- Technical Paper -

OBSERVED DEFORMATION AND DEGRADATION OF COEFFICIENT OF THERMAL EXPANSION OF MORTAR SUBJECTED TO FREEZE-THAW CYCLES

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ABSTRACT

The paper presents the experimental results obtained during a freeze-thaw cycle (FTC) test of meso-scale size mortar under controlled and varying moisture conditions. The results include the strain behavior of specimens which varies depending on the amount of moisture and the degradation of its coefficient of thermal expansion (CTE). Findings show that the CTE drastically changes. The level of the drastic change increases as the amount of moisture present in specimens increases, on which the deformation during FTC is strongly dependent.

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

1. INTRODUCTION

There are plenty of available experimental studies which deal with the damage evolution of concrete pertaining to freezing and thawing actions. Commonly in the available studies, concrete specimens subjected to FTC tests are exposed to 100% relative humidity or submerged under water to promote frost damage and allowing the continuous absorption of moisture. This test condition is different from what the actual (outside) condition is – that is, concrete seldom reaches full saturation. These kinds of tests are termed as open-freeze thaw tests as what Fagerlund [1] referred to, and the ones under constant moisture condition are what he referred to as closed-freeze thaw tests. Specimens are completely sealed in this condition, not allowing any water uptake or loss during the entire test.

Moreover, in experimental study of FTC damage in concrete, large (macro) scale size specimens are often used. In this study, closed-freeze thaw is used to test meso-scale size (40x40x2mm) specimens. This size is chosen so that moisture content and temperature change will be uniform in the entirety of the specimen, resulting in uniform frost damage due to the small size and thinness of the specimen once undergoing FTC. Hysteresis effect also does not take place with this meso-scale size. This uniformity is not observed in larger size specimen due to the fact that at different location the moisture distribution and temperature hysteresis are different.

The experiments presented were carried out to observe the strain behavior of meso-scale size specimens under constant and varying moisture condition which are not commonly observed in large scale specimen and in open-freeze thaw tests. And significantly, after specimens accumulate FTC damage, the CTE is measured and drastic changes were observed. The observations are presented and the findings could be relevant in the prediction of life cycle assessment of structures wherein CTE is determined for the management of the expansion of civil structures such as road, bridges, pavements etc.

2. EXPERIMENTAL METHODS

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. Different mix proportions were used in this study as shown in Table 1 based from ACI 211.1 design mix. 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 (see Fig. 1). 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 undamaged (to FTC) mortar. 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

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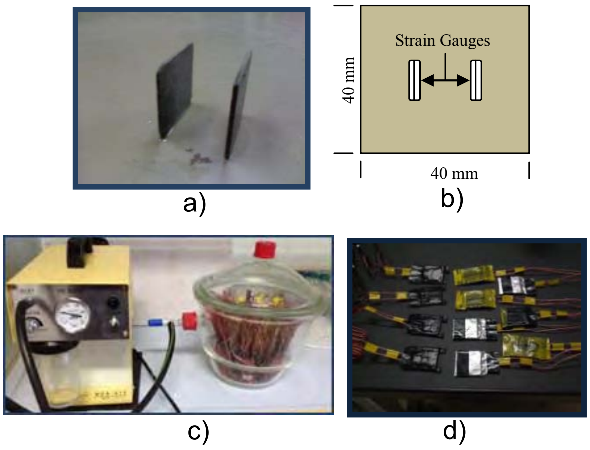
measurement.

For the attainment of different moisture content specimens were exposed to different conditions. For fully saturated condition, specimens were submerged under water and subjected in a vacuum condition to effectively remove entrapped air inside the specimen (Fig. 1c). For partially saturated conditions, specimens were exposed to 99% and 80% relative humidity (RH). All specimens were exposed to their respective RH (or moisture conditions) for 24 hours or until their weight is constant. Table 2 displays the condition in which specimens were subjected and their moisture content. When the desired moisture content is attained, specimens were sealed with vinyl mastic tape to ensure that there will be no water uptake or loss during FTC test.



a) 40 x 40 x 2mm cut specimens; b) attachment of strain gauges; c) adjustment of moisture content (under vacuum condition); d) sealed specimens
Fig. 1 Preparation of specimens

Table 1 Mix proportions of mortar

Mixture	W/C (%)	Water (kg/m^3)	Cement (kg/m^3)	F. 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

Table 2 Water content of specimens

Saturation Degree (%)	Moisture Content (g/cc)	RH (%) Condition
Dried	-	0
100	0.228	underwater
92	0.208	99
68	0.152	80

2.2 Freeze-Thaw Cycle Tests

Tests for FTC were set-up as illustrated in Fig. 2. To undergo FTC, specimens were placed inside the environmental chamber which can control the temperature and RH. Temperature history of FTC is shown in Fig 3. This FTC was repeated 30 times for all saturated specimens and 10 times for the dried 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.

