Strain Variations in Concrete under Freeze-Thaw Conditions

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1. INTRODUCTION

Freeze-thaw deterioration of concrete has for long been a major cause of deterioration of concrete structures. Ageing infrastructure has added to deterioration problems it has become important to address deterioration problems from all possible directions and get a deeper insight into the basic mechanism of deterioration. Initial relatively simpler explanations of freeze-thaw deterioration, e.g. tensile force in pores due to water expansion; have given way to newer theories more accurately accounting for observations of researchers. This study is an attempt to better understand the physical implications of cyclic freezing and thawing and the damage caused in the process.

2. EXPERIMENTAL

2.1 Specimens

This study focuses on strain variation in concrete specimens subjected to rapid freezing and thawing. The mix proportions of concrete used are shown in **Table 1**. Sand from Fuji River, with 2.63 gm/cm^3 density and absorption coefficient of 2.19% and crushed coarse aggregate, from Ryojin village, with dry density of 2.73, absorption coefficient 0.57% and G_{max} 20 mm was used in the mix. This study reports the findings based on four specimens as described in **Table 2**. Specimen numbers 1 and 3 had strain mold gauges cast at the center to measure the variation of strain with temperature. The other three specimens had temperature sensors embedded within at different locations, as shown in the table. The temperature sensors were distributed along a diagonal of the specimen and duplicate placing was avoided to prevent congestion and ease placing. Specimens were cured under water for 8 weeks so as to achieve proper hydration.

2.2 Test Conditions

The specimens were subjected to 4-hour rapid freeze-thaw cycles with the temperature of the thermal exchange fluid varying between +20˚C and -25˚C. The specimens were placed inside rubber sleeves and water was poured into the sleeves to allow proper fluid and thermal exchange. The typical temperature variation in the exchange fluid is shown in **Fig. 1**. The strain and temperature readings within the specimens were made at a regular interval of 5 minutes for a total of 324 such cycles. The specimens were removed from the chamber after every 36 cycles and the weight and dynamic elastic modulus was measured. After the completion of these cycles, the specimens were subjected to further similar 36 cycles without pouring water inside the sleeves.

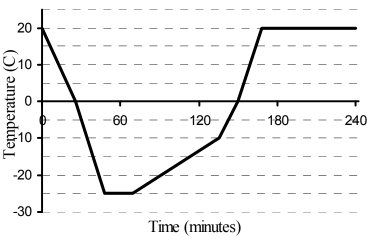

Figure 1 Typical temperature variations

Table 1 Mix proportions of concrete

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)
160	291	826	1032	78S – 1.1%	0.6%	4.7%	39.8

Table 2 Details of specimens used

S.No.	Specimen Code	Size (cm x cm x cm)	Sensor Type (number)	Distance (cm) from center for sensor no.			
				1	2	3	4
1	7-M	7x7x38	Mold Gauge(1)	0.0			
2	7-T		Thermocouple(3)	0.0	2.0	4.0	
3	10-M	10x10x38	Mold Gauge(1)	0.0			
4	10-T		Thermocouple(3)	0.0	2.5	5.0	

3. OBSERVATIONS

Table 3 Weight loss and relative dynamic modulus

Sp. Code	Weight Loss	R.D.M.
7-M	0.83%	102.7%
7-T	0.99%	103.0%
10-M	0.48%	102.4%
10-T	0.60%	102.6%

Table 3 lists the percentage weight loss and relative dynamic modulus of specimens at the end of 324 freeze-thaw cycles. As can be seen from the table, the damage in the specimens, as represented by weight loss, is not significantly high and a slight increase in the dynamic modulus was observed. Freezing and thawing is accompanied by hydraulic flow within concrete with water being pushed out of pores upon freezing and being sucked back in upon thawing. However, during the dry cycles, this water was lost from the surface and was not recovered upon thawing.

3.1 Temperature Variation

Fig. 2 shows isothermal plot of measured temperatures inside specimens near minimum temperature. It should be noted here that the minimum temperature peak at the center of the specimens was not reached at the same time, with there being a time lag for the larger specimens.

3.2 Strain Variation

Mold gauges were used to measure strain and temperature variation at the center of one specimen of each of the three sizes. Before starting the cycles, the specimens were allowed to stand in water for around 20 hours in order to make up for any lost water during transportation. The strain values were then set to 0 at the temperature of 25.5˚C. The strain values measured include thermal expansion and contraction of concrete and negative values denote compression.

