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Total Strain Behavior of Mortar under Freeze-Thaw Cycles in Consideration of the in Coefficient of Thermal Expansion of Frost Damaged Mortar

Evdon Sicat[1], Fuyuan Gong[1*], Ueda Tamon[2] and Zhang Dawei[3]

[1]*Graduate School of Engineering, Hokkaido University, Japan*
[2]*Faculty of Engineering, Hokkaido University, Japan*
[3]*College of Civil Engineering and Architecture, Zheijiang University, China*
[*]*Laboratory of Engineering for Maintenance System, Graduate School of Engineering, Hokkaido University, Kita 8, Nishi 13, Kita-ku, Sapporo, 060-8628, Japan, evdonsicat@gmail.com, gongfy07@gmail.com, ueda@eng.hokudai.ac.jp, david@eng.hokudai.ac.jp*

ABSTRACT

In this paper, the total strain behavior during freeze-thaw cycles (FTC) is presented as composed of expansion strains caused by ice formation, shrinkage strain caused by movement of unfrozen water from small capillary pores to larger or partially filled pores, and thermal strains as a response of the material to the change in temperature. The model which is in mesoscale is based on experimental findings showing that the degree of saturation dictates the behavior of mortar under FTC. Interestingly, for the enhancement of the model, supplementary experimental findings imply that the coefficient of thermal expansion (CTE) of FTC subjected mortar changes in accordance to the damage it accumulated. Based on these findings, it is proposed that the change in CTE due to FTC damage should be incorporated in the determination of the total strain during FTC.

Keywords: Frost damage, freeze-thaw cycles (FTC), coefficient of thermal expansion (CTE), moisture, temperature

BACKGROUDND

Frost damage has long been a deterioration problem in cold regions. Because of its porous structure, concrete has the ability to absorb moisture when it is in contact with it. This makes concrete susceptible to frost damage once the moisture inside freezes and causes disruptive pressures. There has been plenty of research regarding the mechanism of freezing and thawing action in concrete however no unified mechanism has been widely accepted (Chatterji, 1999). It is a known experimental fact the damage to freeze-thaw cycles (FTC) deteriorates the mechanical properties of concrete due to micro cracking (Hassan, 2003) and these results in the change in microstructure of concrete.

The change in microstructure due to FTC may have an adverse effect on the coefficient of thermal expansion (CTE) of concrete. Similar with the modulus of elasticity, the CTE of a homogenous material is unaffected by the change in microstructure. However, this may not be the case for concrete – a heterogeneous and multiphase material. CTE is an important property of concrete, it must be known to manage the expansion of concrete due ranging temperatures and predict the behavior of concrete structures during their service life (Mallela et al., 2005 and Uygunoglu et al., 2009). Studies about the CTE of concrete commonly deal with its change due to elevated temperatures while when used in design is usually derived from undamaged concrete (Sicat et al., 2012). As of the moment, it may not be realized that the deterioration due to FTC could unfavorably alter the CTE of concrete. This change in CTE should be considered in modeling of the frost damage mechanism of concrete and could be of importance in life cycle prediction of concrete structures.

This study is presented as a part of a series of studies which aims to develop a mesoscale deformation model of mortar under FTC, in which, it is also a part of a bigger project aiming to predict the structural performance of member with frost damage (Ueda and Arai, 2010). A previous experimental study (Sicat and Ueda 2011) to clarify the effect of temperature and moisture variation have been performed. Based on the experimental findings the mesoscale deformation model of mortar under FTC has been developed (Sicat and Ueda 2011). The proposed mesoscale deformation model however does not consider the increase in pore structure during FTC and further improvement is needed. In order to enhance this model, the collection of data of deformational behavior of mortar under variation in temperature and moisture is needed. Thus, the objective of this study is to further enhance the mesoscale deformation model of mortar under FTC considering the change in CTE observed from the collected data from a supplementary experiment undertaken.

THE MESOSCALE DEFORMATION MODELOF MORTAR UNDER FTC

The mesoscale deformation was first proposed by Oiwa et al. (2008). The model is developed 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) (Sicat and Ueda, 2011 and Oiwa et al., 2008). The developed analytical method in mesoscale, combines mechanical analysis with heat-moisture transfer analysis, to simulate the deformational behavior of mortar under FTC (Ueda and Arai, 2010). The equations shown below are heat and moisture equations for three phases. These were derived from balance of heat and moisture (Matsumoto et al., 1993).

