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論文　THE DAMAGE MECHANISM AND STRAIN INDUCED IN FROST CYCLES OF CONCRETE

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ABSTRACT: The damage of concrete under frost cycles was associated with the hydraulic pressure in the pore space system and the internal shrinkage due to water redistribution during sub-zero temperature. Some experimental works on different size of concrete specimens were conducted to study the strain induced in concrete under frost cycles effect. Finally, the damage mechanism on frost cycles of concrete is proposed.

KEYWORDS: Damage mechanism, plastic tensile strain, frost cycles, hydraulic pressure

1. INTRODUCTION

Theory of hydraulic pressure was applied in frost damage first by Powers based on the fact that the volume of water expands about 9 % during freezing [1]. During cooling, the water in larger pores freezes first and the freezing point of water in pore structure is lowered depending on pore radius. The small the pore radius is, the lower the freezing point [2]. If the larger pores are partially filled by water, due to the lower chemical potential of water than ice, the water from the smaller pores moves toward the existing ice and freezes there [3]. This water redistribution causes shrinkage in concrete and also creates the negative hydraulic pressure [4,5].

The wet mortar has high expansion during first frost cycle, but dry mortar has no expansion. The positive hydraulic pressure occurs if the pore structure is fully filled by water and negative hydraulic pressure if pore structure partially filled by water [4]. The same phenomena happen for concrete. The concrete preserved in 100 % of relative humidity can damage and has high plastic tensile strain during two frost cycles, but no damage happens for concrete preserved in 96 % of relative humidity or less [5,6]. In this paper the damage mechanism of dry concrete is proposed based on presented experimental result and previous research consideration.

2. EXPERIMENTAL PROGRAM

The specimens used in this study were cylinders with the diameter of 100 mm and height of 200 mm, prisms with the size of 100 mm x 100 mm x 400 mm (small prism), and a prism with the size of 300 mm x 300 mm x 700 mm (big prism). The cylinder and small prism specimens were used to study in the rather uniform temperature while the big prism was used to study in the effect of the variation of temperature in concrete on the resulting damage. The number of cylinder and small prism specimens was 18 and 8 specimens respectively, while only 1 big prism specimen was prepared. To have damage on the concrete specimens, no air-entraining agent was added. The mix proportion for all concrete specimens was the same as shown in **Table 1**. The early strength Portland cement was used. The air content for the cylinder specimens was 1.5 % while for the small and big prism specimens was 1.2 %.

Table 1 Mix proportion of concrete specimens for 1 m^3 volume (unit in kg)

Cement	Water	Gravel	Sand
320	160	1165	777

The cylinder and small prism specimens were demoulded after 2 days of casting and cured in the water for 23 days (cylinder specimen) and 20 days (small prism). The big prism specimen was covered by wet jute soon after casting and demoulded at the age of 22 days. Before casting 81 mould strain gages and

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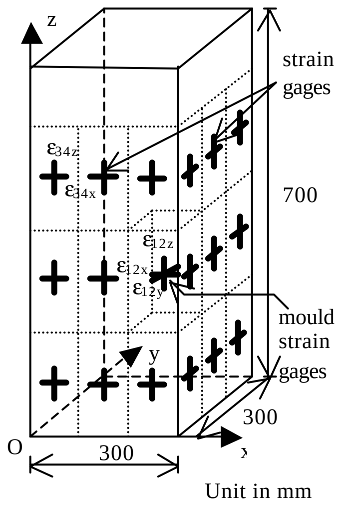
27 temperature gages were fixed at 27 different locations inside the big prism specimen (points 1 to 27 in **Fig. 1**). 3 mould strain gages were placed in one location in different x, y and z directions. On the surface of big prism specimen, 54 strain gages were placed at different 27 locations (points 28 to 54 in **Fig. 1**), which mean 2 strain gages in one location in different x or y and z direction. On the surface of big prism specimen 3 temperature gages were also mounted at 3 different sides. The location of strain and temperature gages on the big prism specimen is shown in **Fig. 1** On the surface of cylinder and small prism specimens, 4 strain gages were mounted. Inside 2 cylinder specimens, 3 temperature gages respectively were also placed before casting. For the small prism specimens, 3 temperature gages were put in only 1 specimen. The location of strain and temperature gages for cylinder and small prism specimens is shown in **Fig. 2**.

