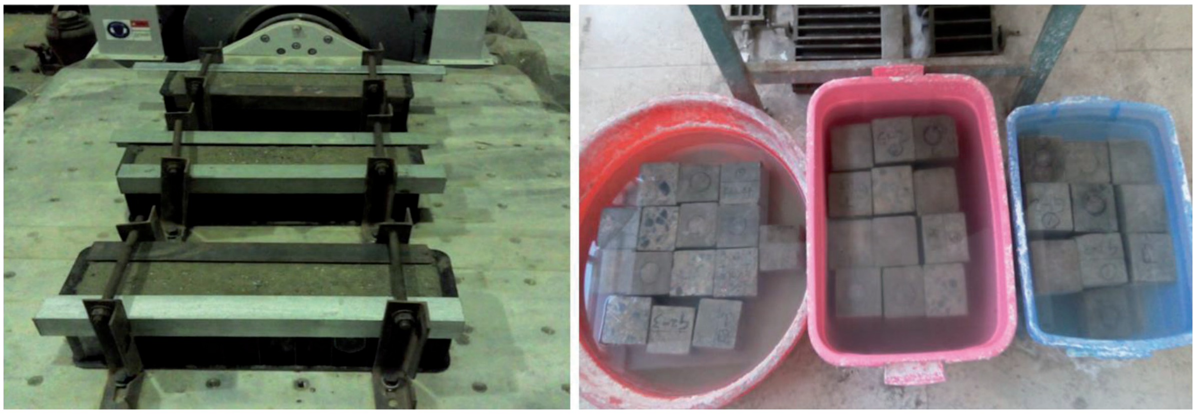
3.2.2. Test method

According to the analysis of previous literatures, the disturbance in the setting stage seriously influences concrete's performances. So in this experiment, the disturbed age of concrete was defined as 'early' in this experiment. 'Early disturbance' is the disturbance of concrete before the completion of the initial setting and the final condensation. The setting time of concrete was determined by penetration resistance method. According to the relation between penetration resistance value and setting time, the method of drawing fitting was used to determine the initial setting time and final setting time of concrete, as shown in Fig. 1.

According to Fig. 1, it was concluded that the setting time of penetration resistance value of 3.5 MPa and 28 MPa was the initial setting time and final setting time of concrete mixture was 8 h and 13 h, respectively. That is to say, the concrete is in the plastic flow stage before 8 h and completely hardened after 13 h. In the present experiments, 6 kinds of disturbed conditions were designed with different penetration resistance values: 3.5-6.9, 6.9-10.7, 10.7-14.8, 14.8-19.6, 19.6-30.9 MPa, respectively.

The perturbation test was referenced to the previous method of the reference [28]. The disturbance was provided by horizontal electric vibration table. According to literature [29, 30], the vibration frequencies of various forms of disturbance are basically between 10-30 Hz. Therefore, taking into account the influence of various disturbance forms, the frequency in this experiment was chosen as 15 Hz and the amplitude was 4 mm. The disturbance was sinusoidal vibration and the disturbance time was 40 min.

After the specimens were disturbed, they were removed from the shaking table and placed in an environment with temperature of (20 ± 2) °C centigrade. The specimens were cured in standard conditions. And Flexural strength test and sulfate attack test were carried out after the predetermined age. The sulfate attack test was carried out according to GB/T 50082-2009 (Standard for test methods of long-term performance and durability of ordinary concrete, China). After erosion, the dried concrete specimens were taken out and the ultrasonic wave velocity of each specimen was measured. The experimental setup was showed in Fig. 2.



(a) Disturbance test device *(b) Concrete specimens in sulfate attack*

Fig. 2. Experimental setup

Age of disturbed concrete (Penetration resistance value) /MPa					
Not disturbed	3.5-6.9	6.9-10.7	10.7-14.8	14.8-19.6	19.6-30.9
1	0.72	0.69	0.67	0.64	0.72

Table III: Residual coefficient of flexural strength of concrete (μ value)