After strains for saturated specimens were obtained, specimens were dried in an oven at 105°C for 24 hours to remove any remaining moisture then sealed once again and undergone 10 FTC. Thermal strains were then obtained and changes CTE was calculated and compared with undamaged (dry) specimens.

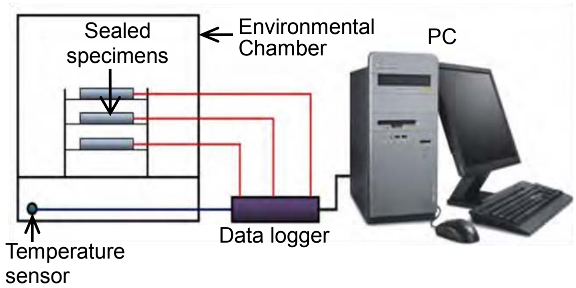


Fig. 2 Experimental set-up

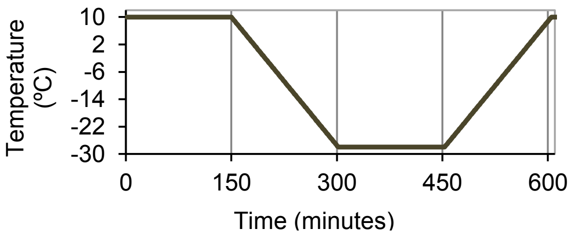


Fig. 3 One cycle of FTC

3. RESULTS AND DISCUSSION

The measured strain by strain gauge includes the strain of gauge itself due to temperature change. In order to estimate the temperature-induced strain, a quartz cube (30x30x30 mm) was used and undergone temperature variation – strain gauge was attached. The strain induced by the gauge was obtained by eliminating the strain of quartz determined by its known coefficient of thermal expansion which is relatively small (0.4 x 10^{-6}/°C) from the strain induced by the attached gauge.

3.1 The Effect of Temperature

The linear expansion coefficient of mortar for each moisture condition was obtained from the apparent strain of mortar during FTC. The strain induced by strain gauge is removed from this apparent strain. To observe the strain behavior under the effect of moisture alone for saturated specimens during FTC test, the effect of temperature on the specimen was eliminated using the equation below:

$$\varepsilon_f = \varepsilon - \alpha_T \times (T - T_i)$$

Where ε_f is the strain during FTC, ε is the apparent strain of mortar excluding gauge strain, T is temperature, T_i is the initial temperature and α_T is the coefficient of thermal expansion obtained from strain behavior of dry specimens strain (no moisture) presented in the next section.

3.2 Clarification of Oven Drying

Oven drying was performed in order to remove the moisture content of specimens for the purpose of obtaining their respective CTE. Studies in the past have suggested that oven drying have an effect on the microstructure of cement based materials. This may or may not have an effect on the CTE of such materials. With this regard, pretesting on the clarification of oven drying was performed.

The procedure involves two different specimens, one of which undergone oven drying for 24 hours at the temperature of 105ºC and the other without any drying involved. Both specimens were then fully saturated by vacuum process similar with Section 2.1. This was done so that moisture effect will be similar for both specimens especially on the CTE. In literatures, it is found that moisture affects the CTE of cement based materials [2]. Specimens were then sealed, and undertook a heat-cool temperature cycle as shown in Fig. 4 for 3 times. A heat-cool cycle is chosen instead of FTC to remove the effect of ice formation on the deformation of the specimens.

