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The damage model of concrete under coupling action of calcium leaching and load

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Abstract: For calcium leaching and loaded concrete in engineering structures, defining the initial damage state as basic state, the damage model of calcium leaching and loaded concrete is established using damage mechanical theory and principle of strain equality. It is shown that the mechanical properties of calcium leaching and loaded concrete are determined by calcium leaching, load and coupling effect. For calcium leaching and loaded concrete, the influence factors to stress at any point are elastic modulus, maximum strain, strain at this point and the degree of calcium leaching.

Introduction

In Recent Half Century, a lot of concrete structure were damaged because of insufficient durability home and abroad., the study of durability became a research focus in engineering field. To improve the durability and service life of concrete was brought into the technology developing outline of the Eleventh Five-Year Plan of China[1]. The durability of concrete structures is considerably affected by the accumulation of damage resulting from time variant external loading in conjunction with environmentally induced mechanisms such as moisture and heat transport, freeze-thaw actions, chemically expansive reactions, chemical dissolution or by the corrosion of the reinforcement. Out of the wide range of environmentally induced deterioration mechanisms the coupled effects calcium leaching and mechanical damage in structures made of cementitious materials such as concrete exposed to aggressive environmental conditions are addressed in the present paper.

Long-term degradation of concrete structures under permanently aqueous environmental conditions is mainly controlled by interacting chemical and mechanical processes leading to the destruction of the microstructure of the material resulting from the dissolution of soluble cement constituents such as calcium hydroxide, calcium silicate hydrate (CSH) and ettringite and the opening and propagation of micro-cracks[2,3].

Based on the experimental results on calcium leaching and coupled chemo-mechanical damage, material models equationted on a macroscopic level of observation, have been developed for numerical predictions of the life time of concrete structures. One type of models is based on the pioneering work by Gérard (1996) and subsequent publications (Gérard, 2000; Gérard et al., 1998; Pijaudier-Cabot et al., 1998a,b, 2002; Le Bellégo et al., 2000, 2001a,b). It is based on a phenomenological chemical equilibrium model relating the calcium concentration of the skeleton and the pore solution s(c) and on the concept of isotropic damage mechanics[2-13].

Coupled chemo-mechanical damage constitutive relation of concrete under calcium leaching and load

According Strain equivalent principle put forward by Prof. Lemaitre,

$$\varepsilon = \sigma / \mathrm{E}' = \sigma' / \mathrm{E} \tag{1}$$

Where E means the elastic modulu of undamaged material， E' means the elastic modulu of damaged material.

ZHANG Quamhong et al., defined the initial damage state as the reference damage state, present the following extended strain equivalent principle[14].

$$\varepsilon = \sigma_1 / \mathrm{E}_2 = \sigma_2 / \mathrm{E}_1 \tag{2}$$

Where σ_1 means the effective stress under the first damage state，σ_2 means the effective stress under the second damage state；E_1 means the elastic modulu of concrete under the first damage state，E′means the elastic modulu of concrete under the second damage state.

Acording the extended strain equivalent principle, defined the reference damage state as the first damage state, defined the calcium leaching damage state as the second damage state, then

$$\sigma_0 \mathrm{A}_0 = \sigma_n \mathrm{A}_n \tag{3}$$

$$D_n = \frac{\mathrm{A}_0 - \mathrm{A}_n}{\mathrm{A}_0} \tag{4}$$

Where：σ_0, A_0 means the effective stress and the effective loading area under the reference damage state, σ_n, A_n means the effective stress and the effective loading area under the calcium leaching damage state. D_n means calcium leaching damage variable。Acording Eq.3 and Eq.4,then

$$\sigma_n = \sigma_0 / 1 - D_n \tag{5}$$

$$\varepsilon = \sigma_0 / \mathrm{E}_n = \sigma_n / \mathrm{E}_0 \tag{6}$$

Where E_0 means the elastic modulu of concrete under the reference damage state，E_n means the elastic modulu of concrete under the calcium leaching damage state.

Acording Eq.5 and Eq.6, then

$$\mathrm{E}_n = \mathrm{E}_0(1 - D_n) \tag{7}$$

$$\sigma_n = \mathrm{E}_0(1 - D_n)\varepsilon_n \tag{8}$$

Acording the extended strain equivalent principle, defined the calcium leaching damage state as the first damage state, defined the calcium leaching and loading damage state as the second damage state, then

$$\sigma = \mathrm{E}_n(1 - D)\varepsilon \tag{9}$$

where D means loading damage variable.

