Experimental Methods to Clarify Mortar Behavior under Freeze-thaw Cycles and Varying Moisture Content

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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 degrade 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 freeze-thaw cycles (FTC). However, in spite of the large volume of research, the mechanism of frost damage still remains unresolved [1].

2. EXPERIMENTAL PROGRAM

The aim of the experiment is the collection of reliable data to clarify the effect of variation in moisture content.

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 for specimens is 1:2:6 (water: cement: fine aggregate). 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). After cutting, specimens were oven dried at 105^{0}C for 24 hours or until all the water was removed. The purpose of drying the specimens was to obtain the dried weight which will be used to acquire the desired moisture content. Once specimens were 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 sets of specimens by subjecting them in dessicator with different salt solutions; Table 1 shows moisture content of specimens. Absolutely dry specimens were used to measure the linear coefficient of expansion of mortar. When the desired moisture contents were obtained specimens were sealed with vinyl tape to prevent water uptake or loss.

Table 1 Water content of specimens

Degree of saturation	Salt solution	Moisture Condition (g/cc)	Specimens per condition
Absolutely dry	-	-	3
100 % Saturated	KNO_3	0.228	3
92% Saturated	KCl	0.208	3
68.4% Saturated	NaCl	0.152	3

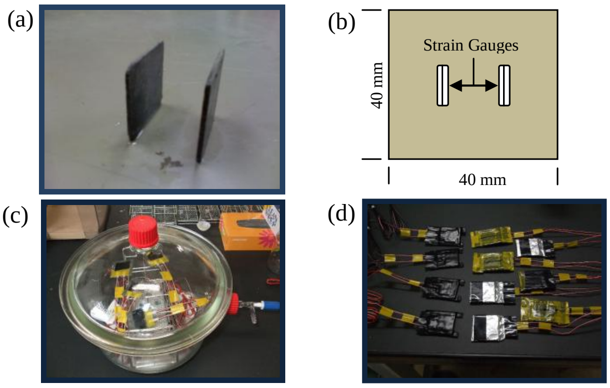

Fig. 1 Preparation of specimens

a) 40 x 40 x 2mm cut specimens; b) attachment of strain gauges; c) adjustment of moisture content; d) sealed specimens

2.2 Experimental Set-up

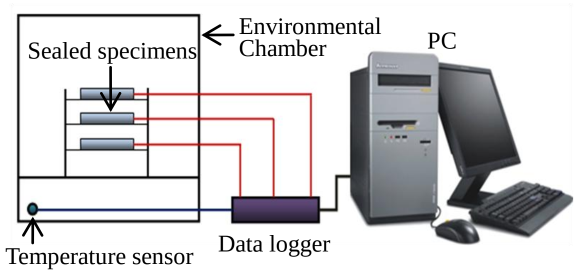

Fig. 2 Experimental set-up

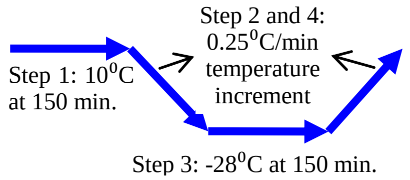

Fig. 3 One cycle of FTC

The experiment set-up is illustrated in Figure 2. Specimens were placed inside an environmental chamber to undergo FTC. One temperature history of FTC is shown in Figure 3. This FTC was repeated 5 times for absolutely dry specimens, 100% saturated, and 68.4% saturated while for 92% saturated specimens the FTC was repeated 20 times.