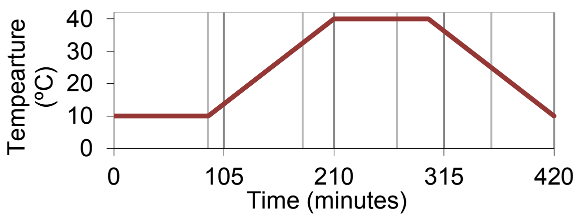


Fig. 4 One heat-cool cycle

Strain results for oven-dried and un-dried saturated specimens are shown in Fig. 5 for the 3 heat-cool temperature cycles. As can be observed, the strain behaviors are (almost) similar from the first and 2nd cycle, and then begin to differentiate on the 3rd cycle. This difference and the observed continued decrease in strain behavior as the cycle progresses is caused by the presence of large moisture content in the specimens. This has been explained to be product of temperature induced redistribution of moisture between gel and capillary pore and influence of relative humidity inside the specimen [2]. The detailed mechanism on the influence of moisture on CTE of mortar will not be discussed in this paper since the purpose of this section is to clarify the effect of oven-drying in the deformation and CTE of mortar.

With the similarity of the strain behavior of both oven-dried and un-dried specimen until the 2nd cycle, then it can be said that oven-drying which causes slight microstructural change does not have much effect on the deformation of mortar, thus the CTE (as a product of the strain behavior) is also not affected.

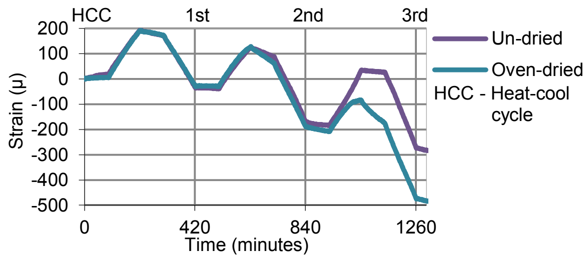


Fig. 5 Strain behaviors of oven-dried and un-dried saturated specimens

3.3 Dry Specimens Strain

Fig. 6 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.

Slight differences [3] 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) [3]. Therefore the larger the amount of fine aggregates (referring to Table 2) 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.

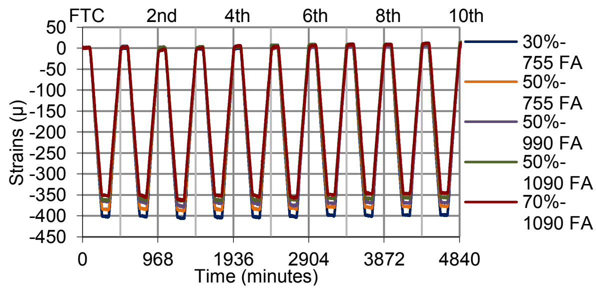
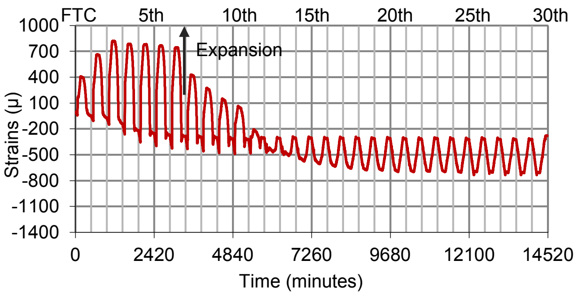


Fig. 6 Dry specimens' strain (undamaged)

