The Effects of Concrete Pavement Mix Design Parameters on Durability under Freeze and Thaw Condition

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Abstract

This paper is based on an experimental research that examined the effects of concrete`s major parameters on durability of concrete pavements and curbs under freeze - thaw cycles. These parameters include concrete mix design parameters such as water-cement ratio, fine aggregate percentage and using air entraining admixture and simulating real freeze-thaw cycles that infrastructures undergo by considering deicing salt and water flow. Four types of concrete samples were prepared and submerged in four different freeze-thaw conditions. Their weight and compressive strength were measured and the results were analyzed. Based on results, regression analysis was used and two linear models were developed to predict the weight loss and compressive strength loss of concrete under freeze-thaw cycles. The results indicated that fine aggregate percentage is a key factor in durability of concrete, and concrete samples with 6% air underwent less deterioration in comparison to concrete with lower water-cement ratio. In addition, water flow increases the deterioration of concrete under freeze-thaw cycles specially when deicing salt is present.

Keywords: Concrete pavements, freeze-thaw cycles, water-cement ratio, fine aggregate percentage. air entraining admixtu

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1. Introduction

Roads and bridges are some of the most important and most expensive assets in which large amount of money is spent each year for maintaining and repairing these assets. Constructing concrete pavements with a long service life has always been an interesting subject for engineers, but there are so many different parameters that affect the concrete service life.

Generally, these parameters can be divided into two categories including mix design parameters such as water-cement ratio, fine aggregate percentage and using air entrainment admixture, and environmental parameters such as water flow and deicing salt or chemicals. Several freeze-thaw cycles occur in cold regions and result in sever deterioration of the infrastructures. In some cities such as Calgary in the Province of Alberta, Canada approximately 300 freeze-thaw cycles occur per year [Alberta Municipal Affairs, 2008] and therefore detailed evaluation of mix design under precise simulation of freeze-thaw cycles is critical.

Water or salt solution frost in concrete pores can cause severe deterioration and considerable reduction of service life. Plain water freezes at 0 ºC under normal atmospheric pressure and when water freezes a 9% increase in volume occurs as water turns to ice and causes hydraulic pressure within the pores of the concrete. However, water that is trapped within the capillary pores of concrete does not necessarily freeze at 0 ºC. The temperature at which water freezes in capillary pores is a function of the size of the pores and pore chemistry. As pore size decreases, the temperature required to freeze the water also decreases [Hale et al, 2009]. The hydraulic pressure within the concrete pores causes damage to the concrete. When this pressure exceeds the tensile strength of the concrete, damage will occur. A second mechanism is the formation of ice lenses. Differences in vapour pressure between the ice in the larger pores and the water in the smaller pores, causes the water to flow to the ice where it will freeze immediately. Because of volume differences between ice and water, the freezing water pushes the rest of the water and the first mechanism will occur. The third mechanism involves osmotic pressure. The materials present in the pore water, like lime and salt, influence the freezing point. Because of the fact that these materials will not be part of the ice, the concentration near the ice will gradually rise as ice is formed. The difference in concentration with the rest of the pore water will cause water to flow towards the ice (osmoses). Because the concentration is lowered, this water will freeze. The rest of the water is pushed and causes pressure. There are three main types of deterioration:

- Expansion, followed by internal cracking and or spalling. This is the kind of damage that is found when a large volume of the concrete is saturated with water, the same as concrete pavements.
- Scaling: application of salt. This is the kind of damage that is found when only a surface layer is saturated and or when de-icing salts are used. Because of the wide usage of deicing salt this kind of deterioration happens in concrete pavements.
- Pop-outs: This kind of damage is found when certain types of aggregates are used. The most common cause is stress resulting from freeze-thaw action within the coarse aggregate particle, whereby the stress is relieved through cracking of the particle and simultaneous bursting of the concrete between the particle and the nearest concrete face [Kaufmann 2004, Harrison and Dewar 2001, and European Union 2000].

Generally the flow of ground water is present in the vicinity of concrete structures due to rain and snow melt and this makes concrete saturated and more vulnerable to freeze-thaw cycles in cold regions. The flow of water can slow the process of ice formation and can have adverse effects on the durability of concrete under freeze-thaw cycles. Furthermore, because of the wide usage of deicing salt for melting ice on the roads, salt is mostly available near pavements, curbs and other parts of the roads or concrete structures. Each year around 5 million tons of deicing salt is used in Canada to provide safe and reliable access during winter in Canadian roads while the corresponding amount in United States is around 15 million ton [Salt Institute, 2014]. Deicers deteriorate the concrete by physical deterioration of surface by salt scaling, chemical reactions between concrete and deicers and aggravating aggregate-cement reactions [Shi and Fay, 2010].

