- Technical Paper -

DEVELOPMENT OF A MESO-SCALE DEFORMATIONAL BEHAVIOR MODEL OF MORTAR UNDER FREEZ- THAW CYCLES

Evdon SICAT[*1] and Tamon UEDA[*2]

ABSTRACT

This paper presents the experimental method and findings to obtain the deformational behavior of mortar in meso-scale under arbitrary moisture and temperature history under freeze thaw cycles (FTC). Based on experimental results, the frost damage mechanisms of mortar under different moisture conditions were presented and a deformational behavior model is proposed based on moisture behavior during FTC. The presented model is combined with heat and moisture balance for three phases and is able to calculate temperature, ice and water content and total strain of a specimen.

Keywords: freeze-thaw cycles (FTC), moisture, ice, temperature, frost damage

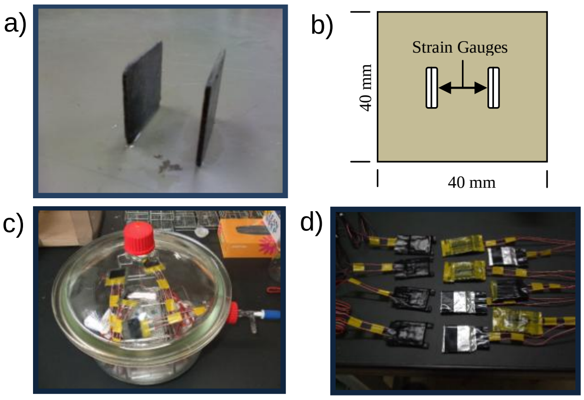
1. INTRODUCTION

In cold regions, concrete's most persistent problem is deterioration caused by freezing and thawing. Since concrete readily absorbs water, it is susceptible to damage if the water within its system of pores can freeze and generate disruptive pressures. Frost damage deteriorates the structural performance of concrete structures such as safety and serviceability due to reduction in strength and stiffness. Frost damage not only degrades the aesthetics of concrete structures due to surface scaling but also decreases its durability against other deterioration factors such as chloride attack, carbonation, alkali silica reaction (ASR) and chemical attack. With this regard, many researches have been carried out to study the response of concrete to FTC. However, in spite of the large volume of research, the mechanism of frost damage still remains unresolved [1]. As a first step in understanding the damage mechanism of frost damage in concrete, this study aims to clarify the effect of temperature and moisture variation during FTC.

2. EXPERIMENTAL PROGRAM

2.1 Specimens

Mortar specimens were used in this experimental program. The materials used were ordinary Portland cement with density of 3.14 g/cm^3, fine aggregate which is 1.2mm or less in size with density of 2.67 g/cm^3 at 1467.6 kg/m^3 of concrete without air entraining agent to promote damage. Mix proportion is 1:2:6 (water: cement: fine aggregate). After mixing of all materials, it was cast into 40mm x 40mm x 160mm form and cured for 24 hours prior to removing the form. Once demolded, specimens were cured under water for 60 days at the temperature of 20 to 23ºC. After curing, specimens were cut into 40mm x 40mm x 2mm size (Fig. 1a); thickness is in meso-scale. The order of millimeter is the meso-scale. This size is small enough to get the information for the model in meso-scale. After cutting, specimens were oven dried at 105^{0}C for 24 hours or until all the water was removed. This was done to obtain the dried weight of specimens which will be used to acquire the desired moisture content. Once dried, attaching of strain gauges was done. Strain gauges used were self-temperature compensation gauges having base size of 4 x 2.7 mm, gauge length of 1 mm and gauge resistance of 120Ω, lead wires were 3-wire cable, and adhesive was made of polyurethane, all were designed for low temperature strain measurement. Specimens were submerged underwater until mass was constant to attain full saturation. Moisture condition was then adjusted to different set of specimens by subjecting them in desiccators with supersaturated salt solutions; Table 1 shows moisture content of specimens. Absolutely dry specimens were used to measure the coefficient of expansion of mortar. When the desired moisture contents were obtained specimens were sealed with vinyl tape to prevent water uptake or loss. Then the deformation of the specimens under temperature variation can be measured with the constant moisture condition in the specimens.



a) cut specimens; b) attachment of strain gauges; c) adjustment of moisture; d) sealed specimens
Fig. 1 Preparation of specimens

