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MODELING FOR FROST DAMAGE AND SERVICE LIFE PREDICTION

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ABSTRACT :

This paper briefly presents the outcomes of a series of studies conducted by the author's group on the service life prediction of concrete structures with frost damages. The outcomes are the overall picture to predict the service life, which includes the meso scale approach for the deformation model under freeze thaw cycles and the simulation of mechanical and durability property degradation of frost damaged concrete. At the end the remaining tasks for the better service life prediction are shown.

KEYWORDS :
Frost damage, Degraded concrete model, Meso scale model, Service life prediction

1. Introduction

The amount of resources and energy to be used for infrastructure is enormous. In order to realize sustainable development on a global scale, it is important to conduct life cycle management (LCM) of concrete structures in the world. It is because LCM makes it possible to effectively use resources and energy, reduce the effects on the environment, and optimize the economic burden in the society. For LCM service life prediction of new and existing structures with and without remedial actions under deterioration effects is the most important issue.

The service life prediction under frost attack, which is a major effect among the various deterioration effects, is rather difficult in comparison with the cases of the other major deterioration effects, such as chloride ion ingress and carbonation.

This paper briefly presents the outcomes of a series of studies conducted by the author's group on the service life prediction of concrete structures with frost damages.

2. Service Life Prediction of Structures with Frost Damage

2.1 Introduction

For prediction of service life of structures suffering from frost damage we need to develop the rational scheme to predict performances of a structure with frost-damaged concrete (see Figure 1).

Previous studies [1][2] disclose that material properties, such as mechanical and durability-related properties, of frost-damaged concrete can be simulated by meso scale modeling. However, no study has ever presented the numerical model to predict how much frost damage would occur under arbitrary environmental condition (temperature and moisture condition). Only after predicting the frost damage and the material properties of the corresponding frost-damaged concrete [3] for given environmental condition, the structural performance of concrete member with frost damage can be predicted (see Figure 1). The deformational model in meso scale under temperature and moisture variation can simulate the frost-damage, such as cracks and plastic deformation, in mortar under freeze thaw cycles (FTC) [4]. Thus, we need to develop the general deformational model of mortar with various mixtures in meso scale under various conditions of temperature and moisture history. Besides we need to develop the model of mortar-aggregate interface model in meso scale under temperature and moisture variation for simulation of properties of frost-damaged concrete.

Figure 2 explains why deformation characteristics in meso scale can lead eventually to prediction of service life of structure. Collecting experimental data on deformation behavior of mortar, aggregate and mortar – aggregate interface in meso scale as shown (a) in Figure 2, we can develop the deformation models in meso scale (b). Implementing the deformation models in the simulation program in which heat-moisture transfer analysis is coupled with mechanical damage analysis, cracks and plastic deformations due to freeze thaw cycles can be simulated (c). Using the results of the cracks and plastic deformations, the degraded mechanical and durability properties can be simulated (d). Up to this stage, all the analyses are conducted in meso scale. Based on the simulated results of the degraded properties, the mechanical and durability properties of frost damaged concrete can be modeled in macro scale (e). Structural analysis, such as FEM, with the frost-damaged concrete material models can predict performances of concrete structure with frost damage (f). Considering the time effects, we can finally predict the service life of structure under the effects of FTC (g).

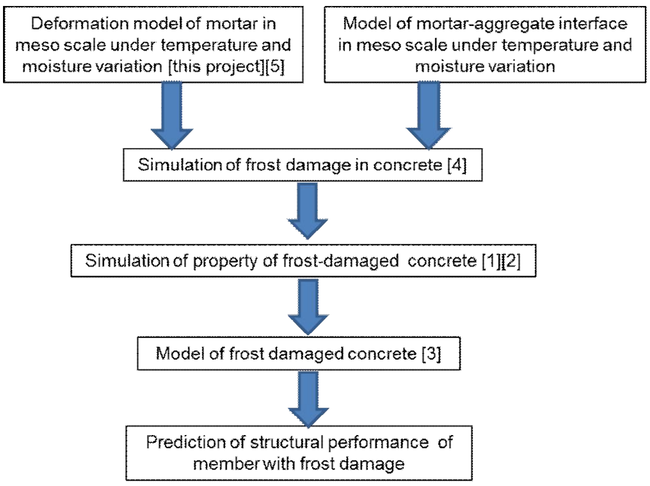


Figure 1 Necessary schemes for prediction of structural performance of member with frost damage