Deicing chemicals create pressure through osmosis and crystallization and increase the degree of concrete saturation and keep concrete pores at or near maximum fluid saturation and increase the risk of frost damage [Litvan, 1976]. The salt in deicing solution also decreases the freezing point of concrete pore solution, leading to significant hydraulic pressure [Setzer, 1976]. Because the salt concentration varies with the distance from the exposed concrete surfaces, various amount of ice may form in different layers under the concrete surface resulting in deformation of the layers and generation of pressure between the layers. Freezing of an upper layer, such as the surface layer which often occurs at a low deicing chemical concentration, may prohibit escape of the super-cooled liquids from the internal layers, thus developing considerable hydraulic pressure [Harnick et al, 1980]. Aggravated damage may also be attributed to chemical interactions between deicing chemicals and concrete materials. Chemical deterioration of the concrete may result from leaching and decomposition of cement hydration products [Wang et al, 2006].

It is now widely accepted that a low water–cement ratio and good curing, which are normally considered as important factors in achieving durable concrete, are insufficient in aggressive environments. This includes highway infrastructures where there are freeze–thaw cycles and the action of chloride as de-icing salt. Air entrainment agents are widely used to improve the durability of concrete infrastructures in freezing and thawing environments [Basheer and Cleland, 2006].

There are several different studies about concrete durability under freeze-thaw cycles. Basheer and Cleland [Basheer and Cleland, 2006] studied the freeze-thaw resistance of concretes treated with pore liners. Parsad studied the behavior of concrete in freeze-thaw environment of sea water in 2003. Penttala [2006] studied the surface and internal deterioration of concrete due to saline and non-saline freeze-thaw loads. Du and Folliard [2005] studied the mechanisms of air entrainment in concrete. Cho [2007] studied the prediction of cyclic freeze–thaw damage in concrete structures based on response surface method (RSM). Shang and Song [2006] studied the strength and deformation of plain concrete under biaxial compression after freezing and thawing cycles. Shi and Fay [2010] evaluated the freeze-thaw damage and chemical change of Portland cement concrete in the presence of diluted deicers.

As briefly mentioned, there are several studies about the effects of freeze-thaw cycles on concrete durability and the ice formation process, but there is no study that examines the importance of different mix design parameters under freeze-thaw cycles with the simulation of water flow and presence of deicing salt during the cycles. Therefore, this paper simulates the real environmental condition by considering water flow to make the laboratory results much more in line with freeze-thaw cycles in field and evaluates the effects of mix design factors on durability. It is anticipated that this study will provide useful information for a better understanding of the real damaging effects of freeze-thaw conditions and the positive effects of concrete mix design parameters.

2. Experimental Design

This section of the paper explains the preparation of the concrete samples and performing the freeze-thaw cycles.

2.1 Mix Design and Sample Preparation

The concrete samples were prepared according to ACI211.3R [American Concrete Institute, 2002]. Coarse aggregates were crushed stones (diameter ranging from 5 mm to 20 mm) and fine aggregates were natural river sand (fineness modulus of 2.6). Four types of concrete were prepared with water-cement ratio of 0.4 and 0.45 and fine aggregate percentage of 0.35 and 0.45. Also air entraining admixture was used in two concrete types. Table 1 shows the major characteristics of the mixtures. These ingredients were mixed for about 1 minute and then water was added. Finally, the ingredients were mixed for about 2–3 min. Beams were cast in three approximately equal layers. Each layer was vibrated using a vibrating table. The vibration was carried out until the bubbles stopped coming to the top. Lower water-cement ratio concrete samples were vibrated longer. For each concrete type, three beams with the dimensions of 70×10×10 cm were cast. All concrete samples were submerged in plain water and cured for 28 days. Because of the space limitations, 35 cores were drilled out of each concrete sample with the diameter of 5 cm. Finally, 128 cylindrical samples with the dimensions of 5×10 cm were placed in four different freeze-thaw exposure conditions. In each exposure condition 32 samples were submerged. After each 7 cycles, weight changes of all the samples were measured. Also, for measuring the compressive strength loss, two samples of each concrete type were tested after each 7 cycles.

2.2 Freeze-Thaw Cycles

In order to simulate the real freeze-thaw conditions that occur in the vicinity of concrete pavements and curbs, water flow and deicing salt were considered in this study. Water flow is mostly available after rainfalls or snow melting and deicing salt is commonly used for melting the ice and snow. Therefore, four exposure conditions were designed including flowing plain water, still plain water, flowing salt water, and still salt water. Water flow was produced by an electromotor with a propeller. The electromotor rotated 2.4 times per second providing slow water flow (0.2 m/s). The electromotor was running continuously during the freezing part of the freeze-thaw cycles. Also 3% sodium chloride solution was used to simulate the presence of deicing. The still salt water and flowing salt water containers were all water solutions containing this amount of salt.

The samples were submerged in each freeze-thaw exposure condition. The freeze-thaw chamber was planned to provide varying temperature ranging from +4.4 ºC to -17.8 ºC. Typical cycles were designed in a way to simulate the real freeze-thaw conditions considering that freezing usually start in the evening and continue until the next morning and thawing starts in the next morning and continue during the day. The test procedure was accomplished in accordance to ASTM C666 [ASTM C666, 2008]. A total of 28 freeze-thaw cycles were performed in this research. Weight and compressive strength of the samples were measured before, during and after the tests.