*1 Graduate School of Engineering, Hokkaido University, JCI Member
*2 Professor, Faculty of Engineering, Hokkaido University, Dr.E., JCI Member

Table 1 Water content of specimens

Degree of Saturation	Medium for saturation	Moisture Condition (g/cc)	Specimens per condition
Absolutely dry	-	-	3
Fully saturated	H_2O	0.228	3
Partially saturated	NaCl	0.152	3

2.2 Experimental set-up

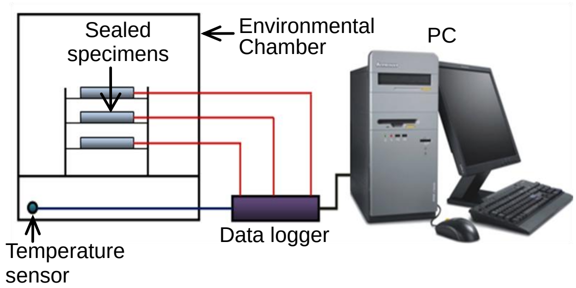


Fig. 2 Experimental set-up

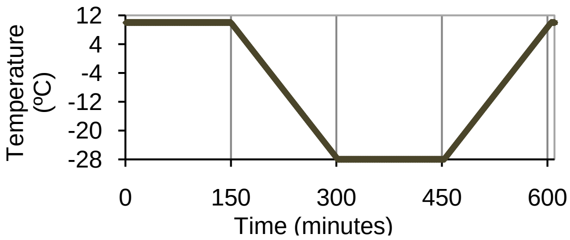


Fig. 3 One cycle of FTC

The experiment set-up is illustrated in Figure 2. Specimens were placed inside an environmental chamber to undergo FTC. The chamber is capable of controlling the temperature. One temperature history shown in Figure 3 is used in this study. This FTC was repeated 5 times for all specimens. This temperature range of 10ºC to -28 ºC was adopted in this test based on a previous study [2] involving the early development of experimental methods using meso-scale size specimens subjected to FTC.

3. RESULTS AND DISCUSSIONS

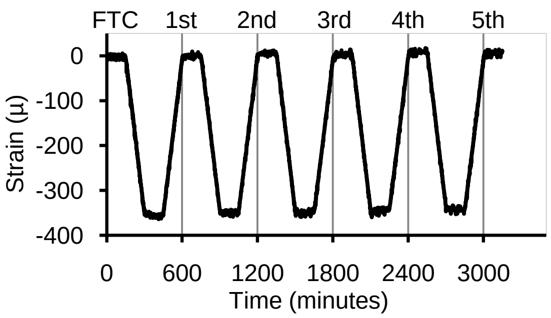


Fig. 4 Dry specimen's strains

Strains obtained from specimens include strains due to temperature change and moisture content, to observe the effect of moisture during FTC; thermal strains as shown in Figure 4 which was obtained from absolutely dry specimens was directly excluded from the obtained strains of saturated specimens. Figure 5 and 6 shows saturated specimen's strain caused by moisture behavior, the thermal strains were removed.

