Modeling and Simulation of Frost Damage of Concrete and its Combined Effect with Fatigue Loadings

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Introduction

Frost damage mechanism under freezing and thawing cycles (FTC) is an important issue for service life evaluation of concrete structures in cold regions. Once frost damage happens, deterioration process like chloride ion, carbon dioxide migration and even the frost action itself will be largely accelerated, result in shorter service life. In addition, the frost damage is always coupled with external loads, and the combined effect will also affect the material degradation and structure performance significantly.

In order to simulate the frost damage mechanism and the combined effect, the following steps have been conducted: (1) the thermodynamic model of moisture in pores, which tells the phase equilibrium and amount of ice formation; (2) the pore pressure model, which can quantitatively explain the material deformation during FTC under different environmental conditions; (3) the mesoscale model and simulation of pure FTC damage, which includes the mechanical interaction between the porous body and the ice-water system; (4) the macroscale mechanical property change due to ice strengthening effect at low temperatures; (5) the simulation of the combined FTC and mechanical loading.

Stress analysis under FTC

Once ice forms in highly saturated concrete material, internal tensile stress will be generated and causes damage to the material, which is a serious problem for concrete structures in cold and wet regions. On one hand, each component (porous body, ice and liquid) should satisfy the compatibility of stress and strain, which has been discussed by the poromechanical theories. On the other hand, if some empty voids exist, the hydraulic pressure will release when liquid water escapes from the expanded area according to Darcy's law. Recent closed freeze-thaw tests on the saturated mortar showed a consistent tendency: as the number of freeze-thaw cycles (FTC) increases, the deformation changes from the expansion to the contraction. In order to make clear the physical and mechanical changes during this process, a more comprehensive hydraulic model is developed, which combines both the mechanisms mentioned above. The estimated strain behavior by this model is in a good agreement with experimental measurements, and also, it has good potential and is more flexible to be applied to different cases such as different saturation degrees and cooling rates. The permeability change can be also considered in this model as a reflection of frost damage level.

Mesoscale model of pure FTC

After achieving a more comprehensive internal pressure model, the mesoscale model using Rigid Body Spring Method (RBSM) is developed to simulate the deformation behaviors of concrete under FTC cycles. On one hand, the macroscopic material is divided into small rigid elements of mesoscale; on the other hand, the microscale internal pore pressures are regarded as average values in mesoscale based on poromechanical theories. The constitutive relation is also developed to reflect deformation compatibility between porous body and ice-water system. The simulation results can show the internal cracking and residual deformation clearly, which are also found in a good agreement with previous experimental data.

Properties at low temperature

Although the internal stresses generated during freeze-thaw process would cause serious damage and other durability problems to concrete structures, if just concerning the stage while the temperature is below 0oC, ice could reduce the stress concentration within the concrete by filling the capillary and gel pores and result in a significant increases in elastic modulus and strength, which is usually beneficial for concrete under external loads (either static or fatigue). In order to distinguish and simulate the strengthening effect induced by ice quantitatively, a theoretical model explaining the change of elastic properties has been developed based on the theories of multiphase composite media. The predicted elastic modulus is in a good agreement with experiment data.

Mesoscale simulation using RBSM

The constitutive laws for the mortar and concrete under external fatigue loading is also developed based on RBSM, which is a simplification and modification of previous model. Finally different types of loading condition are simulated, which includes:

- Pure FTC deformation and damage.
- The static loading with ice strengthening effect.
- Pure fatigue test for mortar and concrete.
- Fatigue test with different level of FTC damage.