Evaluation of the Effects of Deicer Chemical Methodologies on Pervious Concrete & Development of a Deicer Chemical Testing Method for Pervious Concrete

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FINAL REPORT

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EXECUTIVE SUMMARY

This research was based on the premise that chemical changes might be a significant factor in degradation of pervious concrete due to calcium chloride or magnesium chloride deicer applications. The hypotheses are based on complexation and precipitation chemistry. The results indicate that compared to water or sodium chloride controls the following occurs. Specimens subjected to calcium chloride deicer applications show a visible degradation. Specimens exposed to magnesium chloride deicer applications show a large increase in loss of calcium ions. For both deicers, these effects were only evident after many, many weeks of deicer applications which allowed for the deicer solutions to concentrate within the specimens and the chemical reactions to slowly occur. There was only gravity dripping and ambient drying of the specimens, with no flushing of the chemicals. The changes were greater under ambient laboratory conditions than in a cold room, and the negative effects were typically increased with specimens that were freshly molded (little surface carbonation). There was no conclusive evidence as to the benefit of using some fly ash substitution for ordinary Portland cement (OPC) in the mixes.

This research has resulted in the outline of a testing method that might be used to compare various mix designs and treatments to pervious concrete that are intended to reduce possible negative impacts of these deicing chemicals. The suggested procedure uses control and test specimens that receive weekly applications of the subject deicing chemicals under ambient laboratory conditions for a period of approximately four months. Ancillary testing includes recording volumes and masses of influent and effluent samples, and masses of the specimens for testing of either of these deicers. The testing protocol for the magnesium chloride also includes chemical analyses of the influent and effluent samples for calcium ion concentrations. An ancillary abrasion test on a subset of the specimens after treatment did not prove effective, most likely due to variations in porosity between and within specimens, and its impact on resistance to abrasion. It is suggested that further research be conducted to determine if and how much the changes that are evident from this suggested testing protocol affect other properties of pervious concrete such as strength or freeze-thaw resistance.

1. INTRODUCTION

1.1. Background

There is strong evidence that certain deicing chemicals and salts can negatively affect pervious concrete and initiate a rapid degradation of the paste matrix, aggregate bonding, pavement durability and strength. The main deicing chemicals of concern that will be the focus of this study are magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$). They have in many instances replaced rock salt (sodium chloride or NaCl) over the last decades. There are other deicing chemicals that are used on pavements, particularly at special locations such as airports. Some of these include CMA (calcium magnesium acetate) and sodium acetate. However, these have not been extensively used on pervious concrete placements and will not be included at this time. Note that the proposal initially focused on magnesium chloride, but due to the extensive use of calcium chloride and deleterious impacts that the initial literature review indicated in some cases on traditional pavements, this deicer will also be included. In addition, this proposal is related to chemical attack on the concrete, not physical freeze-thaw action, which has been extensively studied by others on traditional concrete pavements and by some on pervious concrete. The research objectives were summarized in the proposal as follows:

A: Based on previous studies, input from the industry and past laboratory trials and field studies, the issue will be better identified. Currently, it is hypothesized that 'complexation' with the magnesium ion from magnesium chloride as preferred to the calcium ion, and subsequent precipitation of magnesium hydroxide are the major issues. This might cause deterioration by both leaching the calcium from the paste matrix, and also by adding solids and associated stresses in the pores.

B: It is then proposed to develop a standardized laboratory procedure to evaluate the impact of various deicing methodologies on pervious concrete. The procedure would:

1: Set a standard laboratory specimen size.
2: Establish a range of 'loading' the specimen with various deicers applicable to the field methods.
3: Investigate a series of temperature related scenarios.
4: Make suggestions for a series of tests that could evaluate field performance e.g. possibly compression test, freeze-thaw test, etc.

This report covers the results from the research working towards these two overall objectives. The following sections contain an updated literature review (Haselbach 2015), followed by a summary of the initial hypotheses made. Chapter 2 summarizes the testing protocols developed. Chapter 3 provides an overview of the testing results. Chapter 4 provides more details on the $CaCl_2$ results and outlines a suggested testing procedure. Chapter 5 provides more details on the $MgCl_2$ results. Chapter 6 includes additional chemical and physical testing performed, summarizes the work and outlines possible future work. These chapters are followed by several appendices. Appendix A has some additional details on the specimens tested. Appendix B contains summary sheets of the physical data collected. Appendix C provides summaries of much of the additional chemical data collected.

1.2. Updated Literature Review

Traditional Concrete Surfaces

A study by Copuroglu and Schlangen (2007), explored the idea that some of the surface spalling of concretes under cold conditions is from the ice shrinking as it cools and promoting tensile stresses in the upper layer of the concrete, called the glue-spall theory. In addition, others have concluded that there can be scaling in concrete from freeze-thaw action without the use of deicers. Fabbri et al. (2008) performed studies showing that ice formation in the saturated porous media can cause damage. However, much of the damage to traditional concrete surfaces has been shown to be correlated with deicer use as some of the following studies indicate.

A study by Farnam et al. (2014) focused on the mechanisms of surface deterioration under freeze-thaw conditions from concrete pavements in conjunction with the use of NaCl as a deicer. It was shown that, with specimens saturated with highly concentrated NaCl solutions, the damage is worse than with less concentrated solutions. There was much discussion on the possible mechanisms from water transfer in pores through gradients, to crystal formation.

Jain et al. (2011) studied the impacts of $CaCl_2$, $MgCl_2$ and several other deicers on concrete pavements and joints. One part of the study on pavements evaluated specimens that were wetted with a deicer solution and then allowed to dry for many cycles. They were wetted at 4ºC and dried at 23ºC. The specimens exposed to very concentrated (28% by mass) $CaCl_2$ deicer exhibited more mass loss and visual surface spalling more quickly than the specimens exposed to the concentrated (25%) $MgCl_2$ solution. Those in the $MgCl_2$ solution maintained a higher relative dynamic modulus of elasticity as measured through resonance for a longer number of cycles than the $CaCl_2$ specimens, but when tested for compressive strength had a lower compressive strength at the end of the wetting/drying cycles (although the specimens in the calcium-based deicer had many fewer cycles). If the pavements were made with 20% fly ash replacement then little mass loss was experienced for either deicer.

The second part of the Jain et al. (2011) study on the pavements evaluated specimens exposed to freeze-thaw cycles. The specimens were in either 15% $MgCl_2$ or 17% $CaCl_2$ solutions. The specimens exposed to the magnesium-based deicer continuously gained mass, while those exposed to the calcium-based deicer lost mass over time. Results were again different when the concrete contained 20% supplementary fly ash, with increases in masses for both exposures, but slightly more for the calcium-exposed specimens.

The Jain et al. study (2011) also considered what might happen in joints with respect to water saturation and associated deicer impacts. The study was not conclusive, but rather detailed many different mechanisms that might occur within the system. Future studies are needed to understand the causes of deterioration in these joints under winter conditions.

Darwin et al. (2008) compared weekly exposure to sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$) and calcium magnesium acetate (CMA) over a nearly two year period at both low and high molal concentrations. Control (exposed to water and/or air only) and NaCl specimens had little change in mechanical properties. $CaCl_2$ specimens had significant loss of material and reductions in strength only at the high molal concentrations. Both magnesium-based deicers resulted in noticeable reductions in strength at both low and high

concentrations. All of the specimens were tested just after casting, implying little or no carbonation impacts on the study.

Sutter et al. (2008) noted that both $CaCl_2$ and $MgCl_2$ have deleterious impacts on traditional concrete pavements based on field observations with loss of strength, increased permeability, expansion and cracking. Lower concentrations of either chemical have less of an impact. Their laboratory tests were performed on mortar using concentrations of 17 and 15 weight % for $CaCl_2$ and $MgCl_2$ respectively. The impacts were shown to be both physical and from chemical attack. Usually concrete made with some fly ash performed better. Usually mixtures with a low w/c (water to cement ratio) performed better, but not in low temperature immersion tests. The values of w/c used ranged from 0.40 to 0.60.

Sutter et al. (2008) also studied mortar specimens at three molar concentration of the solutions. They used petrographic analysis that indicated that expansive calcium oxychloride and magnesium oxychloride formed for the use of $CaCl_2$ and $MgCl_2$ respectively. Both showed an increase in length on length change bars, significant loss in compressive strength in the mortar cubes and microcracks in back-scattered electron images. Interestingly, they also compared these to bars and cubes exposed to $Ca(OH)_2$ solutions. These bars and cubes showed no length change and an increase in compressive strength respectively. The lime water images also did not indicate cracking.

More recently, Dang et al. (2016) performed tests on laboratory prepared specimens with and without various sealers to determine the effectiveness of the sealers for protection from the possible deleterious impacts of $MgCl_2$ and NaCl deicers. The specimens were soaked in 2.5-3% solutions of the deicers and also went through up to 15 wet-dry and then freeze-thaw test cycles in these solutions. The control specimens (without any sealant treatment but subject to these deicer solutions for freeze-thaw cycles) showed significant scaling for the NaCl tests, but little or no scaling with the $MgCl_2$ solutions. Both deicers did not have a significant impact on compression testing (except for the NaCl specimens near the end of the test cycles due to excessive scaling). The $MgCl_2$ specimens gained a small amount of mass (1%) after the 15 cycles, although they were weighed only after air drying for 12 hours, while the NaCl specimens lost up to 30% mass due to scaling. Split tensile testing indicated little change for the NaCl from over the cycles, but a decrease for the $MgCl_2$ specimens.

Xie et al. (2016) performed similar cyclic testing as Dang et al. (2016), but comparing 3% NaCl and 3% potassium acetate (KAc) concrete specimens with specimens only exposed to water. The NaCl specimens again showed mass loss, and they had a slightly lower split tensile strength than the water specimens.

Pervious Concrete Deicer Studies

There have been several freeze-thaw studies on pervious concrete (Kevern et al. 2010, Mata 2008, Wu et al. 2016). Some of these research endeavors included deicing chemicals. Yang (2011) performed freeze-thaw tests on many different mix designs of pervious concrete. They did perform a series of tests which included a 2% NaCl solution, which had slightly fewer cycles to failure than the water only tests. Cutler et al. (2010) performed freeze-thaw tests under both saturated and slowly-draining conditions with the following performance from worst to best:

$CaCl_2$, NaCl, and CMA (calcium magnesium acetate). A NaCl-based freeze-thaw study was performed with varying concentrations and also various amounts of fly ash substitution for Portland cement (Anderson and Dewoolkar 2015). Tsang et al. (2016) published on developing a freeze-thaw test method for pervious concrete using three different deicing chemicals. They found that the performance from best to worst was ranked as $MgCl_2$, urea, $CaCl_2$, and NaCl with mainly saturation near the bottom of the specimens.

Weathering and Carbonation Impacts

Concrete pavements that have been exposed to different environmental conditions might be affected by deicing chemicals differently. A study by Jacobsen et al. (1997) using NaCl as the deicing salt, indicated that freshly-placed pavements are less protected from freeze-thaw than mildly dried surfaces, and that highly-dried surface also had more damage. This was found in both simulated laboratory experiments and under naturally weathering conditions. The assumption was that the pores from the entrained air gave the most protection under the partially-dried condition.

In addition to differences in wetting and humidity, exposure can also change the properties of concrete due to carbonation, where atmospheric carbon dioxide reacts with the hydrated species in the paste, forming carbonated species. An interesting study on surface impacts of deicing salts on traditional concretes indicates that with OPC the cement paste densifies when carbonated and the impact is less, but with slag-based cement paste concretes there is an opposite effect, apparently from interstitial weak spaces having developed (Copuroglu and Schlangen, 2007).

Pervious Concrete and Winter Maintenance

From discussions with producers and installers in the fall of 2014, it was indicated that there might be more damage to pervious from deicing salts if applied in the first year of use, and that this decreases afterwards. Most likely this is due to the protective effects of carbonation (perhaps densification). In fact, as a result of meetings with the Pervious Concrete Promotion Committee a guidance published in 2015 lists the following (NRMCA 2015) with calcium chloride use suggested only after the first year.

- "Anti-icing pre-treatments should never be used on pervious concrete pavements. If these products are used on adjacent pavements, care should be taken to prevent the adjacent runoff from infiltrating the pervious concrete.
- Deicers containing magnesium chloride, calcium magnesium acetate or potassium acetate should never be used on pervious concrete pavement.
- Deicing agents that contain fertilizer ingredients such as Ammonium Sulfate and Ammonium Nitrate cause chemical deterioration to any Portland cement-based concrete pavement and should never be used.
- Calcium Chloride impregnated sand can be used for deicing pavements after the first year.
- Coarse sand (minimum 1/8 inch), or small crushed aggregate (1/4 – 10, or similar gradation) can be used as an anti-skid material with the understanding that vacuum cleaning will be performed after the winter season. Fine sands such as masonry sand or play sand should NOT be used on pervious concrete pavements!"