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

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

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

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 ºC) , Ψ_i is ice content, H_{li} is melting heat. In the heat and moisture transfer analysis for three phases Oiwa et al (2008) 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:

$$\varepsilon_i = \alpha_i \times \Psi_i \tag{4}$$

where, ε_i is expansion strain under freezing and α_i is the constant. The method does not consider the effects of increase in pore structure, abrupt freezing of supercooled water nor shrinkage due to flow of unfrozen water. 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.

Development of the Mesoscale Deformation Model. The experimental methods used in this study were discussed in detail by Sicat and Ueda (2011). In the study (Sicat and Ueda, 2011), mortar specimens of 40mm x 40mm x 2mm was used. This size is assumed to represent the deformation of mortar in mesoscale under any temperature and moisture condition. Specimens were prepared into three different moisture conditions and then sealed to avoid water uptake and loss, then undergone 5 FTC starting from 10ºC until -28°C. Moisture condition includes, dry specimens to measure the thermal strains and 100% saturated and 68% saturated specimens to observe the behaviour of moisture during FTC. Obtained specimens' strain include strains due to temperature change and moisture content, to observe the effect of moisture during FTC; thermal strains as shown in Figure 1 obtained from absolutely dry specimens and were excluded from the obtained strains of saturated specimens. Figure 2 and 3 are saturated specimen's strain without the thermal strains.

Uniform strain behavior is evidently observed during the entire FTC for dry specimens in Figure 1. This is because of the absence of moisture and the strain behavior is only influenced by the thermal expansion of the material responding to temperature change. For fully saturated specimens in Figure 2 increasing strain behaviour is observed, this is pointed to be product of the volume expansion of water when it turns into ice. Even specimens are sealed; there is an increase in strain as the FTC progresses which is explained that the pore structure is damaged by the expansion during freezing, resulting in increase of pore size in

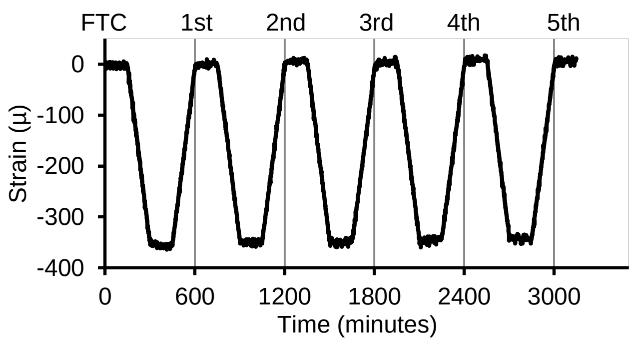

Figure 1 One freeze-thaw cycle (temperature history)