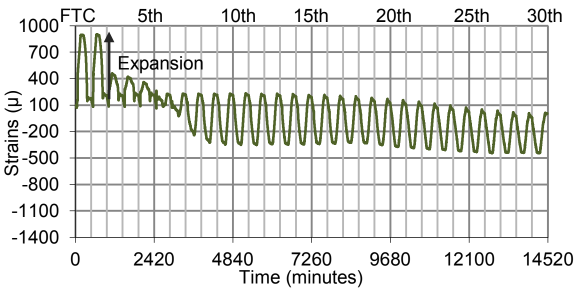
3.4 Saturated Specimens Strain

(1) Fully Saturated specimens

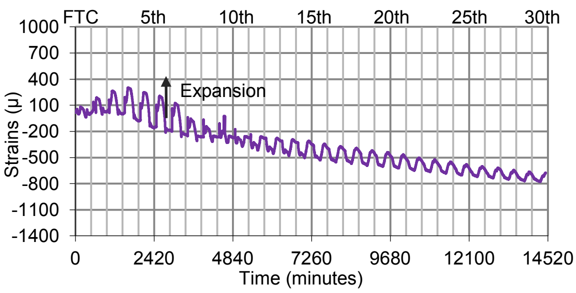
Strains obtained from saturated specimens are shown in Fig. 7. The effects of thermal strains are removed by eliminating thermal strains from dry specimens observed from Fig. 6. Figs. 7.a, 7.b, 7.c and 7.d show large expansions at the initial stages of the FTC. These expansions are product of volume expansion of water when it turns into ice. The volume expansion of water creates a hydraulic pressure causing the large increase in strain. And, at the initial stage of the FTC, even with constant moisture content the maximum strain continues to increase. Furthermore, for these specimens we can observe a decreasing



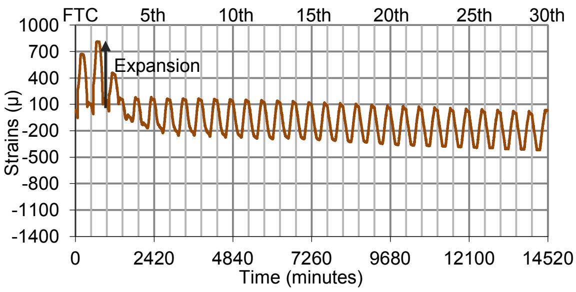
a)70% W/C & Fine aggregate of 1090 kg/m^3



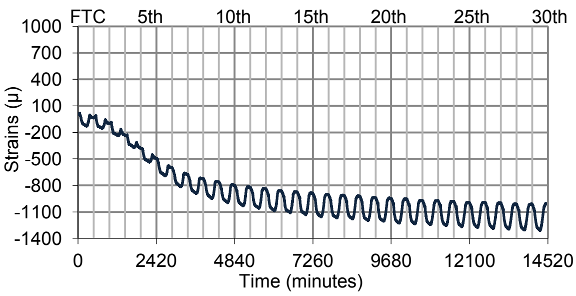
b) 50% W/C & Fine aggregate of 1090 kg/m^3



c) 50% W/C & Fine aggregate of 990 kg/m^3

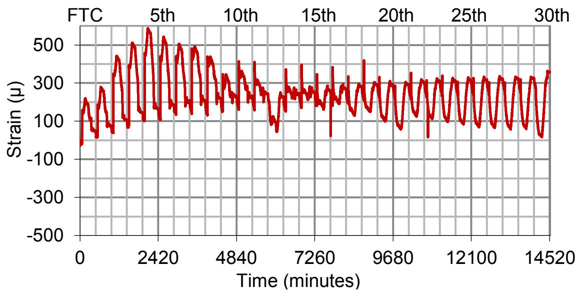


d) 50% W/C & Fine aggregate of 755 kg/m^3

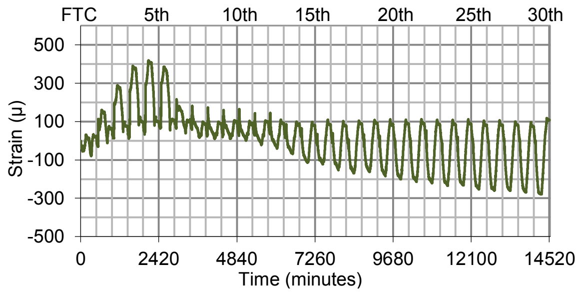


e) 30% W/C & Fine aggregate of 755 kg/m^3

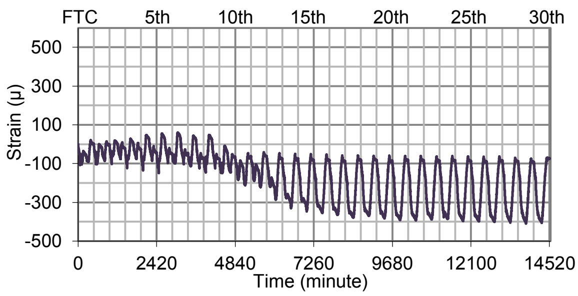
Fig. 7 Fully saturated specimens' strain



