# THE INFLUENCE OF THE CHANGE IN COEFFICIENT OF THERMAL EXPANSION ON THE STRAIN BEHAVIOR OF MORTAR DURING FREEZE-THAW CYCLES

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## ABSTRACT

The presented experiments were carried out to observe the strain behavior of meso-scale specimens under constant moisture condition. The coefficient of thermal expansion (CTE) of each specimen was determined before freeze-thaw tests or prior to FTC damage. After FTC tests and specimens accumulate damage, the CTE is obtained and its drastic changes were observed. The newly obtained FTC damaged CTE was applied in the strain history of the specimen and results show a changed strain behavior from the strain history using undamaged CTE.

**Keywords:** freeze-thaw cycle (FTC), coefficient of thermal expansion (CTE), strain, temperature.

## 1. INTRODUCTION

Concrete is a heterogeneous and multiphase material. This characteristic of concrete makes it complicated when predicting its behavior especially when deterioration takes place such as caused by freeze-thaw cycles. There have been plenty of studies dealing with the deterioration due to freeze-thaw cycles (FTC), and according to literatures there have been no widely accepted frost damage mechanism of concrete. This could be attributed to the complicated characteristics of concrete. Moreover, there is almost no attention given to the coefficient of thermal expansion (CTE) of concrete once damaged by FTC or other factors. This is perhaps because the common knowledge is that CTE of materials is constant and not affected by microstructural changes. This may be true for homogenous materials, however when we deal with concrete – a heterogonous and multiphase material – this may not be the case. When concrete undergoes microstructural changes, such as when damaged due to FTC resulting in micro cracking, its mechanical properties changes, e.g. a reduction in elastic modulus. This is an experimental fact as previous studies have presented (Fagerlund 2002, Hasan et al. 2004). Yet, by definition the elastic modulus is a measure of the interatomic bonding forces and also commonly known to be unaffected by microstructural change. Similarly for CTE when defined, it is the movement of a material's atom when variation of the

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energy stored takes place as a result of temperature change. If experimental evidence suggests that microstructural change causes reduction or change in the elastic modulus of concrete, then concrete's CTE can also be affected because of the change in microstructure. Based on these indications, this study aims to investigate whether the strain behavior of specimens is affected when its CTE change.

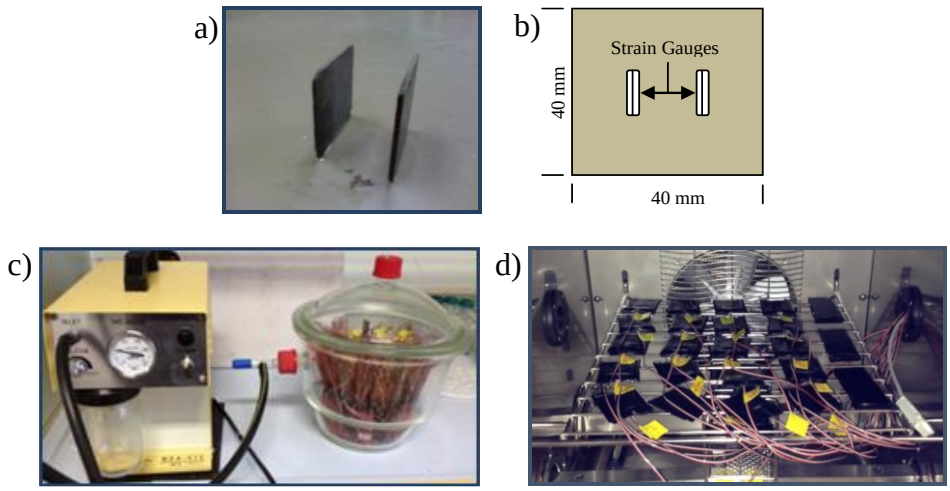
## 2. EXPERIMENTAL PROGRAM

### 2.1. Specimen Preparation

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. Table 1 shows different mix proportions used in this study, which were based from ACI 211.1 design mix.

