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Research Article

INVESTIGATING THE EFFECT OF FREEZE-THAW CYCLES ON STRENGTH PROPERTIES OF CONCRETE PAVEMENTS IN COLD CLIMATES

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ABSTRACT
Damages caused by freeze-thaw cycles in concrete structures like concrete pavements in regions with cold climate such as Zanjan city is of great importance. This therefore leads to complexity of actual analysis and modeling of concrete behavior. Accordingly, the present study is an attempt to investigate the effect of extreme daily temperature changes on performance of concrete pavements via measuring concrete compressive, tensile and flexural strength. In this regard, samples produced in ready-mixed concrete plan undertook various freeze-thaw cycles from 0 to 100 times in vitro. Then, we compared corresponding compressive, tensile and flexural strength. The results indicate that in case of lack of freeze-thaw cycles, concrete samples show their maximum strength. But by an increase in the number of cycles, the decreeing rate of strength intensifies and damages created over concrete surface become significant. Moreover, the findings suggest that flexural strength is more affected by freeze-thaw cycles than compressive and tensile strength and shows the maximum possible rate of decrease. Additionally, exploring the effect of sample curing conditions on flexural strength in different freeze-thaw cycles reveals that in concrete curing in the open air, we have the minimum strength.

Keywords: *Freeze-Thaw Cycles, Concrete Pavements, Curing, Compressive, Tensile, Flexural Strength*

INTRODUCTION
Presently, the concrete pavement design has been centralized around analyzing stress, climates and geometrical effects. While, in cold regions exessive use of anti-icing salt as well as freeze-thaw cycles have casued rupture of concrete surface. So, in case of employing bar in concrete it results in corrosion of steel and consequently, the service life of pavement consdierably reduces. Despite a large body of research on properties of concrete and still, concrete deterioration mechanisms have been remained unknown. The initial studies in this regard were focused on the fact that when water freezes, its volume increases by 9%. Future studies revealed some more mechanisms, however. For instance, the hydraulic pressure theory discusses that if water allows created ice to move along concrete, it can produce destructive stress in concrete that in case it exceeds tensile strength of concrete, it ends to concrete rupture. The causes to concrete damage have been always at the heart of researchers’ attention. This is because of huge costs associated with repair and maintenance of concrete structures. However, methods of maintenance and repair could not have positive effects in long-run if the main source of damage is not correctly identified. Accordingly, the present study aims to investigate the effect of freeze-thaw cycles on concrete performance.

Related Works
In this section we review the previously performed studies on damage mechanisms of concrete caused by freeze-thaw cycles. When the temperature drops, water molecules gather in one place. But, at temperature below 4 °C, water begins to raise in volume and its density decreases. Then, when ice crystals are shaped in water saturated pores, due to 9%-volume increase as a result of the change of water from liquid to solid state, tensile stress occurs in the cement paste. When ice structures are formed in pores, additional non-frozen water moves towards outside and the network around the hole until then pores are completely filled. This flow takes place under a compressive load and the strength against this flow is proportional to the length of path and pore diameter. Therefore, in some conditions because of insufficient volume of pores, the flow is prevented and causes resistance to flow of hydraulic pressure. This developed pressure

may reach a level it exceeds concrete tensile strength and creates some cracks on it. In addition, the movement of water along the freeze-thaw cycles may lead to water movement resulted by capillary action into very tiny cracks. Following to freezing cycles, water may end to crack propagation and so in long-time it generates widespread damage in concrete.

Degree of Saturation Effect

Degree of saturation (DOS) effect is a critical factor affects freeze-thaw damages. Li et al (Li, Pour, Castro, Weiss, 2012) showed that concrete samples with saturation degree above 88%, as illustrated in Fig.1, reveal evidences of damage in thaw cycles. This DOS appears to be independent from percentage of air. But, concrete, which reaches critical saturation degree or exceeds it, is damaged after some freeze-thaw cycles, regardless of the percentage of air.

