- Technical Paper -

TEMPERATURE AND STRAIN VARIATION IN CONCRETE UNDER FREEZE-THAW CONDITIONS

Shashank BISHNOI*1 and Taketo UOMOTO*2

ABSTRACT: The effect of size of specimens on freeze-thaw deterioration of concrete was studied. Three different mixes with varying water-cement ratios and air content were used to cast prismatic specimens of three different sizes. Mold-gauges were cast inside one specimen of each size for one mix to measure the variation of strain. Also, thermocouples were cast within the specimens to study the variation of temperature at various locations. The temperature gradient generated within the specimens and the variations of strain with temperature under rapid freeze-thaw conditions have been presented.
KEYWORDS: freeze-thaw, deterioration, durability, temperature, strain, hysteresis, rapid freeze-thaw tests

1. INTRODUCTION

Durability related problems of structures have gained a large amount of exposure in the recent years since a large amount of infrastructure investment is being made into repair and rehabilitation. Freeze-thaw deterioration in concrete structures poses a grave problem in many countries. First attempts to understand the mechanism of freeze-thaw deterioration were made in the early 20th century; however, the concepts have evolved with time. Early studies attributed this deterioration to expansion of water on cooling and freezing[1]. Under normal conditions, water expands by 9% upon freezing due to formation of ice-bonds in ice which create a much looser molecular structure than that of water. This expansion translates as tensile pressure on saturated pore walls and leads to cracks on cyclic freezing and thawing of the pore water. This expansion also drives away water from saturated pores generating hydraulic pressure inside the pores leading to local cracking in pores[2]. Further, movement of unfrozen water to freezing locations, causing "ice accretion", generating additional pressure, has also been reported[3]. Microscopic studies have shown the formation of cracks when this pressure exceeds the tensile strength of concrete[4] and various mathematical and constitutive models have been proposed to explain the phenomenon of freeze-thaw deterioration [3,5]. However, continuous modifications are being made to theories with the increasing experience of the researchers. This work is an attempt to better understand this phenomenon by investigating the variations of actual temperature and strain in concrete subjected to rapid freeze-thaw conditions.

2. OBJECTIVES

Rapid freeze-thaw tests are widely used to gauge the durability of concrete exposed to freeze-thaw conditions. It is understood that the exposure conditions in these tests can often be quite different to that in reality; however, these tests can be properly utilized to qualitatively evaluate the effect of environmental conditions on concrete[2]. The current work attempts to study the mechanism of freezing and thawing deterioration of concrete specimens submerged in water subjected to rapid freeze-thaw cycles. The variations in strain and temperature inside test pieces have also been studied for specimens of three different sizes of specimens, using thermocouples and mold strain gauges, when subjected to similar external conditions inside the testing chamber.

*1 Department of Civil Engineering, The University of Tokyo, Graduate Student, Member of JCI
*2 Institute of Industrial Science, The University of Tokyo, Dr.E., Member of JCI

3. EXPERIMENTAL

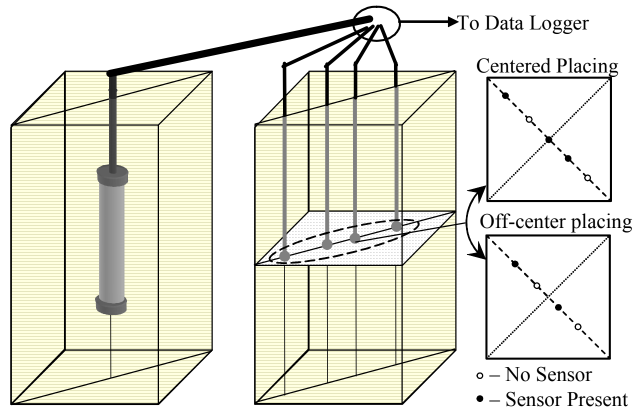
3.1 SPECIMENS

The strength and the mix proportions of concrete used to prepare the specimens are shown in **Table 1**. Sand from Fuji River with a density of 2.63 gm/cm^3 and absorption coefficient 2.19% was used in the concrete. The crushed coarse aggregate was acquired from Ryojin village in Saitama prefecture and had a dry density of 2.73, absorption coefficient of 0.57% and G_{max} of 20 mm. The Prismatic specimens of three different sizes were cast with square cross-section of 7 cm, 10 cm and 15 cm sides. A total of 38 thermocouples to measure the temperature and 3 Mold gauges to measure the strain and temperature were cast inside the specimens. The low elastic modulus and water proof construction of mold gauges are ideally suited to make sensitive strain measurements. The specimens were cured under water for 8 weeks duration in order to achieve sufficient hydration before exposing to freeze-thaw cycles.