Age/d	Age of disturbed concrete (Penetration resistance value) /MPa					
	Not disturbed	3.5-6.9	6.9-10.7	10.7-14.8	14.8-19.6	19.6-30.9
0	0	0	0	0	0	0
10	-0.08	-0.03	-0.05	-0.08	-0.12	-0.10
30	-0.13	-0.07	-0.10	-0.10	-0.19	-0.15
50	-0.14	-0.08	-0.10	-0.11	-0.19	-0.15
70	-0.13	-0.08	-0.09	-0.11	-0.17	-0.16
90	-0.14	-0.10	-0.10	-0.12	-0.18	-0.14
110	-0.12	-0.09	-0.09	-0.11	-0.15	-0.13
130	-0.12	-0.06	-0.05	-0.10	-0.12	-0.10
150	-0.11	-0.02	-0.03	-0.10	-0.10	-0.03
170	-0.06	0.00	-0.01	-0.05	-0.01	0.02
190	-0.02	0.01	0.01	-0.01	0.09	0.04
210	0.09	0.04	0.05	0.05	0.15	0.12
230	0.10	0.09	0.10	0.13	0.30	0.15
250	0.17	0.10	0.14	0.13	0.40	0.22
270	0.20	0.14	0.19	0.18	0.42	0.25
300	0.25	0.15	0.20	0.23	0.50	0.29

Table IV: Damage factors of disturbed concrete at different erosion time (D_n value)

4. RESULTS ANALYSIS AND DISCUSION

4.1. TEST RESULTS

To evaluate the effect of early disturbances on strength, the residual coefficient of flexural strength is calculated according to Eq. (22):

$$\mu = \frac{f_t'}{f_t} \quad (22)$$

Where μ is residual coefficient of flexural strength, f_t' is flexural strength of 28 d for disturbed concrete and f_t is 28 d flexural strength of reference concrete. Table III lists values of μ for different disturbed stages.

In order to characterize the degree of deterioration of concrete by sulfate attack, the damage factor is defined by the continuum damage mechanics method [31], calculated by Eq. (23).

$$D_n = 1 - \left(\frac{v_n}{v_0}\right)^2 \quad (23)$$

Where D_n is damage factor, v_n is ultrasonic wave velocity of specimens after n cycles, v_0 is initial ultrasonic wave velocity before erosion. Table IV shows D_n value of disturbed concrete at different erosion age.

4.2. MODEL PARAMETER SOLVING

According to the model of erosion damage evolution of Eq. (21), the damage factors of concrete in different erosion age can be obtained. As mentioned above, when the expansion stress produced by the erosion product exceeds the tensile strength of concrete material, damage and deterioration of concrete materials will initiate. So the critical stress σ_{th} of micro crack nucleation was calculated according to the design value of concrete axial tensile strength. For C40 concrete, σ_{th}=2.2 MPa. It has been demonstrated that the early disturbance can cause micro cracks that can not be healing, and thus reduce the strength of concrete, especially the flexural strength [32-34]. Therefore, considering the influence of perturbation on the critical stress of microcrack nucleation, the critical stress σ_{th} in the present experimental conditions can be expressed as:

$$\sigma_{th} = 2.2\lambda \quad (24)$$

Where λ represents the influence coefficient of tensile strength. Its value is determined by the residual coefficient of flexural strength μ. Substituting λ=μ into Eq. (24), we can get:

$$\sigma_{th} = 2.2\mu \quad (25)$$

Taking the reference time t_0=365 d and bring Eq. (25) into Eq. (23), the damage evolution equation of concrete under 6 kinds of disturbed conditions under sulfate erosion can be obtained as shown as following Eq. (26):

$$\begin{aligned}
D_1 &= 43.6k\eta\left[1-\exp\left(\frac{0.55}{\eta}t-\frac{F_0^*}{2920\eta}t^2\right)\right]\\
D_2 &= 60.6k\eta\left[1-\exp\left(\frac{0.40}{\eta}t-\frac{F_0^*}{2920\eta}t^2\right)\right]\\
D_3 &= 63.2k\eta\left[1-\exp\left(\frac{0.38}{\eta}t-\frac{F_0^*}{2920\eta}t^2\right)\right]\\
D_4 &= 65.1k\eta\left[1-\exp\left(\frac{0.37}{\eta}t-\frac{F_0^*}{2920\eta}t^2\right)\right]\\
D_5 &= 68.1k\eta\left[1-\exp\left(\frac{0.35}{\eta}t-\frac{F_0^*}{2920\eta}t^2\right)\right]\\
D_6 &= 60.6k\eta\left[1-\exp\left(\frac{0.40}{\eta}t-\frac{F_0^*}{2920\eta}t^2\right)\right]
\end{aligned} \quad (26)$$

According to Eq. (26) and the damage factor test data listed in table IV, the damage evolution curves of disturbed concrete under sulfate attack condition were fitted .Table V lists the parameters of Eq. (26).