3. RESULTS AND DISCUSSIONS

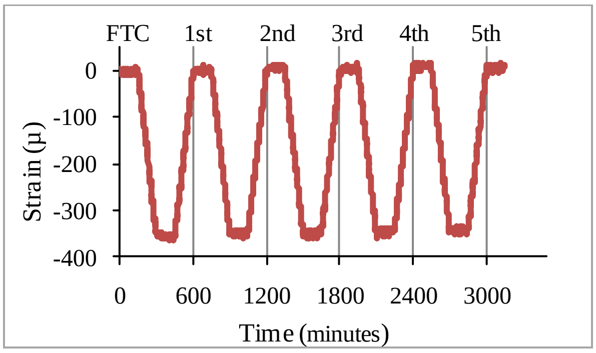

Fig. 4 Dry mortar strains

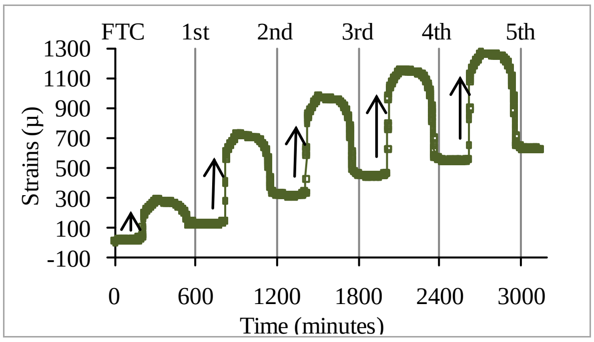

Fig. 5 100% saturated mortar strains without thermal effect

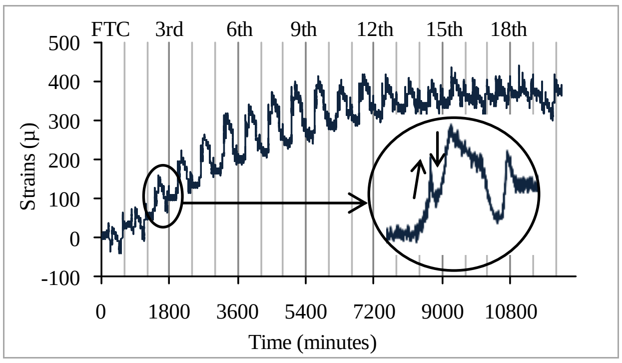

Fig. 6 92% saturated mortar strains without thermal effect

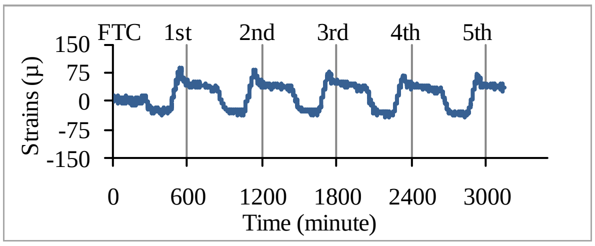

Fig. 7 68% saturated mortar strains without thermal effect

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 were directly excluded from the obtained strains of saturated specimens. Figure 5, 6 and 7 shows saturated specimen's strain caused by moisture behavior, the thermal strains were removed.

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 remain constant though the number of cycle increases. This constant behavior is due to the absence of water in the specimens and only the effect of the linear expansion of the material is observed which causes deformation depending on the temperature change. By average the 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.

3.2 100% saturated specimen's strain

For fully saturated specimen's strains shown in Figure 5, sudden 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. This immediate expansion is caused by rapid ice formation due to freezing of supercooled water as illustrated in Figure. 8. In accordance to the hydraulic

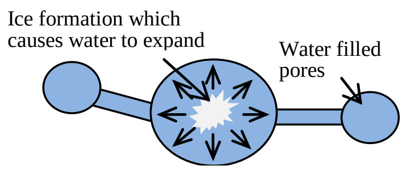

Fig.8 Pores inside a fully saturated mortar: Ice formation causing large expansion and water filled pores

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 [5]. 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 which is also shown in Figure 8, 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 water causes tensile stresses in the surrounding matrix. This stresses causes micro-cracks which increase the pore volume of 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.

3.3 92% saturated specimen's strain

Figure 6 shows strain for 92% saturated specimen. Slight increase in expansion strains and residual strain at the end of each cycle is observed as the FTC progresses, however lesser in extent as compared with 100% saturated specimens. This is due to the difference in moisture content of the specimens, with greater moisture content as with 100% saturated specimens the larger will be the expansion for every FTC.

At the temperature range of -3ºC to -10ºC a slight but sudden expansion is observed and is followed by a contraction as shown in the enlarged strain behavior at the 3rd FTC in Figure 6. However in comparison with specimens saturated at 100% the increase in sudden expansion strain is lesser due to lesser

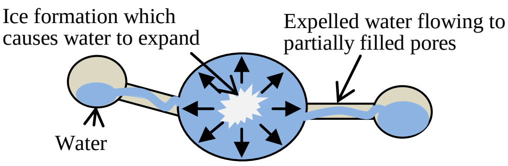

Fig.9 Pores inside a partially saturated mortar: Ice formation and expelled water flowing to partially filled pores

moisture content of the specimens. The sudden expansion is caused by a temporary hydraulic pressure brought by the abrupt expansion when supercooled water freezes. In the following scenario since specimens are not at full saturation there remain pore spaces not filled with water, consequently the expelled water from the freezing sites migrates into partially filled pores as shown in Figure 9 [5] relieving the pressure experienced and thus the contraction takes place.

It can also be observed at around the 10th until the last cycle there is no significant increase in the expansion strain, in addition the difference in increase in expansion strain decreases as the number of FTC progresses. This decreasing increment in expansion strain at every cycle can also be observed for 100% saturated specimens. Since the experiments were restricted to water uptake, the first few cycles produced a sufficient amount of space during ice expansion. This expansion caused micro-cracks which slightly increases the pore volume of the mortar structure as the FTC progresses. With the moisture content being constant and with the increasing volume of pore due to micro-cracks, the pressure brought by ice expansion (which is dependent on the moisture content) decreases as the FTC progresses and therefore the increase in strain must also decrease [5]. From this it can be said that there will be a maximum number of FTC wherein the amount of moisture will no longer be enough to cause expansive pressure to the matrix.