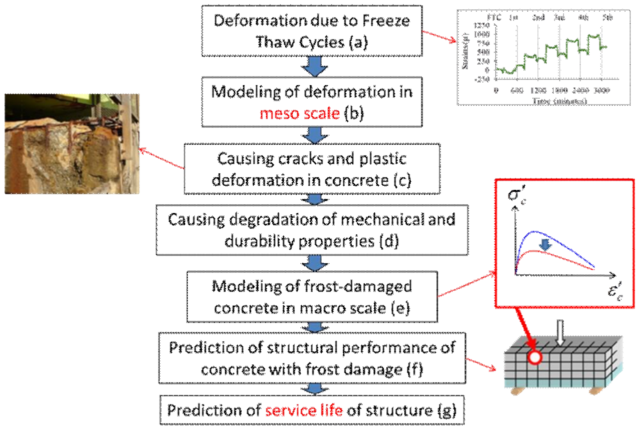


Figure 2 Steps from deformation model to prediction of service life

In the following sections the results on the deformation model, the simulation of mechanical and durability properties of frost-damaged concrete are briefly introduced. The details information can be found in the relevant references.

2.2 Deformation Model of Mortar in Meso Scale [5]

(1) Experimental Results of Mortar Deformation

In order to observe the deformation behavior of mortar in meso scale, we need to conduct test with a meso scale. The size of specimen is 40×40×2 mm (as shown in Figure 3 (a)(b)). The specimen was kept in a desiccator with a constant relative humidity to have its moisture content with a certain value (Figure 3 (c)), and then was sealed to keep the moisture condition (Figure 3 (d)). The specimen deformation was measured with strain gages that were attached on the specimens before the sealing (Figure 3 (b)). The specimens were placed in an environmental chamber to undergo freeze thaw cycles. The temperature range was 10°C to -28°C as shown in Figure 4. With the given size it can be considered that temperature and moisture in the specimen are uniformly distributed during the test. Mix proportion of the specimen was 1:2:6 as the weight ratio of water, cement and fine aggregate. The aggregate maximum size was 1.2 mm. The experimental parameter was the moisture content of the specimen, which was 100% saturation, 92% saturation, 68.4% saturation and fully drying (0%).

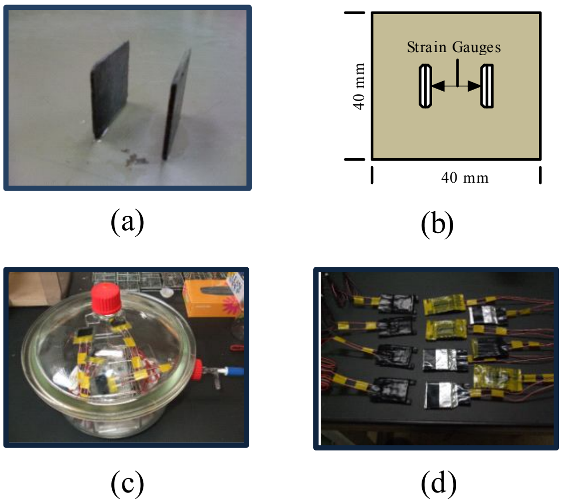


Figure 3 Preparation of mortar specimen in meso scale

Observed strain changes under five to twenty FTC of the specimens with the different moisture conditions are shown in Figure 5. The dry specimen shows a very regular and linear strain variation, which are the thermal strain characteristics. The coefficient of thermal expansion was 10.04×10^{-6}/°C. The strains of the fully and partially saturated specimens are the measured strains subtracting with the thermal strains, which were obtained from the test of the dry specimen. The fully (100%) saturated specimen shows a deformation component other than the thermal deformation. During freezing expansion can be seen, while during thawing contraction can be seen. As FTC increases, the maximum expansion during a certain FTC and the remaining expansion after that FTC gradually increase. The 92% saturated specimen show a similar nature to that of the fully saturated specimen. However, the magnitude of expansion and the remaining expansion for the same number of FTC are less. During freezing small contraction is also observed. The increase in the expansion with the increase in FTC seems to stop after certain FTC. For the 68.4% saturated specimen there is much smaller deformation, which is contraction during freezing, and the remaining deformation is negligible.