In addition to the comments in the NRMCA guide (NRMCA 2015), some other literature on cold climate use follows, but at this time probably the NRMCA guide is the most up-to-date. Weiss et al. (2015) provided a summary of full depth permeable pavement systems particularly in cold climates. They have found recommendations to not use deicers on pervious concrete in a reference for Denver, CO, by the local flood control district. The UDFCD (2010) states that for pervious concrete: "Mechanical snow/ice removal only. Do not use liquid or solid deicers or sand." The CPG (2013) for Kansas City mentions that "Salt/Sand is generally not necessary. Salt may be required in certain ice or seasonal conditions. Sand maybe applied, however, it will reduce permeability. Sanded pavements will require more routine vacuuming for maintenance."

Application Rates of Deicers

On the Pullman Campus of Washington State University (WSU), both $CaCl_2$ in pellet form and $MgCl_2$ in a solution are used for deicing. The calcium based deicer is commonly applied to walks and stairs, whereas the magnesium-based deicer is used frequently on roads and parking areas, although it is also now being used on walks that have equipment access. The pellets are not usually applied prior to a winter storm as the pellets might roll, whereas the liquid magnesium deicer is sometimes sprayed on surfaces prior to a winter event, but not on the walks (Adams et al. 2014). Many times this practice of spraying the deicer on prior to a winter precipitation event is called anti-icing, and, as noted in the previous section, is never recommended on pervious concrete as much of the solution will run into the system.

Based on meetings with WSU Facilities Services the calcium deicer is only applied to the pervious concrete installations if, after plowing, the surface is icy. There is one road section on this WSU campus of pervious concrete and it initially received calcium deicers, but from the winter of 2013-2014 and forward the magnesium deicer solution has been used as an anti-icer and there has been a noticeable increasing in raveling. In addition, when there is evidence of icing on pervious concrete on the campus, then either one of the deicers is used as needed, with the calcium chloride pellets used in areas that are not easily accessible to motorized equipment, and the magnesium chloride solution used in equipment applications. The application rate varies depending on the amount of icing. The suggested rate for the magnesium chloride solution per the heavy equipment manager on the campus is 30 gallons per lane mile.

Table 1.1 summarizes the concentrations used in some major studies on the impacts of deicers on traditional concrete and information on both deicers used on the Pullman campus. The data was also used to correlate the solution concentrations into similar units for comparison. As can be seen in Table 1.1, the wet/dry cycle study by Jain et al. used concentrations similar to what would happen if the chemicals were not diluted by rain or snowmelt. This might happen inside of pervious concrete if applied directly on the surface as an anti-icer, with calcium chloride dissolved at a similar concentration. To give this more perspective, the tests listed for studies in Table 1.1 which use around 15-17% would then represent the equivalent of a one to one dilution of the typical magnesium chloride deicer solution with water, and those around 3-4% represent a mass dilution of about 9 (water) to solution. If the recommendation is 30 gallons per lanemile then we can see what this might be for a ¼ inch equivalent rainfall. The specific gravity of this magnesium chloride solution deicer is around 1.29, or a density around 11 lbs per gallon (manufacturer specification). Thus this amount of melted precipitation would be approximately 1320 cf or 30350 liters (30 million grams). The 30 gallons would contain 330 lbs solution or 99

lbs $MgCl_2$. This converts to a 0.15% solution when diluted with the melted precipitation. Thus applying as an anti-icer would give a concentration that might be two orders of magnitude greater than what might occur if diluted as part of a substantial snow or ice melt event.

Table 1.1: Deicer Application Concentrations from Literature and Analysis of Deicers used on Pullman Campus

Laboratory Testing Concentrations					
Source	**% solution^**	**Molal Ion* Solution**	**NaCl**	**$CaCl_2$**	**$MgCl_2$**
Darwin et al. 2008 Wet/dry Cycles Concrete	16% $MgCl_2$ 17% $CaCl_2$ 15% NaCl	6.04	850 g water 150 g solid NaCl	1000 g water 223.5 g 92.36% solids	612.5 g water 579.2 g 33.1% solution Or 1000 g water 192 g solid
Darwin et al. 2008 Wet/dry Cycles Concrete	3.3% $MgCl_2$ 3.8% $CaCl_2$ 3% NaCl	1.06	970 g water 30 g NaCl solid	1000 g water 42.4 g 92.36% solids	932.1 g water 101.5 g 33.1% solution Or 1000 g water 33.6 g solid
Jain et al. 2011 Wet/dry Cycles Concrete	25% $MgCl_2$ 28% $CaCl_2$		-	1000 g water 389 g solid	1000 g water 333 g solid
Jain et al. 2011 Freeze-thaw Cycle Concrete	15% $MgCl_2$ 17% $CaCl_2$		-	1000 g water 205 g solid	1000 g water 176 g solid
Sutter et al. 2008 Wetting Mortar	15% $MgCl_2$ 17% $CaCl_2$ 17.8% NaCl		1000 g water 217 g solid	1000 g water 205 g solid	1000 g water 176 g solid
Dang et al. 2016	2.54% $MgCl_2$ 3.0% NaCl				
Deicer Chemical Information on the Pullman Campus (not diluted)					
Peladow™	- $CaCl_2$ pellets	-	-	90-92% of the solids**	-
Freezgard®CI Plus	30% $MgCl_2$	-	-		29.8% mass*** 1000g water 471 g solid

^ Assume mass solid per mass solid plus water.
*Sum of all ions: cations and anions.
**Other chemicals include potassium chloride, water, sodium chloride, calcium bromide.
***Other chemicals include sulfate, potassium, calcium and a corrosion inhibitor for 2.25% more solids.

Pervious Concrete and Miscellaneous Chemistry Studies

Lee et al. (2014) performed a pollutant removal study on pervious concrete focusing on saltwater, pH and organics (oils, etc.). In their study, in addition to a pH test, they tested for conductivity in the solutions, which provides some information on the amounts of ions in solution. Conductivity tests are usually fairly simple to perform and provide quick results. Although they cannot detect which ions are there, the data might give some indication if there is salt uptake taking place. The Lee et al. (2014) experiment found a correlation between salinity changes and conductivity changes with respect to the influent and effluent on seawater purification tests. Haselbach et al. (2014b) studied the uptake of dissolved zinc and copper from simulations of heavily laden stormwater runoff in laboratory columns of pervious concrete. When pouring these solutions onto the columns they found removal rates of these metals greater than 85% in the effluent and this occurred in less than just a few minutes.

Fly Ash

Wet/dry cycles on 20% fly ash caused no mass change for either deicer, but still a significant loss in strength for both, although slightly worse for $CaCl_2$ and slightly better $MgCl_2$ (Jain et al. 2011). Additional work is needed to determine why the fly ash supplemented traditional concrete specimens tend to perform better than those with only ordinary Portland cement. So, one question is what are the chemical differences between concrete made with only ordinary Portland cement and concrete with some fly ash substitution? Table 1.2 provides some elemental analyses of the two cementitious materials from a recent study. In general, the fly ash has more silicates and aluminum oxides, whereas the ordinary Portland cement has much more calcium oxides. This implies that the main difference will be in the calcium-based chemistry with the ions in the deicers. However, due to the additional complexity with the fly ash, the first part of this research project focused more on concrete made with ordinary Portland cement.

Table 1.2: Elemental Analysis of Cement and Low Calcium Fly Ash (Haselbach et al. 2014a)

	Unnormalized Major Elements (Weight %)			
	Ordinary Portland Cement		**Fly Ash**	
	Sample 1	Sample 2	Sample 1	Sample 2
SiO_2	19.67	19.69	53.17	53.06
TiO_2	0.258	0.259	1.467	1.461
Al_2O_3	4.70	4.72	27.49	27.44
FeO (total Fe)	3.28	3.27	7.42	7.40
MnO	0.039	0.039	0.030	0.029
MgO	1.08	1.09	1.02	1.01
CaO	61.41	61.18	1.32	1.27
Na_2O	0.17	0.17	0.39	0.39
K_2O	0.55	0.55	2.79	2.79
P_2O_5	0.198	0.199	0.303	0.301
Sum	91.36	91.18	95.39	95.15
LOI	5.66	5.37	2.90	2.99
SO_3>/=	0.07	0.05	0.01	0.02

Ecological Impacts of Deicers

A study by Cui et al. (2015) overviews the literature of direct stress from deicers on "receiving roadside soil, water bodies, aquatic biota, and vegetation through snowmelt runoff, infiltration and wind blow." Their study further explored the methods for assessing these stresses and future needs. Note that the deicers enter the natural environment through runoff, infiltration and wind blow. There was no mention in their review of studies on permeable or pervious pavements. They did mention that Meriano et al. (2009) and Perera et al. (2013) indicate that from these pavements (impermeable assumed) that 40-55% of the salt migrates via runoff.

Testing Methods Used in Previous Research

Temperatures

Darwin et al. (2008) used room temperature and elevated temperatures. Jain et al. (2011) reviewed the temperature ranges used by several other researchers in previous deicer wetting/drying tests, and also in freeze-thaw studies. They used wetting temperatures around 4ºC and drying around 23ºC. For their freeze-thaw tests, the temperatures were -20ºC and 20ºC respectively. Other studies used similar ranges in varying amounts.

Nondestructive testing

Darwin et al. (2008) used the dynamic modulus of elasticity based on the fundamental transverse resonance frequency of each specimen over time. However, the changes are not just due to impacts of strength changes and the deicers, they are also due to water being absorbed as can be seen by the water and the air control specimens, with the former improving in strength and the latter decreasing. Therefore, developing a methodology based on this method would be difficult. In addition, there are no established nondestructive tests for measuring these properties in pervious concrete with its very expansive pore network and variable porosity.

Strength

Several researchers reported compressive strength results on traditional concrete specimens after various exposures to dry/wet cycles and deicers, or freeze-thaw cycles and deicers. However, with pervious concrete compressive strength is highly variable with porosity and very difficult to correlate with other variables without many specimens. In addition, compressive strength may be related more to the aggregate to aggregate contact than to the strength of the hydrated cement paste. Previously, little or no information was provided about using a split tensile test, which may be more indicative of the loss of strength at the interface of the hydrated cement paste and the aggregate which may be more applicable for pervious concrete testing with deicers. However, Dang et al. in 2016 has published on traditional concrete specimens subject to 2.5-3% NaCl or $MgCl_2$ solutions in freeze-thaw cycles, where there was a drop in split tensile strength using this testing method for the $MgCl_2$.

Aquatic Chemistry Correlations

The atomic weight of magnesium is 24.3 while that of calcium is 40.1. This means that if a process is a simple ion exchange of magnesium for calcium in the hydrated cement paste that the mass should decrease, not increase. However, in the study by Jain et al. (2011) it was shown that the concrete specimens undergoing a wetting/drying cycle in a concentrated $MgCl_2$ solution actually exhibited a small mass gain, but this was only after many cycles.

The specimens in the Jain et al. (2011) study that were exposed to highly-concentrated solutions of $CaCl_2$ under wetting and then drying cycles showed significant mass loss and surface deterioration. This is not consistent with the common ion effect as described by Snoeyink and Jenkins (1980). The common ion effect is when solids "dissolve in a solution containing a species that is the same as one of the species that results from dissolution of the precipitate." This common ion reduces the dissolution. However, the aquatic system in this case is more complex, with many carbonate species and also hydroxide equilibria to consider. Table 1.3 provides some typical solubility products (K_{SO}) for some of the common carbonate and hydroxyl species associated with calcium and magnesium. Note that the solubility product tends to increase with temperature, but there are some notable cases where the effect is the opposite. These include $CaCO_3$, $Ca_3(PO_4)_2$, $CaSO_4$ and $FePO_4$ (Snoeyink and Jenkins 1980).

$$K_{SO} = (A^{y+})^z(B^{z-})^y/(A_zB_y) \quad \text{where } A_zB_y \text{ is the solid} \tag{1.1}$$

Table 1.3: Solubility products at 25ºC (Snoeyink and Jenkins 1980)

	pK$_{SO}$	**K$_{SO}$ at 25ºC**
$CaCO_3$	8.34	4.57×10^{-9}
$CaMg(CO_3)_2$	16.7	2.00×10^{-17}
$Ca(OH)_2$	5.3	5.01×10^{-6}
$MgCO_3$	5.0	1.00×10^{-5}
$Mg(OH)_2$	10.7	2.00×10^{-11}

So instead, it is speculated that the dissolution of concrete surfaces in highly concentrated solutions of $CaCl_2$ under wetting and then drying cycles is related to complexation chemistry interactions. In all the referenced systems this means between the various metal ions (calcium, magnesium, etc.) and associated ligands (carbonates, hydroxides, etc) in the concrete and in the water/deicer solution. Some representative stability constants (positive logscale) are provided in Table 1.4. As can be seen in the values in Table 1.4, the chloride ion is not a player in this type of chemistry, and the sodium ion really only participates in the carbonate chemistry forming carbonate and bicarbonate complexes. Based on the hydroxide and carbonate ligand complexes with calcium, a very concentrated solution of calcium chloride might have the tendency to bring these ions into solution to form these associated ligands and may be the explanation for the surface deterioration found in some of the referenced literature for traditional concrete. These would happen with both the carbonate and hydroxide ligand species, and the carbonates tend to be a surface phenomenon in concrete, increasing their availability. This might account for mass loss due to surface dissolution as seen in the studies, but not compressive strength loss, which is more an internal phenomenon.

