Modeling and Simulation of Moisture Condition and Strain Behavior for Mortar under Freeze-thaw Cycles

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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. In order to simulate the frost damage mechanism, at least two basic parts are needed: (1) physical model, which tells the moisture transport and the phase equilibrium inside the concrete; (2) mechanical model, which can explain the strain behavior of the structure members due to the physical change of the moisture when suffering FTC.

In this paper, the heat and moisture transfer analysis and also the ice formation analysis will be conducted on the Rigid Body Spring Model (RBSM). After that, a degradation constitutive model is proposed to describe the deformation behavior under several FTCs. Finally, in order to evaluate the effectiveness of this method, the simulation results are compared with experimental data of the strain behavior under FTCs and found in satisfactory agreement with the experimental data. Another contribution of this study is the empirical estimation of pore size distribution.

Method of analysis

RBSM

The analytical model is divided into polyhedron elements, and the mesh is arranged randomly using a Voronoi diagram (see Fig. 1). Each Voronoi cell represents a mortal element in the model.

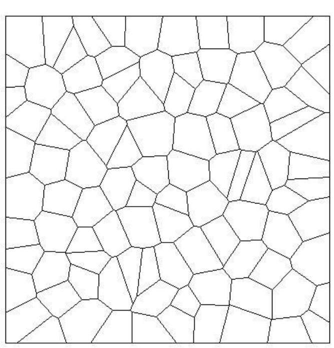

Fig. 1 Elment mesh of analysis

For two adjacent elements, there are two springs connecting them: normal spring and shear spring, which are placed at the boundary of the elements (see Fig. 2). Each element has two transactional and one rotational degree of freedom at the center of gravity [1].

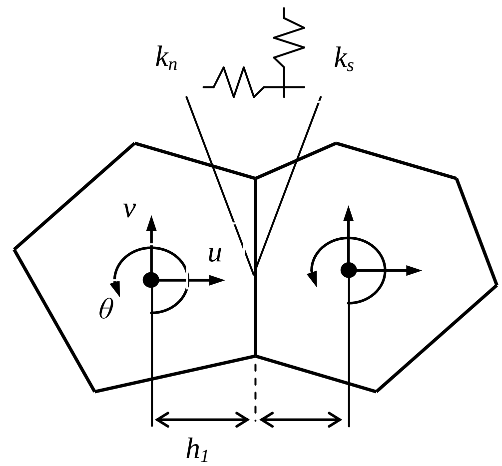

Fig. 2 Elements, degree of freedom and springs

Moisture equilibrium

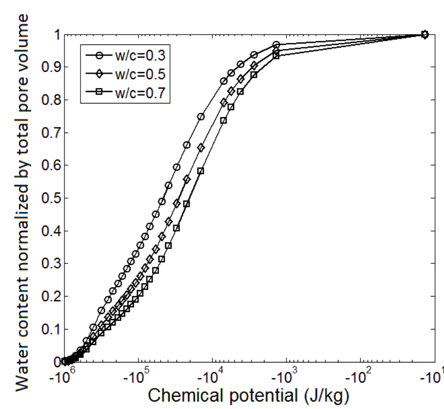

Fig. 3 Water content regarding chemical potential

Fig. 3 shows the equilibrium between liquid and vapor phase. And by combining the chemical potential of ice, the equations can be as follows [2]:

$$\begin{cases} \mu_i = H_{li} \ln \dfrac{T}{T_0} \\ \mu_l = f(\psi_l) \end{cases} \quad (1)$$

The relation of ice initiation temperature regarding saturation degree can be obtained:

$$T_{ini} = T_0 \times \exp\left(\frac{f(S_r)}{H_{li}}\right) \qquad (2)$$

The ice content depending on local saturation degree and temperature will become clear as follows:

$$y_i = S_r - f^{-1}\left(H_{li} \ln \frac{T}{T_0}\right) \qquad (3)$$

Mechanical model

The constitutive law for ice system can be assumed as a linear relation:

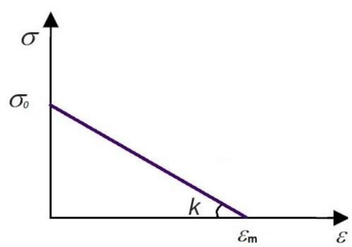

Fig. 4 Stress-strain curve of ice

The strain-stress curve of pore wall can be assumed as in Fig. 5, the vertical axis after each cycle will shift to guarantee that the new loading curve will pass the origin point.