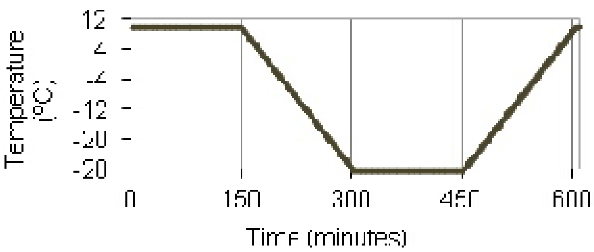
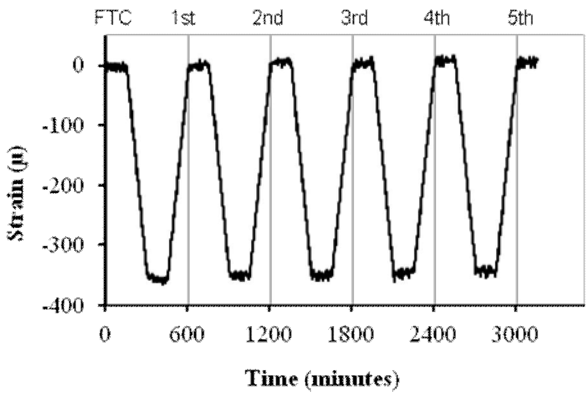
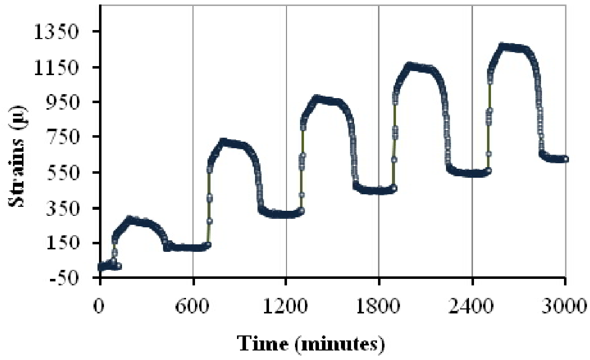