Table 1.4: Stability Constants for Formation of Complexes and Solids. Solids have the 's' notation. (Stumm and Morgan 1996)

		Ligand (L)			
Metal		**OH^-**	**CO_3^{2-}**	**Cl^-**	**SiO_3^{2-}**
Na^+		-	NaL 1.27 NaHL 10.08	-	-
Ca^{2+}		CaL 1.15 CaL_2.s 5.19	CaL 3.2 CaHL 11.59 CaL.s 8.22 CaL.s 8.35	-	CaL 4.2 CaHL 14.1 CaH_2L_2 29.9
Mg^{2+}		MgL 2.56 Mg_4L_4 16.28 MgL_2.s 11.16	MgL 3.4 MgHL 11.49 MgL.s 4.54 MgL.s 7.45	-	MgL 5.3 MgHL 14.3 MgH_2L_2 30.8

With respect to the use of magnesium deicers on traditional concrete, the values in Table 1.4 imply that the calcium and the magnesium chemistry is similar, with preference for magnesium in many cases, but not usually with the carbonates. This implies that magnesium replacement of calcium is not as much a surface phenomenon, but rather may be due to diffusion and ion exchange, or internal surface complexation, especially with hydroxides. Thus, this explains a mass gain and a loss of compressive strength. In fact, Lee et al. (2000) have performed scanning electron microscopy (SEM) on specimens exposed to wet/dry cycles of magnesium chloride deicers and have found internal formation of brucite ($Mg(OH)_2$) and magnesium silicate hydrates (MSH) as would be indicated by the chemistry in Table 1.4. Another related study that implies that there may be some interaction with the calcium and the magnesium was the previously mentioned one on the effective removal of dissolved zinc and copper ions by pervious concrete (Haselbach et al. 2014b). An ion exchange with the calcium ion in the concrete was hypothesized based on similar surface complexation chemistry data and this was found to occur.

The impact of the silicate complexation chemistry is also not known. In concrete, the silicate species tends to be calcium silicates written for instance as $2CaO.SiO_2$, and in solution a species might be $CaSiO_3$ (Neville 1975). From Table 1.4 the chemistry seems to be very similar for both of the metals (calcium and magnesium), and as such there might not be as big of an impact as with the hydroxides. This adds even more complexity to the system, so for now the examples will be with the simpler, yet still very complex hydroxide and carbonate species.

Emails with industry representatives have indicated that in a field previous concrete experiment with copious amounts of $CaCl_2$, $MgCl_2$, and NaCl placed on separate sections of pervious concrete over a winter, both the $CaCl_2$ and NaCl showed much more surface impacts than the $MgCl_2$ (Cody 2014). This supports the hypothesis that this might be a preference for the carbonate chemistry complexes. In addition, this test plot may have been severely impacted by freeze-thaw cycles which are not being explored herein. According to Shi et al. (2010), significant surface deterioration can be found with NaCl deicers in freeze-thaw cycles on traditional concrete due to various impacts in the micropores. According to another study by Shi et al. (2011), exposure to the magnesium chloride impacts the strength adversely more than the other deicers studied herein, but that would not be apparent from surface observations only.

1.3. Initial Hypotheses

The purpose of this research is to focus on chemical impacts of deicers, particularly through the aqueous phase. Based on the aforementioned initial review of literature and associated chemistry the following hypotheses were used for developing this testing procedure:

1: The magnesium ion in the magnesium chloride deicer has a preference for the hydroxide species in pervious concrete and will diffuse in, or remain in internal pores, exchanging with the calcium ion and/or precipitating magnesium hydroxide. There might be mass gains, and a strength loss. A possible way to detect this might be with a reduced mass of magnesium ions exfiltrating a specimen with a related increase in calcium ion, or by a larger mass gain with application of magnesium chloride as compared to other deicing chemicals.

2: Calcium chloride might leach the ligands from the pervious concrete, particularly from the carbonated surfaces. This might be indicated by mass losses, but little strength loss unless the loading is severe. A possible way to detect this is by an increase in alkalinity in the effluent from a specimen, or a visible loss of mass from the specimens.

3: Sodium chloride might leach some carbonate species from the pervious concrete, but this should be significantly less than what is seen with calcium carbonate.

4: Chloride ions do not participate in the aforementioned complexation reactions, but still might remain in the pervious concrete through water remaining in the pores, diffusion and various chemical reactions. However, these differences are not expected to be detectable between the influent and effluent.

2. TESTING PROTOCOLS

Based on the literature review, a laboratory testing protocol was established for testing deicer applications of both calcium chloride and magnesium chloride. The protocols were established in an effort to mimic the conditions that might occur with frequent applications during a winter season. The protocols set and justification for these decisions follow.

2.1. Specimen Size (Objective B1) and Characteristics

The intent herein was to produce specimens that would represent the baseline condition of pervious concrete without additives or treatment to mitigate deterioration by deicer application. The main group of specimens would represent the worst conditions based on the literature review, i.e. only made with ordinary Portland cement (OPC) without any fly ash addition, and freshly made with little or no carbonation. This group had four specimens of similar porosities for each treatment for statistical averaging and this then provided at least two of each treatment type available for a subsequent physical durability or strength test. There were also specimens with some common variations (fly ash addition and carbonation), for which two specimens were used for each variation, as acceptable by statistical design and useful to decrease the total number of specimens. In addition, the availability of older specimens (carbonated) for the test was limited.

The specimens were 4 inch diameter pervious concrete cylinders, all approximately 7 inches in height. They were made by placing sufficient mix in a 4 inch diameter by 8 inch high mold and then surface compacted approximately 10% to obtain a porosity around 22-25%. The molds were capped and allowed to cure for at least seven days under ambient laboratory temperature conditions. This procedure is similar to field installation compaction techniques with plastic covering for seven days, and results in specimens with a field representative vertical porosity distribution (Haselbach and Freeman 2006, Delatte et al. 2009). This procedure also follows the standard diameter for a specimen, and the single lift methodology for mimicking field compaction conditions of ISO 17785-1 (ISO 2016). The specimens were not made with any admixtures as these would introduce additional independent variables to the experiments. They were all made with an approximately 0.28 to 0.30 water to cementitious material mass ratio (w/cm) and an approximately 4.0 aggregate to cementitious material mass ratio.

The main sets of specimens were cast in January 2016, shortly before starting the deicing application experiments. These represent a condition with little carbonation and therefore higher hydroxide levels on the surface which is expected to be one of the worst conditions for resistance to degradation by various deicers. For this experiment, most of the specimens were made with ordinary Portland cement without addition of fly ash, as those types of specimens seem to not perform as well with deicers from research on traditional concrete as compared to specimens with some supplementary addition of fly ash as previously discussed in the literature review. However, a smaller set of specimens were made with 25% fly ash substitution. These sets of specimens cast in January 2016 are herein referred to as the noncarbonated specimens.

Additional sets of the specimens were cast several years ago (2008 to early 2009) and left exposed to air in the laboratory and are therefore highly carbonated on the surfaces. Some of these older specimens were made with ordinary Portland cement without the addition of fly ash, and some with 25% fly ash substitution. These specimens cast many years ago will be referred to herein as the carbonated specimens. The carbonated specimens represent a condition in the field where the pervious concrete is older than a year or two, i.e. the longterm condition.

All the specimens were tested for porosity with a modified ASTM C1754 (2012), with the modification that the dry mass was taken as air dried in the laboratory for more than a year for the older specimens, or for the newly cast specimens, just after unmolding.

2.2. Solution Loading Protocols (Objectives B2 and B3)

The following variables were considered for the applications of the deicers. Justifications based on the literature review and wintertime and field conditions are provided.

Solution types

This research focused on calcium chloride and magnesium chloride deicers. The control used was tapwater, and also some of the testing was performed using sodium chloride, which was not expected to have as detrimental impacts as the other two deicers based only on chemistry, but was of interest and also used partially for control.

Solution concentrations
Deicer chemical concentrations used in studies on traditional concrete as listed in Table 1.1 tended to run from 3% to 30% solutions by mass. If applied under anti-icing conditions, these would likely be on the high range, whereas if applied as deicers, the chemicals would generally become more dilute. Remember that based on traditional concrete studies, the 15% solutions were destructive for both the magnesium and calcium based deicers, whereas the 3% solution was mostly destructive with the magnesium deicer. However, pervious concrete is different in that it does not have chemical laden solutions pooled on top. Instead the solutions drain into the specimens, with some passing through into the aggregate storage bed below, but some remaining in the pervious concrete layer in the various pores. As the deicer solutions that remain in the pervious concrete layer slowly evaporate, they will become more concentrated. Thus, the decision was made to focus on applying approximately 3% solutions, but allowing them to concentrate in the specimens in between applications so that a range of possible conditions would be handled with one testing protocol.

Water Source
Tapwater was mainly used instead of deionized (DI) water as the make-up water. It is felt that DI water might result in some leaching and not be representative of rainwater or melting snow. (Note that a few applications were made with DI water in order to see the difference in the effluent, but mainly the testing was performed with tapwater.)

Volume of Influent
Previous studies indicate that pervious concrete of a depth of 6 inches will hold approximately 1 cm depth of water without effluent or 80 mL for a 4 inch diameter specimen (Haselbach et al. 2011). In this case, we are interested in a worst-case scenario where significant amounts of the solutions are retained in the specimens in order for additional chemical reactions to take place, but we are also interested in obtaining enough effluent for both the chemical analyses and to do a summary mass balance on the system. Increasing the depth of influent to approximately 2.5 cm on the 4 inch diameter specimens or 1.5 cm more than would be held within an average specimen should provide for at least 100 mL of effluent based on this additional volume of influent. Therefore, the influent volume for the testing was set at 200 mL.

Chemical Tests
Testing for pH on the influent and effluent samples was performed as per ASTM E70 (ASTM 2015). In the first weeks in the ambient laboratory, alkalinity was measured as per ASTM D3875 (ASTM 2008), but was found to be very variable, particularly for the calcium chloride tests and was stopped. Other chemical testing has been experimented with on the effluent and influent samples using a Seal Analytics AQ400 Discrete Water Analyzer and those results will be analyzed in future research efforts or as noted in the results.

Physical Tests
Porosity was determined on the pervious concrete specimens as per a modified ASTM C1754 with the modifications being room, not oven dried (ASTM 2012). The older specimens were room dried for many months, but the freshly made specimens were tested just after demolding. Surface infiltration rates were performed on the pervious concrete specimens as per a modified ASTM C1701 with the modification being a 4 inch diameter ring and one liter of water for

pretest and test (ASTM 2009). Masses on the specimens were taken on many occasions to a precision of 0.1g. Masses and volumes were taken on the effluents and the influents starting several weeks into the testing to estimate solution densities.

Temperature

A simpler testing protocol would be on that could be performed under ambient laboratory conditions versus one that would need to be performed under near freezing temperatures. However, there are two conflicting impacts of temperature that might occur. Based on the increased solubility (equilibrium) of calcium carbonate under colder conditions, a colder temperature may be the worst scenario, but at the same time the kinetics of reactions tend to go faster when warmer. Thus, the main focus of the testing will be under ambient laboratory conditions, but a portion of the testing will also be performed under just above freezing conditions.

2.3. Testing

Prior to testing, an alphanumeric identification scheme was developed to identify the specimens. The first letter was an 'H' or 'C' to stand for the hot (ambient) or cold room. The second letter was the type of solution (W for water, S for sodium chloride, C for calcium chloride and M for magnesium chloride). The third letter identified the specimen mix (O for OPC and F for with fly ash addition). The fourth letter identified the specimen age (C for carbonated, i.e. case several years earlier, or N for noncarbonated, i.e. cast in January 2016). This was followed by a number for the specimen (1 to 4 for the main tests, and 1 to 2 for the ancillary testing variations). Thus, for the ambient (hot) room with calcium chloride applied with a mix using OPC, and which was newly cast in 2016 the four specimens were labeled: HCON1, HCON2, HCON3 and HCON4.