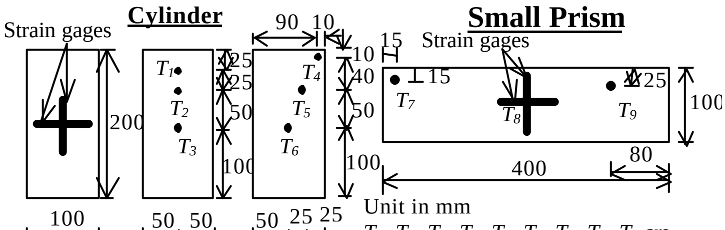


Point 1-27: Location of mould strain gages
Point 1-27; 35; 44; 53: Location of temperature gages
Point 28-54: Location of strain gages

Inside concrete				Concrete surface			
Po-int	x mm	y mm	z mm	Po-int	x mm	y mm	z mm
1	50	50	100	28	50	0	100
2	150	50	100	29	150	0	100
3	250	50	100	30	250	0	100
4	50	150	100	31	50	0	300
5	150	150	100	32	150	0	300
6	250	150	100	33	250	0	300
7	50	250	100	34	50	0	500
8	150	250	100	35	150	0	500
9	250	250	100	36	250	0	500
10	50	50	300	36	300	50	100
11	150	50	300	38	300	150	100
12	250	50	300	39	300	250	100
13	50	150	300	40	300	50	300
14	150	150	300	41	300	150	300
15	250	150	300	42	300	250	300
16	50	250	300	43	300	50	500
17	150	250	300	44	300	150	500
18	250	250	300	45	300	250	500
19	50	50	500	46	250	300	100
20	150	50	500	47	250	300	100
21	250	50	500	48	250	300	100
22	50	150	500	49	150	300	300
23	150	150	500	50	150	300	300
24	250	150	500	51	150	300	300
25	50	250	500	52	50	300	500
26	150	250	500	53	50	300	500
27	250	250	500	54	50	300	500

Fig. 1 Location of strain and temperature gages for big prism specimen

Frost cycles test was started when the age of the specimens of 50 days in a climate chamber, in which the maximum input temperature was 20 ^{o}C and the minimum one was -25 ^{o}C. The cylinder specimens were exposed up to 300 cycles while the small and big prism specimens were exposed up to 200 cycles. Before frost cycles test was started, the room temperature was kept at 20 ^{o}C. When the input temperature reached 19 ^{o}C during thawing, water was sprayed on the specimens for 15 minutes.



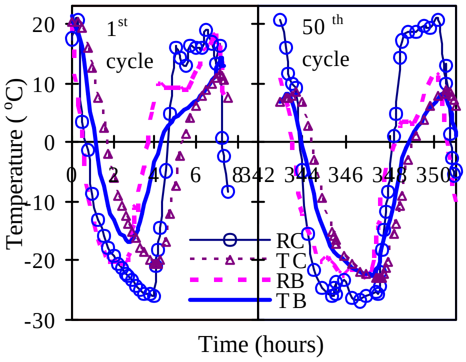
Unit in mm
T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8, T_9 are location of temperature gages

Fig. 2 Location of strain and temperature gages for cylinder and small prism specimens