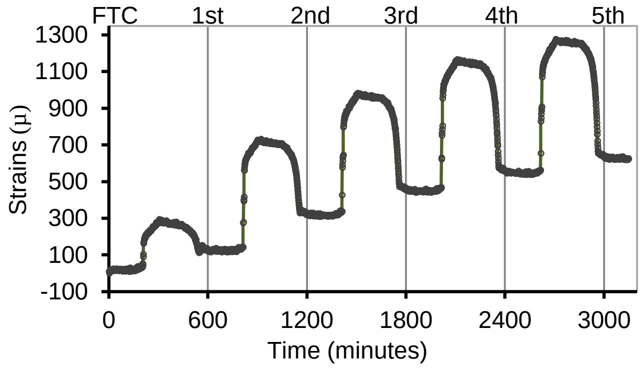

Figure 2 Fully saturated specimen's strains

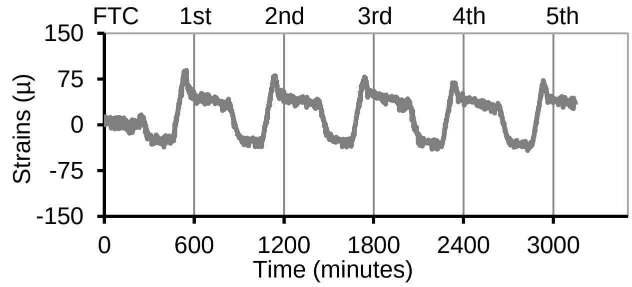

Figure 3 Partially saturated (68.4%) specimen's strains

which more volume of water can be frozen. While for partially saturated specimens, during the entire FTC uniform contraction is observed at the lowest temperature. These phenomena happened because there were air voids large enough and not filled with water; this accommodates the increase in the volume of frozen water in the specimen (Ueda and Arai, 2010), moreover these partially water filled pores permits unfrozen water from smaller pores to flow to freezing sites resulting in contraction. Detailed explanation of the mechanism during FTC in mortar is explained further by the previous study (Sicat and Ueda, 2011).

Based on the presented experimental results (Sicat and Ueda, 2011) the expansion and shrinking behavior under freezing process changes according to the moisture condition. Depending on the moisture content either contraction or expansion is dominant. Therefore, it was proposed that the total strain ε during FTC is assumed as a combination of three strain components as seen in Eq. (5):

$$\varepsilon = \varepsilon_i + \varepsilon_s + \varepsilon_t \tag{5}$$

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. Thus, 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.

$$\varepsilon_i = \alpha_i \times \left(\Psi_i - \Psi_{ic}\right) \tag{6}$$

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 (Sicat and Ueda, 2010) 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.

The calculation of α_s was obtained from the experimental data for partially saturated specimen's strain of 68.4% in Fig. 5, by the fact that the behavior of the specimens during the entire FTC is purely contraction. 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.

$$f\left(\Psi_w\right) = 589.32 \cdot \ln \Psi_w + 1272 \quad (9)$$

The calculation of the material constant α_i was obtained from the experimental data for fully saturated specimen's strain. Moisture content Ψ 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 0.03 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 2116 x 10^{-6}.

By combining 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 and the presented mesoscale model, the method is able to predict the strain behavior of a specimen under ambient temperature and moisture history. Furthermore, the reliability of the material's constant and values (α_i and α_s) were confirmed by an experiment and the flow of unfrozen water was considered. These were not previously considered in Oiwa's model. However, further enhancements of the model are still needed. The next section of the paper is the first attempt to further improve the model.

DATA COLLECTION FOR THE ENHANCEMENT OF THE PROPOSED MESOSCALE DEFORMATION MODEL OF MORTAR

For the refinement of the model, a secondary experiment was done (Sicat et al., 2012). Five different mixture proportions were prepared in this experiment as shown in Table 1. Specimens were also conditioned to be fully saturated. Preparation of the specimens before undergoing FTC was explained in detail by Sicat et al. (2012). To further observe the strain behavior during FTC, saturated specimens undergone 30 FTC, the maximum and lowest temperature is similar with the previous study (Sicat and Ueda, 2011). Dry specimens and saturated specimens' strain during FTC were observed. Specimen size of 40 x 40 x 2mm was also used in this experiment and similar (Sicat and Ueda, 2011) procedure and equipment were used to obtain the strain during FTC.

Experimental Results: The moisture behavior during FTC were primarily observed; as a requirement, thermal strains were removed from saturated specimens' strain which were obtained from dry specimens from each mixture in Table 1. Figure 4 shows strains (gray lines) for all dry (undamaged to FTC) specimens for 10 FTC. It can be observed that during the whole FTC, the strain behavior of the spepecimens remains constant as the number of cycle increases similar with the experimental results in the previous section. This is obviously because of the absence of moisture, and strains are due to temperature change.

Table 1 Mix Proportions of Mortar

Mixture	Water-Cement Ratio (%)	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)
A	70	207	296	1090
B	50	207	414	1090
C	50	207	414	990
D	50	207	414	755
E	30	207	690	755

The results obtained from fully saturated specimens are shown in Figure 5 excluding the thermal strains. Large expansions can be observed at the initial stages of the FTC. This is observed from Figs. 5a, 5b, 5c and 5d. As explained previously (Sicat et al., 2011), these expansions are product of the volume expansion of water when it turns into ice resulting in a temporary hydraulic pressure. If the stresses can't be relieved by the matrix micro cracks develop which increase the pore volume of the specimens. As the FTC progresses, the positive strain comes to a point where it decreases, and eventually reverses to contraction as can be observed again from Figs. 5a, 5b, 5c and 5d. This happens when enough pore space is created due to micro cracking caused by large expansion strains in the initial FTC, since specimens are sealed and without water supply filling the pores then moisture can be redistributed from gel pores or unfrozen water from smaller pores to the newly developed spaces creating negative hydraulic pressure which results in the contraction of the system.

