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Damage constitutive models of concrete under the coupling action of freeze–thaw cycles and load based on Lemaitre assumption

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HIGHLIGHTS

- Damage under freeze–thaw cycles and load was studied by Lemaitre strain equivalent assumption for the first time.
- Evolution laws of coupling damage were entirely different owing to the freeze–thaw cycles and load.
- The damage model reflected the characteristics of the σ-ε curve of concrete under freeze–thaw cycles and load.
- The peak strain can be the critical point of the coupling damage.

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ABSTRACT

In cold environments, concrete structures are subjected to a combined action of load, freeze–thaw cycles, and salt attack. The performance degradation of some concrete structures in such areas is serious, thus shortening their service life. In this study, a macro-mesoscopic coupling damage model was established to determine the durability of concrete under the coupling action of freeze–thaw cycles and load based on the Lemaitre strain equivalent assumption. Meanwhile, the an indoor accelerated test was conducted to verify the rationality of the model. Results indicated that the damage in different kinds of concrete under freeze–thaw cycles and load can be predicted by the theoretical model. The structural coupling damage was determined by the *meso*-damage caused by the freeze–thaw cycles and the macro-damage caused by the applied load, which showed a nonlinear superposition relationship. The evolution laws of coupling damage were entirely different because of the freeze–thaw cycles and strain. The coupling damage and peak strain increased with the increase in number of freeze–thaw cycles but the variation range of damage and peak stress decreased. The peak strain can be the critical point of the coupling damage when the number of freeze–thaw cycles was constant. The growth of coupling damage was not significant before the peak strain. When the deformation approached the peak strain, the coupling damage increased considerably, and the concrete was destroyed rapidly.

1. Introduction

During the Second International Conference on Concrete Durability in 1991, Professor P. K. Mehta elucidated that freeze–thaw had become the major factor that affects the durability of concrete structures [1]. Fig. 1 is the freeze proof and durability grade of the concrete structures in some major cities in China, based on the study of W.L. Jin team on the difference between the laboratory test and the actual freeze–thaw environment. As shown in Fig. 1 below, concrete structures were damaged heavily under freeze–thaw in the northern cities of China. Every year, the freeze–thaw damage in the northeast area is more than 110 cycles in the indoor simulation test [2]. Therefore, the damage mechanism of concrete under freeze–thaw cycles must be quantitatively described.

M. Ohtsu detected the damage in the concrete duct by acoustic emission device and combined the acoustic rate with Loland damage model to measure the damage degree of the concrete [3]. H.F. Yu [4] and D.T. Niu [5] used the relative dynamic elastic modulus of as the damage variable and established the prediction model of concrete life in freeze–thaw cycles condition; in addition, the conclusion of macro data analysis is confirmed by thermal analysis, electron microscopy, mineral composition, and pore changes [5]. L. Basheer established a microscopic mech-

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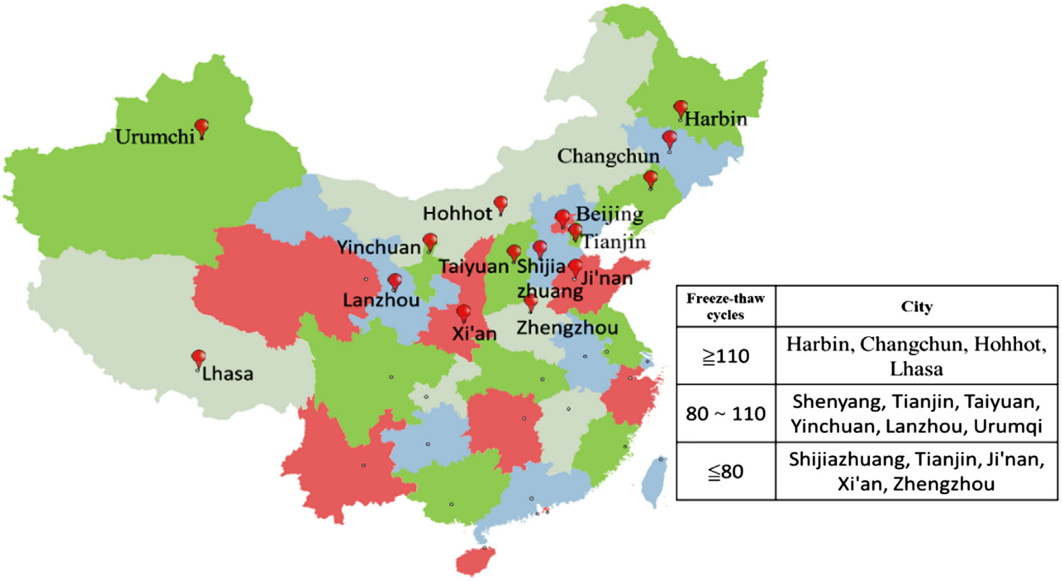