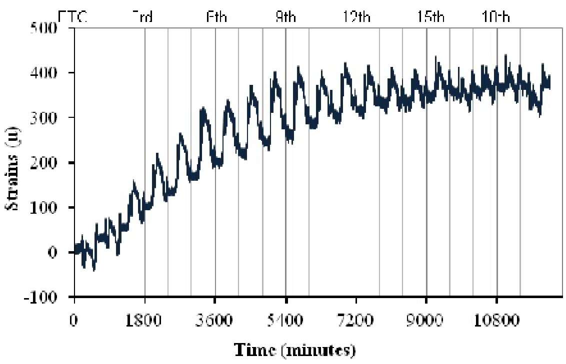
Figure 4 Temperature cycle



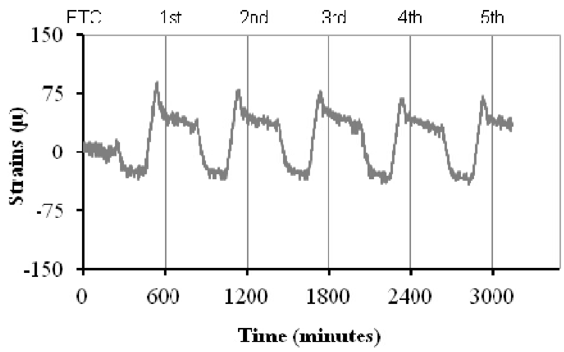
(a) Dry specimen



(b) Fully (100%) saturated specimen



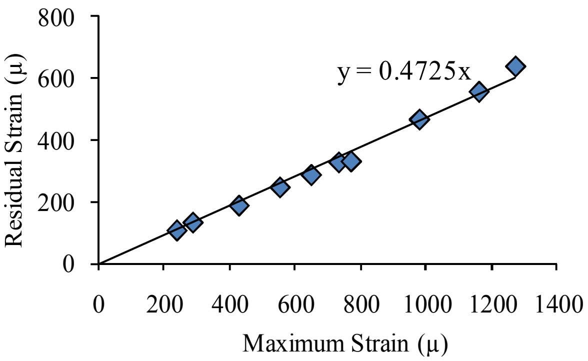
(c) Partially (92%) saturated specimen



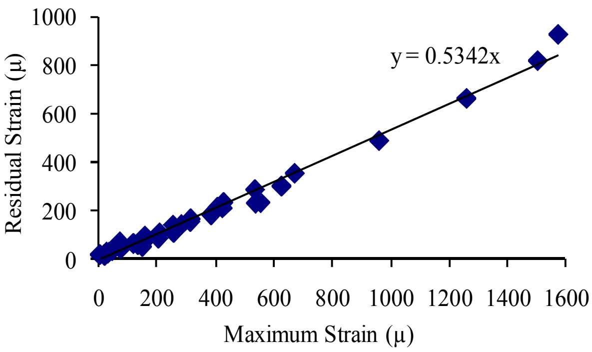
(d) Partially (68.4%) saturated specimen

Figure 5 Strain variations under FTC

We consider that the deformation component other than the thermal deformation is caused by frost action. The remaining deformation found in the fully and 92% saturated specimens are the evidence of frost damage. Interestingly there is a linear relationship between the maximum expansion during a certain FTC and the remaining expansion after that FTC as shown in Figure 6. The expansion during freezing is considered to be caused by volume increase from liquid phase to solid phase of water. On the other hand the contraction during freezing is considered to be caused by movement of unfrozen water towards ice, which can create negative pressure in surrounding cement paste. The reason for the expansion increase with increase in FTC has not been well explained yet. This may be due to the possible fact that the amount of water which can be frozen is increased because of the pore structure change. Frost damage may increase in amount of larger pore, so that more water can be frozen. Or this may be due to the fact that the stiffness of mortar could decrease due to frost damage. Thus, the same amount of ice can cause the greater expansion.



(a) Results from [5]



(b) Results from [6]

Figure 6 Relationship between maximum tensile strain and residual tensile strain

(2) Developed Deformation Model

The proposed meso scale deformation model for mortar [5] is based on the concept proposed by Arai et al [6]. The deformation model presented in this study predicts the deformation of mortar for given moisture and temperature history. Based on experimental results the expansion and shrinking behavior under freezing process changes according to the moisture condition. Depending on the moisture content either contraction or expansion is more dominant. Therefore, the apparent mortar strain ε is assumed as a combination of three strain components as seen in Eq. (1):

$$\varepsilon = \varepsilon_i + \varepsilon_s + \varepsilon_t$$

where ε_i is the expansion strain under freezing, ε_s is the shrinkage strain under freezing, and ε_t is thermal strain. The freezing expansion during FTC as summarized in the experimental findings is suggested as a product of ice formation. Therefore, it is proposed that the freezing expansion strain ε_i be a function of ice content Ψ_i and is assumed as Eq.(2) considering the fact that there would be no expansion for the water contents less than a certain value:

$$\varepsilon_i = \alpha_i \times (\Psi_i - \Psi_{ic})$$

where α_i is the material constant depending on mortar stiffness and Ψ_{ic} is the ice content when the deformation starts depending on the ice content and assumed to be 0.038. Since the contraction under freezing is caused by unfrozen water movement [7], it is assumed that the deformation depends on the unfrozen water content as seen in Eq. (3).

$$\varepsilon_s = \alpha_s \times \Psi_w$$

where α_s is the constant representing the contribution of unfrozen water content to the shrinkage, which depends on the mortar stiffness, and Ψ_w is the (unfrozen) water content. The thermal strain is obtained from Eq. (4) using the linear expansion coefficient α_t:

$$\varepsilon_t = \alpha_t \times \Delta T$$

where Δ_t is the temperature variation.