However, for Figure 5e the specimen displays an increasing contraction during the entire FTC. To understand how this behavior happened, we have to consider the pore structure of the specimen. To have contraction behavior, there should be available pore space where moisture can be redistributed (partial saturation). It is a known matter that low water to cement (W/C) ratio for concrete results in higher pore volume while low W/C ratio as in the case for the specimen mentioned results in low pore volume, indicating that it could also have large volume of smaller pores than large pores. Due to low W/C, it may be possible that the specimen contain greater amount of small capillary and gel pores containing unfrozen water responsible for contraction rather than large pores. During saturation process it may also be difficult for moisture to fill empty smaller pores resulting in partial saturation of the specimen. These may be the cause of the unusual dominant contraction behavior of the said specimen. This also suggests that the pore structure and moisture content of specimens dictates their strain behavior during FTC.

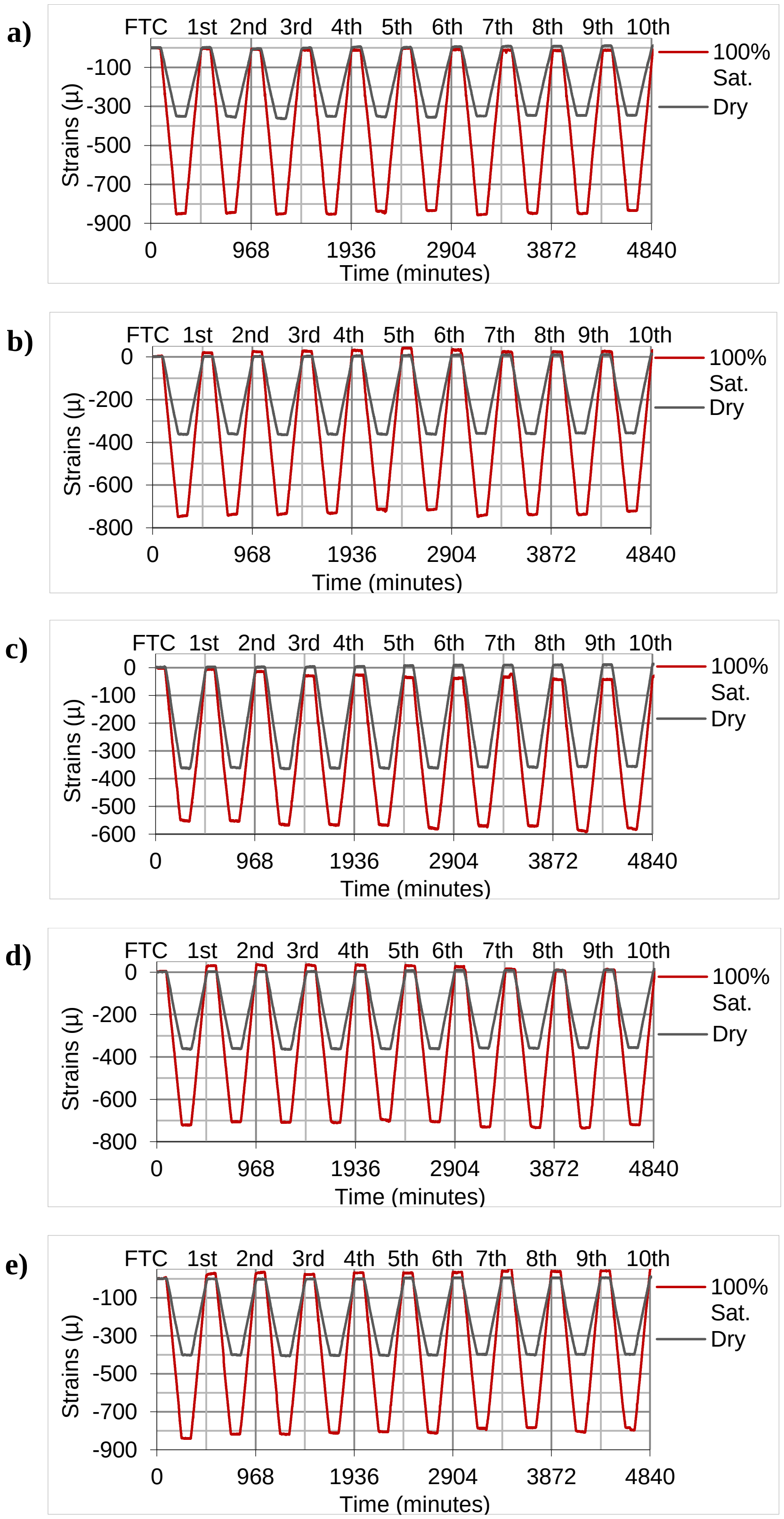

Figure 4 Thermal strains (FTC damaged – 100% Sat. and dry/undamaged) for Mixture a) A, b) B, c) C, d) D, and e) E