**Table 1: Mix proportions of mortar**

| Mixture | *Water Cement Ratio - w/c* (%) | *Water (kg/m$^3$)* | *Cement (kg/m$^3$)* | *Fine Aggregate (kg/m$^3$)* |
|---|---|---|---|---|
| A | 70 | 207 | 296 | 296 |
| B | 50 | 207 | 414 | 414 |
| C | 50 | 207 | 414 | 414 |
| D | 50 | 207 | 414 | 414 |
| E | 30 | 207 | 690 | 690 |




a) 40 x 40 x 2 mm cut specimens; b) attachment of strain gauges; c) moisture adjustment (under vacuum); d) sealed specimens inside the environmental chamber

**Figure 1: Preparations of specimens.**

After all materials were properly mixed, 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 size of 40mm x 40mm x 2mm. Then, specimens were oven dried at 105ºC for 24 hours or until the weight is constant. The purpose of drying the specimens was to obtain the dried weight which will be used to determine the moisture content of specimens and obtain the CTE of mortar before FTC. Once dried, strain gauges were attached. 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. Then, specimens were put in water under vacuum condition until their mass is constant to attain full saturation. When fully saturated, specimens were sealed with vinyl tape to prevent water uptake or loss followed.

### 2.2. Freeze-thaw Cycle Tests

To undergo FTC tests, specimens were placed inside an environmental chamber which can control the temperature and relative humidity (RH). Temperature history of FTC is shown in Figure 2. This FTC was repeated 1, 3, 5 and 30 times for saturated specimens and 5 times for dry specimens. The temperature history was measured by a sensor and the strains induced were measured by strain gauges, both temperature and strains were processed by a data logger and were recorded by a computer. While the environmental chamber can control the RH, its effect on the specimens is insignificant since specimens are completely sealed. Test involving sealed specimens or limited moisture content are termed as closed freeze-thaw test by Fagerlund (2002).

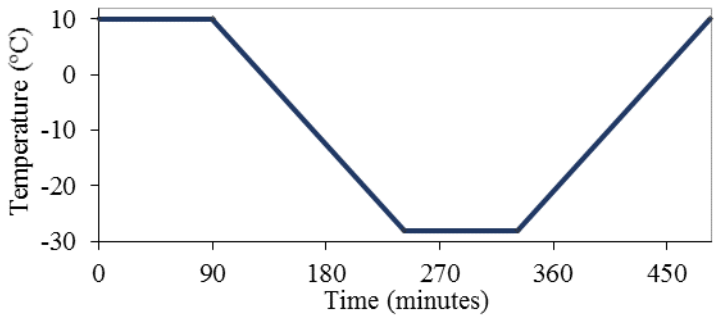



**Figure 2: Temperature cycle (1 FTC).**

After strains for fully saturated specimens were obtained, the same specimens were dried again in the oven at 105ºC for 24 hours to remove the influence of moisture then sealed once again and finally subjected under similar FTC for 5 cycles. Thermal strains were then obtained and applied.

## 3. RESULTS AND DISCUSSIONS

### 3.1. Dry Specimens Strain

Figure 3 shows strains for absolutely dry specimens, from all specimens' results it can be observed that during the whole FTC the behavior of the strains remains the same though the number of cycle increases. This behavior is due to the absence of water in the specimens and only deformation

caused by the effect of CTE of the material is observed which depends on the temperature change. Obviously, with the absence of moisture there will be no frost damage.

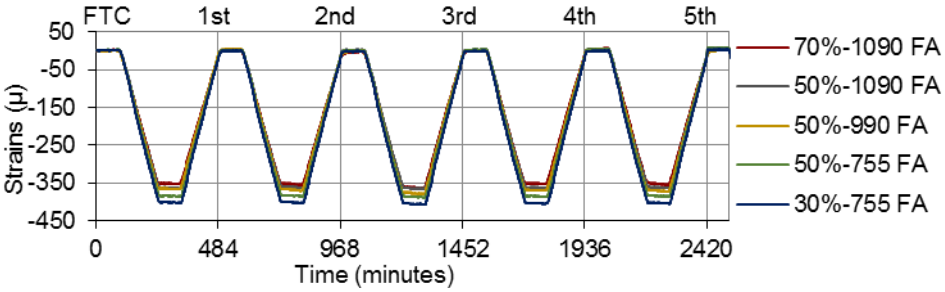



**Figure 3: Dry Specimens Strains.**

Slight differences (Sicat et. al 2012) in thermal strain can be observed from each specimen. This difference is attributed to the fact that the CTE of mortar is affected primarily by the amount of its constituent parts – fine aggregate and hardened cement paste. Fine aggregates have much lower CTE (0.3 to 5.4 x $10^{-6}$/°C) in comparison with hardened cement paste (11 to 20 x $10^{-6}$/°C) (Uygunoǧlu and Topcu 2003). Therefore the larger the amount of fine aggregates (referring to Table 1) the lower the CTE as in the case for the thermal strains of specimen having 70% W/C and while the amount of hardened cement increases (and fine aggregates decreases) the higher will be the CTE as with specimen having 30% W/C referring to the thermal strains.