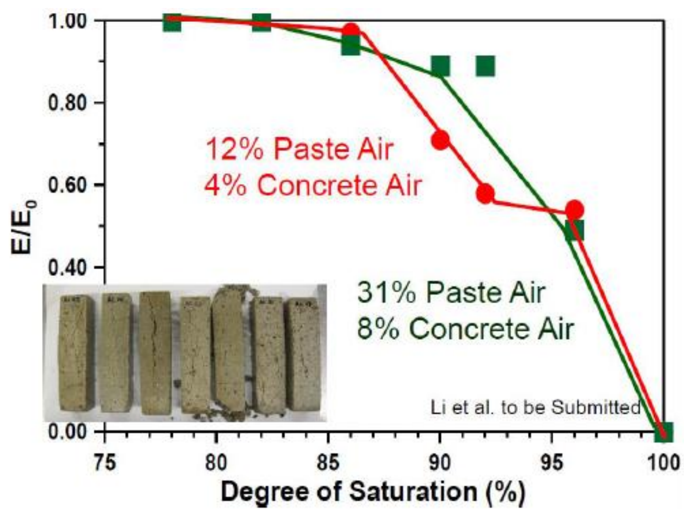

Figure 1: The relationship between degree of saturation and freeze-thaw duration (Li *et al.*, 2012)

The air system is available in concrete, causes delay in reaching concrete the critical DOS. A concrete structure without air system may reach critical DOS within 4-6 days, while as Fig.2 shows, in concrete with huge air percentage, the time to reach DOS could take 3 -6 years.

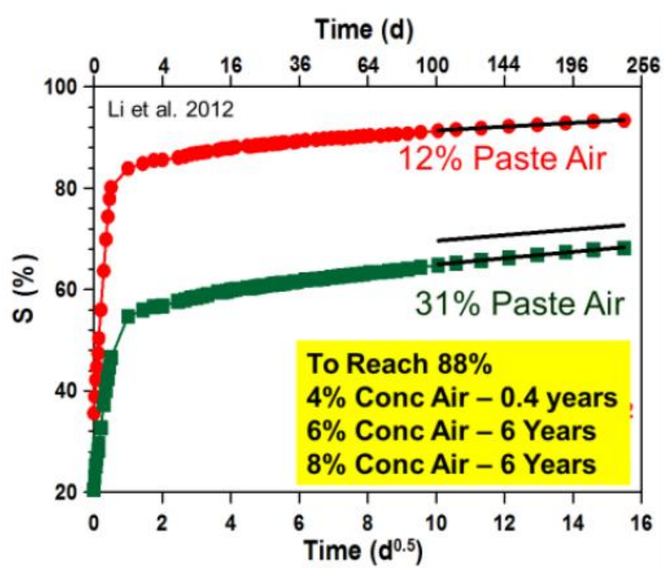

Figure 2: The required time for reaching critical saturation degree for concrete with different air percentage (Li *et al.*, 2012)

The Distance Factor Effect

Distance factor (L), is other parameter which influences concrete duration against freeze-thaw. In other words, L is the distance which water can flow from freezing point to the nearest filled space with adjacent air. Power (Pigeon, 1995) stated that L lower than 0.2 mm (0.008 inches) and specific surface 24 mm^2/mm^3 of air space is necessary for concrete in order to prevent from freeze-thaw damages. As shown in Fig.3, for a given amount of air, small spaces located in their proximity, indicate better protection compared with larger air spaces and located in distance away from each other (Klieger, 1952).

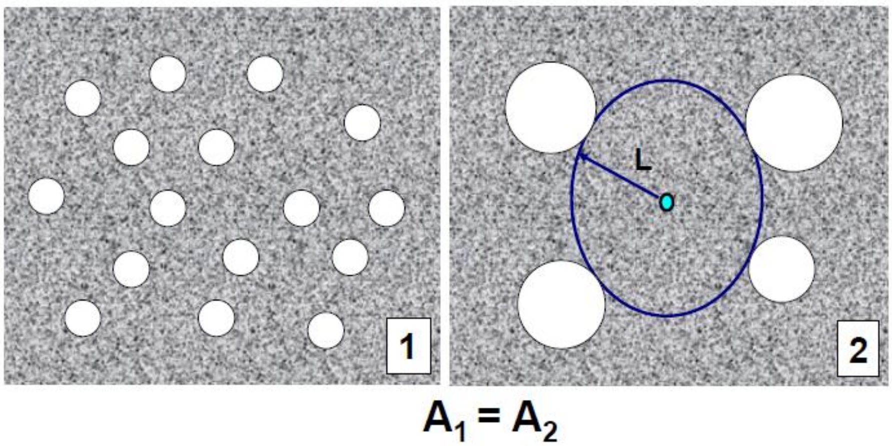

Figure 3: Total air with different distance factor (Klieger, 1952)

The Salt Scaling Effect

In cold climates areas, anti-icing salts are used over concrete roads in order to protect from pavement function in winter. This strategy therefore leads to scaling, which is one of the crucial phenomenons which concrete may face with in cold climates. This phenomenon is some type of progressive surface damage is created because of freezing an anti-freezing solution over the surface of a concrete object. Scaling might not cause damage in whole concrete system alone, but it can make concrete sustainable to moisture ingress and consequently affects its durability. In addition, scaling sometimes causes coarse aggregate are exposed to the open air and are prone to erosion (Valenza and Scherer, 2006).