3. Experimental Results and Analysis

3.1 Deterioration Monitoring

Monitoring the deterioration of the concrete was performed after each cycle. Monitoring still plain water and flowing plain water showed that the most important deterioration in plain water is cracking and the depth and number of concrete cracks are significantly more when the water flow is present in the freeze-thaw chamber.

Table 1. Major parameters of concrete samples

Concrete Type	Water-Cement Ratio	Air Entrainment	Fine Aggregate Percentage
A	0.4	-	0.35
B	0.45	6%	0.35
C	0.4	-	0.45
D	0.45	6%	0.45

In still plain water, the water surface freezes when the temperature reaches 0 ºC, and gradually the depth of ice increases, but in flowing plain water, the water flow does not allow ice formation at 0 ºC. In locations in the chamber which the water flow is at the lowest level, small ice particles form. Gradually, the ice formation continues forward to the highest water flow area. Finally, the ice stops the electromotor and a thin layer of ice forms on the surface and the depth of this layer increases as the freezing cycles continue.

Freezing is mostly initiated from the pre-existing ice and ice front penetrates the pore system. The water in concrete pores freezes when the pore is connected to the surface through pores in which the pore solution freezes at a higher temperature than the actual one [Kaufmann, 2004]. As a result, because of late formation of ice in the presence of water flow, the freezing temperature of water in the pores decreases and the hydrostatic pressure is increased significantly inside the concrete. Therefore, concrete deterioration process becomes faster and more severe by the presence of water flow in freezing and thawing cycles. According to the temperature measurements in the freezing chamber, water flow decreases the freezing temperature of the outer water layer about 1.1 ºC in plain water and about 1.9 ºC in salt water.

The comparison of freezing-thawing cycles in flowing salt water and other freeze-thaw conditions showed that erosion and deterioration of concrete is much more severe in this situation, and many of the samples were destroyed completely during the cycles. Water flow and deicing salt have negative effects on the concrete strength and durability. The presence of water flow and deicing salt together, decreased the freezing temperature of the outer water layer of concretes about 5.3 ºC in comparison to still plain water and resulted in great hydrostatic pressure. As a result, the number and depth of cracking and crumbling increased significantly. Due to physical deteriorations, concrete became more permeable and more vulnerable to ingress of deicing salt, so deterioration of concrete was provoked. The water flow and rotation of salt water around the samples, increased the speed and the rate of chemical reactions significantly which resulted in faster deterioration. Figure 1 shows the condition of the specimens after 28 freeze-thaw cycles in still salt water condition.

Chemical analysis of the remained water in each type of freeze-thaw condition showed that salt increases the pH of water significantly, and especially in flowing salt water the maximum pH of water was 11.76. Furthermore, So4 ion was about 200 ppm in both still and flowing salt water and about zero in plain water. Also, the Cl ion was approximately 21000 ppm in flowing salt water, 19400 ppm in still salt water and 3000 ppm in plain water. Analysis of water showed that great chemical reactions occurred between deicing salt and concrete materials. White blubber on the water, calcium hydroxide sediment and severe deterioration of concrete samples were the results of severe chemical reactions.

3.2 Weight Loss Measurements

Weight loss of Saturated Surface Dry (SSD) samples was measured before and after each seven freeze-that cycles. Weight loss measurements were performed by placing the samples in a tub of tap water and removing loose particles gently by hand and drying the sample surface using a paper towel. Samples were rotated periodically to facilitate drying all faces and weighted after 20 minutes.

Figures 2, 3, 4 and 5 illustrate the weight change of type A, B, C and D concrete under different freeze-thaw conditions. As Figure 2 shows, type A concrete with water-cement ratio of 0.4 and fine aggregate percentage of 35% underwent 16% weight loss in still plain water after 28 freeze-thaw cycles while the relative percentages for flowing plain water, still salt water and flowing salt water were 26%, 77% and 100% respectively. Figure 3 shows the SSD weight of type B concrete which was prepared with water-cement ratio of 0.45, fine aggregate percentage of 35% and 6% air. Type B concrete remained intact during 28 freeze-thaw cycles in both still and flowing plain water conditions, while it lost 14.7% of its weight in still salt water during the last 7 cycles and 100% of its weight in flowing salt water condition during the first 14 cycles.

The comparison of type A and B concrete shows that using air entraining admixture even with higher water-cement ratio has great influence on durability of concrete under freeze-thaw cycles. Type A concrete underwent weight loss in all different freeze-thaw conditions, while type B with 6% air remained intact during freeze-thaw cycles in still plain water and flowing plain water, and the rate of its deterioration was considerably less than type A concrete.