### 3.2. Saturated Specimens Strain

Dry specimens strain have uniform strain behavior during the entire FTC, saturated specimen's total strain behavior on the other hand is more complicated. To understand the effect of FTC to specimens, thermal strains were removed first. This was done by removing the strains calculated using CTE obtained from dry specimen's strain. Specimens strain at different FTC is shown in Figure 4 using CTE from undamaged mortar while using FTC damaged CTE are shown in Figure 6.

Different specimen is used for each cycle being presented since after FTC the change in CTE will be determined, all specimens are pre-saturated in the same condition though. The detailed discussion of the strains observed will be discussed in the next section, these will also be compared from strains obtained using FTC damaged CTE.

### 3.3. Change in CTE after FTC damage and Change in Strain of Specimens

After saturated specimens were subjected to FTC and frost damage were accumulated, specimens were dried and sealed once more to undergo FTC. This is to obtain whether the CTE changed and to verify whether the strain behavior particularly the large negative strains (contraction observed in Figure 4d) at the later stages of FTC is caused by moisture behavior alone or a component of the thermal strains. Since these contractions are large, it has been suspected that these may not be caused by moisture behavior alone.

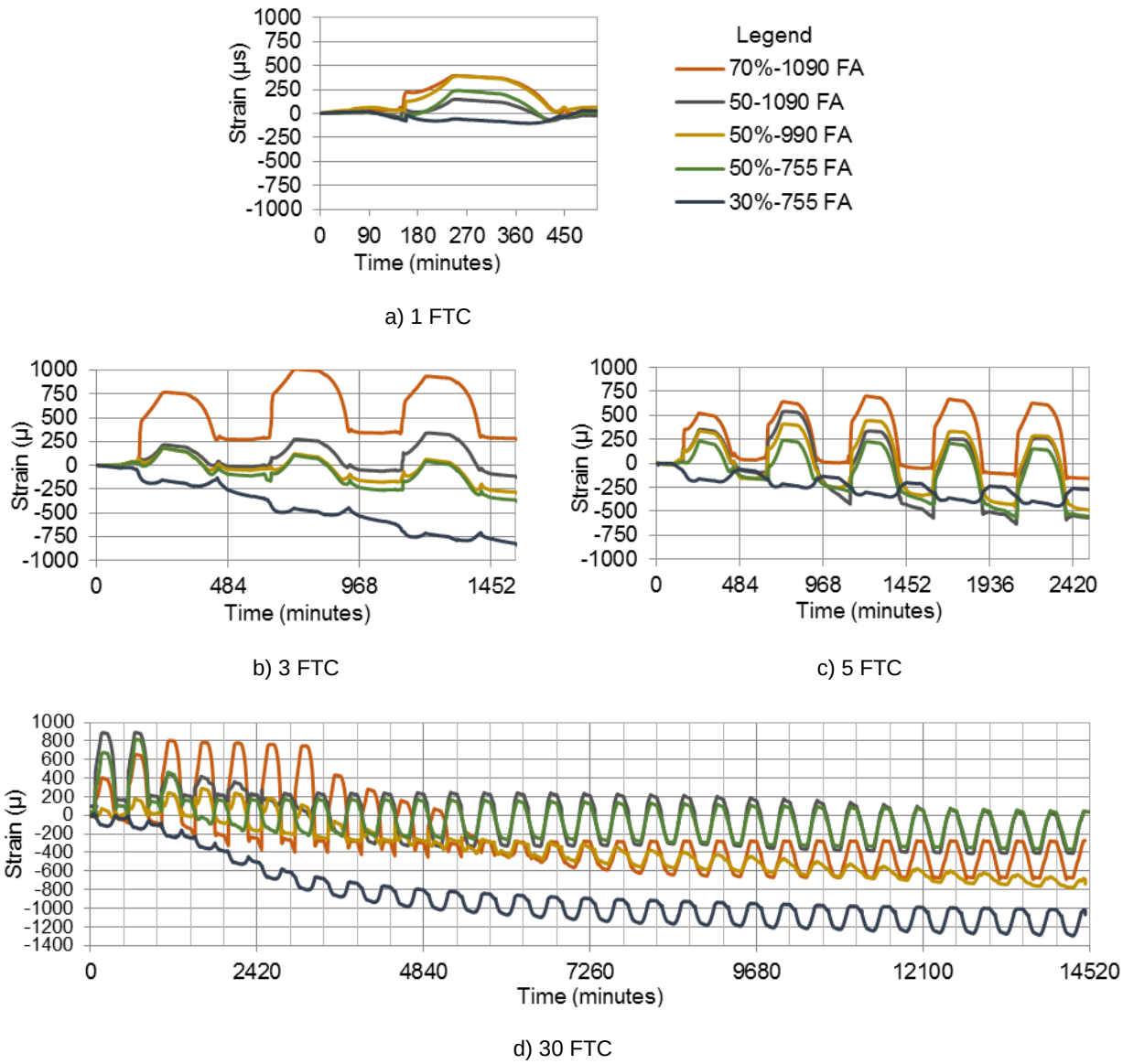



**Figure 4: Strain behavior of saturated specimens (using undamaged CTE for thermal strains).**

The CTE after each FTC damage is summarized in Figure 5 which were calculated from thermal strains of FTC damaged specimens. From Figure 5 it is evident that the change in CTE is sudden after the first FTC. In the succeeding cycles of 3, 5 until the 30th FTC there seems to be minimal change, enough to consider that the CTE may not be changing. The change in CTE of the specimens is associated with the damage during FTC. The damage was measured by determining the elastic modulus of specimens after FTC. The average reduction in elastic modulus obtained after the first FTC is 31%. While after the 3rd and 5th FTC, the average decrease in elastic modulus is 34% similarly. After the 30th FTC, the average reduction in elastic modulus is 52%. From Figure 5 relating to the reductions in elastic modulus, results shows that there is a certain damage level (or change in micro structure as a result of frost damage) wherein the CTE could change, further damage will no longer affect the CTE (Figure 5) as what is observed in the 30th FTC where the CTE remains almost similar with the previous values though there is a reduction is elastic modulus.