Acording Eq.7 and Eq.9, then

$$\sigma = \mathrm{E}_0(1 - D - D_n + DD_n)\ \varepsilon \tag{10}$$

If $D_m = D + D_n - DD_n$, then

$$\sigma = \mathrm{E}_0(1 - D_m)\ \varepsilon \tag{11}$$

Where D_m means calcium leaching and loading damage variable, DD_n means the coupled effects of calcium leaching and loading damage.

The chemo-mechanical damage evolution of concrete under coupling action of calcium leaching and load

It is possible to describe Chemical damage of concrete using calcium concentration according chemical damage mechanism under calcium leaching. So the calcium leaching damage variable D_n was defined as following,

$$D_n = 1 - \exp(kL)$$
$$L = \frac{m_x}{m_0} \quad (12)$$

Where m_0 means calcium concentration of concrete before calcium leaching（mg/mg）, m_x means accumulative leaching calcium concentration（mg/mg）, k is material constant, negative value, which is determined by experiment.

The strength of concrete submit Weibull distribution under loading, so damage variable D submit Weibull distribution under loading also. damage variable D discribed by two-parameter Weibull distribution as following,

$$D = 1 - \exp[-(\frac{\varepsilon}{a})^n] \quad (13)$$

Where ε means strain, n means Shape parameter and a means Scale parameter.

$$\sigma = \mathrm{E}\varepsilon(1-D) = \mathrm{E}\varepsilon\exp[-(\frac{\varepsilon}{a})^n] \quad (14)$$

The Stress -Strain Relationship should meet the following geometric conditions,

When $\varepsilon = 0$, $\sigma = 0$;
$\varepsilon = 0$, $d\sigma/d\varepsilon = \mathrm{E}$;
$\varepsilon = \varepsilon_f$, $\sigma = \sigma_f$;
$\varepsilon = \varepsilon_f$, $d\sigma/d\varepsilon = 0$ (15)

Where σ_f means stress maximum, ε_f means strain corresponding the stress maximum.

AccordingEq.14,

$$\frac{d\sigma}{d\varepsilon} = \mathrm{E}[1 - n(\frac{\varepsilon}{a})^n]\exp[-(\frac{\varepsilon}{a})^n] \quad (16)$$

AccordingEq.14, Eq.15 and Eq.16,

$$\mathrm{n} = \frac{1}{\ln(\frac{\mathrm{E}_0\varepsilon_f}{\sigma_f})} = \frac{1}{\ln \mathrm{E}_0 - \ln \mathrm{E}_m} \quad (17)$$

Where E_m was secant modulus.

$$a = \varepsilon_f (\frac{1}{n})^{-\frac{1}{n}} \tag{18}$$

According Eq.13 and Eq.18

$$D = 1 - \exp[-\frac{1}{n}(\frac{\varepsilon}{\varepsilon_f})^n] \tag{19}$$

According Eq.12 and Eq.19,

$$D_m = D + D_n - DD_n = 1 - e^{[-\frac{1}{n}(\frac{\varepsilon}{\varepsilon_f})^n] + kL} \tag{20}$$

$$\dot{D}_m = (1 - D_n)\frac{\partial D}{\partial \varepsilon} + (1 - D)\frac{\partial D_n}{\partial n} \tag{21}$$

According Eq.11 and Eq.20,

$$\sigma = E_0 e^{[-\frac{1}{n}(\frac{\varepsilon}{\varepsilon_f})^n + kL]} \varepsilon \tag{22}$$

The stress at any point of concrete related to initial elastic modulus, strain maximum, the strain and the calcium leaching degree under coupling action of calcium leaching and load.

Conclusion

Acording the extended strain equivalent principle, defined calcium leaching damage state as the first damage state, defined the calcium leaching and loading damage state as the second damage state, constitutive relation of concrete was derived under coupling action of calcium leaching and load.

The total damage of concrete aggravated under coupling action of calcium leaching and load. The action of calcium leaching could induce local damage of concrete, the action of load could induce the dislocation glide of microstructure element of concrete, the local stress increased, microcrack extended and even the stress at any point of concrete related to initial elastic modulus, strain maximum, the strain and the calcium leaching degree under coupling action of calcium leaching and load.

The damage modle of concrete under coupling action of calcium leaching and load should be verified using reliable test date.

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