3. EFFECT OF SIZE OF SPECIMEN ON TEMPERATURE VARIATION

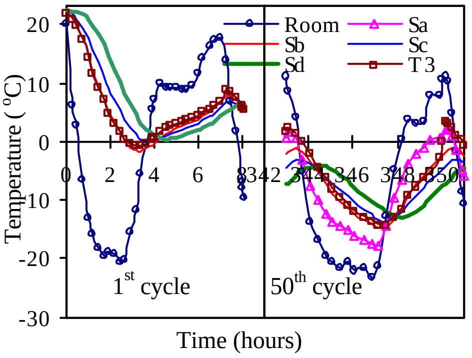
The temperature on cylinder and small prism specimens is rather uniform. The average value of temperature at different location is shown in **Fig. 3**. However, the big prism specimen has different temperature at different locations. At the points which are at the same distance from surface, the temperature is rather same, except point 3 where higher maximum temperature is observed. The temperature on big prism specimen is shown in **Fig. 4**. The maximum temperatures at all points inside the big prism specimen are below 0 ^{o}C except point 3 at which it is around 3 ^{o}C. For the small specimens (cylinder and small prism), the minimum temperature was reached at the first cycle while for the big prism specimen reached at the sixth cycle. In the big specimen before the minimum temperature was reached at one location, the room temperature had increased already. From the first to sixth cycle, the minimum temperature gradually decreased until it reached the constant value at the sixth cycle.

4. STRAIN INDUCED IN FROST DAMAGED CONCRETE



RC: room temperature for cylinder test;
TC: average of T_1, T_2, T_3, T_4, T_5, and T_6
RB: room temperature for small prism test;
TB: average of T_7, T_8, and T_9

Fig. 3 Temperature in cylinder and small prism specimens



Sa: average at surface; Sb: average of 1,7,9,10, 12,16,18,19,21,25, and 27; Sc: average of 2,4,6, 8,11,13,15,17,20,22,24, and 26; Sd: average of 5,14, and 23; T3: temperature at point 3

Fig. 4 Temperature in big prism specimen

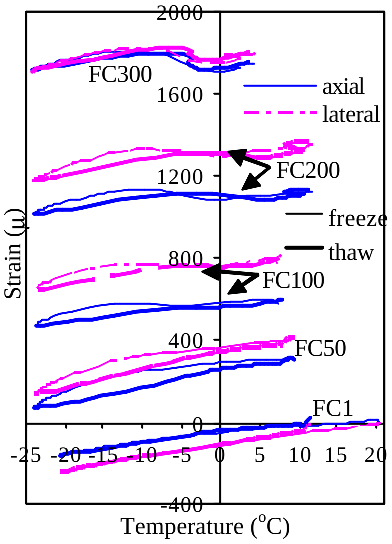


Fig. 5 Strains induced in cylinder specimens

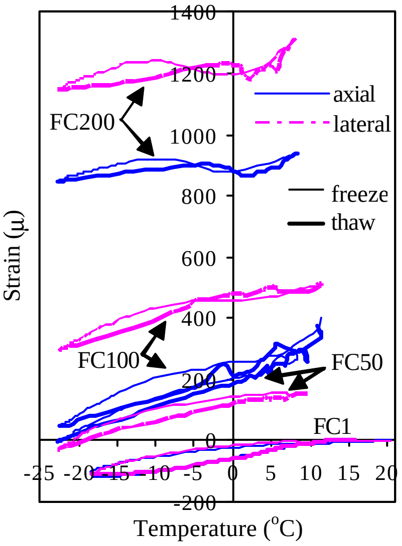


Fig. 6 Strains induced in small prism specimens

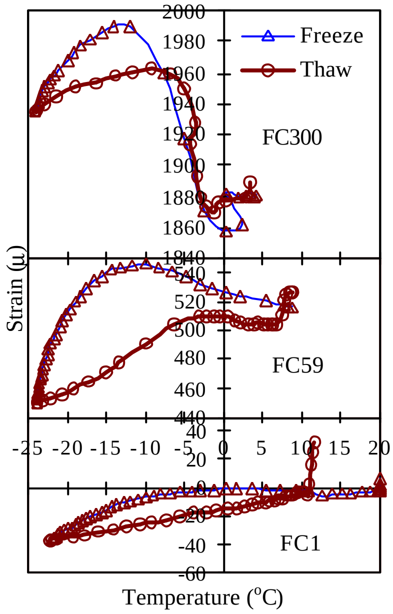


Fig. 7 Strains induced in cylinder specimens (thermal strains were excluded)