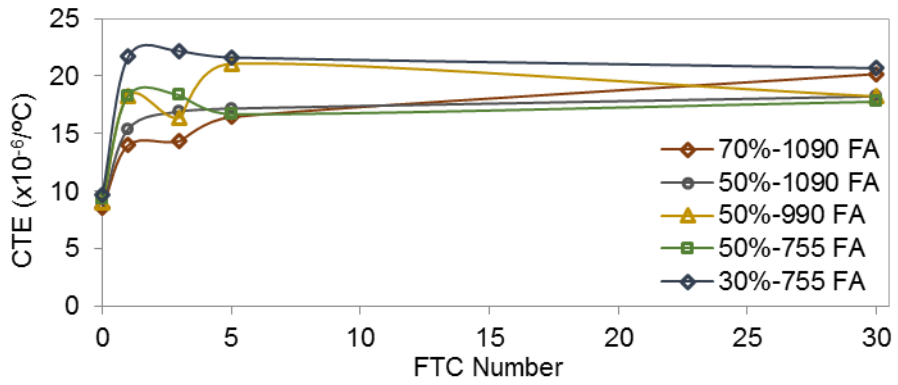
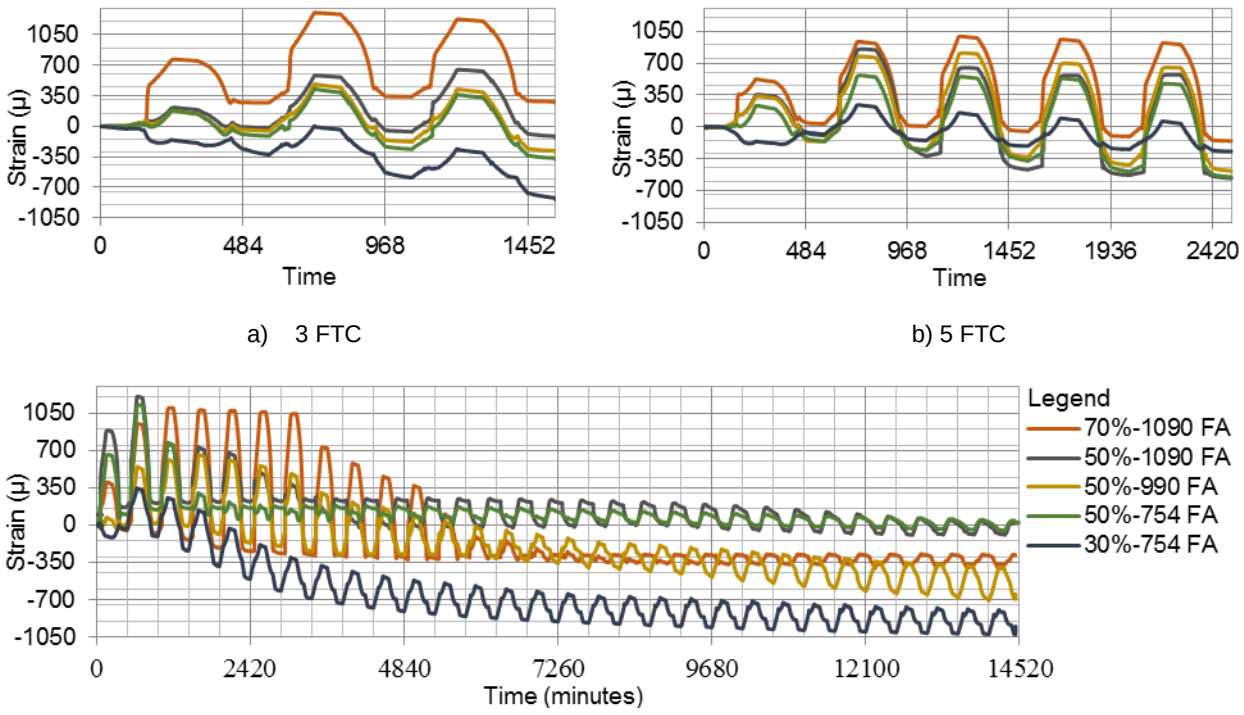



**Figure 5: Change in CTE after designated FTC.**

The change in CTE implies that the strain behavior of specimens shown in Figure 4 may not be the actual strain history since it has been observed that the CTE changed after the first FTC. Through the course of the 1st FTC the change in CTE variably changes in relation to the micro cracking until a point where the maximum change in CTE happened either before the 1st cycle ends or when it ended. However for simple presentation, it is assumed that the maximum change in CTE happened after the 1st FTC. To obtain the actual strain history, the average change in CTE (after the first FTC until the 30th FTC) is obtained and this was used to remove the thermal strain after the first FTC. The actual strain history of specimens is shown in Figure 6 and an example comparison of the strain behavior of specimens is presented in Figure 7 using undamaged CTE and FTC damaged CTE.




c) 30 FTC

**Figure 6: Strain behavior of saturated specimens applying the change in CTE or FTC damaged CTE after the first cycle (undamaged CTE used in the first FTC).**