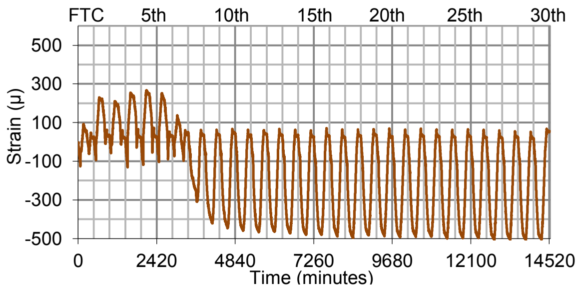
a) 70% W/C & Fine aggregate of 1090 kg/m^3



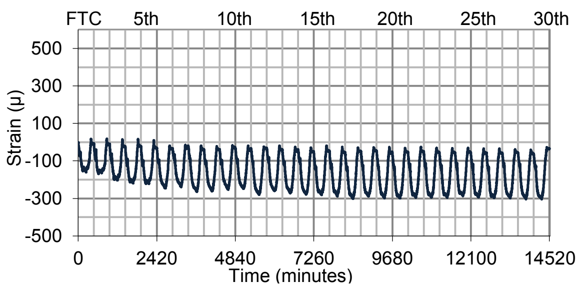
b) 50% W/C & Fine aggregate of 1090 kg/m^3



c) 50% W/C & Fine aggregate of 990 kg/m^3



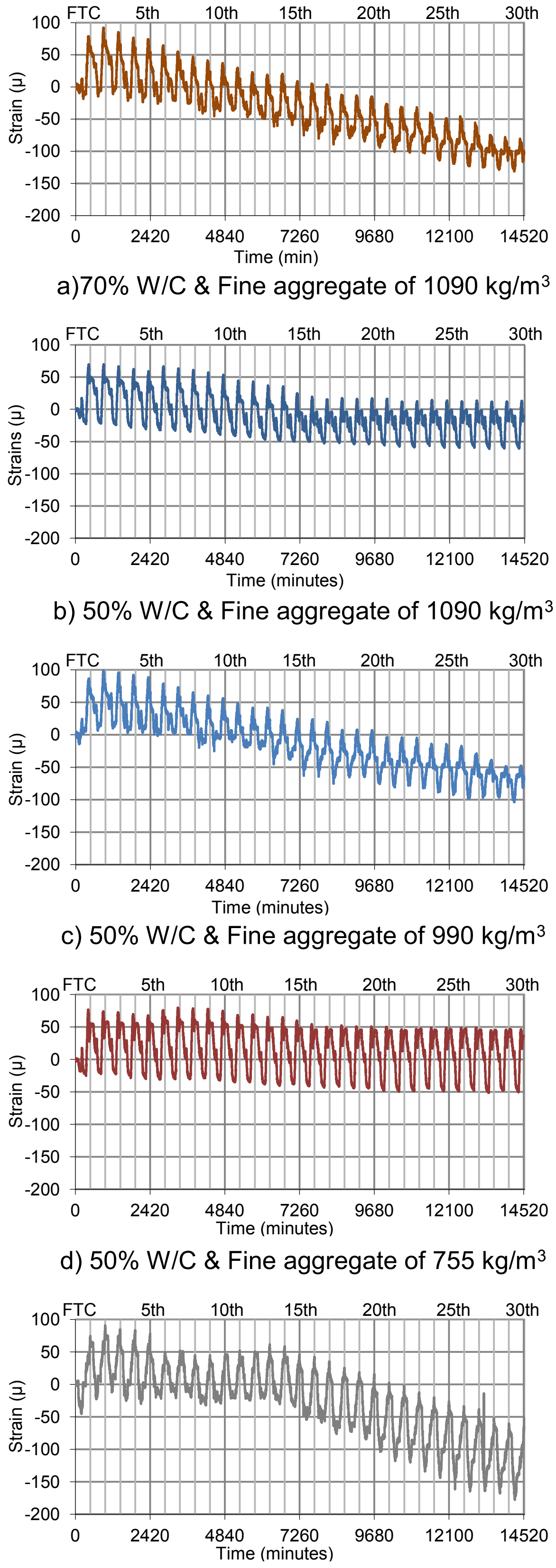
d) 50% W/C & Fine aggregate of 755 kg/m^3



e) 30% W/C & Fine aggregate of 755 kg/m^3

Fig. 8 RH99% conditioned specimens' strain

magnitude of the expansion strain until it is reversed to contraction. This has not been observed in experimental studies which involves open-freeze thaw test. The decreasing contraction behavior is attributed to the limitation of moisture content of specimens indicating that there is a maximum strain associated with the amount of moisture. When enough pore space is created due to micro cracking caused by ice formation in the