The average strains induced during frost cycles of cylinder concrete specimens and small prism specimens are shown in **Fig. 5** and **Fig. 6**. The number of frost cycles is notated by FCx, in which x is the number of frost cycles. The strain-temperature relationship for cylinder and small prism specimens was almost same. At the first cycle, the strain decreases to be compression as decreasing temperature under the effect of thermal contraction and negative hydraulic pressure due to small amount of water in pore structure [4,9]. Once the frost cycle increases, which means that the degree of pore saturation increases, the expansion of concrete can be seen when the water freezes for the temperature below 0 °C. The higher the frost cycles, the higher of degree of saturation is, resulting in the higher expansion of concrete.

The strains induced during frost cycles shown in **Fig. 5** and **Fig. 6** contains the thermal strain. To find out the strain induced by hydraulic pressure, which causes the damage of concrete, the thermal strain should be excluded. After excluding the thermal strain, the strains induced by hydraulic pressure for cylinder specimens at different frost cycles are shown in **Fig. 7.** The strains for small beam specimens showed the same phenomenon. As shown in that figure, the strain induced under the effect of hydraulic pressure in frost cycles of dry concrete can be divided into 3 phases and will be discussed in **Chapter 5**.

Due to the different temperature variation, the damage between surface and inside of big prism specimen is different. No plastic tensile strain happened in measurement point inside specimen, except in point 3. In point 3 the maximum temperature was around 3 °C which means the water can be penetrated to pore structure during thawing at the temperature higher than 0 °C. So, in point 3 the degree of saturation of pores structure can be increased and damage could occur. In other locations, the maximum temperatures were below 0 °C, which means that the degree of saturation could not be increased and result in no plastic tensile strain occurring up to maximum frost cycles. The strain induced in the surface of big prism specimens is almost same as that in cylinder specimens, because in the surface the maximum temperature was higher than 0 °C from the first cycles. However, in the surface of big prism specimen, the plastic tensile strain in lateral direction is much higher than that in axial direction. This phenomenon may be caused by the cylindrical shape of pore structure, which results in the phenomenon that the hydraulic pressure in small dimension direction is higher than that other direction. Further study, however has to be done to prove this phenomenon. The strains induced in the surface big prism specimen are shown in **Fig. 8.**

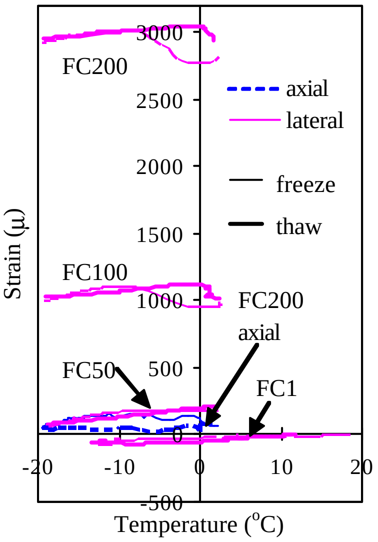


Fig. 8 Strains induced at surface of big prism

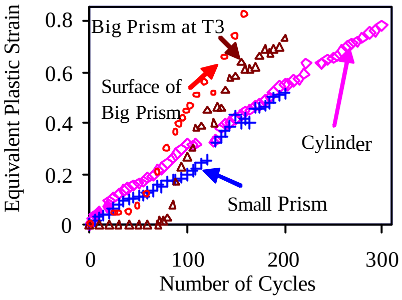


Fig. 9 Increment of plastic tensile strain

Fig. 9 shows the increment of plastic tensile strain in the concrete specimens tested in this study. The equivalent plastic tensile strain was used instead of plastic tensile strains in axial and lateral directions. The equivalent strain (E) is function of axial strain (e_a) and lateral strain (e_l) as defined in Eq. 1 [7].

$$E = \sqrt{\left(\frac{0.31\sqrt{2}}{e'_{co}}(e_l + e_a)\right)^2 + \left(\frac{0.49\sqrt{2}}{e'_{co}}(e_l - e_a)\right)^2} \qquad (1)$$

where e'_{co} is compressive strain of concrete at uni-axial strength and the value of 2000 μ was taken.