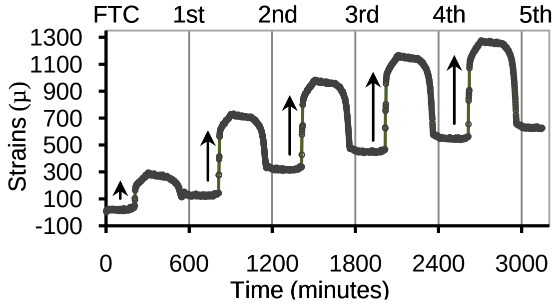


Fig. 5 Fully saturated (100%) specimen's strains

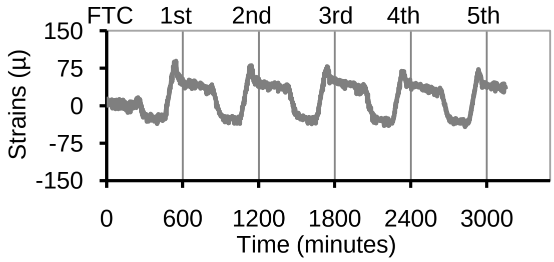


Fig. 6 Partially saturated (68.4%) specimen's strains

3.1 Dry specimen's strain

Figure 4 shows strains for absolutely dry specimens, it can be observed that during the whole freezing and thawing cycle the behavior of the strains for every cycle remains the same though the number of cycle increases. This unchanging behavior is due to the absence of water in the specimens and only deformation caused by the effect of linear expansion of the material is observed which depends on the temperature change. Using the relationship of strain and temperature change in Figure 4 the average calculated coefficient of linear expansion of the material is 10.04 x 10^{-6}/ºC, wherein according to many researches the linear expansion of mortar or concrete is 8 – 12 x 10^{-6}/ºC.

3.2 Fully saturated (100%) specimen strains

For fully saturated specimen's strains shown in Figure 5, immediate large expansions at every FTC as illustrated by the arrows can be observed during the freezing process at a temperature range of approximately -5ºC to -8ºC. These expansions are caused by rapid ice formation due to freezing of supercooled water as illustrated in Figure 7. In accordance to the hydraulic pressure theory a temporary hydraulic pressure is generated which caused the abrupt expansion during freezing of supercooled water. Supercooling in concrete happens when the water is in contact with the surface of a solid matter or contains dissolved solids. The degree of the lowering of the freezing point depends upon the kind and the quantity of the dissolved matter, the interaction between liquid and the surface of the solid matter and the diameter of the pores [3]. After the voluminous expansion of supercooled water, a continued gradual expansion dominates, since there are no available pore spaces for the expelled water to flow to, assuming all pores are filled with water as shown in Figure 7, the continued expansion of the material occurs. As the number of cycles increases, it can be noticed that the maximum strain reached at the lowest temperature for every cycle increases even with a constant moisture content. It also follows with the increase in maximum strain the residual strain at the end of every FTC also increases. During FTC the expansion of frozen water causes tensile stresses in the surrounding matrix. This stresses causes micro-cracks which increase the pore volume oaAf the mortar structure as the FTC progresses. Due to chemical potential difference, unfrozen water from fine pores flows to these larger pores which results in increase of water that can be frozen. The greater is the amount of water that can be frozen the greater will be the expansion that can cause frost damage. This phenomenon occurs repeatedly at every FTC which is the reason for the increase in maximum strain and residual strain at the end of every cycle even with constant moisture content.

In summary of the above discussed, the mechanism which describes the expansions strains during freezing is pointed as a product of ice formation in pores (see Fig. 7). When ice is formed the volume of water expands which causes tensile stresses in the surrounding matrix.

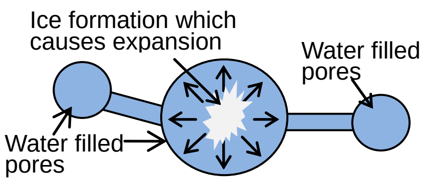


Fig.7 Representation of interconnected pores inside mortar: Ice formation causing large expansion and water filled pores

3.3 Partially saturated (68.4%) specimen strains

For specimens having saturation condition of 68.4% in Figure 6, during the entire FTC contraction is observed at the lowest temperature. This differs from Figure 5 (100% saturated specimens) which exhibited expansion during FTC. The strain behavior also does not change even though the number of FTC increases. These phenomena can be explained by stating that there were air voids large enough and not filled with water; this accommodates the increase in the volume of frozen water in the specimen [2] relieving the pressure (see Fig. 8). The contraction may be due to the insufficient water content present in the specimen which is not enough to cause expansion. In literatures [4][5], there are various mechanisms of contraction during freezing. In this paper it is assumed that the contraction is a product of chemical potential difference between unfrozen water and ice. During freezing ice is formed first in larger pores while water in smaller pores remains unfrozen because their freezing temperature has not yet been reached. Ice formation in concrete pores is related to their sizes. The thermodynamic equilibrium in pore solution is disturbed by the ice formation. At freezing temperature, ice has a lower chemical potential than unfrozen water. Particles tend to move from areas of higher chemical potential to areas of lower chemical potential. Thus because of chemical potential difference, unfrozen water tends to move or flow towards ice in order to bring the pore solution into a thermodynamic balance which results in the contraction [5]. This occurrence is described in Fig. 8.