Salt Crystallization

Salt crystallization is another mechanism, which gives rise to concrete scaling. A supersaturated solution has higher potential energy compared with a corresponding saturated solution. The additional potential energy can be employed for working against an external inhibitory pressure, when the solute is crystallized outside its supersaturated solvent. Saturation is necessary for crystallization to happen and without it, is impossible. Crystals which are growing under supersaturating conditions can generate the required pressure for paste mass rupture in limited space inside concrete (Thaulow and Sahu, 2004). Corns (Correns, 1949) have offered an equation similar to 1, for computation of crystallization pressure.

$$P = \frac{\mathrm{R.T}}{\mathrm{V_s}} \times \ln\frac{C}{C_s} \quad (1)$$

Where,
P = crystallization pressure,
R = gas constant (0.082 L-atm/mol K),
T = absolute temperature in K,
V_s = molar volume of solid salt in L/mole,
C/C_s = the degree of supersaturation, and C is the existing solute concentration and C_s is the saturation concentration.

The generated crystallization pressure from supersaturated anti-freeze salts is about 16 MPa during the temperature drop, which is 5 to 10 times of concrete tensile strength (Thaulow, Sahu, 2004).

MATERIALS AND METHODS

Method

We conducted the present test on concrete produced in concrete plant. River sand with the size of 0-2 mm and natural sand with 8 mm diameter in maximum were used in the composition. Table 1 illustrates the properties and composition of concrete. The samples of freeze-thaw tests were performed under ASTM (UNE-CEN/TS 12390-9 EX) standard. Also, the samples were undertaken curing process in identical conditions and in the open air. The temperature changes during the test are shown in Fig.4.

Table 1: Composition and concrete properties

Mix Proportions	
Fine Aggregate (kg/m^3)	620.8
Coarse Aggregate (kg/m^3)	1146.7
Cement (kg/m^3)	450
Water (kg/m^3)	180
w/c ratio	0.4
Properties of Concrete	
Slump (cm)	9
Air Content (%)	7.5

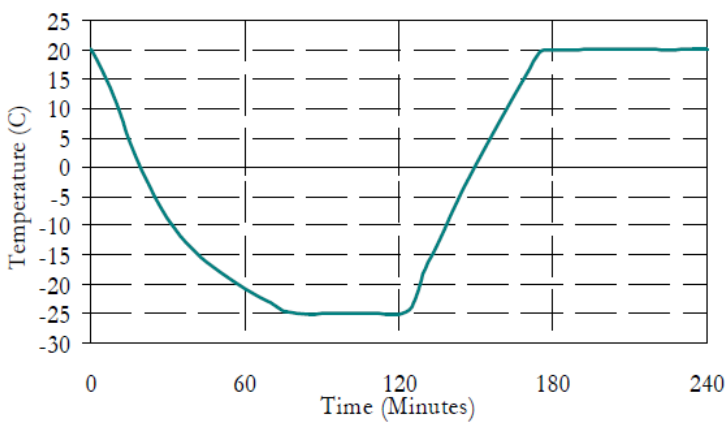

Figure 4: Temperature changes of samples during the test

The prepared samples received different freeze-thaw processes in different cycles. Then, we performed tests of compressive, tensile and flexural strength in order to measure the impact of freeze-thaw cycles on strength properties of concrete. Table 2 represents the test age, size of samples, and properties of the test and Figure 5 shows the test machine for freeze-thaw test.