4.3. ANALYSIS AND DISCUSSION

Substituting the parameters in Table V into Eq. (26), the damage evolution of disturbed concrete under sulfate attack was calculated. The calculated results were compared with the experimental data, as shown in Fig. 3.

As seen from Fig. 3, the early disturbance accelerates the deterioration of concrete under sulfate attack. It can be seen from Fig. 3(b) and Fig. 3(f) that the disturbance has the least influence on concrete when the penetration resistance values are 3.5-6.9 MPa and 19.6-30.9 MPa. After 300 days erosion, the damage degree of these specimens is slightly higher than the reference concrete. It can be seen from Fig. 3(c) and Fig. 3(e) that when the penetration resistance values are 3.5-6.9 MPa and 19.6-30.9 MPa, the influence of disturbance on concrete is larger. And the damage degree of these specimens has been higher than 0.3 after 300 days erosion. It can be seen from Fig. 3(d) that when the penetration resistance value is 10.7-14.8 MPa, the disturbance has the greatest influence on the concrete. The disturbed concrete in this stage is corroded seriously in sulfate corrosion solution. After 300 days erosion, the concrete damage degree is more than 0.5. Therefore, the disturbance in this stage has a significant influence on the deterioration process of concrete in sulfate attack environment.

The influence of disturbance on sulfate attack of concrete is also the embodiment of its influence on the strength of concrete. It can be seen from the above table 3 that the early disturbance significantly reduces the flexural strength of concrete. Especia-

Age of disturbed (Penetration resistance value) /MPa	k	η / MP/d	F_0^*/MPa	Correlation coefficient
Not disturbed	1.519xe^{-10}	91.667	8.323	0.979
3.5~6.9	1.897xe^{-10}	55.556	6.164	0.981
6.9~10.7	2.119xe^{-10}	52.778	5.548	0.984
10.7~14.8	3.669xe^{-10}	51.389	6.002	0.989
14.8~19.6	2.702xe^{-10}	48.611	5.394	0.980
19.6~30.9	2.382xe^{-10}	57.143	5.840	0.982

Table V: Fitting fesults of damage evolution parameters of disturbed concrete under sulfate attack