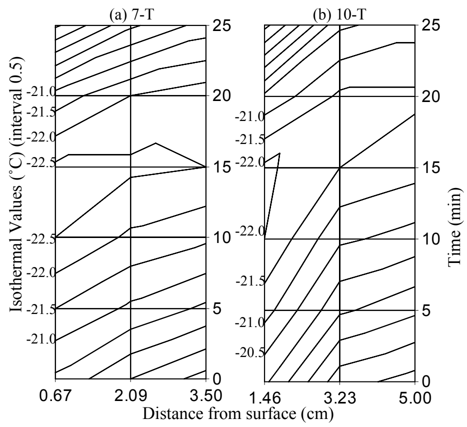

Figure 2 Isotherm chart at minimum temperature

KEYWORDS: Freeze-thaw, Deterioration, Durability, Temperature, Strain, Hysteresis, Rapid freeze-thaw tests
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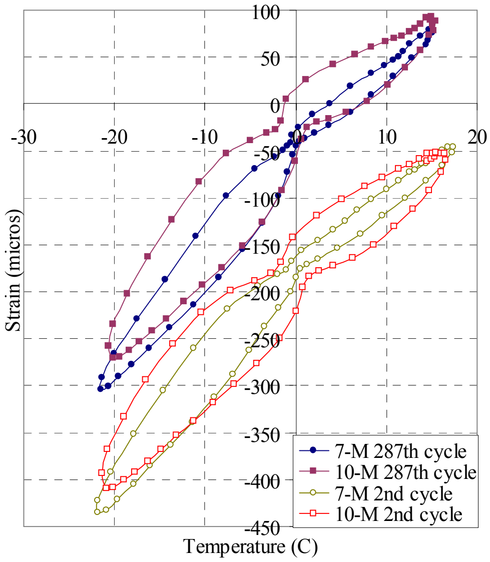

Figure 3 Strain variations during wet cycles

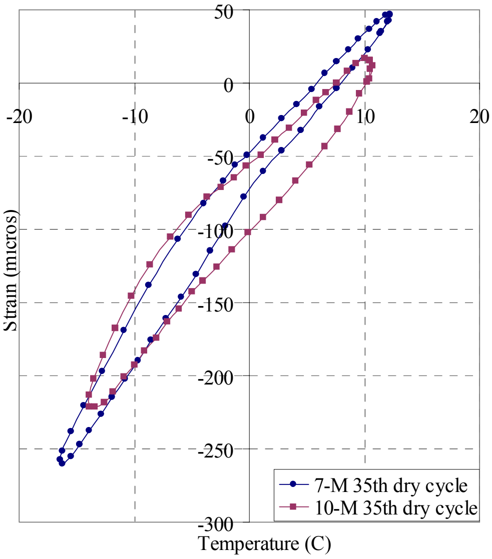

Figure 4 Strain variations during dry cycles

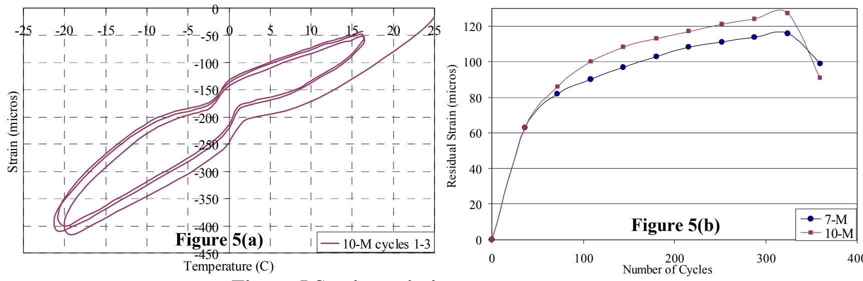

Figure 5 Strain variations during wet cycles

Fig. 3 shows the variation of measured strain with temperature during the 2nd and 287th cycle. Predominantly linear contraction in concrete upon cooling down to -20˚C has been reported in previous studies[1,2]. Most of the expansion in concrete upon freezing has been found to occur at temperatures about and below -20˚C[3]. A clear hysteresis can be observed in the figure with the strains at the same temperature being higher during thawing than during freezing. Though similar hysteresis has been reported in other physical properties[4,5], some of the hysteresis can be accounted for by the thermal gradients within the concrete that cause unequal thermal contraction and expansion in the outer and inner layers, thus adding to mechanical strain. Similar hysteresis was observed in the specimens during the dry cycles (**Fig. 4**), however, due to the absence of water outside, the temperature range was smaller and no intermittent peaks were noticed in the immediate vicinity of 0˚C, when the water outside starts to freeze leading to a reduction in the rate of change of temperature. Hysteresis was relatively more pronounced in larger specimens, with the variation in smaller specimens closer to a linear behavior.

Alongside, the strain was found to increase continuously with the progress of cycles during the wet cycles. **Fig. 5(a)** shows this phenomenon during the first 3 cycles in specimen 10-M. As can be seen from the figure, this residual strain was found to be highest between the first and second cycles. The difference in the strain measured at 6˚C between the first and second cycles was found to be 16μ and 27μ for the 7-M and 10-M respectively. **Fig. 5(b)** shows the progress of residual strain, plotted at an interval of 36 cycles. Residual strains were found to lower in 7-M compared to 10-M, though the temperature variations within the specimens were quite close to each other. Further, as can be seen in the figure, a continuous reduction in this strain was found to occur with the progress of the dry cycles due to water being irrecoverably squeezed out of concrete and thus causing drying shrinkage. It should be noted here that any strain increase due to freeze-thaw damage during the dry cycles is superceded by drying shrinkage causing an overall reduction in the strain. It is proposed here that this measurement of residual strain can be used to quantify freeze-thaw damage in concrete, after considering other factors such as temperature, physical loads and pore water saturation.

4. CONCLUSION

Experimental results of strain variations during rapid freeze-thaw tests were presented with hysteresis in strain variation and increasing residual strain being the major effects observed. Residual strain, increasing with the progress of cycles, can be potentially used to quantify freeze-thaw damage in concrete.

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