Table 2: Properties of samples test

Properties	**Size of samples(inches)**	**Test age**	**Test**
AASHTO T22 (2007)	Cylinder 4× 8	28	Compressive strength
AASHTO T198 (2009)	Cylinder 4× 8	28	Rupture tensile strength
AASHTO T97 (2003)	Bar 6 × 6 × 21	28	Flexural strength
ASTM C469 (2010)	Cylinder 6 × 12	28	Young's modulus

Figure 5: Freeze-thaw machine

RESULTS AND DISCUSSION

Findings

Compressive Strength

The first step in testing concrete is the test of compressive strength since concrete is basically used for resistance against compressive stress. Table 2 illustrates the prepared cylindrical samples with specified sizes. After, curing and drying processes, the samples were put beneath loading jack of compressive strength testing machine with 2000 KN capacity. At time of rupture, the maximum imposed load on the samples was recorded. Then, we computed, the compressive strength of the samples using Equation 2. Table 3 and Figure 6 show the results.

$$\sigma_c = \frac{P}{\pi r^2} \tag{2}$$

Where, P is the maximum load on the sample, and r is the radius of the cylindrical sample.

Table 3: Average compressive strength of the samples in different freezing and thaw cycles

Average compressive strength in terms of MPa	Freezing ad thaw	Sample size
6.35	0	1
34.4	10	2
31.2	20	3
29.7	´30	4
28.6	40	5
25.9	50	6
22.3	60	7
21.7	70	8
20.5	80	9
19.8	90	10
18.1	100	11

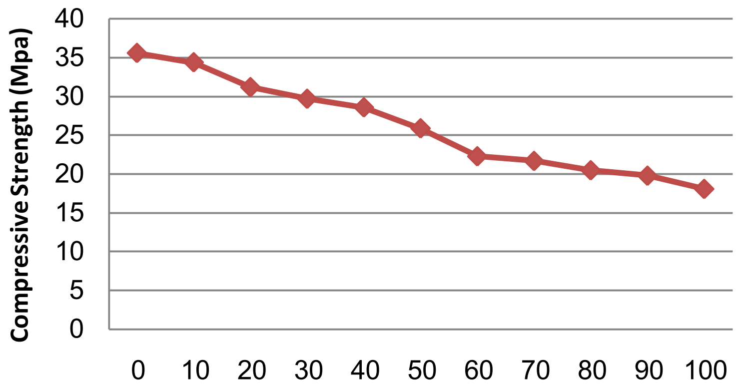

Figure 6: Compressive strength changes of concrete samples in association to freezing ad thaw cycles

Tensile Strength

We measured the tensile strength of samples at the age 28 of days indirectly. Here, linear time pressure was applied along the cylinder diameter. To compute tensile strength, we used Equation 3, in which P= the maximum load induced over the sample at time of rupture, D= cylindrical sample diameter and L= the cylindrical sample length. Table 4 and Figure 7 show the results.

$$\sigma_{sp} = \frac{2P}{\pi LD} \tag{3}$$

Table 4: Average tensile strength of samples in different freeze-thaw cycles

Average tensile strength in terms of MPa	Freeze-thaw cycle	Sample No.
4.56	0	1
4.64	10	2
4.32	20	3
4.12	30	4
3.88	40	5
3.64	50	6
3.31	60	7
3.18	70	8
3.11	80	9
2.98	90	10
2.76	100	11

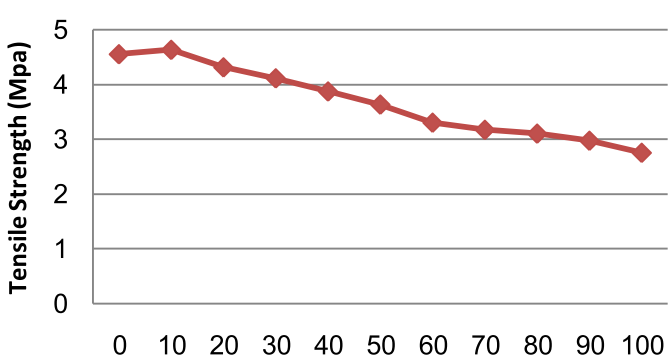

Figure 7: Tensile strength changes of concrete samples versus freeze-thaw cycles

Flexural Strength

Flexural strength testing is important because its results can be used to compute the load under which concrete elements are cracked. We performed the flexural strength test through three-point shot method. In this method, by measuring the maximum induced load at time of rupture (P), span length (L= 18 in), sample height (h= 6 in) and samples thickness (b=6in) were computed via Equation 4 of tensile strength. Table 5 and Figure 8 represent the results.