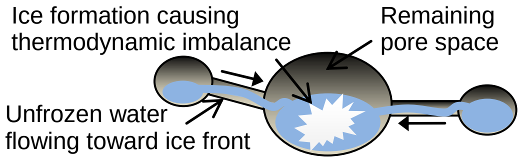


Fig.8 Representation of interconnected pores inside mortar: Ice formation in partially filled pores causing thermodynamic imbalance

3.4 Relationship between maximum and residual strain

The relationship between the maximum strain during freezing and the residual strain at the end of each FTC (both partially and fully saturated) were obtained, and interestingly results show that the residual strain obtained at the end of every FTC is almost 50% of the maximum strain during freezing as presented in Figure 9. Similar relationship was also observed by a study presented by Arai and Ueda [2].

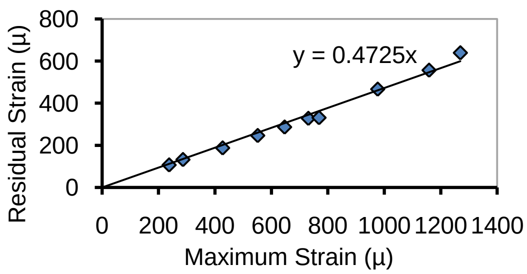


Fig.9 Relationship between maximum and residual strain

4. DEVELOPMENT OF THE MESO-SCALE DEFORMATION MODEL OF MORTAR

4.1 Oiwa et al model

Oiwa et al presented the model to calculate the moisture content of free water, ice content and temperature at any location of mortar by solving the coupled transfer equations of moisture and heat in mortar considering three phases of water (gas, liquid and solid) [2][6]. The developed analytical method in meso scale, combines mechanical analysis with heat-moisture transfer analysis, to simulate the deformational behavior of mortar under FTC [2]. The equations shown below are heat and moisture equations for three phases. These were derived from balance of heat and moisture [6].

$$\rho_\ell \frac{\partial \psi}{\partial \mu}\frac{\partial \mu}{\partial t} = \nabla \cdot \{\lambda'_\mu (\nabla \mu)\} + \nabla \cdot (\lambda'_T \nabla T) - \frac{\partial \rho_i \psi_i}{\partial t} \quad (1)$$

$$C\rho \frac{\partial T}{\partial t} = \nabla \cdot \{(\lambda + R\lambda'_{Tg})\nabla T\} + \nabla \cdot \{R\lambda'_{\mu g}(\nabla \mu)\} + H_{li}\frac{\partial \rho_l \psi_i}{\partial t} \quad (2)$$

$$\mu = H_{li} \log_e \left(\frac{T}{T_0}\right) \quad (3)$$

Where: μ is chemical potential of moisture, ρ is density for each phase, T is absolute temperature, C is specific heat, t is time, Ψ is moisture content, λ is thermal conductivity, λ'_μ is moisture transfer ratio in gas and liquid phase caused by chemical potential gradient, $\lambda'_{\mu g}$ is moisture transfer ratio in gas phase caused by chemical potential gradient, λ'_T is moisture transfer ratio in gas and liquid phase caused by temperature gradient, λ'_{Tg} is moisture transfer ratio in gas phase caused by temperature gradient, R is evaporation heat, T_0 is freezing temperature of free water (0℃) , Ψ_i is ice content, H_{li} is melting heat. In the heat and moisture transfer analysis for three phases Oiwa et al calculated the ice content and applied it in the following equation representing the expansion deformation under freezing, which is proportion to ice content, is assumed as:

$$\varepsilon_i = \alpha_i \times \Psi_i \quad (4)$$

where ε_i is expansion strain under freezing and α_i is the constant. The method does not consider the effects of pore structure on freezing condition of water, abrupt freezing of supercooled water nor shrinkage due to flow of unfrozen water [3]. The reliability of the constant in Eq. (4) was not confirmed by experiment due to the fact that the test method to measure it has not been developed when the model was proposed.