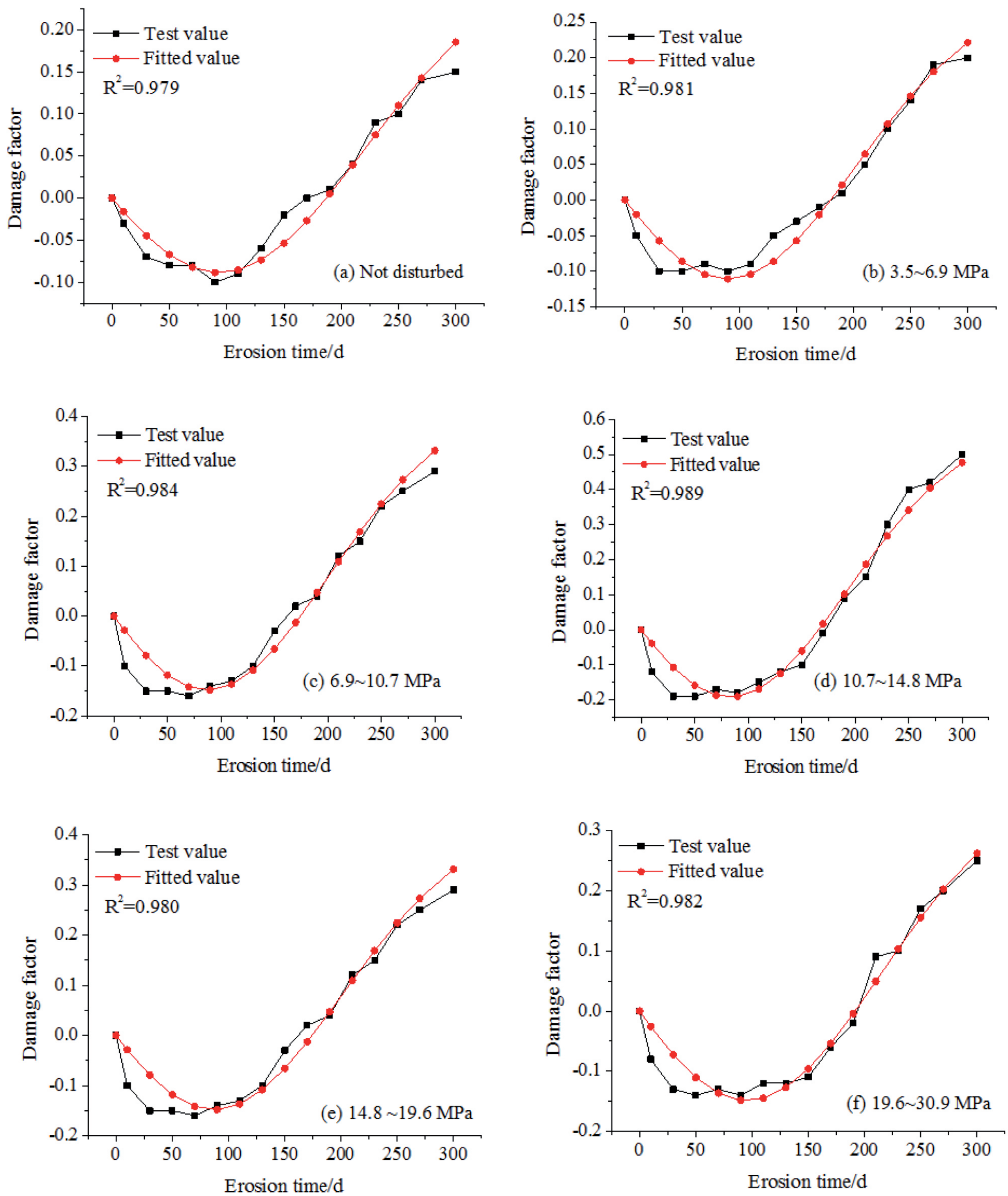


Fig. 3: Damage evolution of concrete with different disturbed ages under sulfate attack

lly when the penetration resistance value is 10.7-14.8 MPa, the flexural strength of concrete disturbed at this stage is 33 % lower than that of the reference concrete. The decrease of flexural strength of concrete leads to the decrease of tensile strength, which affects the critical stress of concrete microcrack nucleation. The lower the flexural strength of concrete is, the smaller the critical stress of microcrack nucleation is. Therefore, the damage deterioration degree of concrete under sulfate attack increases with the increase of the degree of disturbance.

It can be seen from Fig. 3 that, by employing the micro crack growth to characterize the mechanical properties of concrete after corrosion and considering the disturbance of the micro crack effect of nucleation of critical stress, the damage model agrees well with the experimental results. The correlation coefficients (R^2) of fitting results are all above 0.98. This indicates that it is feasible to derive the statistical evolution equation of concrete under sulfate attack based on the theory of nucleation and growth of micro-crack. The damage evolution model established in this research can reflect the damage evolution law of early disturbed concrete under sulfate attack. The corrosion degree of concrete under different disturbed conditions can be predicted in different erosion age based on this model.

5. CONCLUSIONS

To evaluate the damage evolution of early disturbed concrete under sulfate attack environment, starting from the initiation conditions of micro cracks produced by sulfate attack, a new damage model of early disturbed concrete was proposed based on damage mechanics theory. The model was verified by experimental data. The following conclusions could be drawn:

(1) Using micro crack growth to characterize the mechanical properties of concrete after corrosion damage, the statistical evolution equation of sulfate attack damage of concrete was obtained by the calculation method of nucleation rate of microcracks.

(2) Considering the influence of early disturbance on the critical stress of concrete microcrack nucleation, the damage model curve fits well with the test curve of damage factor, and the correlation coefficients were above 0.98. The damage evolution model established in this paper can well reflect the damage evolution law of early disturbed concrete under sulfate attack environment and predict the corrosion degree of concrete under different disturbed conditions.

(3) The early disturbance accelerates the deterioration of concrete under sulfate attack. When the penetration resistance value is 10.7~14.8 MPa, the disturbance has the greatest influence on the concrete.

Thus, the damage evolution model can reflect the damage development of early disturbed concrete under sulfate attack. It provides a convenient and accurate technical support for evaluating and predicting the erosion degree of disturbed concrete at different erosion ages. However, there are many factors affecting the durability of concrete in practical engineering. More influencing factors should be considered in future studies.

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