$$\sigma_r=\frac{3PL}{2bh^2} \tag{4}$$

Table 5: Flexural strength of samples in different freeze-thaw cycles

flexural strength of samples in terms of MPa (curing process in immersion under water)	Flexural strength of samples in terms of MPa (curing process in the open air)	Freeze-thaw cycles	Sample No.
12.5	11.8	0	1
11.6	10.6	10	2
10.8	10.2	20	3
10.3	9.3	30	4
9.1	8.7	40	5
8.3	7.5	50	6
7.7	6.8	60	7
6.5	5.9	70	8
5.8	5.2	80	9
4.9	4.4	90	10
4.2	3.8	100	11

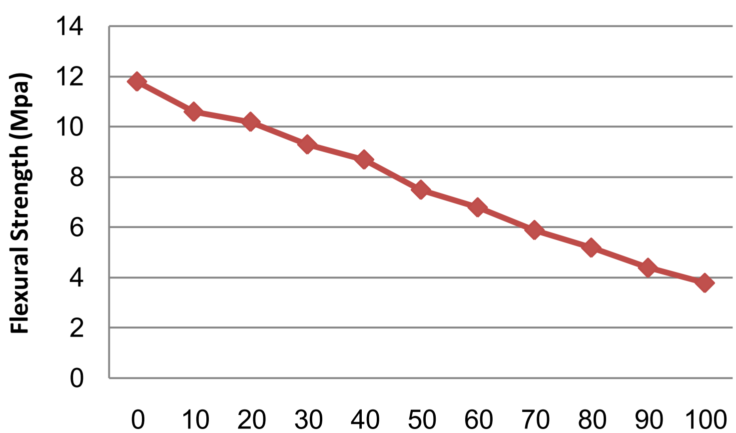

Figure 8: Flexural strength changes of concrete samples versus freeze-thaw cycles

Conclusion

In the present study we investigated freeze-thaw cycles and their impact on compressive, tensile and flexural strength of concrete are exposed to cold climates in order to measure the effect of these factors on the field performance of concrete pavements. In this regard, we tested samples of different sizes and under identical curing processes collected from concrete plant in different freeze-thaw cycles. The results could be of a great help in designing and implementation of concrete pavements located in cold climates as follows:

1. Freeze-thaw cycles have negative effects on compressive, tensile and flexural strength of concrete samples. In a way that, after the 100th repetition cycle the highest negative impact was observed.

2. The highest rate of reduced strength created by freeze-thaw cycles belongs to flexural strength of the samples. We observed that the rate of this decrease after the 100th repetition cycle reaches one third of the initial strength.
3. With regard to the significant effect of freeze-thaw cycles on concrete flexural strength, we carried out the test in two curing modes, a) air curing and b) immersion curing under water in order to measure the impact of curing on the samples strength. The results show that according to Figure 9, curing conditions have an outstanding impact on the samples flexural strength. That is, in all freeze-thaw cycles repetitions, in air curing conditions, we identified the minimum flexural strength compared with immersion curing under water.

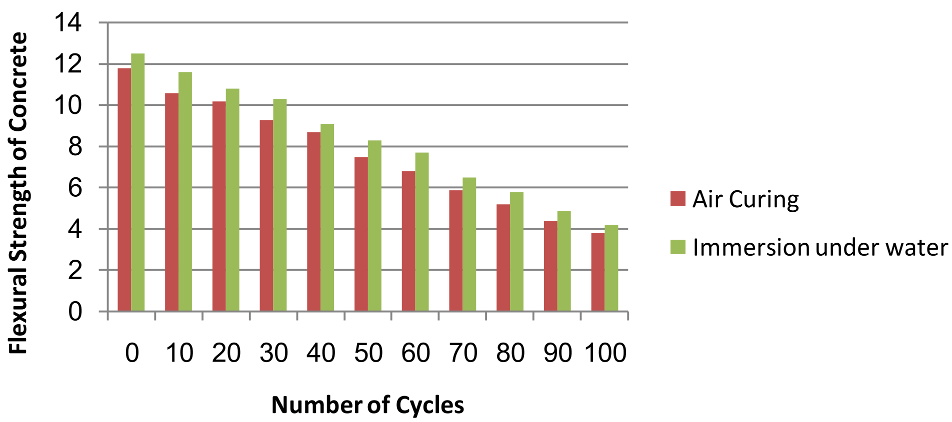

Figure 9: Comparing the impact of samples curing processes on flexural strength of concrete in different freeze-thaw cycles

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