4.2 Developed meso-scale deformation model of mortar

The proposed meso-scale deformation model for mortar is based on the concept proposed by Arai et al [2]. The deformation model presented in this study predicts the deformation of mortar for a 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 combination of three strain components shown in Eq. (5):

$$\varepsilon = \varepsilon_i + \varepsilon_s + \varepsilon_t \quad (5)$$

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.(6) considering the fact that there would be no expansion for the water contents less than a certain value:

$$\varepsilon_i = \alpha_i \times (\Psi_i - \Psi_{ic}) \quad (6)$$

where, α_i is the material constant depending on mortar stiffness and Ψ_{ic} is the ice content when the deformation starts to depend on the ice content. Since the contraction under freezing is caused by unfrozen water movement [7] which is caused by chemical potential difference due to ice formation Ψ_i, it is assumed that the deformation depends on the unfrozen water content which is a difference between the water (moisture) content Ψ and ice content Ψ_i. The contraction during freezing is expressed in Eq. (7).

$$\varepsilon_s = \alpha_s \times \Psi_w \quad (7)$$

where, unfrozen water content is Ψ_w and α_s is a value representing the contribution of unfrozen water content to the shrinkage, which depends on the mortar stiffness. The thermal strain is obtained from Eq. (8) using the linear expansion coefficient α_t:

$$\varepsilon_t = \alpha_t \times \Delta T \quad (8)$$

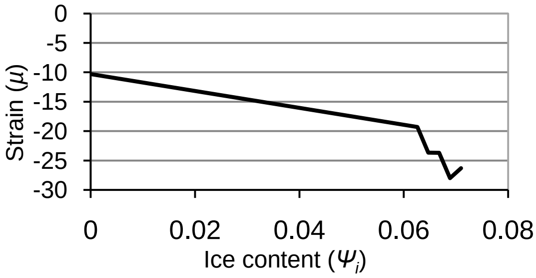
where ΔT is the temperature variation.

4.3 Material constants for the developed meso-scale deformation model of mortar

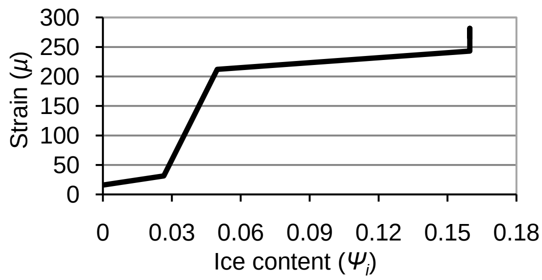
The calculation of α_s was obtained from the experimental data for partially saturated specimen's strain of 68.4%. The behavior of the mortar was contraction due to insufficient moisture content and caused by the flow of unfrozen water towards the ice front. The shrinkage constant was calculated using the equation (5) excluding thermal strains. The freezing expansion ε_i was ignored considering the constant strain behavior which is contraction during the whole FTC. It is explained that there were air voids large enough and not filled (or partially filled) with water that accommodates the increase in the volume of frozen water in the specimen [2] which relieves any expansion of the matrix. Based on calculated values of unfrozen water with relation to experimental strains, it was found out that α_s is a function of the unfrozen water content Ψ_w as expressed in Eq. (9). Moisture content Ψ and ice content Ψ_i values were calculated using equations (1), (2), and (3) from heat and moisture balance for three phases. Figure 10 shows relationship between calculated ice content and experimental strains. The increase in contraction which is due to unfrozen water movement is caused by the increasing difference between the chemical potential of ice and unfrozen water as the temperature continues to drop.

$$f(\Psi_w) = 589 \cdot \ln \Psi_w + 1272 \quad (9)$$

The calculation of the material constant α_i was obtained from the experimental data for fully saturated specimen's strain. The behavior of the mortar was expansion due to sufficient moisture content and caused by the ice formation in pores. The expansion constant was calculated using the equation (5) excluding thermal strains. The shrinkage strain ε_s was considered in the calculation. Unfrozen water Ψ_w and ice content Ψ_i were calculated values using equations (1), (2), and (3) from heat and moisture balance for three phases. The value for Ψ_{ic} is assumed as equal to 0.038 based on observation that during this water content the strain behavior displays significant increase. The calculated value for the material constant α_i is equal to 3410 x 10^{-6}. Figure 10b shows calculated ice content in relation to experimental strains.



a) Partially saturated specimens



b) Fully saturated specimens

Fig. 10 Relationship between experimental strain and ice content

5. ANALYSIS OF DEFORMATIONAL BEHAVIOR OF MORTAR

Calculation flow of the proposed model is illustrated in Figure 11. As of the moment the model is capable of calculating the total strain of specimens caused by freezing expansion, shrinkage contraction and thermal deformation. The method does not consider the effects of pore structure on freezing condition of water and abrupt freezing of supercooled water. In future studies these will be considered.