Table 1 Mix proportions of concrete

Mix No.	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Coarse Aggregate (kg/m^3)	Water Reducer	Air Entrainer (A303A)	Air content	8 week Strength (MPa)
M-55-5	160	291	826	1032	78S – 1.1%	0.6%	4.7%	39.8
M-55-2	160	291	861	1077	78S – 2.2%	0	1.2%	55.4
M-40-5	160	400	785	981	SP – 0.5%	0.6%	5%	55.3

As shown in **Fig. 1,** the thermocouples were placed in a plane at the center, along the diagonal of the cross-section and the mold-gauge was placed at the center of the specimens. **Table 2** lists the details of the specimens prepared. In order to avoid congestion of wires and ease placing, considering the symmetry of the specimens, temperature gauges at similar locations within the specimens were avoided. The sensors were not placed in a continuous manner, but were staggered as shown in **Fig. 1**, and the distance of the sensors from the surface is measured from the closest surface and not from the same surface for all sensors. Also, as can be seen from **Table 2**, in some cases, two similar test pieces were used in order to obtain the temperatures at closer locations. However, it must be noted here that the following work focuses mainly on specimens 1, 2, 4, 5, 7 and 8.



(a) Placing of Mold-Gauge (b) Placing of Thermocouples

Figure 1 Placing of sensors inside specimens

Table 2 Details of specimens used

S.No.	Specimen Code	Mix used	Size (cm x cm x cm)	Sensor Type (number)	Distance (cm) from center for sensor no.			
					1	2	3	4
1	7-55-5-M			Mold Gauge(1)	0.0			
2	7-55-5-5		7x7x38	Thermocouple(3)	0.0	2.0	4.0	
3	7-55-5-0			None				
4	10-55-5-M			Mold Gauge(1)	0.0			
5	10-55-5-5	M-55-5	10x10x38	Thermocouple(3)	0.0	2.5	5.0	
6	10-55-5-0			None				
7	15-55-5-M			Mold Gauge(1)	0.0			
8	15-55-5-7		15x15x38	Thermocouple(4)	0.0	2.5	5.0	7.5
9	15-55-5-0			None				
10	7-55-2-5			Thermocouple(3)	0.0	2.0	4.0	
11	7-55-2-4		7x7x38	Thermocouple(2)	1.0	3.0		
12	7-55-2-0			None				
13	10-55-2-5			Thermocouple(3)	0.0	2.5	5.0	
14	10-55-2-4	M-55-2	10x10x38	Thermocouple(2)	1.25	3.75		
15	10-55-2-0			None				
16	15-55-2-7			Thermocouple(4)	0.0	2.5	5.0	7.5
17	15-55-2-8		15x15x38	Thermocouple(4)	1.25	3.75	6.35	8.75
18	15-55-2-0			None				
19	7-40-5-5			Thermocouple(3)	0.0	2.0	4.0	
20	7-40-5-4		7x7x38	Thermocouple(2)	1.0	3.0		
21	7-40-5-0			None				
22	10-40-5-5	M-40-5		Thermocouple(3)	0.0	2.5	5.0	
23	10-40-5-4		10x10x38	Thermocouple(2)	1.25	3.75		
24	10-40-5-0			None				

3.2 FREEZE-THAW CYCLES

After curing, the specimens were moved to a rapid freeze-thaw chamber. The specimens were placed inside rubber sleeves in order to prevent scaled-off concrete from mixing into the thermal exchange fluid and the sleeves were filled with water up to around 2 cm above the surface of the specimens. The sensors were then connected to an automatic data logger to record temperature and strain values at an interval of 5 minutes. The freeze-thaw machine was operated in automatic cycles of four hours, two hours each of freezing and thawing, with the temperature of the exchange fluid varying between 20˚C and -25˚C (**Fig. 2**). Proper spacing was provided between the specimens to allow flow of the exchange fluid and thus proper thermal flow. It is understood that the freezing point of pore-water in concrete is much lower than 0˚C with certain calorimetric studies showing the presence of unfrozen water at temperatures as low as -55˚C[6]. However these conditions being rare in practice, this study focuses on this, relatively smaller, range of temperatures.