Figure 1. The condition of different samples after 28 freeze-thaw cycles in still salt water

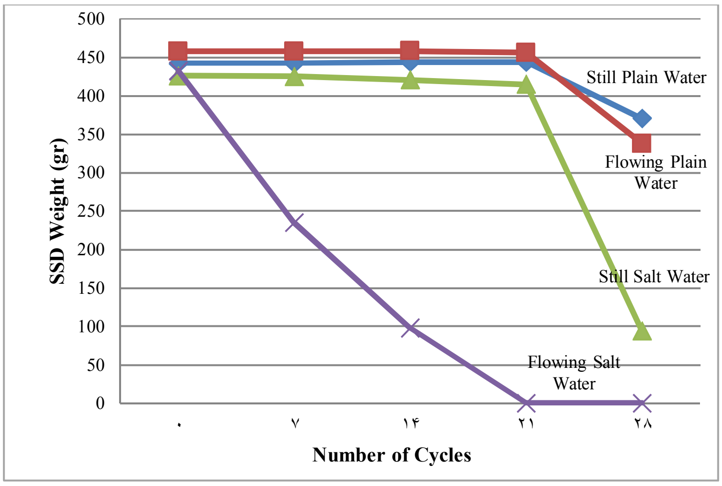

Figure 2. SSD weight of type A concrete under different freeze-thaw cycles

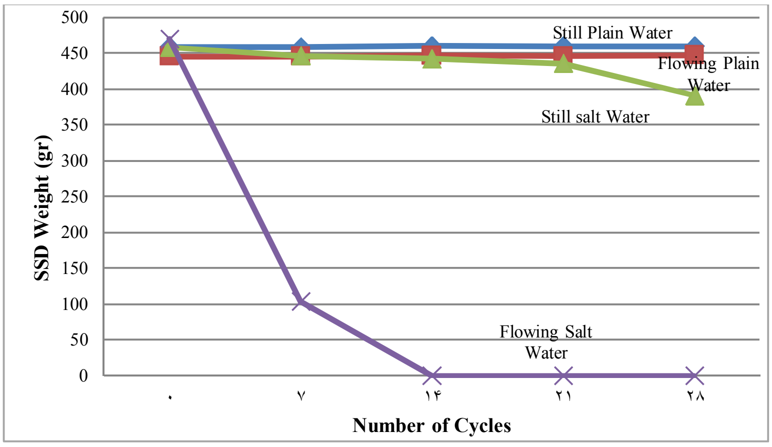

Figure 3. SSD weight of type B concrete under different freeze-thaw conditions

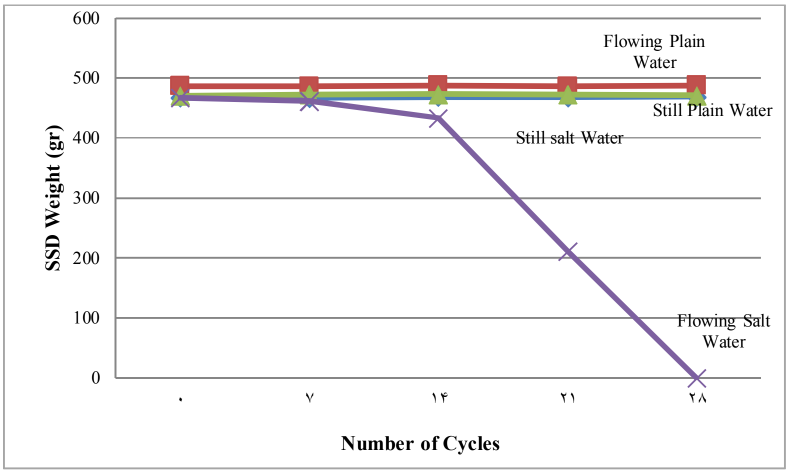

Figure 4. SSD weight of type C concrete under different freeze-thaw conditions

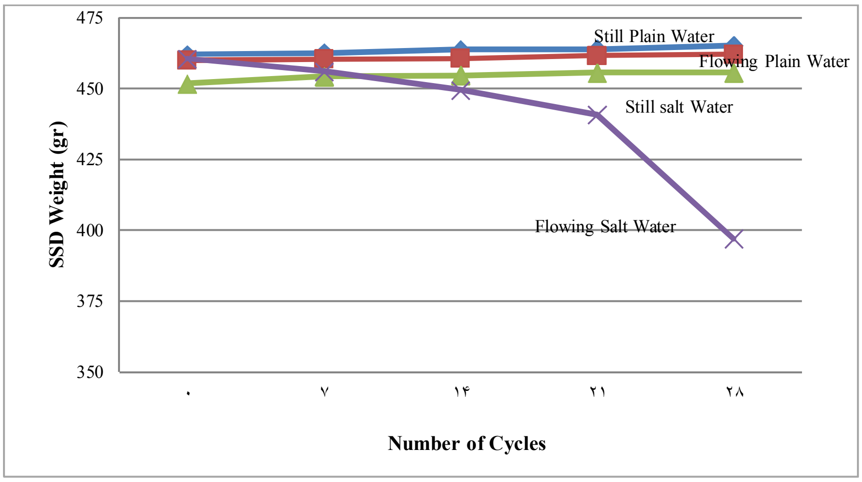

Figure 5. SSD weight of type D concrete under different freeze-thaw conditions

Type C and D concretes were prepared with fine aggregate percentage of 45%, but their water-cement ratio was the same as type A and B concretes. As Figure 3 shows, type C concrete with water-cement ratio of 0.4 remained intact after 28 cycles in still plain water, flowing plain water and still salt water while it was completely destroyed during 28 cycles in flowing salt water. As figure 5 shows, type D concrete remained intact in still plain water, flowing plain water and still salt water freeze-thaw conditions, while it lost 14% of its weight in flowing salt water cycles.