Comparing Figure 4 and 6, it can be observed that the strains have the same tendency wherein large expansion can observed at the initial stages of the FTC which is the dominant strain behavior of the specimens for 70%-1090 FA (% designates water to cement ratio, FA denotes fine aggregates in kg/m$^3$), 50%-1090 FA, 50%-990 FA and 50%-755 FA. These expansions are product of volume expansion of water when it turns into ice. A temporary hydraulic pressure is produced causing the expansion when water suddenly freezes ((Korhonen 2002; Setzer and Liebrecht 2002), this is based from the hydraulic pressure theory. The expansion of frozen water causes tensile stresses in the surrounding matrix which is reflected as expansion in the strain history of specimens. This takes place when the pore structures of the specimens filled with water as assumed in the experimental study. If the stresses exceeds the tensile strength of the matrix, micro cracks develop which increase the pore volume of the mortar specimens. The positive maximum strain reached its peak around the 2nd to 4th cycle for all of the specimens as can be observed from both Figure 4 and 6. This maximum strain is observed in 3 FTC, 5 FTC and initial stages of 30 FTC, then decreases slowly as the FTC progresses (observed in 5 FTC and 30 FTC). As the positive strain continuous to decreases, there will come an instance where it reverses to negative strain as can be observed particularly for 30 FTC (the same reverse action is expected be observed for the other specimens under different FTC if testing progresses until the 30th cycle or more). When enough pore space is created due to micro cracking caused by large expansion strains in the first few cycles, 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 (Kaufman 2002; Setzer and Liebrecht 2002). On the other hand, from the entire FTC of 30%-755 FA specimen in Figure 4d anomalous increasing negative strains is observed even though the specimen is subjected to full saturation. The strain behavior changed when FTC damaged CTE was used, wherein slight expansion is observed then in the initial cycles in Figure 6 however much lesser in comparison with other specimens, the action reverses to contraction afterwards. This could be attributed to its pore structure. Because of the low w/c ratio of the specimen, it may contain very fine pores which makes it difficult for moisture to penetrate during saturation process. This results in partial saturation of the specimen, where it contributed to its dominant contraction during FTC.

If observed more closely, it is apparent that the strains induced have changed. Noticeably the expansion at the initial stages of FTC have increased up to 300 micro strains for all the specimen and every cycle in 3, 5 and 30 FTC in Figure 6 from Figure 4 as a result of the CTE change. More importantly, the large negative strain particularly in Figure 4 observed at the later stages of the FTC decreased significantly in Figure 6 which makes the contraction to a rather credible value where in it could be said a product of moisture behavior. The change in strain (decrease in contraction) is due the change in CTE. This observation on the difference in strain behavior of specimens can be clearly observed in Figure 7. This finding on the change in CTE during FTC suggests that using the undamaged CTE in obtaining the strains induced by moisture may not be the actual strains at all. Obtaining the actual strain behavior with the application of the FTC damaged CTE will be relevant

in modeling of frost damaged in concrete since the factors that caused damage to concrete are the expansive strains induced by moisture behavior during FTC.

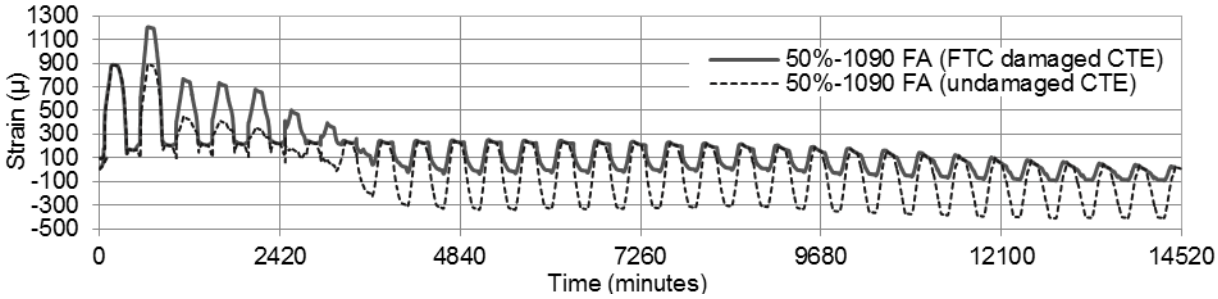



**Figure 7: Comparison of strain behavior of 50%-1090 FA saturated specimens applying FTC damaged CTE and undamaged CTE in removing thermal strain.**

## 4. CONCLUSION AND SUMMARY

The experimental findings shows that the CTE of FTC damaged specimens changed once microstructural changes occur which is caused by the micro cracking of the specimens as expansion occurs during freezing. There is a certain level of damage wherein the change in CTE will occur and any further damage could not cause any further change in the CTE. Based on this change in CTE immediately observed right after the first FTC, it is evident that it should be applied in order to obtain the actual strain behavior caused by moisture and thermal strains during FTC. Using FTC damaged CTE displays a different strain behavior from strains obtained using undamaged CTE which clarify the anomaly that the large negative strains observed in Figure 4 are not contributed by the moisture behavior alone, but rather also contributed by the thermal strains (FTC damaged CTE). The findings in this study could be relevant in simulations and modeling of frost damaged and the prediction of life cycle of concrete.

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