The specimens were subjected to 36 cycles in each step, each step lasting 6 days. At the end of 36 cycles, the temperature was brought up to 20˚C to ease handling. Since the specimens were removed from the apparatus after every 36 cycles, the starting temperature of the first cycle in each step depended on the ambient temperature at that time. At the end of each step, the specimens were removed from the test chamber and washed to remove any scaled off concrete. The corresponding resonance frequency for calculating the dynamic young's modulus was then measured by a digital dynamic Young's modulus meter with a frequency range of 300 Hz to 25 KHz. The specimens were also weighed to get a measure of the scaled off concrete. It may be noted here that to avoid any error in the measured weight due to surface water, the specimens were surface dried in air for about 2 hours. A total of 9 similar steps were carried out, thus subjecting the specimens to a total of 324 rapid freeze-thaw cycles. At the end of 324 cycles, the specimens were subjected to another 36 cycles without filling the sleeves with water, and similar readings of strains and temperatures were made.

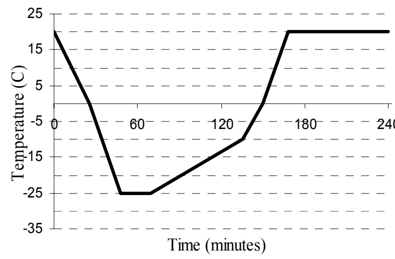


Figure 2 Typical temperature variations

3.3 OBSERVATIONS

Owing to the high strength of the concrete used, no significant change in the dynamic modulus of the specimens was observed, with all the final values being spread within ±3% of the initial value (**Table 3**), including an increase in the dynamic modulus for some of the specimens. Other studies have also indicated a similar increase in the measured dynamic modulus of elasticity[7]. At the end of this experimental study, the concrete appeared to be in a relatively good physical condition without any deep-reaching damage visible from the surface. Also, the weight loss observed in the specimens due to scaling was in the range of 0.01% to 1.89%, with the highest weight loss percentages for concrete with the higher water-cement ratio of 55% and without air entrainment and the lowest values for the concrete with the lowest water-cement ratio of 40% and 5% air content, as expected. However, possibly due to the low deterioration, no direct relationship between the weight loss and the size of the specimen were apparent from the results. **Table 3** also lists the percentage weight loss observed in the specimens at the end of 324 cycles. Further, scaling was still found to occur along with seepage of water to the surface of concrete from within, during the 36 dry cycles.

Table 3 Weight loss (WL) and relative dynamic modulus (RDM) of specimens after 324 cycles

Sp. Code	7-55-5-M	7-55-5-5	7-55-5-0	10-55-5-M	10-55-5-5	10-55-5-0	15-55-5-M	15-55-5-7
WL (%)	0.83	0.99	0.85	0.48	0.60	0.88	0.71	0.69
RDM (%)	102.7	103.0	102.4	102.4	102.6	100.8	97.3	97.1
Sp. Code	15-55-5-0	7-55-2-5	7-55-2-4	7-55-2-0	10-55-2-5	10-55-2-4	10-55-2-0	15-55-2-7
WL (%)	0.01	1.55	1.28	1.39	1.55	1.25	1.10	1.29
RDM (%)	103.0	102	102.4	100.0	98.9	99.9	100.9	101.8
Sp. Code	15-55-2-8	15-55-2-0	7-40-5-5	7-40-5-4	7-40-5-0	10-40-5-5	10-40-5-4	10-40-5-0
WL (%)	1.37	1.89	0.37	0.33	0.31	0.20	1.36	0.28
RDM (%)	99.9	102.8	100.26	100.1	100.49	101.6	101.2	99.6

4. RESULTS AND DISCUSSION

4.1 TEMPERATURE VARIATION

The output from the experiments was obtained in the form of temperature and strain within the specimens at various locations. The temperature within the specimens was found to be dependent on the size of the specimen and the external conditions. However, no effect of the mix proportion was apparent. Due to this reason, only the results from 6 selected specimens (Specimen numbers 1, 2, 4, 5, 7 and 8) have been presented in the following discussion. Since the sensors were not placed in a continuous manner, it was noticed in many cases that the temperature gradient was not symmetrically distributed within the specimens. No major change in the temperature cycles within the specimens could be seen with the progress of cycles, thus, suggesting that the conduction characteristics of concrete remain the same within the present test regime. **Fig. 3** shows temperature isotherms within concrete at various points in time. It must be noted here that the isotherms shown are not for the same time but for the lowest temperature for the same cycle. Larger specimens were found to reach the minimum temperature around 5 to 10 minutes later than the smaller ones. As can be seen from the figure, a relatively