Calculation of temperature, moisture and ice content by heat and moisture balance for three phases Equations (1), (2), and (3)
↓
Calculation of strains by the proposed model Equations (6), (7), and (8)

Fig. 11Flow of calculation

5. 1 Partially saturated mortar with moisture supply

(1) Outline of analysis

Figure 12 shows mortar model used in the analysis. Size of the mortar is 100 mm x 100 mm. The number of elements is about 100. The temperature history is shown in Figure 13; this was applied on top side of the specimen for 3 cycles. On the other hand, the other three faces were insulated with heat and moisture (water) supply as illustrated in the dashed lines. The initial moisture condition inside of the specimen is 85% relative humidity while there is a constant moisture (water) supply on top face of the specimen. Since the boundary conditions used in the analysis (e.g. size, sealing of sides, and supply of water) differ in the test specimen, there is no relevance in using the same temperature history as with the test. In the future studies to verify the model's preciseness, actual experiment will be performed and will be compared with the analysis. As of this moment the analysis was done to observe the effect of moisture in the behavior of mortar subjected to FTC using the formulated model.

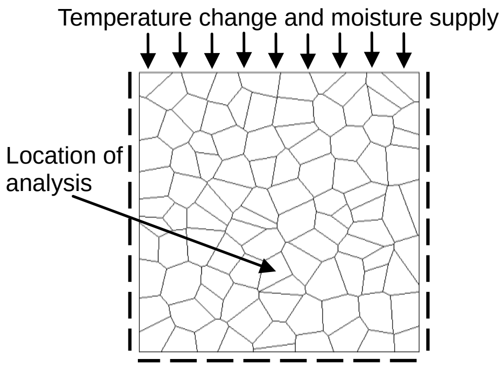


Fig.12 Mortar model

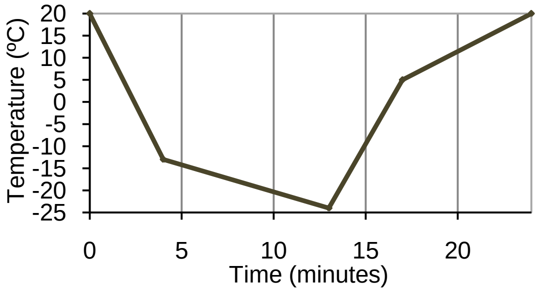


Fig.13 Temperature history applied on top side

(2) Results of analysis

Location of analysis is 60 mm from the top face in the longitudinal direction of the specimen. Figure 14 shows moisture and ice content of the specimen at the specified location. It can observe from Figure 14 that the moisture content of the specimen remains constant until around the 42nd hour. This constant moisture content is because of the initial relative humidity condition of the specimen which is 85%. The moisture content of the specimen begins to increase from the 42nd hour; this is because the moisture supply from the top face of the specimen has reached this point of the specimen and adds to the amount of moisture. However the increase in moisture content decreased from the 52nd hour. This is probably at this time ice formation takes place and blocks the flow of water and disrupting the increase in moisture content. The increase in moisture content continued when the ice formation begun to decrease or when there is no more ice formed blocking the water flow. Meanwhile, there is no ice formation from the start of the cycle until the 52nd hour because of the insufficient moisture content and only begun to take place when there is already a sufficient amount of moisture. The ice formation also took place when the temperature decreased. The ice content continued to increase as the temperature decreased more and subsided when the temperature increases.

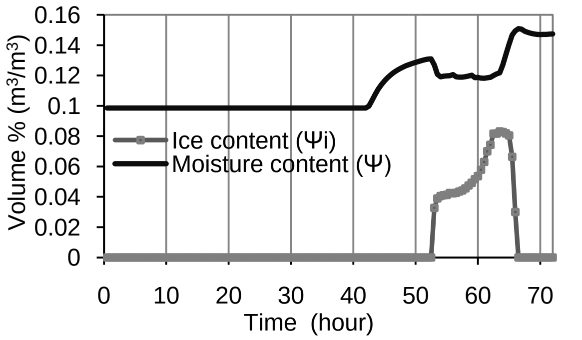


Fig. 14 Ice content and moisture content with time

From Figure 15a and 15b it can be observed that the deformation of the mortar is mainly influenced by the coefficient of expansion/contraction of the material which is caused by temperature difference. From Figure 15b observing strains caused by moisture behavior alone, there were no deformations at the first and 2nd cycle since during these stages there were no ice formation due to insufficient moisture content. When enough moisture is present coming from the top face of the specimen and the temperature decreased at the 3rd cycle, ice formation takes place which influences the deformation of the mortar. With higher ice content the strain is also high.