a)70% W/C & Fine aggregate of 1090 kg/m^3

b) 50% W/C & Fine aggregate of 1090 kg/m^3

c) 50% W/C & Fine aggregate of 990 kg/m^3

d) 50% W/C & Fine aggregate of 755 kg/m^3

e) 30% W/C & Fine aggregate of 755 kg/m^3

Fig. 9 RH80% conditioned specimens' strain

first few cycles, then moisture can be redistributed from gel pores to this created spaces creating negative hydraulic pressure [3].

On the one hand, decreasing contraction is observed from the entire FTC in Fig. 7e. Considering the pore structure of the specimen, keep in mind that the higher W/C ratio the more large capillaries concrete has while lower W/C results in very fine and smaller pores. The less W/C ratio of the specimen caused pore refinement. It may be possible it contain greater amount of smaller capillary pores and gel pores responsible for contraction rather than larger capillary pores responsible for expansion. And, because of the presence of these very fine pores even though specimens undergone full saturation process, it may be difficult to penetrate these very small pores. The large presence of smaller pores and insufficient amount of moisture (needed for contraction to happen) may be the cause for the unusual continued contraction of specimen [3].

(2) Partially Saturated specimens

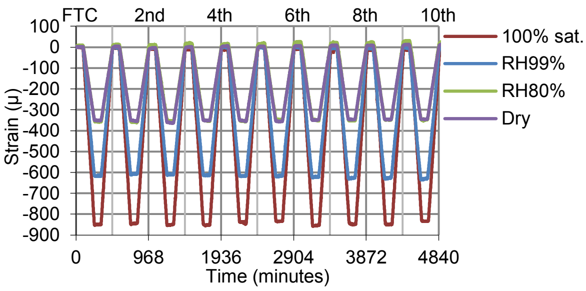
Observations for partially saturated specimens subjected to RH 99% from Fig. 8 indicate similar behavior to fully saturated specimens. However, in comparison with the strains for fully saturated specimens all of the strains' magnitudes are lesser. This is because specimens in this group specimens contain less moisture content as compared with those of the 100% saturated specimens.

For partially saturated specimens subjected to RH 80% shown in Fig. 9 during the entire FTC contraction is observed at the lowest temperature. This differs from 100% saturated specimens and partially saturated specimens of RH 99%. There is also an observed decrease in contraction at the later stages of FTC. However, because of lesser moisture content the magnitude of contraction is much lesser in comparison with fully saturated specimens and RH99% saturated specimens. Thus with less moisture content, there will be lesser deformation due to FTC as with RH99% and 80% specimens. Also, these strongly suggest that the deformation of mortar is dependent on the moisture content regardless of number of FTC.

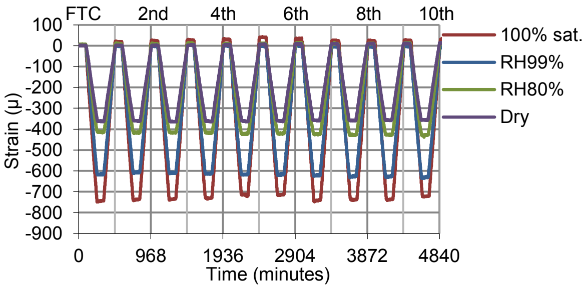
3.5 The Change in CTE of FTC Subjected Specimens

Fig. 10 shows compilation of thermal strains (FTC damaged) of specimens including dry specimens. Observation from the figure suggests that thermal strain for specimens which were subjected at 100% saturation have the largest contraction (almost double with dry specimens). Furthermore, results for thermal strains of specimens subjected under RH 99% also show large increase in contraction during FTC, also suggesting change in CTE. However, lesser in comparison with 100% saturated specimens. Since thermal strain is a product of the CTE, this means that the CTE of the said specimens have changed drastically. For specimens subjected under RH 88%, slight increase or almost equal thermal strain in reference to dry specimens can be observed. This suggests that there are slight or no change in the CTE of the specimens. We can also observe for all specimens the strain behavior is constant; this is because of the absence of moisture.