The values of three constants were obtained from the results of meso scale mortar deformation test under FTC [5] and estimated water content which is calculated by the coupled heat and moisture transfer analysis [4] as follows:

$$\alpha_i = 3410 \times 10^{-6}$$

$$\alpha_s = f(\Psi_w) = 589.32 \cdot \ln \Psi_w + 1272$$

$$\alpha_t = 10.04 \times 10^{-6}$$

(3) Prediction of Mortar Deformation

In order to demonstrate the capability of the proposed model, a mortar specimen with the size of 100×100 mm was analyzed (see Figure 7). The specimen was exposed to moisture on the top side, while the other three sides were sealed against heat and moisture movement. The heat and moisture transfer was calculated by the method shown in the previous study [4].

Figure 8 shows the chronological changes of moisture and ice content at the location pointed by the circle in Figure 7. The strains with and without thermal strain at the same location are shown in Figures 9 (a) and (b), in the latter of which show the expansion due to the ice formation.

We need the further investigation on the reliability of the developed model by collecting more data on the deformational behavior of mortar with various mixes and comparing the predicted results with available test data on deformation of macro scale specimens.

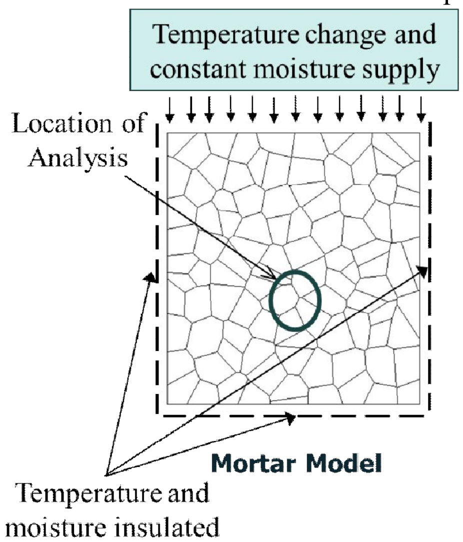


Figure 7 Analyzed mortar model

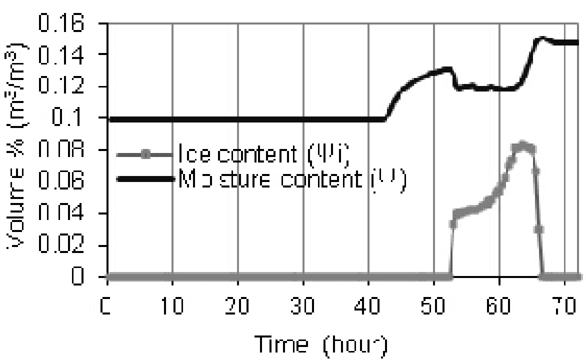


Figure 8 Predicted ice and moisture content variations with time

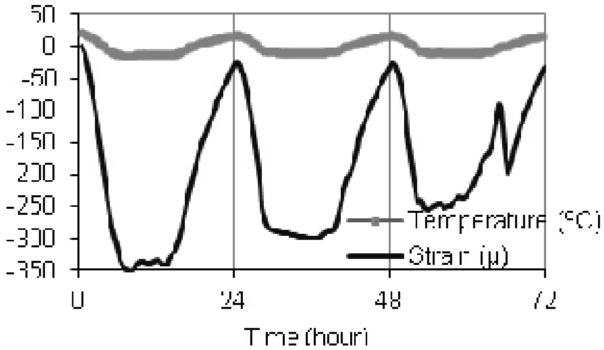
2.3 Simulation of Material Property of Frost Damaged Concrete

(1) Simulation in Meso Scale of Mechanical Property Degradation [1]

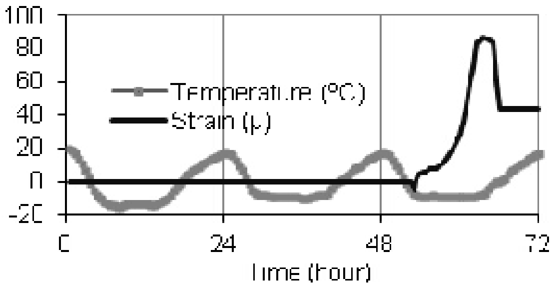
Rigid Body Spring Model (RBSM) in meso scale is a powerful and efficient numerical tool to simulate concrete containing damages, which are cracks in many cases, since cracks in meso scale can be inserted discretely anywhere in an analyzed concrete, such as aggregate-mortar interface. The meso scale here means the order of millimeter. With RBSM concrete is modeled with rigid body network connected by springs (see Figure 10). There are two types of springs; normal and shear springs. The normal springs are modeled to be linear without a limit in compression and with a limit in tension (tension strength, f_t) as shown in Figure 11 (a).