Testing was performed on a large set of similar specimens similar as outlined in the Testing Matrix in Table 2.1. The testing first started on the specimens at ambient laboratory (room) temperature. A few months later, a similar testing procedure began on a smaller set of specimens in a room with the temperature held around 4ºC (cold room). In the testing matrix, OPC stands for specimens made with only Portland cement, water (at around 0.3 water to cement mass ratio) and aggregate at approximately a 4:1 aggregate to cement mass ratio. 24% FA stands for similarly made specimens but which had a 25% replacement of fly ash for OPC. Fresh or 'noncarbonated' specimens were made in January 2016. Carbonated specimens were made in 2008 or 2009 and had been sitting in the laboratory for many years. Prior testing on some of the carbonated specimens only entailed pH testing with tapwater or deionized several years prior (Thomle and Haselbach 2011). Note that prior to the deicing applications all the specimens were wrapped with approximately 18 grams of shrinkwrap along the sides, which was then heated to form columns, with a small lip on the top so that the fluids would pool on the top and then infiltrate into and through the columns from top to bottom. The shrinkwrap was heated on the sides of the specimens so that the wrap held tight to the sides, limiting any channeling along the sides. The effluent was caught in a beaker, and this was allowed to drip for at least 10 minutes. The specimens were then transferred to racks to dry in either the ambient laboratory or cold room as appropriate.

Table 2.1: Testing Matrix

Concrete Type	Temperature	Solution	# of Specimens	Protocol
OPC Fresh	Ambient Room	$CaCl_2$	4	Main Tests all 4 Applications: Ambient Room
		$MgCl_2$	4	
		NaCl*	4	
		Water	4	
	4ºC	$CaCl_2$	4	Main Tests for 3 Applications: Cold Room
		$MgCl_2$	4	
		Water	4	
25% FA Fresh	Ambient Room	$CaCl_2$	2	Fly Ash Variation: Ambient Room
		$MgCl_2$	2	
		NaCl*	2	
		Water	2	
OPC Carbonated	Ambient Room	$CaCl_2$	2	Carbonated Variation: Ambient Room
		$MgCl_2$	2	
		NaCl*	2	
		Water	2	
25%FA Carbonated	Ambient Room	$CaCl_2$	2	Carbonated with Fly Ash Variation: Ambient Room
		$MgCl_2$	2	
		NaCl*	2	
		Water	2	
OPC Carbonated	4ºC	$CaCl_2$	2	Carbonated Variation: Cold Room
		$MgCl_2$	2	
		Water	2	

* Mainly used as a control to see the impact of the chlorides.

As can be seen in Table 2.1, the main tests involved four specimens each of new (fresh) OPC mix designs. These would be subject to all four types of treatments ($CaCl_2$, $MgCl_2$, water and NaCl) under ambient laboratory conditions, and three of the treatments (not NaCl) in the cold room. Pairs of specimens were used for the various combinations in the factorial design, with variations including some fly ash addition and carbonated specimens. The applications were made on a weekly basis. This was intended to simulate a winter condition with frequent storms, but with enough time in between deicer applications to allow for some evaporation of the water inside the specimens, concentrating the solutions within so that there would be a range of deicing concentrations such as was seen in the previous studies in the literature. More frequent applications might not accelerate the process as these would dilute the solutions within the specimens and may not cause as serious deterioration. In addition, as previously stated, the intention of this research was to see if there was chemical deterioration of pervious concrete from simulated deicer applications. Additional testing for physical deterioration such as through freeze-thaw was not considered at this time as the focus was on whether there would be chemical deterioration from the deicing chemicals regardless of possible freeze-thaw cycles.

Those in the ambient laboratory started in March 2016 and those in the cold room started in May 2016. Each day of the week was dedicated to one type of solution application, usually starting on Monday and ending on Thursday, with minor modifications due to schedules. On each testing

day the following procedure was followed on the specimens receiving one of the four solution applications (except in the cold room where the NaCl solution was not used):

- All the specimens were weighed.
- The solution (magnesium chloride, sodium chloride, calcium chloride or water) for that day was prepared, and one sample of the influent saved in a refrigerator.
- 200 mL of the solution was applied to the applicable specimens in all four concrete type combinations in the ambient laboratory, or the two concrete type conditions in the cold room.
- The volume of effluent was measured for each specimen, and then a composite sample from each of the concrete type/temperature combinations saved in a refrigerator. Several weeks into the testing, additional glassware was obtained for more accurate volumetric readings in the ambient laboratory. This glassware was always used in the cold room.
- Several weeks into the testing in the ambient laboratory, taking the mass of the influent and effluent samples was also added to the protocol, and was continued for all tests in the cold room.
- Influent and composite effluent samples were tested for pH. Some additional chemical tests were performed on the refrigerated composite influent and effluent samples as noted in later chapters.

The experimental setup for deicer applications in the ambient laboratory is depicted in Figure 2.1. Figure 2.2 is a photograph of the experimental setup in the cold room.

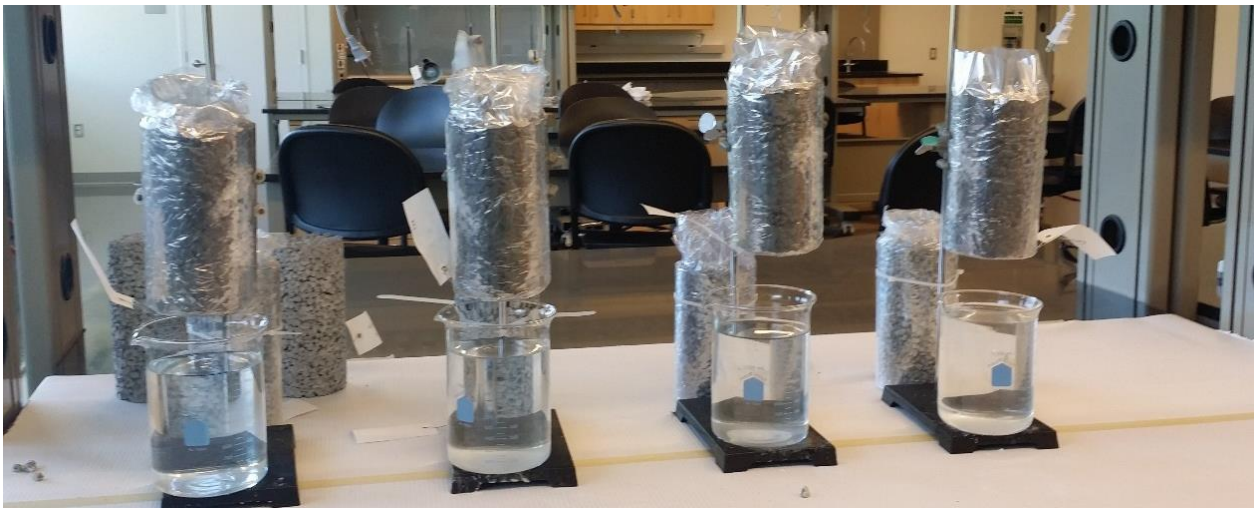

Figure 2.1: Experimental setup for deicing applications in the ambient laboratory.

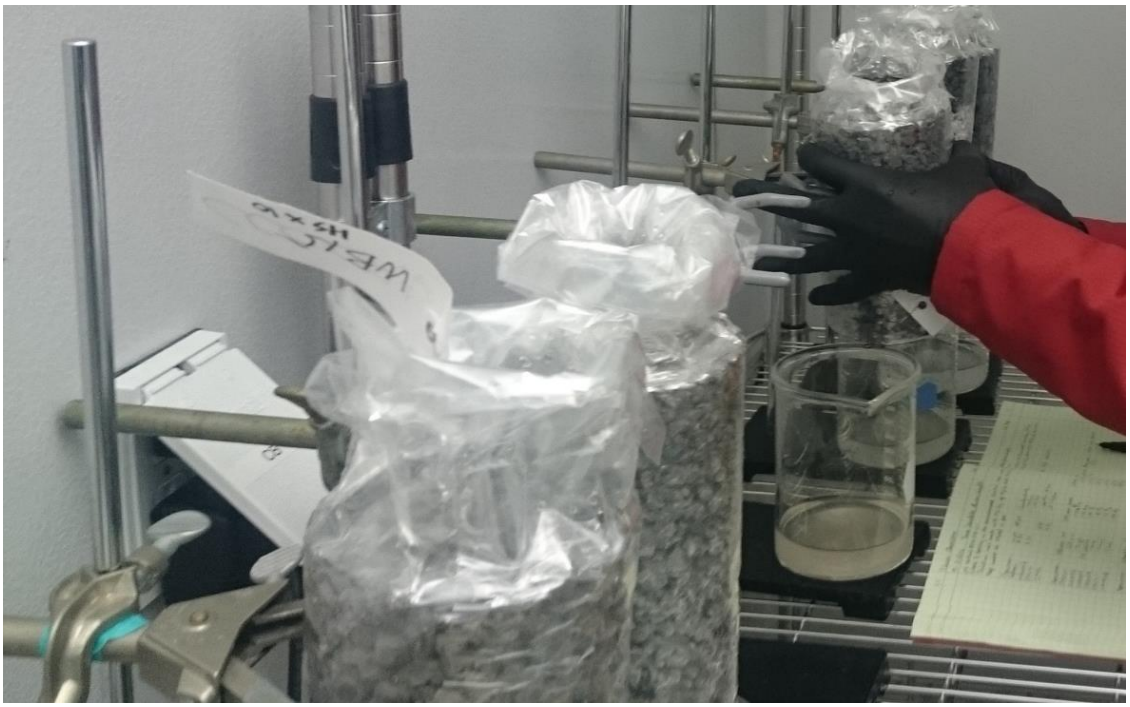

Figure 2.2: Experimental setup for deicing applications in the cold room.

Note also that all the solutions prepared with the deicing chemicals were mechanically stirred until solids were dissolved. This took some time for the calcium chloride solutions, especially in the cold room where the solutions were equilibrated to the cold room temperature prior to application. The stirring plate is shown in Figure 2.3 for the cold room. In the cold room, all specimens were kept at the cold room temperature for the entire four months of testing. The magnesium chloride and calcium chloride solutions were made with the deicing chemical used on the Washington State University Pullman campus as listed in Table 1.1. The sodium chloride solutions were made with typical table salt.

Figure 2.3: Influent dissolution and physical characterization, and storage of specimens and samples in the cold room.

Figures 2.4 and 2.5 depict the racks in the cold room and the ambient laboratory respectively, where the specimens were stored between the weekly applications. Note the dripping pads on the racks below the racks on which the specimens were stored.

Figure 2.4: Photograph of a rack that held specimens in the cold room in between deicer applications with dripping pads below.

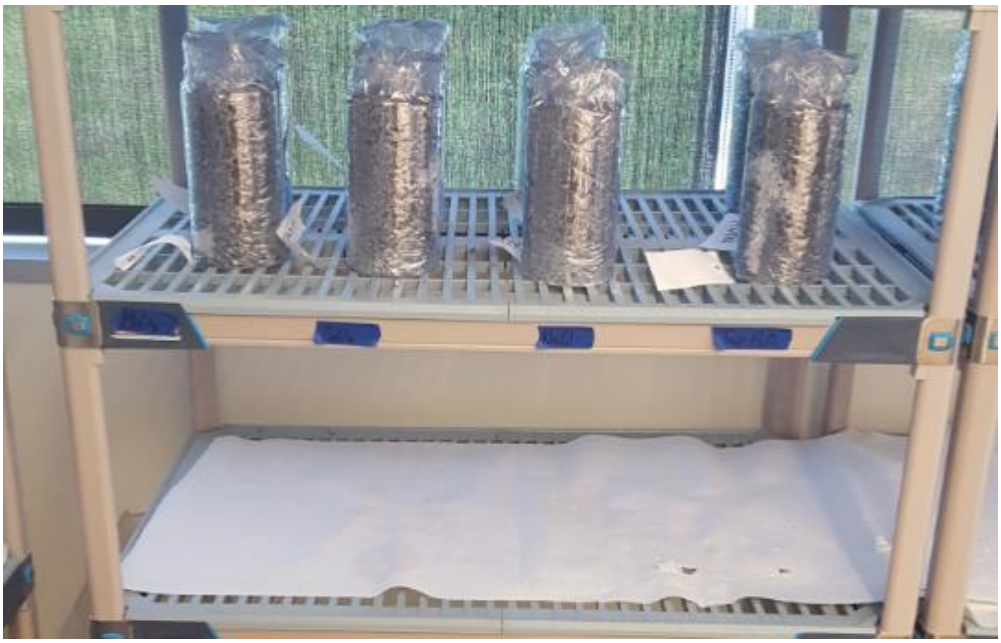

Figure 2.5: Photograph of a rack that held specimens in the ambient laboratory in between deicer applications with dripping pads below.