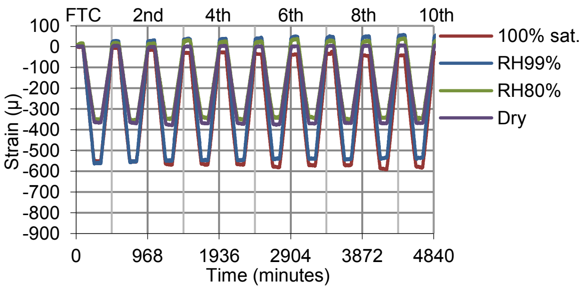
The mechanism on the change in CTE of the specimens may not be understood as of the moment. However, it is an experimental fact that damage due to



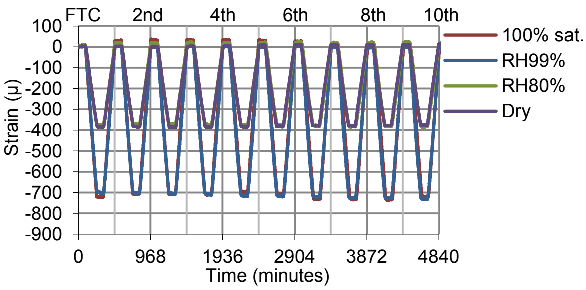
a)70% W/C & Fine aggregate of 1090 kg/m³



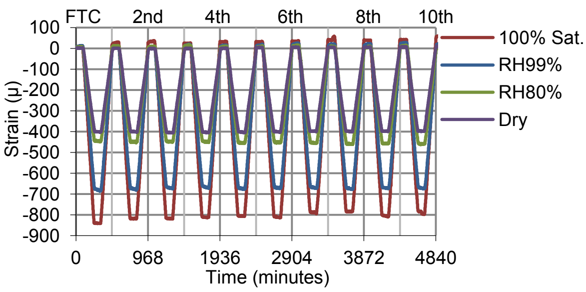
b) 50% W/C & Fine aggregate of 1090 kg/m³



c) 50% W/C & Fine aggregate of 990 kg/m³



d) 50% W/C & Fine aggregate of 755 kg/m³



e) 30% W/C & Fine aggregate of 755 kg/m³

Fig. 10 Comparison of thermal strains

FTC causes micro cracking, evident in the permanent deformation of the specimens as observed in the results. As an effect, this micro cracking apparently changes the microstructure of the specimens. This change in microstructure could be the reason for the change in CTE of FTC subjected specimens; the more pronounced the permanent deformation which depends on the amount of moisture the more drastic will be the change in CTE as can be observed in Fig. 11.

In homogenous materials, the change in microstructure does not affect the CTE. However, as results suggest this is not true for mortar/concrete since it is a complex multiphase and heterogeneous material.

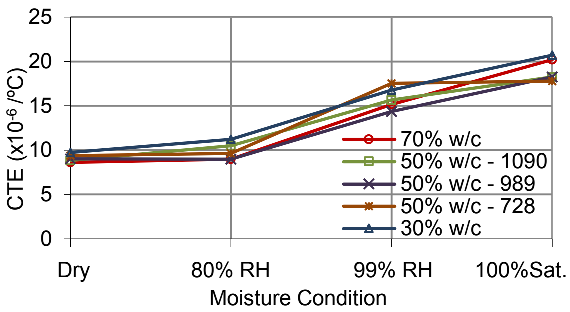


Fig. 11 Degradation of CTE (FTC Damaged)

4. CONCLUSIONS AND SUMMARY

The experimental findings show the different deformation of specimens depending on the amount of moisture and not particularly on the number of FTC. A limitation in the increase in tensile strain is observed during FTC and this decreases until contraction is observed. This is due primarily to the constant moisture content of specimens. The contraction is attributed to the redistribution of moisture when enough pore space is created as a result of micro cracking caused by ice formation in the first few FTC. These observations differ to open freeze-thaw test in which the commonly observed strain behavior is a continuous increase in tensile strain due to the continuous supply of moisture.

Interestingly, experimental results show that the CTE of mortar could drastically change. This could be because of the microstructural change as a result micro cracking due to FTC damage of the specimens. Further tests and evidence are suggested to justify this claim. This finding on the CTE could be significant for precise understanding of frost damage mechanism and its simulation.

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