3.4 68.4% saturated specimen's strain

For specimens having saturation condition of 68.4% in Figure 7, during the entire FTC contraction is observed at the lowest temperature. This differs from Figures 5 and 6 (100% and 92% saturated specimens) which exhibited expansion during FTC. The contraction is due to the insufficient water content present in the specimen which is the least as compared with the other saturated specimens. The contraction is caused by the formation of ice in incompletely filled pores. The thermodynamic equilibrium in pore solution is disturbed by the ice formation. Due to the lower chemical potential of ice than that of water, unfrozen water from smaller pores or locally supercooled regions flows toward ice front [4]; this water redistribution creates negative hydraulic pressure.

3.5 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 maximum strain obtained during freezing is almost 50% of the resulting residual expansion as presented in Figure 10. Similar relationship was also observed by a study presented by Arai and Ueda [1].

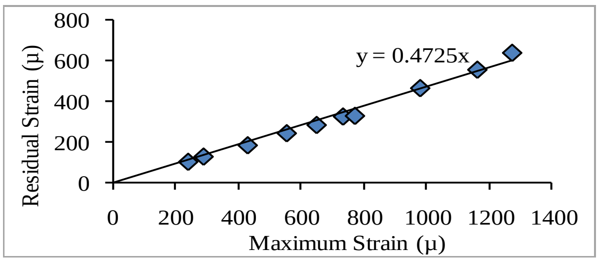

Fig. 10 Maximum and residual strain relationship

4. OBSERVED MICROSTUCTURE OF FTC DAMAGED MORTAR USING MICRO-FOCUS X-RAY CT

Acquisition of 2D images of the internal structure of specimens (approximately 6.6 mm in diameter) subjected to cyclic freezing-thawing environment was done using a desktop micro-focus CT system (TOSCANER-30000μhd, Toshiba IT & Control Systems Corporation, Japan) [6].

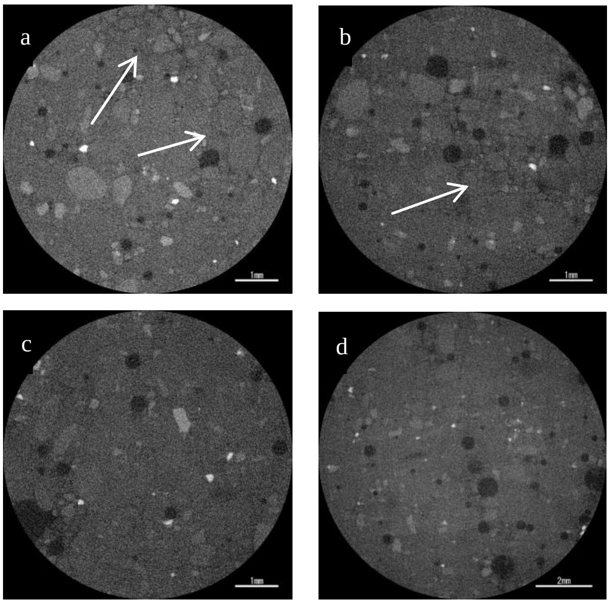

Fig. 11 2D images of the internal structure of mortar
a) 100% saturated; b) 92% saturated; c) 68.4% saturated; d) dry

In these figures, the aggregates (sand particles) were imaged as patches of various shades of gray, and appeared to be brighter relative to darker shades of gray of the surrounding cement paste. On the other hand, the air voids and cracks (lines) were seen as black or very dark pixels in the images [6]. Though the images are not distinct and clear, most of the cracks can be observed for Figure 11a as pointed by the arrows, fewer crack occurrences can also be observed for Figure 11b. These crack occurrences support the findings that expansion strains brought by ice formation causes cracking of the mortar matrix as for the case of fully saturated specimens and 92% saturated specimens. In addition, these cracks also verify the residual strains observed at the end of every FTC. While for the dry specimens and 68.4% saturated specimens in Figures 11c and 11d no visible cracking is observed, which supports the finding that during the entire FTC no expansion strains occurred due to the lower or absence of moisture content of the specimens.

As of this time only qualitative observations is possible on the scanned images, the image quality of the scanned microstructure of FTC damaged mortar is of low quality and in need of enhancement and further research is suggested in order to acquire more reliable data in the future.

CONCLUSIONS

Based on gathered data, the experimental method presented is feasible in clarifying the deformation of mortar subjected to FTC under different moisture content. The level and variation in deformation of mortar specimens depends on the amount of its moisture which causes expansion of the matrix. These deformations were supported on occurrence or non-occurrence of cracks observed in the 2D images of the internal structure of mortar in which for fully and 92% saturated specimens cracks were observed as evidenced on their increasing strain for every FTC caused by their large amount of moisture content while for dry and 68% saturated specimens there were no visible cracks as evidenced on the constant strain behaviour during the entire FTC which is due to the absence or low moisture content.

For a closed freeze-thaw test similar with the presented experiment, it is interesting to find that the relation of the residual strain at the end of each FTC is almost 50% of the maximum strain.

There seems to be a relation between the moisture content and the number of maximum FTC where in the expansion strain can increase. This is evident for test specimens saturated at 92% in which during the 10th until the last FTC there is no significant increase in the expansion strain at the lowest temperature. This is also evident on the decreasing difference between the maximum strains reached for two consecutive FTC on fully saturated specimens.

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