学　位　論　文　内　容　の　要　旨

DISSERTATION ABSTRACT

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

(コンクリートの凍害および凍害-疲労複合劣化モデルとシミュレーション)

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. The frost damage is thought caused by the internal pore pressures generated during FTC, which includes both physical cycles and mechanical cycles. While for external loading like fatigue, it can be simply regarded as the mechanical cycles. Although the two effects have different natures, the damage of both can be reflected by the micro cracks initiating and propagating, which will finally result in the increasing residual deformation and reduction in stiffness, strength and so on. Therefore, it is possible to model and simulate the combined effects together. 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.

For the moisture condition in the pores of concrete material, the phase diagram is a useful tool in physics to show the form of water and phase equilibrium. By adding the pore radius to the traditional phase diagram, a three-dimensional phase diagram for pore water can be obtained. The shift of triple point and the phase boundaries can be quantitatively adjusted according to pore radius based on thermodynamic analysis. Therefore, a clearer image of moisture in pores can be shown, which could be a convenient tool to get the overall moisture condition inside the material. As a practical application, the 3D phase diagram is used to determine the ice content at low temperatures.

Once ice forms in highly saturated concrete material, internal tensile stress will be generated and causes damage to the material. 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. Previous freeze-thaw tests on the saturated mortar with closed moisture condition 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 compared with experimental measurement, 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 the proposed model as a reflection of frost damage level.

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.

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.

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:

(1) Pure FTC deformation and damage. The mortar and mortar-aggregate interface are simulated under closed moisture condition with 30 cycles while the concrete is simulated under open moisture condition with 300 cycles. The simulation results can show the damage cumulating, permeability change due to damage, the deformation behavior (reversing from expansion to contraction in closed test while continuously increasing in open test), crack pattern and width and so on, which agree with the experimental data well.

(2) The static loading with ice strengthening effect at low temperatures. The ice strengthened elastic modulus from the multi-phase composite model is adopted in the RBSM simulation, and the compressive, uniaxial tensile and splitting tensile tests are simulated and compared with the strength change in experiments, which also show a satisfactory agreement.

(3) Pure fatigue test for mortar and concrete. The fatigue life by the simplified time-independent model is compared with the previous time-dependent model (in which the creep was also considered). And the fatigue simulation is extended from mortar to concrete which includes the effect of interface. The simulated concrete fatigue life matches previous experiments well.

(4) Fatigue test with different level of FTC damage. In which the FTC test (open moisture condition) is conducted first to obtain the internal micro cracking, then using the FTC damaged concrete, static test is simulated to obtain the residual strength while fatigue simulation is conducted to get the fatigue life. Both the residual strength and fatigue life show a significant reduction, which agree with experimental observations well.