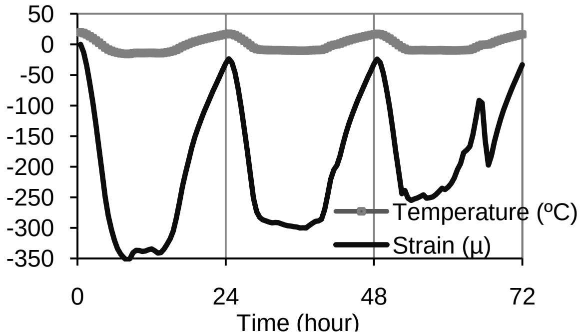


Fig. 15a Deformation with thermal strains

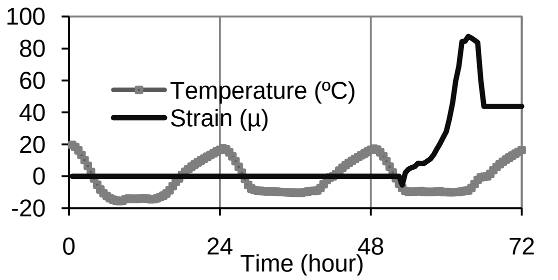


Fig. 15b Deformation without thermal strains

6. CONCLUSIONS

(1) Based on the experimental findings and mechanisms of frost damage in concrete, a deformational behavior model of mortar in meso-scale is presented. The model is based on the observed deformation of mortar which is influenced by the formation of ice, movement of unfrozen water and thermal variation.

(2) The presented method is combined with heat and moisture transfer equations for three phases (solid, liquid, and vapor) which calculates the moisture, temperature, and ice content in a specified location of a specimen. Combined with the presented model, the method was able to predict the strain behavior of a specimen under ambient temperature and moisture history.

(3) At present, the method does not consider the effects of pore structure on freezing condition of water and abrupt freezing of supercooled water which influences the increase in strain during FTC. In future studies these will be considered

ACKNOWLEDGEMENT

The authors are grateful to Dr. Yoshihiko KISHIMOTO of Muroran Institute of Technology for his valuable advises to this study.

REFERENCES

[1] S. Chatterji, “Aspects of the freezing process in a porous material–water system I. Freezing and the properties of water and ice,” Cement and Concrete Research, 199, pp. 627-630.

[2] T. Ueda and S. Arai, “Frost damage Model to Predict Structural Performance”, Proceedings of the 2nd ICDCS, November 2010, pp. 547-556.

[3] P. Gruebl, “Rapid Ice Formation in Hardened Cement Paste, Mortar and Concrete due to Supercooling”, Cement and Concrete Research, Vol. 10, pp. 334-345, 1980.

[4] Max J. Setzer, “Development of the Micro-Ice Lens Model”, Proc. of Int. RILEM Workshop of Frost Resistance of Concrete, April 2002, pp. 133-145.

[5] J.P. Kaufman, “A Qualitative Sequential Frost Deicing Salt Damage Model Based on Experimental Data”, Proc. of Int. RILEM Workshop of Frost Resistance of Concrete, April 2002, pp. 197-204.

[6] Oiwa Y., Sato Y., Ueda T. and Matsumoto K., “Analysis of deformational behavior of mortar under freezing and thawing action”, in Advances in Concrete Structural Durability, Proceedings of the International Conference on Durability of Concrete Structures (ICDCS2008), Hangzhou, China, November , 1, 2008, 615-619.

[7] E. Sicat and T. Ueda, “Deformation of Concrete Mortar with Variation in Moisture Content and Under Freeze-Thaw Cycles” Proceedings of the 2nd ICDCS, November 2010, pp. 537-546.