Construction and Building Materials 82 (2015) 264–273

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Study on crack density of concrete exposed to stress corrosion

Liming Yang [a], Xiang-Chao Zeng [b], Hong-fa Yu [b,*]

[a] Guangxi Communications Planning Surveying and Designing Institute, China
[b] Material of Civil Engineering, Department of Civil Engineering, Nanjing University of Aeronautics and Astronautics, China

HIGHLIGHTS

- Crack density is the only way to effectively evaluate the damage failure and damage process of concrete.
- The relative dynamic elastic modulus of concrete is experimental data which has been considered multiple factors.
- The density of crack is related not only to the depth and the relative dynamic elastic modulus of concrete, but also to the initial elastic modulus of concrete.
- The relative dynamic elastic modulus of concrete can effectively show the damage process and damage degree of the concrete.
- From the three-dimensional distribution map, we can see the formula and character on the propagation of micro-crack density of concrete in corrosive medium.

ARTICLE INFO

Article history:
Received 12 April 2014
Received in revised form 6 October 2014
Accepted 24 December 2014
Available online 11 March 2015

Keywords:
Stress corrosion
Micro-cracking density
Compound brine of magnesium chloride and sodium sulfate

ABSTRACT

A new quantitative method is introduced to depict the micro-cracks in the concrete—crack density, which is closely related to the number and the size of the cracks in concrete. According to the experimental data and relative corrosion depth, the data analysis and numerical simulation are conducted by the scientific plotting and data processing software SigmaPlot 12.0 to the damage process, which can produce the three-dimensional distribution map of propagation of inner crack density of concrete. From the map we can see the formula and character on the propagation of micro-crack density of concrete in corrosive medium. In this paper, three types of concrete under the action of external stress and attack of sulfate was investigated. By analyzing the crack density, we can conclude: GHDC2 has the best stress corrosion resistance in four kinds of concrete; chloride can accelerate the chemical corrosion of magnesium and sulfate brine to concrete; tensile stress and compressive stress can obviously improve the appearance and propagation of micro-cracks.

1. Introduction

When concrete is attacked by sulfate or compound ions, there will be a chemical reaction between hydration product of cement and corrosive ions and produce expansive corrosion product such as Gypsum and Ettringite. Firstly, the formation of corrosion product in the capillary pores can compact the concrete. With the corrosion continuing, the wall of capillary pore will hinder the growth or crystallization of expansive product of corrosion, which will produce the crystalline swelling pressure. When the crystalline swelling pressure is higher than the tensile strength of concrete, there will be many isolated micro-cracks in the concrete. With the development of chemical corrosion reaction or development of crystallized corrosion, the micro-cracks continually propagate and the isolated micro-cracks also propagate until forming the connected net of micro-cracks. This will lead to macro-cracks and serious spalling of the cover concrete, which can result in failure of concrete. External loading can make stress concentrated on the tip of micro-cracks, which accelerate the propagation of micro-crack and then interwork until forming net of micro-cracks. As a result, the chemical corrosion, crystallization corrosion and stress corrosion and the coupling effects are all closely related to the formation, propagation and interworking of the micro-cracks in concrete. Although the damage variable can quantitatively descript the micro-cracks in concrete, it is only macro-scropic and indirect description. As for the quantity, size and the damage variable in development, the damage variable cannot deal with it. It is necessary to introduce new quantitative method to depict the micro-cracks in the concrete.

* Corresponding author.
E-mail addresses: 303471354@qq.com, limingyang@nuaa.edu.cn (L. Yang), zxcgzz@sina.com (X.-C. Zeng), yuhongfa@nuaa.edu.cn (H.-f. Yu).

http://dx.doi.org/10.1016/j.conbuildmat.2014.12.042
0950-0618/© 2015 Published by Elsevier Ltd.

Considering the ion diffusion and the coupling effect between ion diffusion and decline of the physical properties (mainly considered the crack), Samson [1], Ruthven [2] and Shen [3] established damage model of cementing material under sulfate corrosive environment basing on the mechanism of chemical corrosion reaction and the attenuation of physical and mechanical properties of cementing material. In the model they considered diffusion caused by the senior high school entrance examination chemistry activity factor difference concentration gradient and corrosion ion corrosion pore solutions of concrete among, but did not considered diffusion led by the potential difference between the corrosive ions [4].

With the re-understanding of the mechanism and damage process of sulfate attack on concrete, Stora et al. [5] comprehensively considered the ion diffusion, difference of chemical activity between ions, chemical attack, damage accumulation and the change of porosity and property with damage. Then equation of ion diffusion on cracked concrete was deduced. Crack density and critical point of crack density when property of concrete changed, were used as the main parameters.

Stora et al. simulated the chemical attacked reaction and propagation of physical property in the concrete. Then an orthotropic damage model of microphysics was set up to study the long-term workability of cement-based material. The long-term workability includes the diffusion property, physical property and chemical property, etc. Then a multiple-scale homogeneous model was set up by Stora et al. [6], which can wholly evaluate the physical property, mineral composition, diffusion and leaching of cement-based material.