The increment of equivalent plastic tensile strains for cylinder and prism specimens was almost same. The equivalent plastic tensile strain at surface of the big prism specimen in the frost cycles less than 60 was lower than that for cylinder and small prism specimens, because of rather slow increasing degree of saturation. Once the degree of saturation reaches at a certain level, the equivalent plastic tensile strain starts to increase progressively more than that in cylinder and small prism specimens. In point 3, the equivalent plastic tensile strain occurred only after the frost cycles of 75. After 75 cycles, the degree of saturation could increase progressively resulting in quick increase of equivalent plastic tensile strain.

5. FROST DAMAGE MECHANISM

It is proposed that the frost damage mechanism of dry concrete be divided into 3 phase processes as describe below.

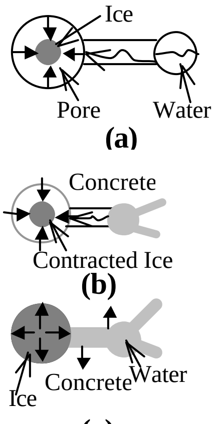
5.1 PHASE 1 (UNSATURATED CONDITION)

In this phase the condition of concrete is unsaturated. The pore structure is filled by small amount of water. The other portion of pore structure is empty or only filled by air. In this phase the following mechanism is happened during freezing and thawing cycles.

a. Once temperature drops from maximum temperature to 0 °C, only thermal contraction of concrete occurs. In this temperature range, no hydraulic pressure is created (see **Fig. 7**).
b. From temperature 0 °C to minimum temperature, water in large pores freezes first. Because chemical potential of ice is lower than that of water, unfrozen water from smaller pores flows toward ice front [3]. This water redistribution creates negative hydraulic pressure (**see Fig. 10 a**) [4,9] and results in

contraction of concrete. During freezing, the volume of pore water expands. Because the amount of the water is small, this volume of frozen water is still smaller than the volume of related pore and results in no tension.

c. From minimum temperature to 0 ^{o}C during thawing, the expansion of ice creates tension. When melting point is reached, the ice melts and the water flows to empty spaces.
d. From 0 ^{o}C to maximum temperature, the water from outside is suck in if available [3,8]. If no water available outside concrete, only thermal expansion occurs. During penetration of water into concrete pore structure, the additional tension occurs.



(a)

(b)

(c)

Fig. 10 Illustration of negative and positive hydraulic pressure

5.2 PHASE 2 (SATURATION PROCESS)

Phase 2 is only possible if there is available water from outside during temperature above 0 ^{o}C. During saturation process, the pore structure is partially filled by water. However in this phase the amount of water in pore structure is more than in phase 1. In this phase, the following mechanism happens.

a. During freezing for temperature below 0 ^{o}C, the water freezes and the volume expands in some pores more than volume of pores. This expansion of water during freezing creates a positive hydraulic pressure and results in a slight tension of concrete. If this tension is lower than fracture strength of concrete, no crack will happen. However this tension will produce a residual plastic strain at the end of frost cycles due to slip at mortar-aggregate interface. When the saturation of pore structures increases, the created tension will exceed the fracture strength of concrete and creates a crack opening (concrete fracture).
b. From temperature below -10 ^{o}C to minimum temperature, beside the mechanism in a, the ice in larger pore structure, in which all water has already frozen, contracts more than surrounding concrete due to the higher linear expansion of ice than concrete [3,9]. The resulting empty pore space is refilled by water from smaller pores which has not frozen yet and creates the negative hydraulic pressure (see **Fig. 10 b**). This mechanism results in contraction of concrete for temperature below -10 ^{o}C.
c. From minimum temperature to -5^{o}C during thawing, the ice expands more than surrounding concrete created tension in concrete. During this process, if the tension is higher than fracture strength of concrete, additional crack will happen.
d. From temperature -5 ^{o}C to 0 ^{o}C, the ice melts and water flows to empty spaces creating a negative hydraulic pressure. An additional compression can happen.
e. From temperature above 0 ^{o}C, again the saturation process from water out side concrete happens. This water will fill the pore structure and the existing crack and will be the cause of the damage in the following frost cycles.