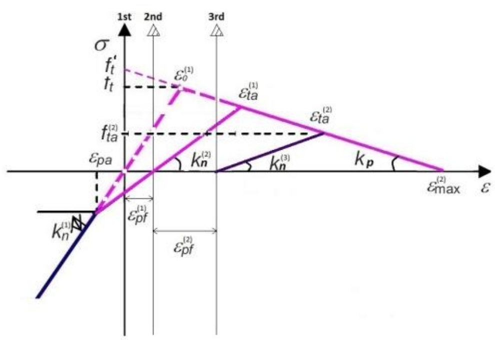

Fig. 5 Stress-strain curve of pore wall

Results and discussions

The ice initiation temperature for different w/c ratio and different saturation degree can be shown in Fig. 6. Since the liquid water will always occupy the smallest pore first, so for lower saturation degree, the more big pores will be empty. And also since the freezing point of smaller pores is lower, lower saturation degree always means lower ice initiation temperature.

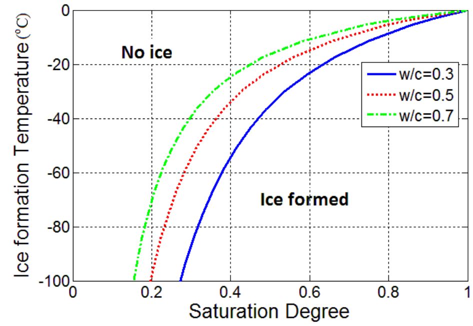

Fig. 6 Ice initiation temperature

The calculated strain using the constitutive laws (Fig. 4 and Fig. 5) is compared with the experiment results, as shown in Fig. 7.

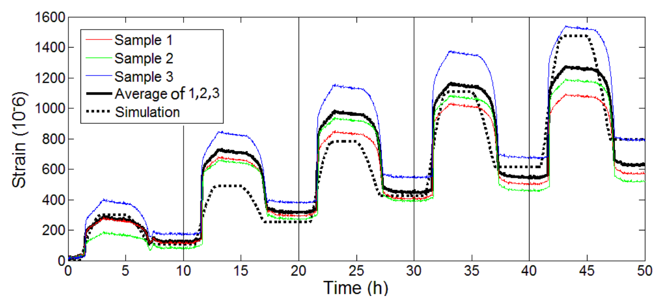

Fig. 7 Comparizion between simulation and experiement results

It can be seen that the simulation results for 5 FTCs are in satisfactory agreement with the experimental results.

Another contribution in this paper is that, by using the water adsorption isotherm and the thermodynamic analysis of liquid-vapor equilibrium, an empirical estimation of pore size distribution can be quantitatively obtained (Fig. 8). These empirical curves can provide a reliable pore size distribution for the concrete durability-related problem conviniently, especially for the numerical analysis.

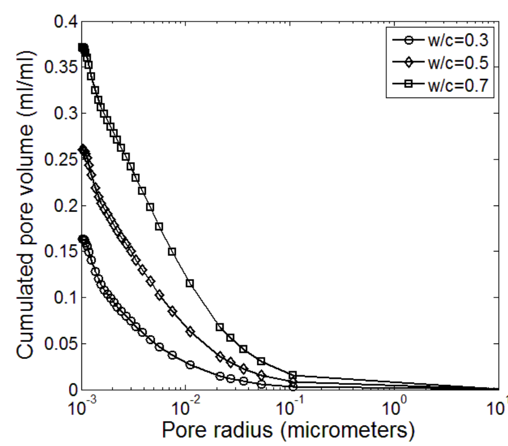

Fig. 8 Calculated cumulated pore size distribution

References

[1] Nagai, K., Sato, Y. and Ueda, T.: Mesoscopic simulation of failure of mortar and concrete by 2D RBSM. Journal of Advanced Concrete Technology, 2(3), 359-374 (2004).

[2] Matsumoto, M., Hokoi, M. and Hatano, M.: Model for simulation of freezing and thawing processes in building materials. Building and Environment, 36, 733-742 (2001).