The comparison of types A and B with types C and D concrete samples showed that the percentage of fine aggregate has great influences on durability of concrete under freeze-thaw cycles. In addition, the results indicated that the effects of increasing the percentage of fine aggregate on durability of concrete under different freeze-thaw cycles were considerably more efficient than decreasing the water-cement ratio or using air entrainment admixture. Furthermore, the results showed that using air entraining admixture for increasing the durability of concrete was more efficient than decreasing the water-cement ratio. Furthermore, weight loss increased by the presence of water flow and the destructive effects were more significant when water flow and deicing salt were both present.

Statistical Analysis

As a preliminary statistical analysis, correlation analysis was performed using SPSS software package to evaluate the effects of water flow, deicing salt, number of cycles, fine aggregate percentage and pH of water on the concrete samples weight loss under freeze-thaw cycles and the results are illustrated in Table 2. Correlation coefficients resulting from the correlation analysis range from -1 to +1. Correlation coefficient with the value of zero represents no relationship between variables while correlation value of -1 shows a strong negative relationship and correlation coefficient of +1 represents a strong direct relation. The closer a correlation coefficient is to -1 or 1, the stronger is the relationship. The correlation coefficients between weight loss versus water-cement ratio, presence of deicing salt and presence of water flow were 0.446, 0.631 and 0.445 respectively showing a direct relationship between weight loss and these parameters. The correlation between weight loss and the number of cycles is 0.292 which shows the direct relationship between deterioration and the number of cycles. Based on the results, decreasing water-cement ratio decreases the concrete`s weight loss due to deterioration under freeze-thaw cycles. In addition, the effects of the number of freeze-thaw cycles is less than the presence of water flow or deicing salt and the effects of deicing salt are more destructive than water flow. The corresponding correlation coefficient between fine aggregate percentage and SSD weight loss was -0.426. This reverse relationship shows that increasing the percentage of fine aggregate in concretes mix design decreases the weight loss of concrete under freeze-thaw cycles significantly.

The correlation coefficient between weight loss and pH of water is 0.489 which shows that the pH of water is strongly related to the deterioration of concrete under freeze-thaw cycles, and it can be used for examining the severity of chemical reaction and deterioration of concrete. The correlation between deicing salt and presence of So4 ion is 0.997 and the relative coefficient for Cl ion is 0.995. This shows that by the presence of deicing salt, chemical reactions occur significantly.

In addition to correlation analysis, a regression model was developed to estimate any relationship between weight loss, W_{loss}, as the dependent variable and the affecting parameters as the independent variables.

Table 2. Correlation coefficients for weight loss

	Water-Cement Ratio	Fine Aggregate Percentage	Deicing Salt	Water Flow	Number of Cycles	pH of Water
Weight Loss	0.446	-0.426	0.631	0.445	0.292	0.489

The regression model with $R^2 = 0.627$, is as follows:

$$W_{loss} = 0.898(N) + 353.068(W) - 136.966(FA) + 21.058(F) + 31.570(S) - 13.433(A) - 115.185 \quad (1)$$

Where the dependent variable in the model is SSD weight loss which is a positive continuous variable and independent continuous variables are the number of cycles (N), water-cement ratio (W) and fine aggregate percentage (FA), and the discrete nominal variables are presence of deicing salt (S), the presence of water flow (F) and 6% air (A). Important parameters of the model are shown in Table 3. The comparison of the model coefficients and their Beta value shows that deicing salt has the most important effect on the deterioration. Water flow with Beta value of 0.305 is an important variable and among environmental factors the number of cycles has the least effect on the concretes weight loss. Among mix design variables water-cement ratio has the most important effect on concrete weight loss. The importance of the fine aggregate percentage in mix design is more than air entrainment in concrete durability under freeze-thaw cycles. This regression model was performed to find the relationship between variables not the prediction of the deterioration.

3.3 Compressive Strength Change

An important fact about concrete durability is maintaining compressive strength under freeze-thaw cycles during service life. Considerable decrease in compressive strength can result in serious problems in concrete bridges or pavements. Therefore, compressive strength changes of concrete samples undergone different freezing-thawing conditions were measured and the results are illustrated in Figure 6, 7, 8 and 9 respectively.