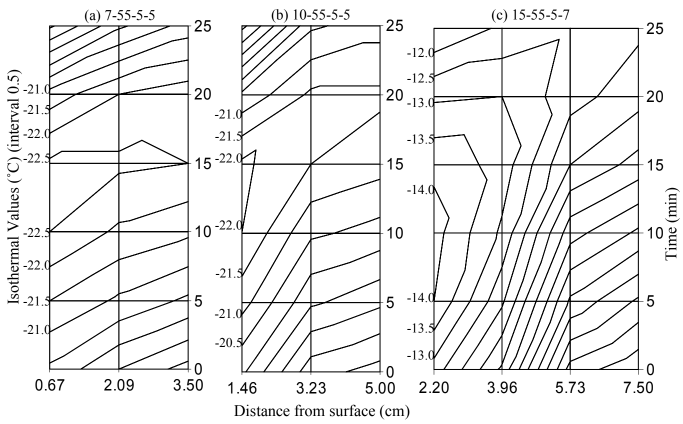


Figure 3 Isotherm chart at minimum temperature during 2nd wet cycle

smooth thermal gradient exists within the concrete, with the inner parts having a time lag in the temperature cycles and also lower peaks. It must be noted here that the relatively higher temperature in the 15 cm specimens is due to a relatively larger amount of water inside the sleeve due to improper sleeve size. Water, with its high specific heat, has a low rate of heating and cooling and reduces the temperature range on the surface of the specimens disproportionately in the larger specimens. **Table 4** gives the average maximum and minimum temperatures reached near the surface and at the center for the three different sizes of specimens. **Fig. 4(a)** shows the variation of temperature at the center of one specimen of each size, for a typical cycle. Further, the temperature range was reduced during dry cycles since the absence of water in the sleeves prevents proper thermal exchange (**Fig. 4(b)**).

Table 4 Average temperatures during freeze-thaw cycles

	7 cm specimens		10 cm specimens		15 cm specimens	
	Center	*Surface*	*Center*	*Surface*	*Center*	*Surface*
Max.	15.7°C	16.0°C	16.2°C	16.3°C	9.5°C	11.2°C
Min.	-21.1°C	-21.6°C	-20.6°C	-21.1°C	-12.1°C	-15.1°C

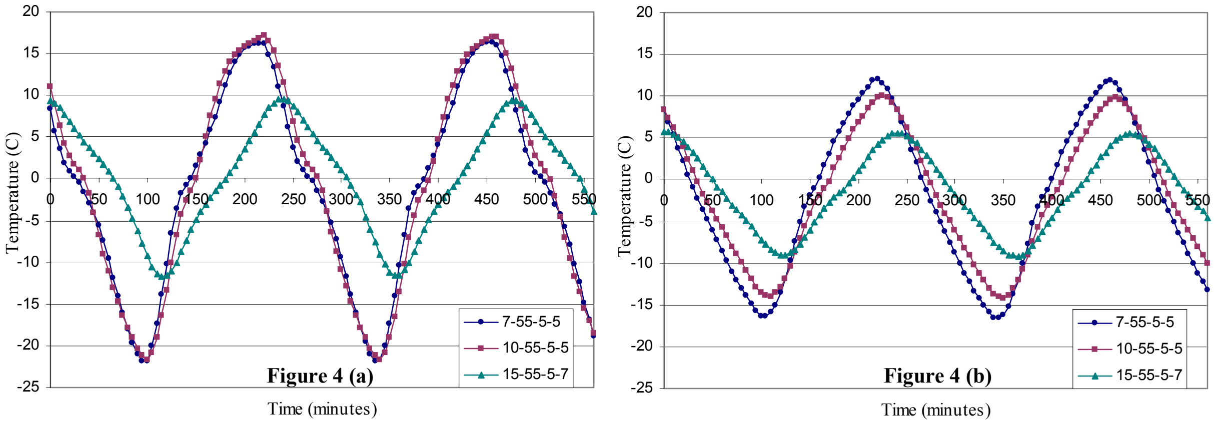


Figure 4 Typical temperature variations at center of specimens in (a) Wet state, (b) Dry State

4.2 STRAIN VARIATIONS

Strain and temperature was measured at the center of three specimens, 7-55-5-M, 10-55-5-M and 15-55-5-M, using mold strain gauges. Thus the size of specimens was the only variable in these specimens, with the mix properties remaining the same. The specimens were allowed to stand in water for around 20 hours before starting the freeze-thaw cycles so as to allow water to diffuse into the concrete to make up for any moisture loss during transportation and to allow the strain to reach a steady value. The strain values were then set to 0 at a temperature of around 25.5˚C. It should be noted here that the strain values here include thermal contraction and expansion of concrete. Negative values of strain denote compression relative to the starting point mentioned above.