3. OVERVIEW OF RESULTS

3.1. Specimen Characteristics of Deicer Laboratory Tests (*Objective B1*)

All the specimens that were tested under ambient room conditions in the laboratory are listed in Table 3.1 with their specific ID alphanumeric, porosity, dates when cast and when the initial masses were recorded as listed in Table 3.1. All the specimens that were tested under cold conditions are listed in Table 3.2 with their specific ID alphanumeric, porosity, dates when cast and also when the initial masses were recorded as recorded in Table 3.2. All the specimens were 4 inches in diameter and approximately 7 inches in height. Since the experimental protocol includes pouring applications of deicer laden solutions onto the tops of the specimens and allowing the fluid to infiltrate through the specimens, an additional test was performed on many of the specimens to look at the variability in the surface infiltration rates. This rate is expected to vary with porosity, and may also be indirectly correlated with the residence time of the infiltrated fluids that exfiltrate in the first few minutes. This infiltration rate does not correlate with the residence time of the fluids that remained in the specimens and were then partially evaporated (and therefore the deicer concentrations raised) each week. It is expected that this latter case is the most important for the experiments as it represents the long-term and concentrated exposure of the concrete to these salts. However, having similar surface infiltration rates is another form of experimental control for similarity among the specimens and may have some more significant meaning with respect to the concentrations seen in the collected effluent under future examinations. Therefore, these are also provided for future reference. The infiltration test was performed in accordance with ISO 17785-1 (ISO 2016), with the modification of one liter of water for each test. These were performed on the specimens made in January 2016 (noncarbonated). The infiltration rate tests are presented in Tables A.1 and A.2 (Appendix A) for these ambient temperature noncarbonated specimens and the cold room specimens respectively.

Table 3.1: Specimens for Ambient Laboratory Room Testing

			ID	Porosity	Casting Date	Initial Mass	Initial Mass Date
NONCARBONATED	100% ORDINARY PORTLAND CEMENT	Water	HWON1	21.8%	Jan. 6 2016	2831g	Jan. 13 2016
			HWON2	21.7%	Jan. 6 2016	2805g	Jan. 13 2016
			HWON3	22.1%	Jan. 6 2016	2802g	Jan. 13 2016
			HWON4	21.7%	Jan. 6 2016	2789g	Jan. 13 2016
		Calcium	HCON1	22.9%	Jan. 6 2016	2804g	Jan. 13 2016
			HCON2	22.6%	Jan. 6 2016	2796g	Jan. 13 2016
			HCON3	22.6%	Jan. 6 2016	2805g	Jan. 13 2016
			HCON4	22.9%	Jan. 6 2016	2795g	Jan. 13 2016
		Magnesium	HMON1	20.9%	Jan. 6 2016	2804g	Jan. 13 2016
			HMON2	21.4%	Jan. 6 2016	2796g	Jan. 13 2016
			HMON3	20.9%	Jan. 6 2016	2804g	Jan. 13 2016
			HMON4	20.6%	Jan. 6 2016	2813g	Jan. 13 2016
		Sodium	HSON1	19.9%	Jan. 6 2016	2810g	Jan. 13 2016
			HSON2	20.1%	Jan. 6 2016	2800g	Jan. 13 2016
			HSON3	19.6%	Jan. 6 2016	2823g	Jan. 13 2016
			HSON4	19.5%	Jan. 6 2016	2856g	Jan. 13 2016
	25% FLY ASH	W	HWFN1	21.6%	Jan. 8 2016	2812g	Jan. 13 2016
			HWFN2	23.4%	Jan. 8 2016	2806g	Jan. 13 2016
		C	HCFN1	22.7%	Jan. 8 2016	2828g	Jan. 13 2016
			HCFN2	22.6%	Jan. 8 2016	2806g	Jan. 13 2016
		M	HMFN1	22.4%	Jan. 8 2016	2818g	Jan. 13 2016
			HMFN2	23.1%	Jan. 8 2016	2807g	Jan. 13 2016
		S	HSFN1	19.9%	Jan. 8 2016	2858g	Jan. 13 2016
			HSFN2	19.8%	Jan. 8 2016	2835g	Jan. 13 2016
CARBONATED	100% OPC	W	HWOC1	25.3%	2008/2009	2822g	Jan. 13 2016
			HWOC2	25.3%	2008/2009	2773g	Jan. 13 2016
		C	HCOC1	23.4%	2008/2009	2833g	Jan. 13 2016
			HCOC2	23.6%	2008/2009	2832g	Jan. 13 2016
		M	HMOC1	24.0%	2008/2009	2785g	Jan. 13 2016
			HMOC2	24.4%	2008/2009	2792g	Jan. 13 2016
		S	HSOC1	23.7%	2008/2009	2825g	Jan. 13 2016
			HSOC2	24.5%	2008/2009	2737g	Jan. 13 2016
	25% FLY ASH	W	HWFC1	26.9%	2008/2009	2759g	Jan. 13 2016
			HWFC2	24.2%	2008/2009	2812g	Jan. 13 2016
		C	HCFC1	24.5%	2008/2009	2808g	Jan. 13 2016
			HCFC2	22.7%	2008/2009	2843g	Jan. 13 2016
		M	HMFC1	25.2%	2008/2009	2810g	Jan. 13 2016
			HMFC2	25.7%	2008/2009	2810g	Jan. 13 2016
		S	HSFC1	27.0%	2008/2009	2785g	Jan. 13 2016
			HSFC2	26.4%	2008/2009	2793g	Jan. 13 2016

Table 3.2: Specimens for Cold Temperature Room Testing

			ID	Porosity	Casting Date	Initial Mass	Initial Mass Date
NONCARBONATED	100% OPC	Water	CWON1	19.7%	Jan. 8 2016	2849g	Jan. 13 2016
			CWON2	20.2%	Jan. 8 2016	2867g	Jan. 13 2016
			CWON3	19.2%	Jan. 8 2016	2858g	Jan. 13 2016
			CWON4	18.7%	Jan. 8 2016	2868g	Jan. 13 2016
		Calcium	CCON1	22.7%	Jan. 8 2016	2816g	Jan. 13 2016
			CCON2	22.4%	Jan. 8 2016	2822g	Jan. 13 2016
			CCON3	22.2%	Jan. 8 2016	2799g	Jan. 13 2016
			CCON4	22.1%	Jan. 8 2016	2809g	Jan. 13 2016
		Magnesium	CMON1	20.9%	Jan. 8 2016	2873g	Jan. 13 2016
			CMON2	20.6%	Jan. 8 2016	2869g	Jan. 13 2016
			CMON3	20.7%	Jan. 8 2016	2821g	Jan. 13 2016
			CMON4	21.8%	Jan. 8 2016	2829g	Jan. 13 2016
CARBONATED	100% OPC	W	CWOC1	25.5%	2008/2009	2803g	Jan. 14 2016
			CWOC2	25.5%	2008/2009	2809g	Jan. 14 2016
		C	CCOC1	25.2%	2008/2009	2814g	Jan. 14 2016
			CCOC2	23.8%	2008/2009	2803g	Jan. 14 2016
		M	CMOC1	25.8%	2008/2009	2784g	Jan. 14 2016
			CMOC2	26.0%	2008/2009	2796g	Jan. 14 2016

3.2. Physical Characteristics of Deicer Laboratory Tests

Influent and Effluent Samples and Characteristics

As previously mentioned, 200mL of water of approximately 3% by mass solutions of each of the three deicing chemicals, or water only, were applied to the specimens in the ambient laboratory room on a weekly basis for 17 weeks starting in March 2016 (Weeks A through Q) according to the protocol in Table 2.1. The effluent volumes (Weeks A through Q) and effluent masses (Weeks F through Q) for each specimen were recorded and are listed in Table B.1 in Appendix B. The effluent volumes were captured for at least 10 minutes in beakers below each specimen and the difference in volume gives an indication of the volume remaining in the specimens, which was then allowed to partially evaporate over approximately a week, concentrating the solutions, until the next application. The effluent volumes and masses together provide information on the densities of the effluents, which are indicative of the total dissolved solids (TDS) in the fluids. The data from Table B.1 has been summarized by averages and standard deviations for the three variables; volume, mass and density in Table 3.3. (Three pairs of volume and mass outliers, those for which there was more than two standard deviations for density, have been removed.)

Table 3.3: Ambient Laboratory Room (H) Testing Effluent Physical Characteristics

		Mass (g)				Volume (mL)				Density (g/mL)			
	-ID	**W**	**M**	**S**	**C**	**W**	**M**	**S**	**C**	**W**	**M**	**S**	**C**
Average Weeks G-Q	**ON1**	149	165	150	149	150	161	147	146	0.994	1.020	1.019	1.021
	ON2	149	165	152	152	150	162	149	148	0.994	1.019	1.015	1.023
	ON3	150	163	147	151	151	159	144	148	0.994	1.022	1.022	1.023
	ON4	152	161	152	150	153	158	149	147	0.994	1.021	1.021	1.021
	FN1	142	160	147	148	143	157	144	144	0.997	1.020	1.024	1.022
	FN2	143	157	144	147	143	154	141	143	0.996	1.019	1.021	1.024
	OC1	163	163	157	171	163	160	153	168	0.998	1.020	1.021	1.020
	OC2	172	168	162	167	172	164	158	163	0.996	1.022	1.026	1.022
	FC1	162	171	167	169	163	168	164	166	0.997	1.019	1.019	1.020
	FC2	164	170	169	170	165	167	166	166	0.996	1.018	1.021	1.022
Standard Deviation	**ON1**	6.7	4.9	5.5	6.0	6.9	4.7	5.5	5.9	0.0062	0.0045	0.0040	0.0075
	ON2	8.2	3.9	2.6	6.5	8.3	3.9	3.8	6.4	0.0033	0.0037	0.0194	0.0027
	ON3	8.1	5.2	5.5	5.6	8.2	5.0	5.5	5.5	0.0046	0.0033	0.0034	0.0041
	ON4	4.2	3.3	4.5	5.2	4.2	3.1	4.8	5.2	0.0038	0.0049	0.0047	0.0055
	FN1	2.3	3.2	3.1	4.7	2.5	3.1	3.0	4.6	0.0053	0.0062	0.0129	0.0048
	FN2	3.1	5.5	4.7	4.2	2.7	5.2	4.6	4.0	0.0055	0.0041	0.0042	0.0045
	OC1	1.7	5.6	2.6	7.7	2.0	5.6	2.6	7.8	0.0042	0.0041	0.0029	0.0057
	OC2	2.1	5.8	1.7	4.6	2.1	5.6	3.5	4.4	0.0052	0.0060	0.0217	0.0037
	FC1	2.4	4.2	3.4	2.9	2.7	4.0	3.1	2.5	0.0037	0.0031	0.0033	0.0047
	FC2	2.5	2.9	2.5	2.6	2.2	2.8	2.2	2.4	0.0041	0.0031	0.0030	0.0044
Total Average						155	161	151	154	0.996	1.020	1.021	1.022
Difference in Density (Deicer – Water)											0.0245	0.0253	0.0261

Table 3.3 provides significant information on the consistency of the experiment. There is a significant amount of variability in the experimental set-up and this is expected to always be the case due to the inherent variability in pervious concrete, environmental conditions, etc. There are variations in the pervious concrete specimens with respect to porosity, height, mix design, and carbonation levels. There is variability in the experiment with respect to temperature and relative humidity in the room, and with respect to the actual hours between applications (on average it was about a week, but some weeks a day earlier or later, and sometimes morning or afternoon). Of course there is always variability due to human errors, solution concentrations, etc. Despite all of these, the results are fairly consistent. Typically around 45 mL of the influent would remain in the specimens after each application and be available for evaporation and solution concentration. On average the density of the effluent indicates approximately 2.5% dissolved solids, regardless of the deicer applied, although the percent increases slightly from the magnesium to the sodium and then to the calcium salts.

Table 3.4 provides both the influent and composite effluent average densities for the various type specimens for weeks G through Q in the ambient laboratory (earlier weeks are not included as additional glassware had not been available then for more accurate volumetric readings since the initial protocols had not included looking for this density variable for all composite samples). Details on volumes and masses for all the specimens can be found in Appendix B, Tables B.1 and B.2.

Table 3.4: Ambient Laboratory Room (H) Testing Influent and Effluent Densities

		Influent (g/mL)				Effluent (g/mL)				Influent/Effluent			
	-ID	W	M	S	C	W	M	S	C	W	M	S	C
Average Weeks G-Q	ON1	0.996	1.019	1.017	1.022	0.994	1.020	1.019	1.021	1.002	0.999	0.998	1.001
	ON2	0.996	1.019	1.017	1.022	0.994	1.019	1.015	1.023	1.002	1.000	1.002	0.999
	ON3	0.997	1.020	1.017	1.022	0.994	1.022	1.022	1.023	1.003	0.998	0.995	0.999
	ON4	0.997	1.020	1.017	1.022	0.994	1.021	1.021	1.021	1.003	0.999	0.996	1.001
	FN1	0.996	1.019	1.017	1.022	0.997	1.020	1.024	1.022	0.999	0.999	0.993	1.000
	FN2	0.996	1.019	1.017	1.022	0.996	1.019	1.021	1.024	1.000	1.000	0.996	0.998
	OC1	0.997	1.019	1.017	1.022	0.998	1.020	1.021	1.020	0.999	0.999	0.996	1.002
	OC2	0.997	1.019	1.017	1.022	0.996	1.022	1.026	1.022	1.001	0.997	0.991	1.000
	FC1	0.997	1.020	1.018	1.022	0.997	1.019	1.019	1.020	1.000	1.001	0.999	1.002
	FC2	0.997	1.020	1.018	1.022	0.996	1.018	1.021	1.022	1.001	1.002	0.997	1.000
Average		0.997	1.019	1.017	1.022	0.996	1.020	1.021	1.022	1.001	0.999	0.996	1.000

As can be seen in the average values in Table 3.4, both the influents and the composite effluents of the deicer solutions had an approximately 2.5% increase in solids over the water control. It can also be seen that there is little or no difference in density between the influents and the effluents. Similar results occurred for the specimens in the cold room, which are summarized in Table 3.5 and for which detailed data are available in Appendix B in Tables B.3 and B.4.