Compressive strength of type A concrete under 28 freeze-thaw cycles in still plain water, flowing plain water, still salt water and flowing salt water decreased by approximately 12%, 37%, 100% and 100% respectively. The corresponding percentages for type B concrete showed 4%, 10%, 43% decrease after 28 freeze-thaw cycles in still plain water, flowing plain water and still salt water respectively and 100% decrease during the first 14 cycles in flowing salt water. The compressive strength loss percentages for type C concrete were 11%, 13%, 20% and 100% in still plain water, flowing plain water, still salt water and flowing salt water respectively, while the corresponding v for type D concrete were 6%, 9%, 22% and 39% in still plain water, flowing plain water, still salt water and flowing salt water respectively. Based on the results, concrete compressive strength decreases during freeze-thaw cycles, but the percentage of compressive strength loss is strongly related to the freezing condition and the reduction was more severe when water flow or deicing salt were present in chamber and the highest reduction was in the chamber with water flow and deicing salt.

Table 3. Parameters of weight loss model

Parameter	Coefficients	Beta	t	Sig
Number of Cycles	0.898	0.252	3.811	0.000
Water Flow	21.058	0.305	4.609	0.000
Deicing Salt	31.570	0.457	6.909	0.000
$\frac{W}{C}$ Ratio	353.068	0.267	3.461	0.010
Air Entrainment	-13.433	-0.194	-2.506	0.013
Fine Aggregate Percentage	-136.966	-0.234	-3.309	0.001

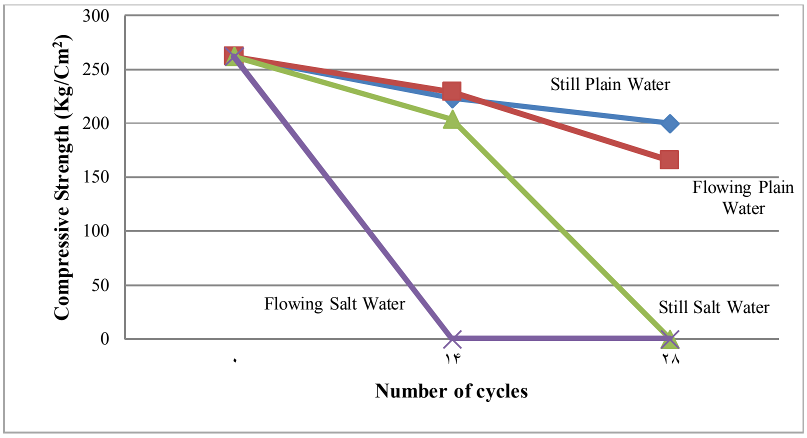

Figure 6. Compressive strength of type A concrete under different freeze-thaw cycles

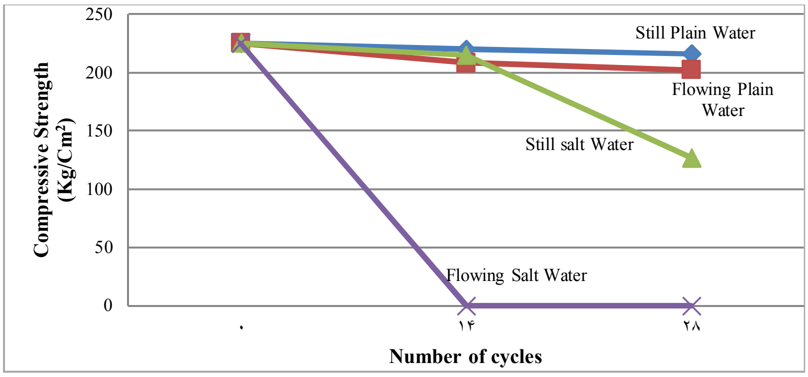

Figure 7. Compressive strength of type B concrete under different freeze-thaw conditions

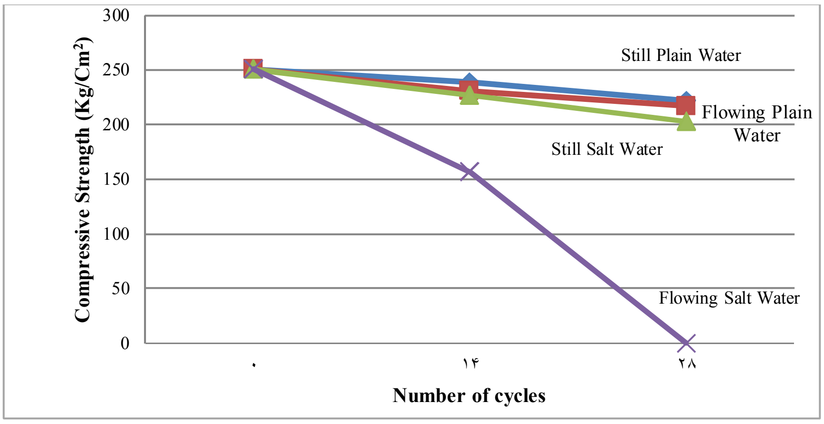

Figure 8. Compressive strength of type C concrete under different freeze-thaw conditions