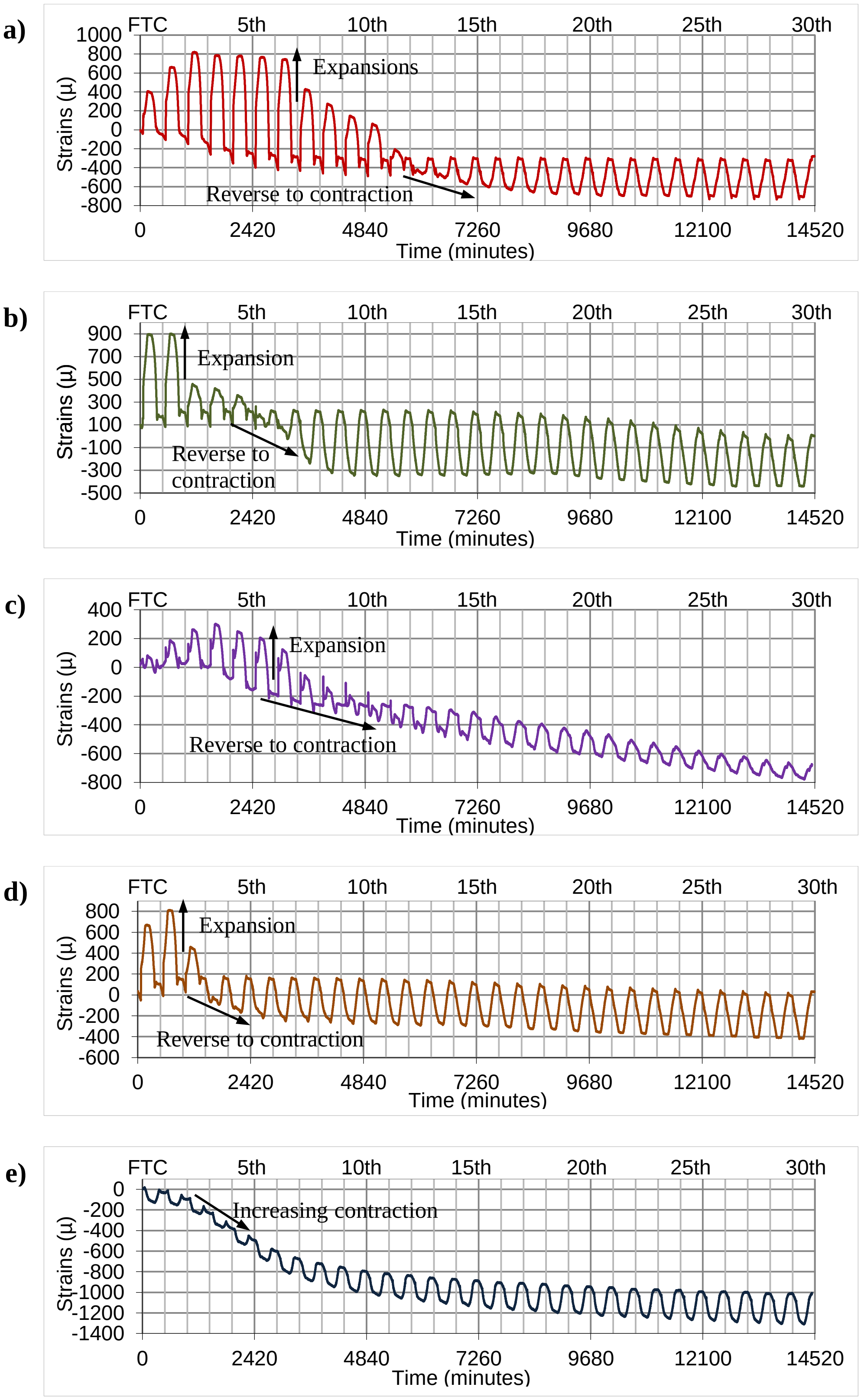

Figure 5 Fully saturated specimens strain for mixture a) A, b) B, c) C, d) D, and e) E

Change in CTE due to Deterioration by FTC. The strain behavior of specimens have been briefly discussed. Detail discussion has been provided by Sicat et al. (2012). From saturated specimens strains the reverse contraction seem to be too large to be caused by the movement of unfrozen water alone. Thus to verify if this behavior is caused by moisture movement or change of CTE of the specimen, a second test was performed. This was done by drying the said specimens (saturated specimens which undergone FTC) to remove any remaining moisture. Then were resealed and subjected under FTC for 10 cycles. Thermal strains were then obtained and compared with the dry (undamaged) strains. Going back to Figure 4, it shows the results of thermal strains of specimens both for FTC damaged (red line) and dry (undamaged) specimens (gray lines). Observations from the figure suggest that thermal strain for FTC damaged specimens have increase significantly than dry specimens. The strain reached at the lowest temperature is almost twice as dry strains. Since the CTE can be calculated in terms of the resulting strains, this means that the CTE of the said specimens have changed drastically.

Based on the results presented, during FTC besides the plastic expansion, plastic contraction are also observed which contributes to the permanent deformation initiated by changes in microstructure of the material caused by micro cracking during freezing. With this observed findings, hence it can be said that the deformation and deterioration of mortar caused by micro cracking of the system during FTC is the main reason for the change of CTE of mortar specimens. In addition, it is a proven experimental fact that the damage due to FTC causing microcracking degrades the modulus of elasticity of concrete, in which, similarly because of this same damage the CTE of concrete changes drastically. The change in both CTE and modulus of elasticity is dependent on the damage it accumulated or how the microstructure has changed (increase in pore structure), with this regard it is also appropriate to say that without frost damage there will be no change in CTE.