In frost damaged concrete there are many small cracks resulting in plastic tensile deformations. It is therefore assumed that during FTC the normal springs fracture in tension and show plastic tensile strain (ε_{pf}) after being unloaded from tension softening curve (see Figure 11 (a)). Considering this fact we assume that the damaged normal spring has the new tensile stress – strain relationship as shown in Figure 11 (b), whose peak stress is f_{ta} and the stiffness k_1 is smaller than that before being damaged (f_t and k_n).

We analyzed specimens shown in Figure 12 with the stress – strain relationship of frost damaged concrete as shown in Figure 11 (b). The extent of frost damage is indicated as the amount of the plastic tensile strain (ε_{pf}). The simulated stress – strain relationships in compression are compared with the tested results as shown in Figure 13. The degraded strength and stiffness are nicely simulated. Figure 14 shows the simulated stress – strain relationship in tension. Both simulated strength and stiffness show degradation with frost damage as observed in previous experiment [8]. The experimental fact that the reduction in compression strength is less significant than that in tension strength can be simulated as well. The interesting fact is that the frost damaged concrete show more ductile behavior in the post-peak region under both compression and tension.



(a) Deformation with thermal strains



(b) Deformation without thermal strains

Figure 9 Predicted strains

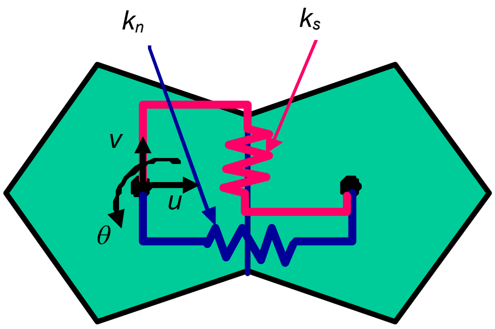


Figure 10 Rigid body spring model (RBSM)

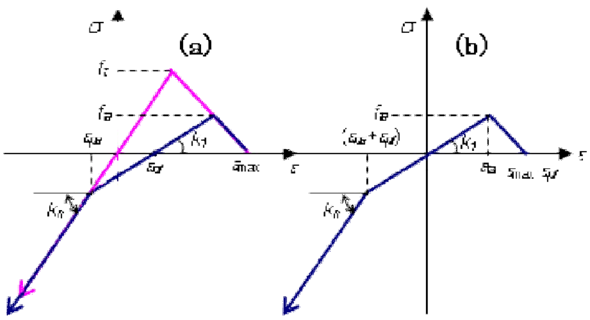


Figure 11 Stress – strain relationships of normal spring without and with frost damage

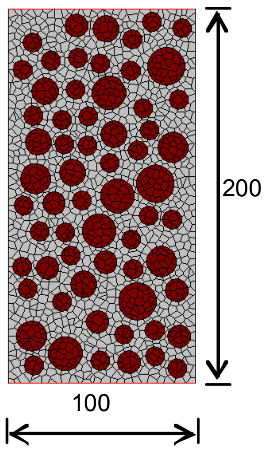


Figure 12 Analyzed concrete specimen

(2) Simulation in Meso Scale of Durability Property Degradation [2]

Truss network model in meso scale in which unidirectional transport units are connected to represent two-dimensional transport phenomena as shown in Figure 15. The unidirectional transport units are located inside aggregate and mortar and along the aggregate – mortar interface. The characteristics of transport phenomena such as permeability are implemented into each transport unit by considering the material property and effects of crack.