(1) Strain-temperature relationship and hysteresis effect

Fig. 5 shows the variation of strain with temperature in the three specimens for the second and 287th cycles. The lower parts of the curves correspond to reduction in temperature. Studies have shown a predominantly linear contraction upon cooling to temperatures up to -20˚C[8,9]. A hysteresis behavior can be clearly seen from these curves with the tensile strain being higher at the same temperature during the increasing part of the temperature cycle, than it was during the reducing part with the larger specimens clearly exhibiting a more marked hysteresis effect. The temperature gradient in the specimens causes non-uniform thermal strains within the mass, thus subjecting the concrete to additional strain, e.g. in the rising part of the temperature cycle, the outer layers would expand faster than the inner layer thus applying extra tensile force to the inner layers. Similarly, during the reducing part of the curve, the outer

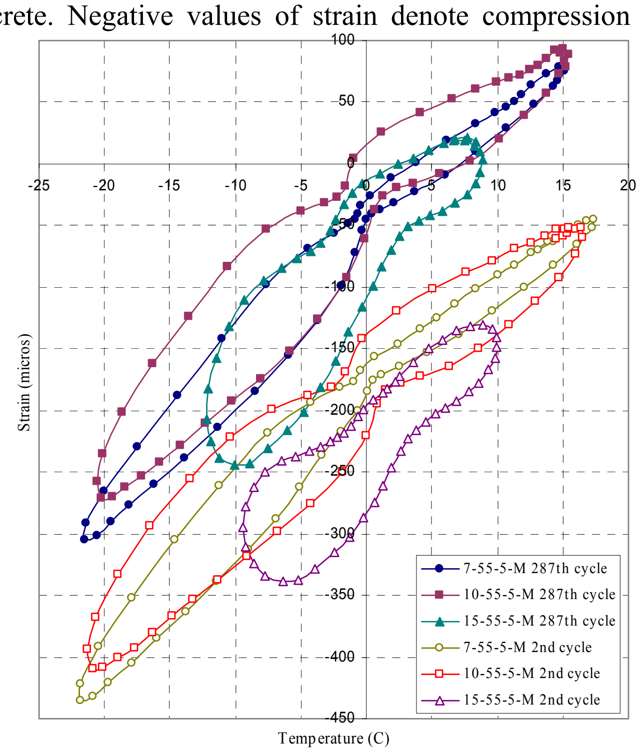


Figure 5 Strain-temperature curves in wet state

layers contract faster than the inner layer subjecting it to additional compressive force. This phenomenon may in part account for hysteresis behavior observed within the specimens, with larger specimens, having a larger temperature difference between the surface and the inner layers and thus showing a greater hysteresis effect. Similar hysteresis behavior in electrical conductivity[10], elastic modulus and damping coefficient[11] of concrete has also been reported due to hysteresis between freezing and melting of water.

It was observed that a sudden change in slope starts to occur at a temperature a little above 0˚C during freezing and a little below 0˚C during thawing. It can also be seen that, in the initial part of the sub-zero region, a higher rate of change of strain with temperature can be seen than in the unfrozen state, however, this rate gradually reduces as the temperature is reduced. This phenomenon wasn't as well marked in the dry state with the curves being relatively flat (**Fig. 6**), thus suggesting the change in slope to be directly related to the saturation degree of pores. Though the range of this study was limited to around -20˚C, studies have shown a pronounced expansion in concrete at temperatures below -20˚C[12] due to the lowering of freezing point of water and subsequent expansion upon freezing.