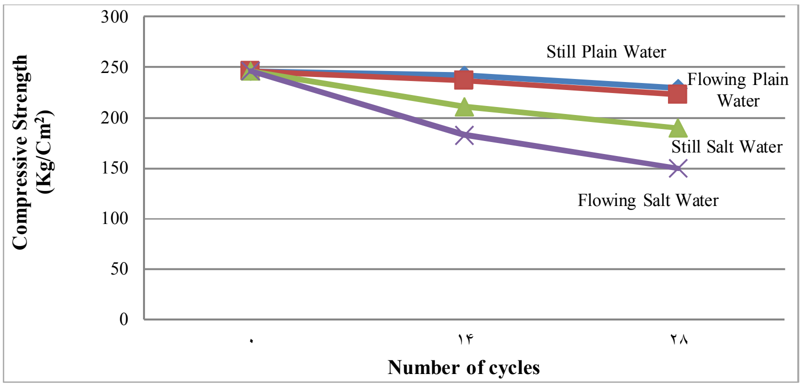

Figure 9. Compressive strength of type C concrete under different freeze-thaw conditions

The concrete mix design should was very important and samples with higher percentage of fine aggregate (45%) had better performance under different freeze-thaw cycles while type A and B concrete with 35% fine aggregate undergone more significant compressive strength loss under freeze-thaw cycles. In addition, the results showed that the effects of using air entraining admixture on durability of concrete is more efficient than decreasing the water-cement ratio from 0.45 to 0.4 and samples with 6% air underwent smaller compressive strength loss during freeze-thaw cycles.

Statistical Analysis

Correlation analysis was used to evaluate the effects of water flow, salt water, number of cycles, fine aggregate percentage and water-cement ratio on the concretes compressive strength loss under freeze-thaw cycles. Correlation coefficients of these parameters were computed and the results are illustrated in Table 4. The correlation coefficient between fine aggregate percentage and compressive strength loss was -0.352. This reverse relationship indicates that increasing the percentage of fine aggregate in concretes mix design, decreases the concretes compressive strength loss significantly.

The correlation coefficient between compressive strength loss versus water-cement ratio, presence of deicing salt, presence of water flow and number of cycles were 0.451, 0.375, 0.318 and 0.277 which show a direct relationship between compressive strength loss and these parameters.

Table 4. Correlation coefficients for compressive strength loss

	Water-Cement Ratio	Fine Aggregate Percentage	Deicing Salt	Water Flow	Number of Cycles
Compressive Strength Loss	0.451	-0.352	0.375	0.318	0.277

Based on the results, decreasing water-cement ratio decreases the concrete`s compressive strength loss under freeze-thaw cycles. In addition, the destructive effects of deicing salt are more than water flow on compressive strength loss.

In addition to correlation analysis, a regression model analysis was performed to find any relationship between compressive strength loss, CS_{loss}, as the dependent variable and the affecting variables as the independent variables. The regression model with $R^2 = 0.661$ is as equation (2).

Where the dependent variable in the model is compressive strength loss which is a positive continuous variable and the independent continuous variables are the number of cycles (N), water-cement ratio (W) and fine aggregate percentage (FA), and the discrete nominal variables are presence of deicing salt (S), the presence of water flow (F) and 6% air (A). Important parameters of the model are shown in Table 5. The comparison of the models coefficients and their Beta value shows that deicing salt has the most important effect on the compressive strength loss. Water flow with Beta value of 0.304 is an important variable and among environmental factors the number of cycles has the least effect on the concretes compressive strength loss. Among mix design variables, water-cement ratio has the most important influence on concretes weight loss and the influence of the fine aggregate percentage is more than air entrainment. This regression model was performed to more closely evaluate the relationship between parameters. Due to the limitations of the number of freeze-thaw cycles, more freeze-thaw cycles should be performed to develop a prediction model.

Table 5. Compressive strength loss model parameters

Parameter	Coefficients	Beta	t	Sig
Number of Cycles	1.032	0.256	3.713	0.000
Water Flow	25.206	0.304	4.427	0.000
Deicing Salt	40.344	0.488	7.088	0.000
W/C Ratio	496.106	0.302	3.839	0.000
Air Entrainment	-22.140	-0.262	-3.368	0.001
Fine Aggregate Percentage	-208.714	-0.285	-4.066	0.000

$$CS_{loss} = 1.032(N) + 496.106(W) - 208.714(FA) + 25.206(F) + 40.344(S) - 22.140(A) - 144.221 \quad (2)$$

4. Conclusions

The importance of a few mix design parameters such as water to cement ratio, air entrainment and fine aggregate percentage on durability of concrete under freeze-thaw cycles were evaluated by simulating real freeze-thaw condition by providing water flow and using deicing salt. This was one of the first studies that evaluated concrete durability while water flow was present during the freeze-thaw cycles. Most current studies only test samples in still water while in real world scenario water flows on the roads and bridges and this study tried to model this flow in the freeze-thaw chamber and filled the gap in the literature. Therefore the results of this study and the methodology used are believed to be more accurate. Different mix design parameters were tested towards the freeze-thaw related deteriorations and the effects of mix design parameter were compared. Based on the results, the following conclusions can be made:

- Among mix design variables, water-cement ratio has the most important influence on concrete durability and the influence of the fine aggregate percentage is more than air entrainment. Therefore concrete with low water-cement ratio and proper fine aggregate percentage and air entrainment could be very durable in severe frost condition.
- Deicing salt showed to have the most significant destructive effects on weight loss and compressive strength loss under freeze-thaw cycles.
- Destructive effects of water flow were less than the presence of deicing salt and more than the number of freeze-thaw cycles.
- The presence of water flow increases the deterioration of concrete under freeze-thaw cycles up to 2 times in comparison to still plain water because of decreasing the freezing temperature of concrete pores. The most important type of deterioration under freeze-thaw cycles in plain water is cracking and presence of water flow increases the number and depth of cracks.
- Considering the effects of freeze-thaw cycles in flowing salt water another important effect of water flow in freeze-thaw cycles is increasing the rate and speed of chemical reactions between deicing salt and concrete materials. By the increase of chemical reactions, deterioration of concrete is increased significantly. Combined effects of salt and water flow increases the deterioration of concrete under freeze-thaw cycles up to 8 times.

5. References

-Alberta Municipal Affairs, Government of Alberta "Building envelope survey. In partnership with the City of Calgary" Accessed online on September 2014 at http://municipalaffairs.gov.ab.ca/documents/ss/0630_BuildingEnvelopeReport-Apr08.pdf, 2008.

-American Concrete Institute (ACI) "Guide for selecting proportions for no-slump concrete, ACI 211.3R, ACI, Detroit, USA, 2002.

-American Society for Testing and Materials (ASTM), "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," ASTM C666, 2008.

-Basheer, L. and Cleland, D. J. (2006) "Freeze-thaw resistance of concrete treated with pore liners," Journal of Construction and Building Materials. Volume 20, Issue 10, 990–998.

-Cho, T. (2007) "Prediction of cyclic freeze–thaw damage in concrete structures based on response surface method," Journal of Construction and Building Materials. Volume 21, Issue 12, 2031–2040.

-Du, L. and Folliard, K. (2005) "Mechanisms of air entrainment in concrete," Journal of Cement and Concrete Research. Volume 35, Issue 8, 1463– 1471, 2005.

-European Union, Brite EuRam III (2000) "Chemical stability, wear resistance and freeze-thaw resistance of lightweight aggregate concrete," Document BE96-3942/R25. Document BE96-3942/R25, Project funded by the European Union under the Industrial and Materials Technologies Program (Brite-EuRam III) Contract BRPR-CT97-0381, Project BE96-3942.

-Harnick, A. B. Meier, V. and Rosli, A. (1980) "Combined influence of freezing and deicing salt on concrete: physical aspects," In: Sereda PJ, Litvan GG, editors. Durability of building materials and components. *ASTM STP* 691. p. 474–84.

-Hale, M., Freyne, S. and Russell, B. (2009) "Examining the frost resistance of high performance concrete," Journal of Construction and Building Materials. Volume 23, Issue 2, 878–888.

-Harrison, T. and Dewar, J. D. (2001) "Freeze-thaw resisting concrete, its achievement in the UK," London.

-Kaufmann, P. (2004) "Experimental identification of ice formation in small concrete pores," Journal of Cement and Concrete Research. Volume 34, Issue 8, 1421–1427.

-Litvan, G. G. (1976) "Frost action in cement in the presence of deicers," Journal of Cement and Concrete Research. Volume 6, Issue 3, 351–356.

-Prasad, A. M. (2003) "Behavior of concrete in freeze-thaw environment of sea water", IE(I) Journal CV.

-Penttala, V. (2006) "Surface and internal deterioration of concrete due to saline and non-saline freeze-thaw loads", Journal of Cement and Concrete Research. Volume 36, Issue 5, 921 – 928.

-Salt Institute (2014) "Deicing salt and corrosion", http://www.saltinstitute.org/th2020s.html.

-Shi, X. and Fay, L. (2010) "Freeze–thaw damage and chemical change of a Portland cement concrete in the presence of diluted deicers," Journal of Materials and Structures, Volume 43, Issue 7, pp.933-946.

-Setzer, M. J. (1976) "Action of frost and deicing chemicals". Basic phenomena and testing. In: Marchand J, Pigeon M, Zetzer M, editors. Freeze–thaw durability of concrete. London: E and FN Spon. p. 3–21.

-Shang, H. S., and Song, Y. P. (2006) "Experimental study of strength and deformation of plain concrete under biaxial compression after freezing and thawing cycles," Journal of Cement and Concrete Research. Volume 36, Issue 10, pp.1857–1864.

-Wang, K., Nelsen, D. and Nixon, W. (2006) "Damaging effects of deicing chemicals on concrete materials," Journal of Cement and Concrete Composites. Volume 28, Issue 2, pp.173–188.