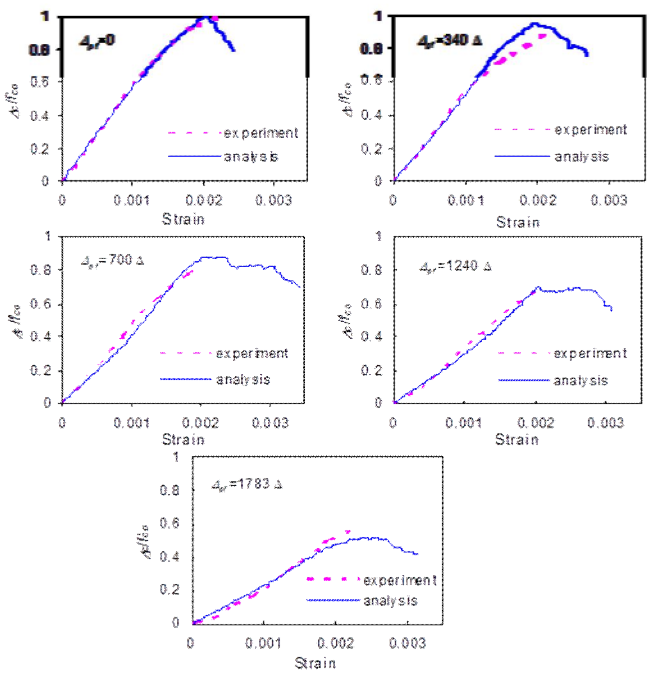


Figure 13 Comparison between tested and simulated stress – strain relationship in compression of frost damaged concrete

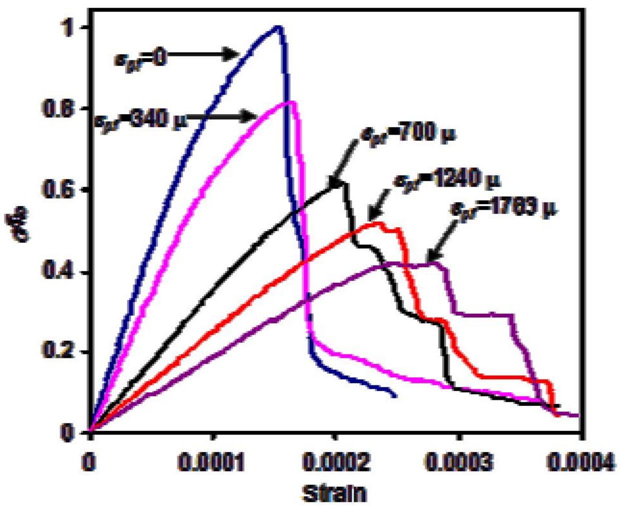


Figure 14 Simulated stress – strain relationships in tension of frost-damaged concrete

The diffusivity of chloride ion in frost damaged concrete is simulated as shown in Figure 16. The frost damage is represented by inserting cracks along all of the aggregate – mortar interfaces which are interfacial transition zone (ITZ) based on experimental evidences. The width of the inserted cracks is given based on experimental observations. However, the volume increase due to the inserted cracks at ITZ, which is calculated using the given crack width is much smaller than the volume increase observed in the experiment. Therefore, it can be considered that the volume increase is caused not only by the cracks at ITZ of coarse aggregate but also the volume increase in mortar due to freeze thaw cycles.