Table 3.5: Average Cold Room (C) Testing Influent and Effluent Densities

		Influent (g/mL)			Effluent (g/mL)			Influent/Effluent		
	-ID	W	M	C	W	M	C	W	M	C
Weeks I-Y	ON1	0.999	1.023	1.025	0.997	1.021	1.025	1.002	1.001	1.000
	ON2	0.999	1.023	1.025	0.997	1.021	1.025	1.002	1.002	1.000
	ON3	0.999	1.023	1.025	0.998	1.021	1.026	1.001	1.002	0.999
	ON4	0.999	1.023	1.025	0.998	1.021	1.026	1.001	1.002	0.999
	OC1	0.999	1.023	1.025	0.998	1.022	1.028	1.001	1.001	0.998
	OC2	0.999	1.023	1.025	0.996	1.022	1.024	1.003	1.002	1.001
Average		0.999	1.023	1.025	0.997	1.021	1.026	1.002	1.002	0.999

Some of the water or the deicer solutions was always retained in each specimen during each application. Therefore, some of the salts remained in the specimens. Table 3.6 is a summary of the volumes of the various solutions that were retained within the specimens after the applications. The average ranged from approximately 30 to 50 mLs and this difference is probably mainly a function of differences in porosity. Note that for the ambient laboratory specimens, collection of this data started at Week G, which was the seventh week of applications in the ambient laboratory. For the cold room specimens, collection of this data started at Week I, which was the first week of applications in the cold room. The cold room data provides additional information since the volumes of the effluent were recorded for the entire application period over the four months. This is portrayed for three specimens with different applications in Figure 3.1. The first week the specimen is dry and therefore during the first two applications a specimen retains more water than later, since after these initial applications, the specimens never fully dry between applications. The difference between the volume retained initially and then over the course of the 17 weeks is approximately 40 mL. Afterwards, the volumes are similar for each respective specimen, indicative of consistency in the experiment. Some conclusions from

this is that each specimen can hold about 80 mL of solution and that about half of that amount evaporates each week, concentrating the solutions within.

Table 3.6: Ambient Laboratory and Cold Room Volumes Retained

Ambient Volume Retained (mL)						Cold Volume Retained (mL)				
	-ID	W	M	S	C		-ID	W	M	C
Average Weeks G-Q	ON1	50	39	53	54	Average Weeks I-Y	ON1	41	34	39
	ON2	50	38	51	54		ON2	39	35	46
	ON3	49	42	56	52		ON3	39	30	46
	ON4	47	42	51	53		ON4	38	31	46
	FN1	57	43	56	56		-	-	-	-
	FN2	57	46	59	57		-	-	-	-
	OC1	37	40	47	32		OC1	29	31	29
	OC2	28	36	42	37		OC2	30	29	37
	FC1	37	32	36	34		-	-	-	-
	FC2	35	33	34	34		-	-	-	-
Average		45	39	49	46		36	32	32	36

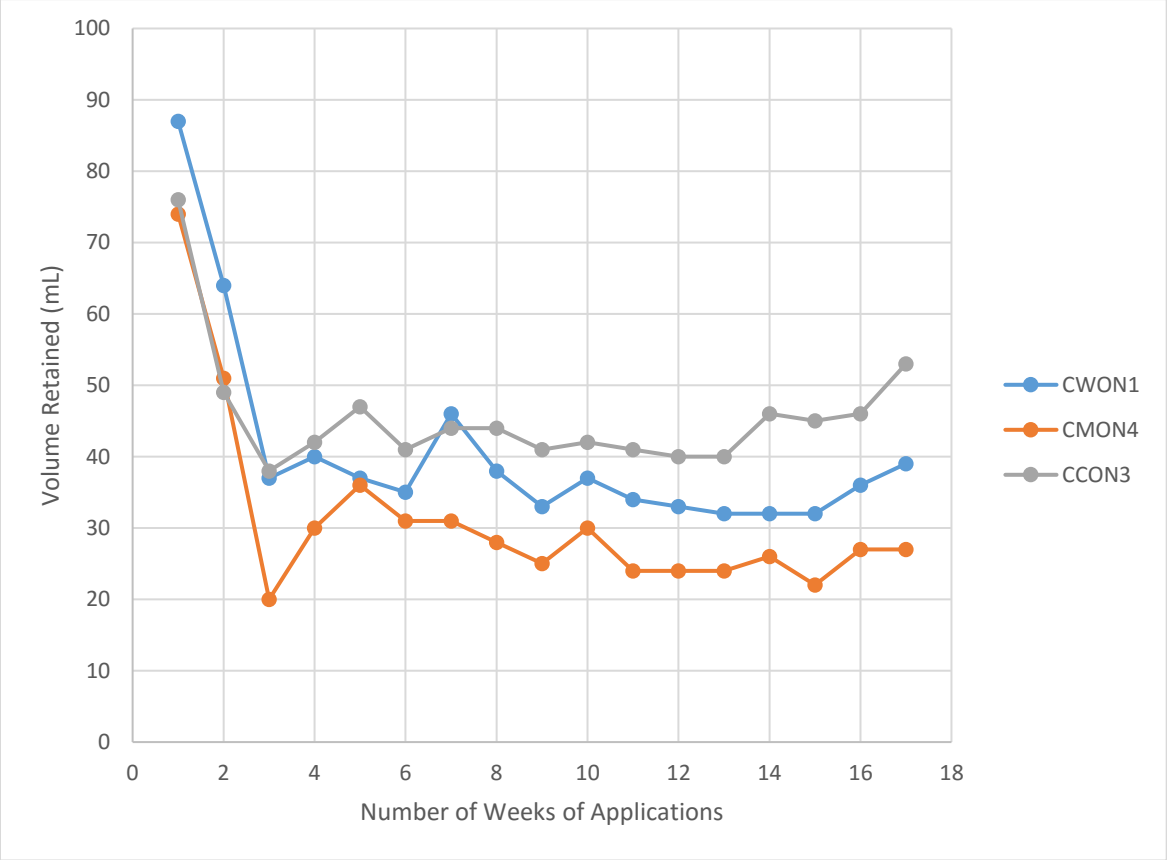

Figure 3.1: Volume of influent retained during each application for a select group of cold room specimens.

Specimen Masses

The masses of each specimen were recorded weekly. Note that there might be variability due to differences in evaporation during the week, etc. These masses were recorded with the specimens wrapped in the shrinkwrap. The trends for the masses provides some information on the effects of the applications. The weekly masses were first corrected for the mass of the shrinkwrap, averaging 18g, and then normalized to the initial masses as listed in Table 3.1 for the ambient laboratory specimens. These values are plotted in Figure 3.2 for the water, calcium chloride and sodium chloride specimens in the ambient laboratory.

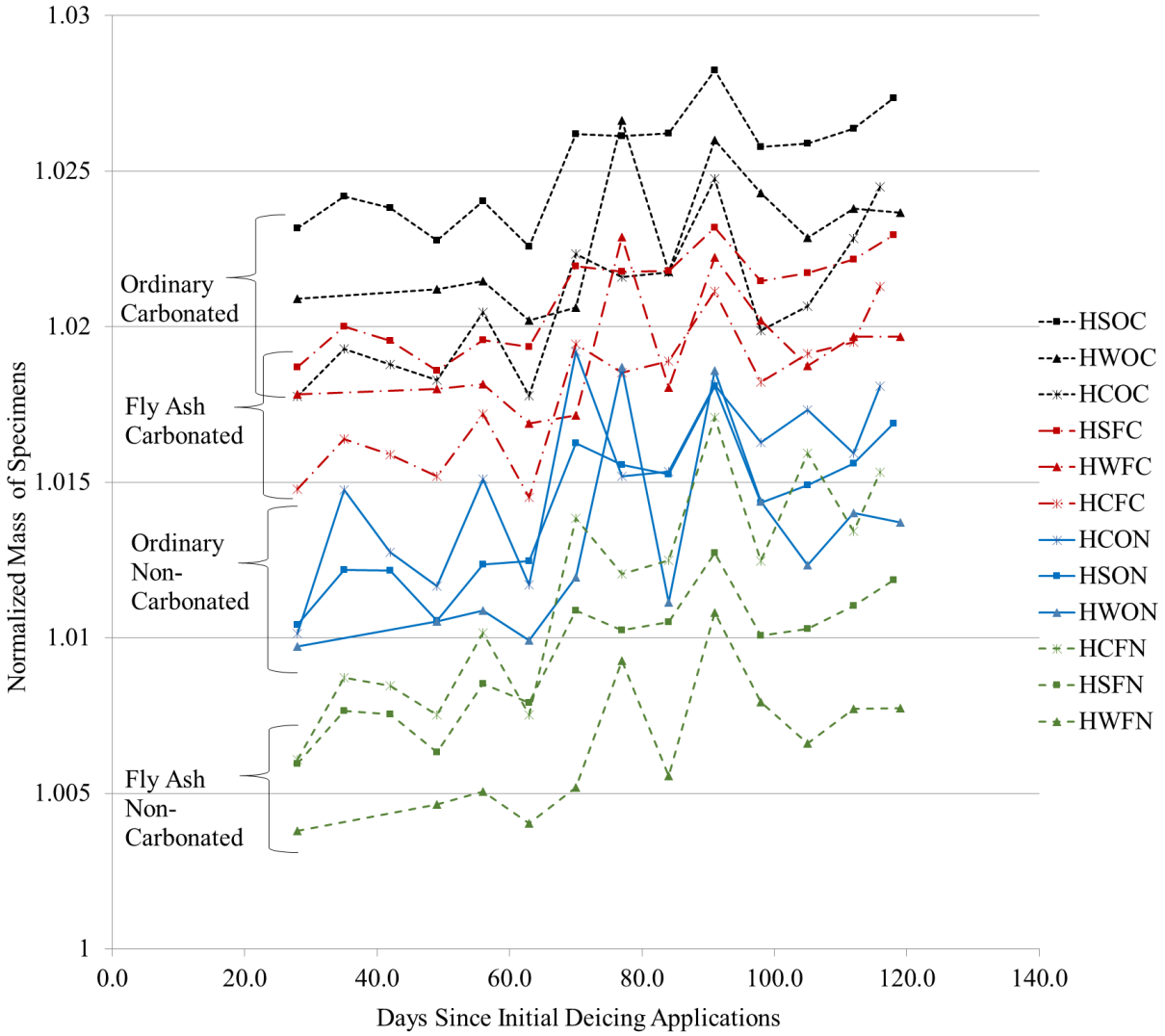

Figure 3.2: Ambient laboratory specimen masses for the water, calcium chloride and sodium chloride applications. Masses are corrected for the mass of the shrinkwrap and then normalized to initial masses as recorded in Table 3.1.

Week-to-week variability due to water retained is evident in Figure 3.2, but the trends are obvious. For all three of the applications, the masses are slowly increasing, regardless of the treatment. Of note is the observation that the fly ash specimens regularly have lower normalized masses than their ordinary Portland cement counterparts. Perhaps there is some initial mass loss

from the different chemistry in the fly ash specimens, but the reason is still unknown. From the data portrayed in Figure 3.2 it might be concluded that the carbonated specimens have a greater mass gain (or smaller mass loss) than the noncarbonated. However, these differences are probably due to the initial masses used for normalization as listed in Table 3.1. The carbonated specimens had been air dried for years prior to taking the initial masses, while the noncarbonated specimens had their initial masses recorded approximately a week after casting, and would still have some water retained during recording of the initial masses. Side experiments on other specimens recording mass over time indicate that it takes weeks for specimens to air dry to a consistent mass under ambient laboratory conditions. Thus, what can be concluded from Figure 3.2 is that in the ambient laboratory, the specimens slowly gained mass over time for these three applications: water, calcium chloride or sodium chloride in a similar manner regardless of application.