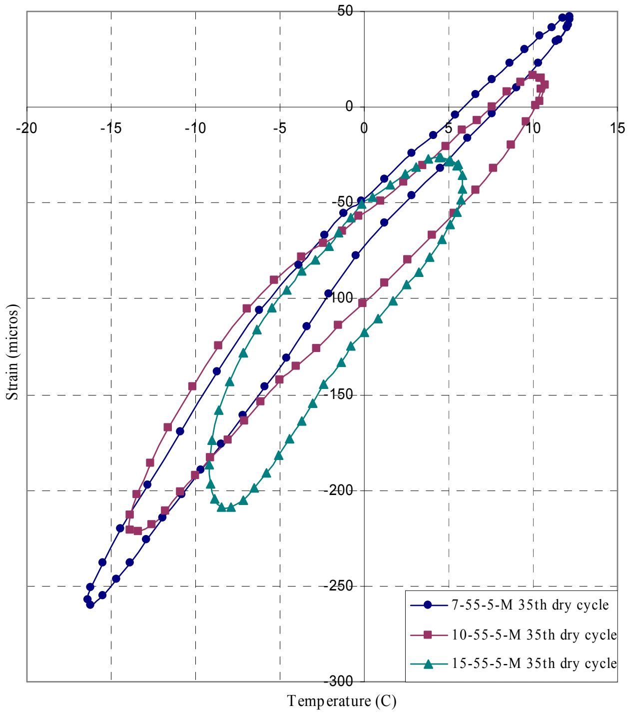


Figure 6 Strain-temperature curves for dry state

(2) Residual Strain

The hysteresis behavior was accompanied by an upward shift in the curve with a progress in the cycles as can be seen in **Fig. 7(a)**. **Fig. 7(b)** shows the residual strain in the specimens with the progress of cycles. It should be noted here that cycles 325 to 360 were carried out in a dry state. The residual strain here is defined as the non-recoverable strain present in the specimens at 19.5˚C, measured after every 36 cycles. The residual strain generated during the first cycle was found to be the highest with the strain difference between the first and second cycles at 6˚C during the receding part of the cycle being 22μ, 27μ and 16μ for 15cm, 10cm and 7 cm specimens respectively (**Fig. 7(a)**). As can be seen from the figure, the 7 cm specimen was found to suffer a lower damage in terms of residual strain when compared to the 10 cm specimen, even though the exposure conditions were quite similar as seen in **Fig. 3(a)**. However, this difference cannot be immediately quantified from the limited amount of data in this study. Though the damage in 15 cm specimen is the lowest overall, a direct comparison is not possible due to the difference in exposure conditions.

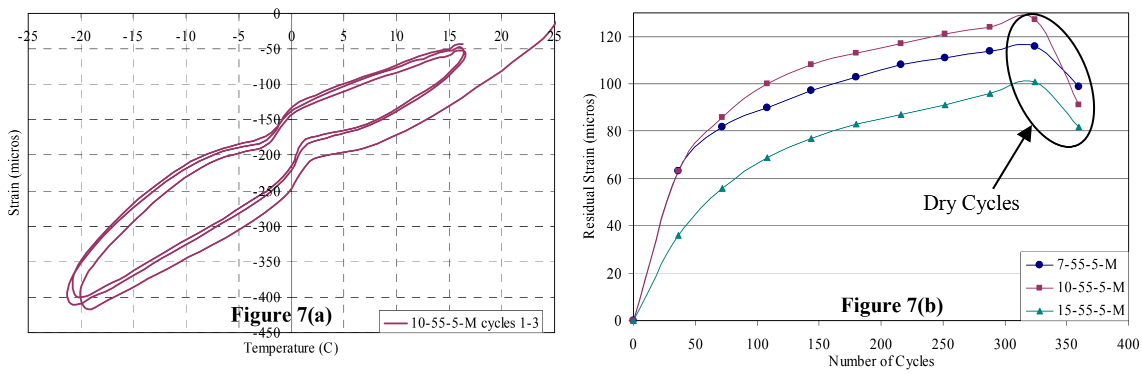


Figure 7(a) Upward shift in strain-temperature curve cycles 1 to 3 in 10-55-5-M, (b) Residual strain in specimens at 19.5˚C

A gradual but continuous reduction in the residual strain was found to occur when the specimens were subjected to dry cycles. It is well understood that water is pushed out of filled pores in order to make up for the expansion. However, upon the availability of excessive water, pores are refilled once thawing occurs. This, however, would not be possible if the water is seeps out of the surface of concrete and cannot re-enter. So, in the dry state, some of this water seeps out of the concrete surface during freezing in successive cycles and cannot re-enter the concrete upon thawing, leading to drying shrinkage and thus explaining the reduction in residual strains. As mentioned earlier, this water could be clearly seen to be collecting at the bottom of the specimen when the specimens were removed after the completion of the dry cycles. It is important to note here that any non-recoverable strain increase in the specimens during these dry cycles was superceded by drying shrinkage showing an overall reduction in the residual strains, even though the presence of scaled off material at the end of the dry cycles suggests continued freeze-thaw deterioration. However, it is expected that, after continued cycles, an equilibrium would be reached, after which the residual strains would resume its upward trend due to deterioration.