Freeze-thaw cycles	City
≥110	Harbin, Changchun, Hohhot, Lhasa
80 ~ 110	Shenyang, Tianjin, Taiyuan, Yinchuan, Lanzhou, Urumqi
≤80	Shijiazhuang, Tianjin, Ji'nan, Xi'an, Zhengzhou

Fig. 1. Distribution of annual freeze–thaw situation in some cities in China.

anistic model in ultra-low temperature environments based on the energy method of fracture mechanics, with the porosity, crack, and freeze–thaw cycles as the influencing factors [6]. P. Soroushian and B. Johannesson observed the evolution of concrete under the salt attack and freeze–thaw cycles by adopting SEM and scanning calorimeter. This study obtained the microscopic appearance of concrete during the salt attack and freeze–thaw cycles process and the change in ice content in the internal micropores [7,8]. Academician W. Sun concludes that the failure in concrete structure is exposed extensively to the combined action of load and environment. Therefore, the study on the durability of concrete should consider the coupling action of load and environment [9]. In the earlier experimental study, Sun team had attained some achievements in the degradation mechanism under the coupling action of bending load and freeze–thaw cycles [10,11]. Z.D. Wang investigated the deterioration process of concrete specimens under the coupling effect of freeze–thaw cycles, salt attack, and external load. The external load can accelerate the damage under the salt attack and freeze–thaw cycles and reduce the dynamic elastic modulus of concrete [12,13].

Although numerous damage theory models of concrete exist under the bad environment, most of them are either macro or micro model. The study cannot satisfy the actual situation due to lack of linkage between micro and macro models. However, thorough analysis was conducted on multiscale coupling in the rock field. In 2000, at the 6th Rock Mechanics and Engineering Conference of Chinese, G.S. Yang proposed a kind of theory of coupling damage about rock mass [14]. When calculating the damage of the rock mass, Liu's team comprehensively considered the macroscopic damage and mesoscopic damage. He obtained a coupling model based on the hypothesis of Lemaitre strain equivalence and verified with experiments [15].

In this study, the multiscale damage model of concrete under the coupling action of freeze–thaw cycles and load is established based on the hypothesis of Lemaitre strain equivalence. On one hand, the microscopic damage under freeze–thaw can use the relative dynamic elastic modulus of as the damage variable. On the other hand, the macroscopic damage in concrete under load can be defined by Weibull Distribution function [16]. Then, the multiscale damage model is verified by laboratory tests of six different kinds of concrete.

2. Damage evolution equation of concrete under freeze–thaw cycles and load

2.1. Damage evolution equation of concrete under freeze–thaw cycles

Concrete is a porous medium material consisting mainly of cement paste and aggregate. The microscopic damage of concrete increases with an increase in the number of freeze–thaw cycles. Then, many microscopic cracks appear inside the concrete and the relative dynamic elastic modulus declines. Based on the definition of damage mechanics, the relative dynamic elastic modulus is introduced to reflect the damage in concrete [17]. The damage degree, D_1, in concrete is defined in Eq. (1).

$$D_1 = 1 - \frac{E_n}{E_0} \tag{1}$$

where D_1 represents the freeze–thaw damage variable, and E_0 and E_n are the dynamic elastic modulus of concrete after 0 and n cycles of freeze–thaw, respectively.

2.2. Damage evolution equation of concrete under load

The destruction in concrete under the load is a cumulative result. During the load process, first, the micro cracks appeared in some regions. Then, the macroscopic cracks developed from microscopic cracks, and finally the concrete reached a state of destruction. In this paper, the micro elements in concrete were assumed to obey a two-parameter Weibull Distribution given that the micro cracks in concrete are randomly distributed. Therefore, the destruction probability of concrete is defined in Eq. (2) [18–20].

$$p(\varepsilon) = \frac{\mathrm{m}}{f}\left(\frac{\varepsilon}{f}\right)^{m-1} e^{-\left(\frac{\varepsilon}{f}\right)^{m}} \tag{2}$$

where $P(\varepsilon)$ is the strength distribution function of concrete microelement, ε is the strain value of concrete, and m and f are the distribution parameters of the model.

The number of broken infinitesimal elements in concrete was assumed as n under a certain level of load. The damage variable, D_2, of concrete is defined in Eq. (3).

$$D_2 = \frac{\mathrm{n}}{N} \tag{3}$$