Considering this finding, for the enhancement of the deformation model, the change in CTE of the specimens should therefore be considered to simulate the strain behavior of specimens. For the calculation of the total strain in Eq. 5, the component for the thermal strain ε_t should be simplistically revised to the equation below when deterioration due to FTC takes place.

$$\varepsilon_d = \alpha_d \times \Delta T \tag{10}$$

Where ε_d is the thermal strain for FTC damaged specimen and α_d is the changed CTE value of FTC damaged mortar. When there is no FTC damage, Eq. 8 will be used to calculate the strains due to temperature variation. The change in CTE could be related to both modulus of elasticty and/or increase in pore structure during FTC which are both product of the microcracking caused by frost damage. This is currently an ongoing undertaking of the authors.

CONCLUSIONS

The sequential development of the mesoscale deformation model has been 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. The model 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. The method can predict the strain behavior of a specimen under ambient temperature and moisture history. However, as of the moment the model has many short comings.

The first attempt, to enhance the model is through the collection of more dependable data. From the supplementary experimental findings, it was found that there is a reverse contraction during FTC. This is explained that when enough pore space has been created from ice expansion, the pressure is relieved and allows the unfrozen water to flow to these partially filled pores which results in the contraction. More interestingly, experimental results show that the CTE of FTC damaged specimens change drastically and this change is dependent on the damage it accumulated during FTC as a result of the microstructural change due to micro cracking.

Considering the finding on the change in CTE, for the calculation of the total strain ε during FTC when deterioration takes place; the component for the thermal strain is calculated using α_d representing the change in CTE for FTC damaged specimens. The change in CTE could be related to both modulus of elasticty and/or increase in pore structure during FTC which are both product of the microcracking caused by frost damage. This is currently an ongoing undertaking of the authors.

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