However, the magnesium chloride specimens had different mass gains over time from the other applications. Figure 3.3 compares the masses of the specimens receiving the magnesium chloride applications to those receiving the calcium chloride applications. The magnesium chloride specimens on average have a greater mass gain than the calcium chloride specimens for similar specimen types. This is particularly true for the carbonated specimens. This might be indicative of a magnesium species, most likely magnesium hydroxide, precipitating and remaining within the pores of the specimens. This would not be a result of a direct ion exchange between the magnesium and the calcium in the specimens receiving the magnesium chloride treatments, as the atomic weight of calcium (40.1) is greater than that of magnesium (24.3). Therefore, the hypothesis that this mass gain is from precipitation of a species appears most likely.

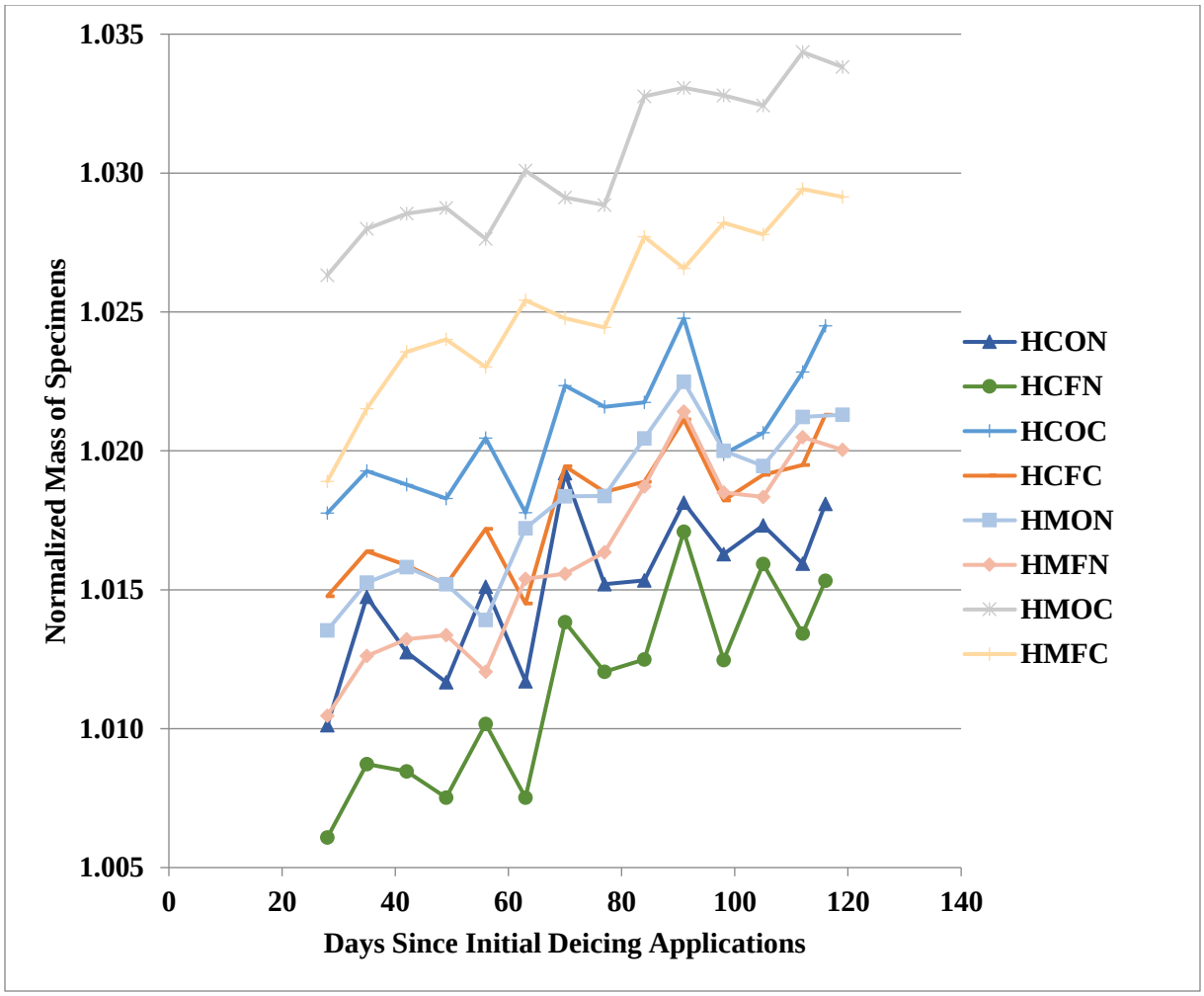

Figure 3.3: Ambient laboratory specimen masses for the calcium chloride and magnesium chloride applications. Masses are corrected for the mass of the shrinkwrap and then normalized to initial masses as recorded in Table 3.1.

4. CALCIUM CHLORIDE DETAILS AND PROPOSED TESTING METHOD

Many qualitative observations were made during the course of the experiments. In the ambient laboratory, approximately two months into the experiment, some dark flakes were noted on the pads below the specimens that were receiving the calcium chloride treatments. This was particularly noticeable for the noncarbonated species. As the weeks progressed, the flakes, and bits of aggregate were collected in vials labeled for the particular treatment received and the specimen type. At the end of the experimental phase, after unwrapping the specimens, this debris and additional debris found in unwrapping were collected and are depicted in Figure 4.1 for the specimens in the ambient laboratory. As can be seen in Figure 4.1, the experimental protocol herein resulted in noticeable degradation of the calcium chloride specimens. This degradation was more severe for the noncarbonated specimens. In addition, there was significant degradation for the specimens with fly ash, but the debris was slightly different. For the OPC specimens, the debris was mainly flakes of hardened cement paste, whereas for the fly ash specimens the debris had less flakes and appeared to be aggregate falling off. As can be seen in Figure 4.1, there was

little or no visible degradation receiving any of the other three treatments in the ambient laboratory.

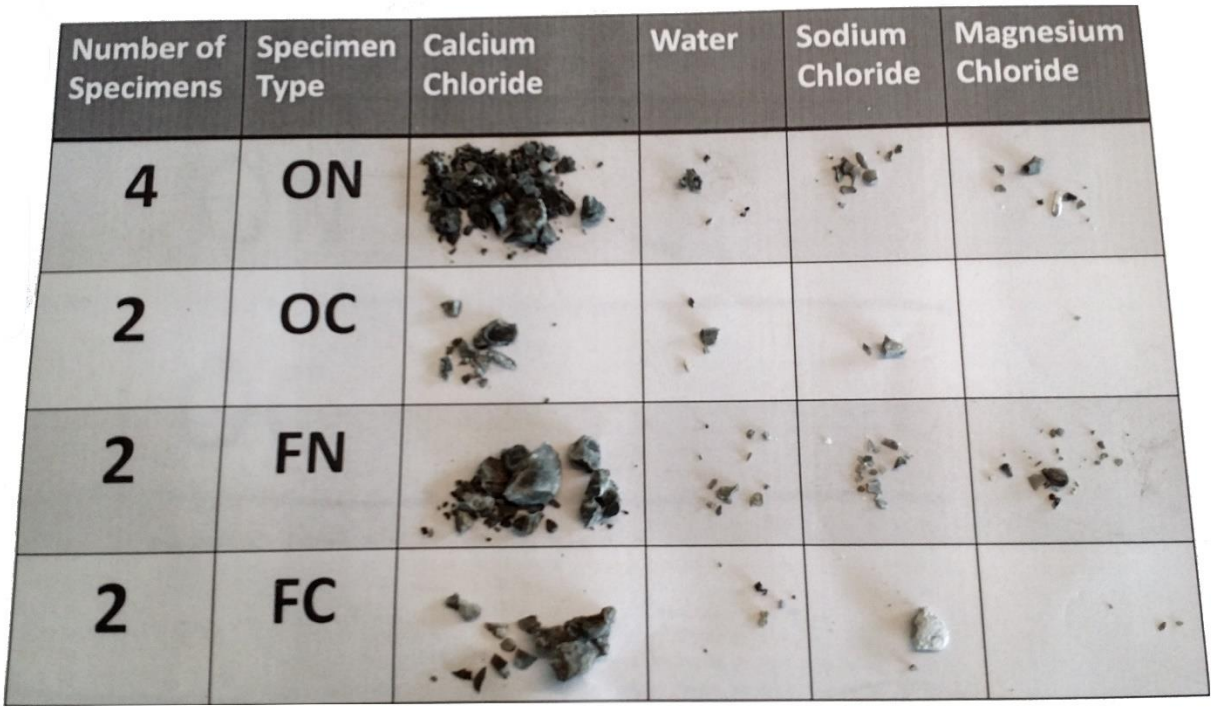

Figure 4.1: Debris from specimens receiving deicing treatments in ambient laboratory.

There was little or no flaking from the specimens during the treatment in the cold room, even for the calcium chloride treatment. This implies that the kinetics in the ambient laboratory are increased and that a protocol of similar testing under ambient laboratory conditions accelerates the degradation in the experiment for the calcium chloride specimens. There was some debris collected from many of the specimens in the cold room when they were unwrapped. However, most of the debris was from the specimens that had the specimen label near the bottom. This label was connected into the specimen with a metal wire and under the cold conditions rusted significantly and much of the debris was rust stained. Those with the wire from the label near the top had less rusting and little debris. Rust spots can be seen on the dripping pads below in Figure 2.4.

Therefore, it is recommended to follow the testing protocol in Section 2.3 for comparing OPC noncarbonated specimens (control) to noncarbonated specimens with other mix designs or treatments (test specimens) that are expected to decrease calcium chloride deicing impacts. This protocol would be performed under ambient laboratory conditions and would need to last several months to mimic the slow deterioration as witnessed herein. It is recommended that the control and the test specimens are similar in porosity, compaction method and size. It is also recommended that at least four control specimens and four specimens of each test type are used to be able to average and account for variability. The test protocol does not provide for a base criteria level for failure, rather, it is to compare the amount of debris formation between a standard mix design and mix designs or treatments intended to decrease chemical deterioration

from calcium chloride deicer applications. This simple testing protocol might serve as an initial screening test of many options. Those mix designs or treatments with less visual deterioration might then be subjected to even more rigorous testing such as freeze-thaw tests.

Measuring volumes and masses of all influent and effluent samples would also serve to aid in validating consistency in the experiments. The testing protocol could also include parallel testing using water or sodium chloride as the treatment for additional controls on testing protocols. Finally, keeping a record of the specimen masses prior to, during and after the testing period would also provide additional information that could be used for further interpretation and validation. Although several months is needed to mimic a winter season of calcium chloride concentration and deterioration, there are little other testing needs in this proposed protocol other than recording masses and volumes.

5. MAGNESIUM CHLORIDE DETAILS AND PROPOSED TESTING METHOD

Previously, in Section 4, it was noted that the magnesium chloride specimens did not visually deteriorate in either the ambient laboratory or the cold room over the course of the approximately four-month experimentation periods. Additional chemical testing on alkalinity proved to be very variable and not reliable to indicate changes in the effluent over time. As will be seen in Section 6, pH also does not appear to be an indicator. Therefore, there was discussion on which chemical results might prove useful to indicate change if the hypothesis is that the magnesium ion is exchanging with calcium ion in those specimens subject to magnesium chloride applications.

The magnesium ion concentrations in the influent are very high, in parts per hundred versus parts per million (ppm) as are in typical water quality tests. Therefore, a small change in ppm, or mg/L in the magnesium ion concentrations in the effluent from the influent would probably not be able to be distinguished from specimen, chemical, environmental and laboratory variability in the experiments. However, an increase in the calcium ion concentration from the influent to the effluent might be a good indicator that this exchange is taking place. Tables C.1 and C.2 in Appendix C provide the composite influent and effluent calcium ion concentrations for the specimens in the ambient laboratory and the cold room respectively, for all applications except the calcium chloride applications, where the calcium concentrations are so high in the influent that small changes would be indistinguishable from variability.

Figure 5.1 is a plot of the composite calcium ion concentrations in the ambient laboratory for the magnesium chloride, water and sodium chloride applications. (Note that data is not available for every week.) It can be seen in Figure 5.1 that the influent calcium ion concentrations are typically lower than the effluent calcium ion concentrations for all three application types.