If saturation process does not happen (maximum temperature below 0 ^{o}C or no water available from outside), the damage of dry concrete under frost cycles will not happen.

5.3 PHASE 3 (SATURATION CONDITION)

In this phase, the pore structure is totally filled by water. Because of this fact, during freezing for temperature below the freezing point, which depends on pore radius, the expansion of volume of water creates a very high positive hydraulic pressure that results in a very big expansion of concrete (see **Fig. 7** and **Fig. 10 c**). This expansion is so high to make stress more than the fracture strength of concrete, resulting in more cracks in the concrete. During this phase the concrete gets damaged. For lowest temperature, the water in smaller pores also starts to freeze, which means expansion of ice in smaller pores also creates crack in the concrete.

6. EFFECT OF FROST DAMAGE ON MECHANICAL PROPERTIES

As a result of damage of concrete during frost cycles, the mechanical properties such as strength and stiffness decay. **Fig. 11** shows the degradation of compressive strength (f'_c), static elastic modulus in compression (E_c), tensile strength (f_t) and dynamic elastic modulus (d_f) of concrete as a function of equivalent plastic tensile strain (E_{ps}) resulting from frost cycles damage. The tensile strength and dynamic elastic modulus is still same as original concrete up to the equivalent plastic tensile strain of 0.2 and reduces for the following increasing of equivalent plastic strain. This means, for equivalent plastic strain less than 0.2, only plasticity of concrete happens during frost cycles, but no fracture of micro structure in concrete. Once the equivalent plastic strain exceeds the value of 0.2, the fracture in concrete occurs beside the plasticity and results in very high degradation of tensile strength and dynamic elastic modulus. However, in the case of compression, the plasticity in tension during frost cycles causes non-plastic part of concrete ineffective to carry compression and results in the reduction of compressive strength and static elastic modulus. Therefore compressive strength gradually decreases as increasing of equivalent plastic tensile strain.

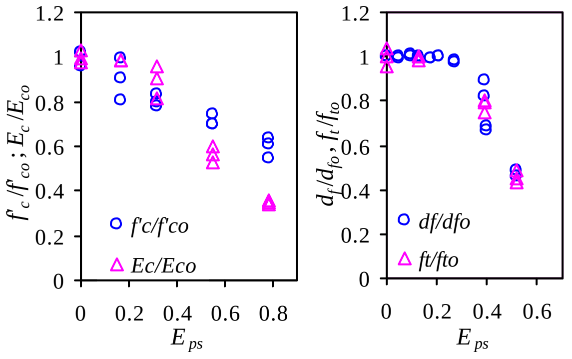


Fig. 11 Degradation of mechanical properties

7. CONCLUSION

The damage mechanism of dry concrete is presented. The damage occurs if there is enough water filled in the pore structure to create positive hydraulic pressure during the freezing of water solution. The degree of saturation increases as increasing of frost cycles by sucking water from outside during thawing process in the temperature above 0 °C. If the maximum temperature below 0 °C or no water contact with dry concrete, the concrete will not get damaged under frost cycles. The minimum temperature of -10 °C is enough to create a positive hydraulic pressure in saturated concrete, which means that concrete can be damaged under that minimum temperature. The damage of concrete can be measured by the equivalent plastic tensile strain during frost cycles.

As a result of damage of concrete, the mechanical properties of concrete, such as compressive strength, tensile strength, static and dynamic elastic modulus reduces. The reduction of tensile strength and dynamic elastic modulus happens after the equivalent plastic tensile strain exceeds the value of 0.2.

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