5. CONCLUSION

The results obtained from freeze-thaw tests of prismatic specimens, prepared using concrete of relatively high strength, of three sizes have been presented in the current study. It was found from the current study that the size of the specimens greatly affects the results obtained from similar freeze-thaw tests. Factors like the presence of excess water and its quantity also have a large role to play in exposing the specimens to the actual desired conditions. Also, the specimens were not always found to be subjected to similar and uniform conditions compared, both, to the other specimens and also to other locations in the same specimen. The temperature gradient in the specimens was found to be largely independent of the mix-proportions. The temperature-strain behavior was found to be hysteretic in nature with a larger hysteresis apparent in larger specimens. Also, a creep-like phenomenon was found to occur in the specimens with continued exposure to freeze-thaw cycles under saturated conditions, continuously increasing the tensile strain in concrete, with the maximum damage occurring in the first cycle itself. It is also seen that measurement of strain can be used to obtain a reliable estimate of freeze-thaw related deterioration of the concrete after taking into consideration the effect of other factors such as pore-moisture and physical loads.

REFERENCES

1. Powers, T.C., "A Working Hypothesis for Further Studies of Frost Resistance of Concrete", ACI Journal Proceedings, Vol.41 Jan. 1945, pp.245-272.
2. Detwiler, R.J., Dalgleish, B.J. and Williamson, R.B., "Assessing the Durability of Concrete in Freezing and Thawing," ACI Materials Journal, Vol.86, Jan. 1989, pp.29-35.
3. Zuber, B. and Marchand, J., "Modeling the Deterioration of Hydrated Cement Systems Exposed to Frost Action Part 1: Description of the Mathematical Model," Cement and Concrete Research, Vol.30, Dec. 2000, pp.1929-1939.
4. Fujii, T. and Fujita, Y., "Effects of Low Temperature and Deicing Chemicals on Property and Microstructure of Hardened Cement Paste," Proceedings of Workshop on Low Temperature Effects on Concrete, Canada/Japan Science and Technology Cooperative Agreement, Sep. 1988, pp.66-91.
5. Olsen, M.P.J., "Mathematical Modeling of the Freezing Process of Concrete and Aggregates," Cement and Concrete Research, Vol.14, Jan.1984, pp.113-122.
6. Jacobsen, S., Sellevold, E.J. and Matala, S., "Frost Durability of High Strength Concrete: Effect of Internal Cracking on Ice Formation," Cement and Concrete Research, Vol.26, June 1996, pp.919-931.
7. Marzouk, H. and Jiang, D., "Effects of Freezing and Thawing on the Tension Properties of High-Strength Concrete," ACI Materials Journal, Vol.91, Nov.-Dec. 1994, pp.577-586.
8. Rostásy, F.S. and Wiedemann, G., "Stress-Strain-Behaviour of Concrete at Extremely Low Temperature," Cement and Concrete Research, Vol.10, July 1980, pp.565-572.
9. Miura, T. and Lee, D.H., "Deformation and Deterioration of Concrete Subjected to Cyclic Cooling Down to Very Low Temperatures," Low Temperature Effects on Concrete, Proceedings of Second Canada/Japan Workshop, Aug. 1991, pp.23-37.
10. Cai, H. and Liu, X., "Freeze-Thaw Durability of Concrete: Ice Formation Process in Pores," Cement and Concrete Research, Vol.28, Sep. 1998, pp.1281-1287.
11. Zech, B. and Setzer, M.J., "The Dynamic Modulus of Hardened Cement Paste. Part 2: Ice Formation, Drying and Pore Size Distribution," Materials and Structures, Vol.22, Mar.1989, pp.125-132.
12. Planas, J., et al., "Thermal Deformation of Loaded Concrete During Thermal Cycles from 20˚C to -165˚C," Cement and Concrete Research, Vol.14, Sep. 1984, pp.639-644.