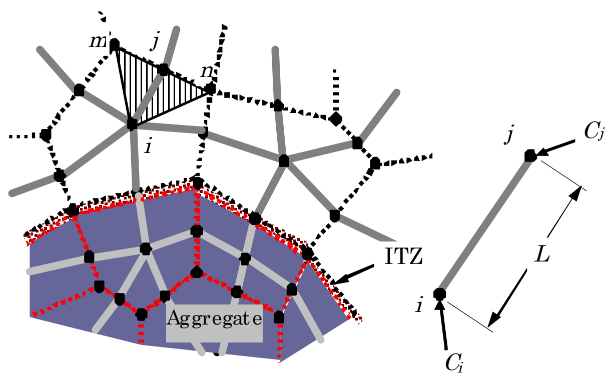


Figure 15 Truss network model for transport analysis

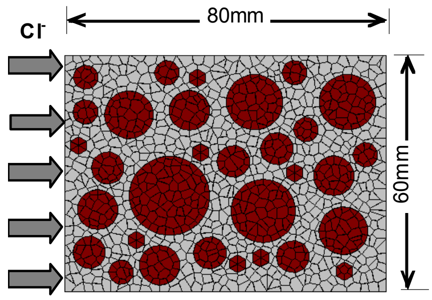


Figure 16 Analyzed concrete specimen for chloride ion diffusion

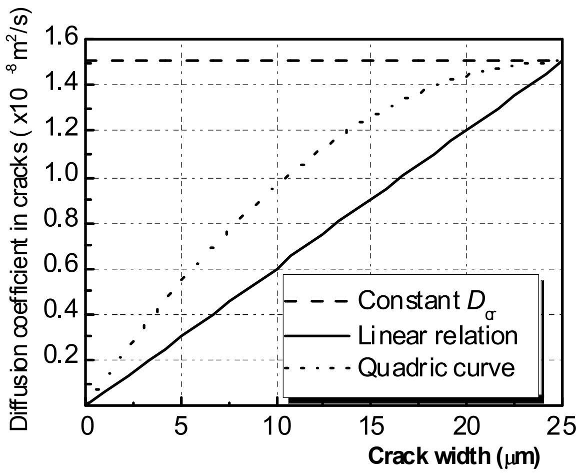


Figure 17 Relationship between diffusion coefficient and crack width

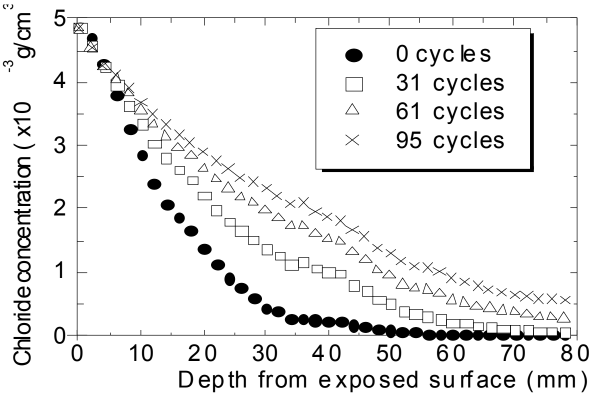


Figure 18 Chloride ion ingress after FTC

By assuming that the mortar volume increase causes the capillary porosity increase, the diffusivity of chloride ion of mortar, which is a function of the capillary porosity, can be calculated. Effects of cracks at ITZ on diffusivity are assumed in three ways; no dependency, quadric dependency and linear dependency on crack width, as shown in Figure 17. Simulation results of chloride ion distribution after different FTCs shown in Figure 18 indicate that the chloride ion diffusion becomes faster as FTC increases, which is supported by some experimental evidences. Figure 19 shows that the simulated diffusivity increases agree well with the experimental ones and that both the increase of mortar diffusivity and ITZ crack width contribute the diffusivity increase of the concrete. The comparison in Figure 19 implies that the crack width dependency of diffusivity is more reliable.

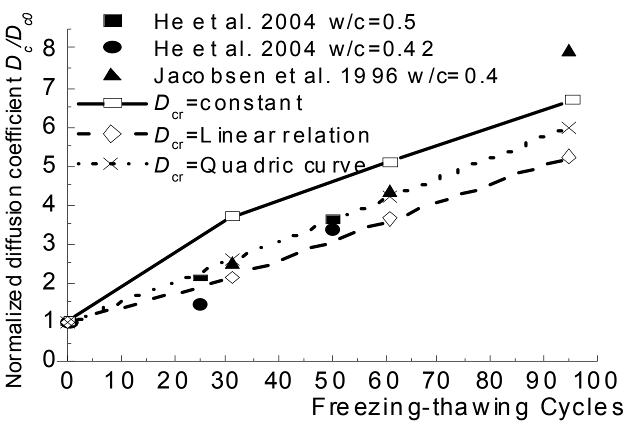


Figure 19 Increase in chloride ion diffusivity after FTC

3. Concluding Remarks

This paper presented the overall picture for prediction of service life of concrete structures under effects of frost damages, which includes the meso scale approach for the deformation model under freeze thaw cycles and the simulation of mechanical and durability property degradation of frost damaged concrete. There are, however, still many things to solve before we attain a rational way for service life prediction. The follows are examples:

- Meso-scale deformational model of aggregate – mortar interface under temperature and moisture hysteresis
- Macro-scale model for bond between reinforcement and concrete with frost damage
- Simplified representation of actual freeze thaw cycle environment
- Simple method for detecting frost damage levels in existing structures

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