Considering the crack and propagation of damage under attack of sulfate attack, Idiart et al. [7] set up a meso-scale model by physical and chemical analysis.

Crack is one of the most important and effective index of the concrete damage failure assessment. Based on literature, it has been found that there is no other way to evaluate the damage failure and damage process of concrete using crack density. And there is no way to study the change law of crack density. Liming [8] introduced the concept of "the crack density". The crack density is a non-dimensional physical quantity describing the relationship between the micro-cracking propagation and the strain in concrete. The physical meaning is the proportion of micro-crack volume per unit volume of concrete, which is closely related to the number and the size of the cracks in concrete. In this paper, three types of concrete under the action of stress and attack of sulfate and chloride were prepared and analyzed. The first set is the fly ash concrete. The second set is the high performance concrete. And the last set is the high performance expansive concrete with fibers reinforcement.

2. Materials and experiments

2.1. Preparation of specimens

The materials used in this experiment were P.II 52.5R Portland cement, class I fly ash, class S95 slag, silica fume, aluminate expansion agent, river sand with fineness modulus of 2.72, and coarse aggregate with maximum size of 10 mm. Naphthalene-type super-plasticizer, polycarboxylate-type super-plasticizer, and a high-range air-entraining agent were added to keep good workability of fresh concrete. Dumbbell steel fiber, polypropylene fiber, and polyester fiber were also used to improve the properties of concrete. The chemical composition of materials is shown in Table 1. The parameters of fibers are shown in Table 2. The compositions of the different mixtures are shown in Table 3. HPHFREC includes two mixtures of GHDC1 and GHDC2 (see Table 4).

Table 2
Parameters of fibers.

Fiber	Aspect ratio	Density (g/m^3)	Elastic modulus (GPa)	Length (mm)
Steel fiber	44.4		200	20
Polypropylene fiber		0.91	⩾3.5	19
Polyester fiber		1.36	14–18	18

First, specimens with size of 40 mm × 40 mm × 160 mm, embedded with inner and outer thread rod at both ends, were cured in sealed condition for 24 h. Then the specimens were cured in saturated limewater from 17 °C to 23 °C for 28 days. Afterwards the specimens were separately underwent four kind of test procedures, which were (1) transferred into solution of 5% by weight of magnesium sulfate; (2) immersed in 5% magnesium sulfate solution after being subjected to a flexural load (the ratio of flexural is 35%); (3) transferred into solution of 5% by weight of magnesium sulfate + magnesium chloride; (4) immersed in 5% magnesium sulfate + magnesium chloride solution after being subjected to a flexural load (the ratio of flexural is 35%);The change of dynamic modulus of elasticity (DME) was detected and recorded as to observe the corrosion of concrete specimens in magnesium sulfate environment.

2.2. Loading tests

The setup for loading test is shown in Figs. 1 and 2. In the Fig. 1, there are fulcrums on and under the samples. These fulcrums are looked as the loading points. Then the box was poured into the chemical solutions. So, the samples were immersed with the chemical solutions when being loaded. The flexural stress loading is controlled by the spring expansion of two section of the loading device in Fig. 1. Tensile stress or compressive stress can be got by F/A, that is, the force except the section area of specimen. The force means tensile loading or compressive loading, which can be obtained by the testing machine in Fig. 2.

In order to guarantee sufficient strength and stiffness for the frame, the size of the steel plates was set to 40 mm × 40 mm × 160 mm and the diameter of the steel bars to 28 mm. The disc springs were used in order to minimize stress loss during the experiment. The external load was controlled and measured by the displacements of the springs.

After the specimens were cured for certain days, they were subjected to different external loads. Compressive stress was applied by two top nuts after three specimens fixed completely to the steel plates by special epoxy glue. And tensile stress was applied by moving up the two middle nuts. The stress level was maintained by monitoring the displacements of the disc springs. The stress level λ was defined as Eq. (1):

$$\lambda = \sigma / f \times 100\% \tag{1}$$

where σ is the applied stress, f is the measured compressive strength (f_c) or tensile strength (f_t) of the concrete specimen. In this paper, λ is 35%.

3. Model of micro-crack density of concrete

According to the mechanism of formation and expansion of micro-crack in concrete during the course of the corrosion, the corrosive micro-crack is the opening model crack formed by crystalline stress from the expansive attacked product. According to the principle of mechanical equivalence, the corrosive micro-crack is equivalent to the tensile crack produced by external tensile

Table 1
Chemical composition of materials (mass fraction, %).

Material	SiO_2	Al_2O_3	CaO	MgO	SO_3	Fe_2O_3	MnO	TiO_2	Na_2O	K_2O	I.L
Cement	20.60	5.03	65.06	0.55	2.24	4.38					1.30
FA	52.37	32.13	2.16	0.47	0.33	4.13			0.25	0.61	1.30
SG	33.48	12.21	36.35	10.59	0.66	1.40	0.34	2.17	1.27	0.56	0.36
AEA	19.82	16.62	28.60	1.58	26.86	2.66			0.32	0.30	3.02
SF	93.1	0.61	0.52			0.22					5.55

Notes: fly ash – FA; slag – SG; SF – silica fume; AEA – aluminate expansion agent.