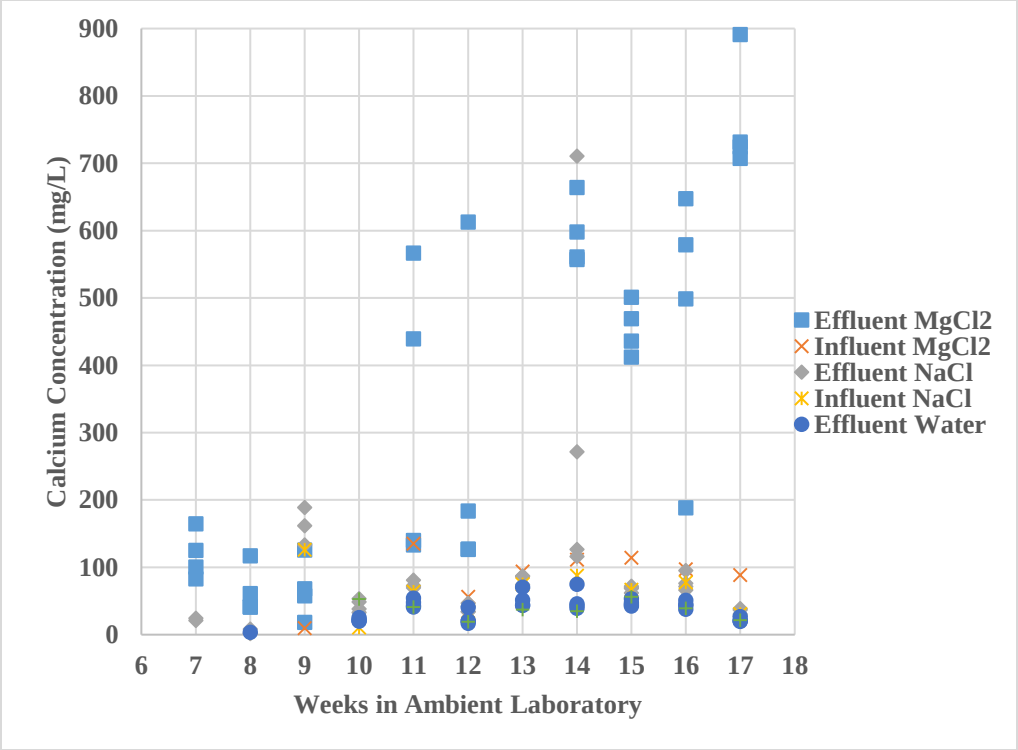

Figure 5.1: Composite calcium ion concentrations in the ambient laboratory in the influent and the effluent of specimens receiving the $MgCl_2$, NaCl or water treatments.

However, in Figure 5.1, the difference in calcium ion concentration between the influent and the effluent is minor for the water applications, somewhat greater in most cases for the sodium chloride applications, and very significant, especially in the last two months for the magnesium chloride treatments. There is variability in Figure 5.1, some of which may be explained by small particles of hardened cement paste falling into the effluent samples. The increases in calcium ion concentration for the magnesium chloride specimens eventually exceed hundreds of mg/L. This is consistent with the theory that the ligands in the concrete will prefer the magnesium ion to the calcium ion, slowly changing the concrete and possibly deteriorating its durability and strength. Further inspection of the data in Table C.1 indicates that the highest effluent calcium concentrations for the magnesium chloride applications in the ambient laboratory are for the ordinary noncarbonated (ON) specimens, and the lowest for the fly ash carbonated (FC) specimens. This is consistent with the higher levels of hydroxides available for magnesium hydroxide formation in the noncarbonated specimens, and previous research indicating that fly ash substitution may improve deicing resistance for traditional concrete (Jain et al. 2011).

Similar results occurred in the cold room. Figure 5.2 depicts the composite calcium ion concentrations in the influent and the effluent for the magnesium chloride and the water applications in the cold room. The effluent from the magnesium chloride treatments has more calcium ion than the influent and this is starting to show an increase over time, but mainly for the noncarbonated specimens, as can be seen in the data in Table C.2 in Appendix C. Both sets of data are further differentiated based on specimen type in both rooms for the magnesium chloride treatment in Figure 5.3. This plot shows how the noncarbonated specimens tend to have higher effluent concentrations of calcium ion than the carbonated, with the fly ash specimens typically

losing less calcium, although they would have less calcium ions available in the concrete to start. Most notably in Figure 5.3 is the time axis. Significant exchange is a slow process, taking about two months to be very evident in the ambient laboratory, and much slower in the cold room.

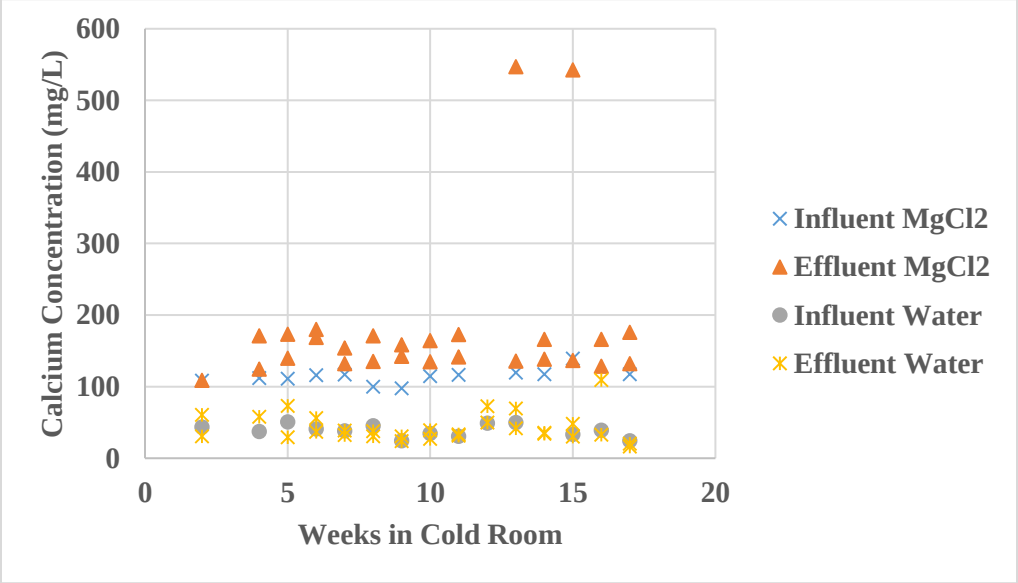

Figure 5.2: Composite calcium ion concentrations in the cold room.

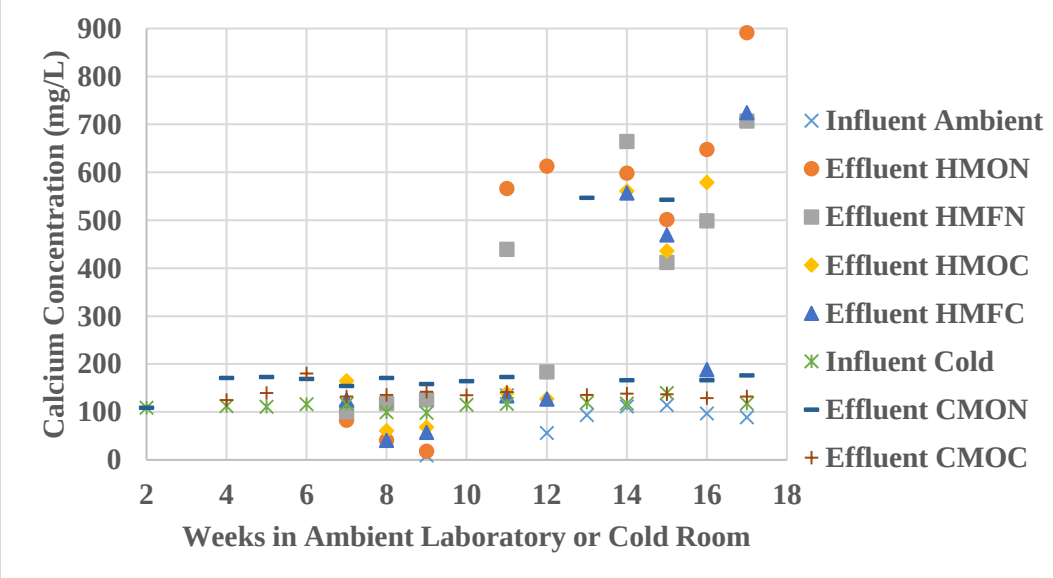

Figure 5.3: Composite calcium ion concentrations for magnesium chloride applications in both rooms, plotted with different symbols by specimen type.

In summary, the noncarbonated specimens appear to have the most leaching of calcium from the specimens in the ambient room and for the magnesium chloride deicer applications. Figure 5.4 is a graph that is similar to the aforementioned figures for the calcium ion, but provides the ratio of effluent to influent calcium ion concentrations for the various ordinary noncarbonated specimens under both water and magnesium chloride applications, and for both rooms. As can be seen significant leaching is found from the magnesium chloride applications after about two months.

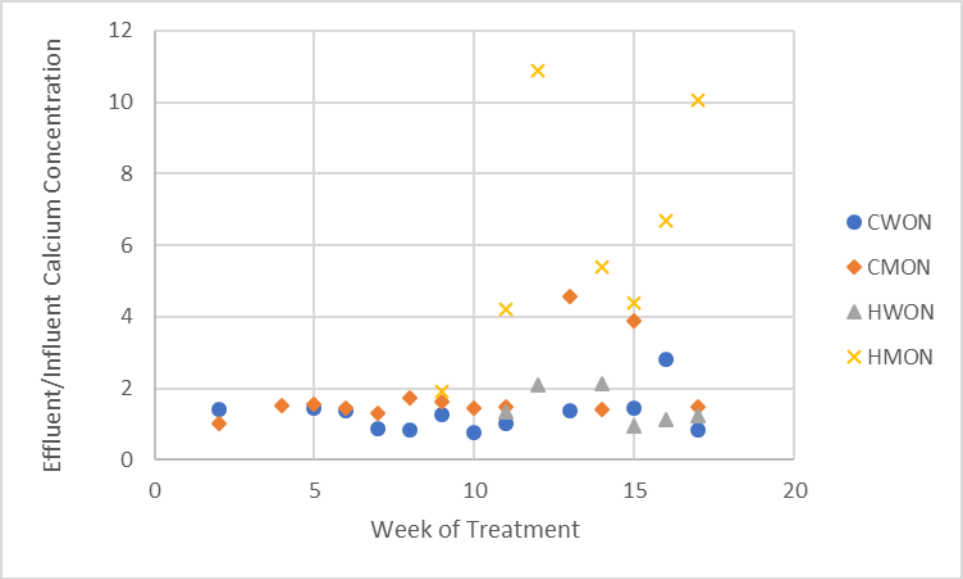

Figure 5.4: The ratio of effluent to influent calcium ion concentrations for magnesium chloride and water applications in both rooms for ordinary noncarbonated specimens.

Thus, it appears that the testing protocol in Section 2.3 is also a good method for determining if calcium is being leached from the use of magnesium chloride deicers. This would be similar to the proposed method in Section 4 for calcium chloride deicer comparisons of various mix designs or treatments, but would also entail adding the calcium ion testing in the influent and effluent samples. At this point, this only indicates calcium leaching and not necessarily loss in strength or durability. Further testing would need to be performed to confirm that loss of calcium ion would indicate a significant degradation. As with the suggested protocol for screening different mixes and treatments for improved resistance to chemical degradation by calcium chloride, this testing protocol for magnesium chloride does not have a baseline criteria for calcium ion loss, instead it would be used for comparing a standard mix design to various alternatives for initial screening for calcium leaching.

In addition, if the mass gains for the magnesium applications, and the calcium losses are indicative of magnesium hydroxide precipitation in the pores of the specimens, then in addition to the chemical degradation implied herein, the precipitates might participate in physical impacts during freeze-thaw cycles and further testing would need to be performed to confirm this. Figure 5.5 is a photograph of some precipitate formation on the bottom of specimens subject to magnesium chloride treatments. However, the photographs of specimens receiving calcium chloride deicing treatments and sodium chloride deicing treatments in Figures 5.6 and 5.7 also show some salt buildup on the bottom of the specimens. Therefore, salt buildup on the bottoms of the specimens may not be indicative of different interior precipitates forming, as these might simply be precipitation of the original salts as the water evaporates from the surface.

Figure 5.5: Solid precipitate formation on the bottom of a specimen subjected to magnesium chloride treatments.

Figure 5.6: Solid precipitate formation on the bottom of three specimens subjected to calcium chloride treatments.

Figure 5.7: Solid precipitate formation on the bottom of three specimens subjected to sodium chloride treatments.

6. ANCILLARY TESTS, SUMMARY AND SUGGESTIONS

Several other chemical tests were performed on various samples. Most of these are not included herein as they were very variable or were difficult to perform due to the very high salt concentrations in the influent and effluent samples. However, the results from the pH tests are provided in Section 6.1 with conclusions, since pH testing is relatively simple to perform. In addition, a side test on abrasion of some specimens from each deicing treatment was performed to see if that test might provide some insight (Section 6.2). Finally, a summary of the conclusions and some further suggestions for testing are provided in Sections 6.3 and 6.4.

6.1. Ancillary pH Tests

pH measurements were taken on all the composite influent and effluent specimens. Details on the values are listed in Tables C.3 and C.4 in Appendix C. The data are also plotted for the magnesium chloride and the calcium chloride specimens in the ambient laboratory in Figure 6.1, and for the water and the sodium chloride specimens in Figure 6.2. The four weeks that DI water was used are excluded from these figures, as they resulted in higher effluent pH values for the water specimens, which is expected for contact with concrete if there is not significant buffering capacity in the solution.

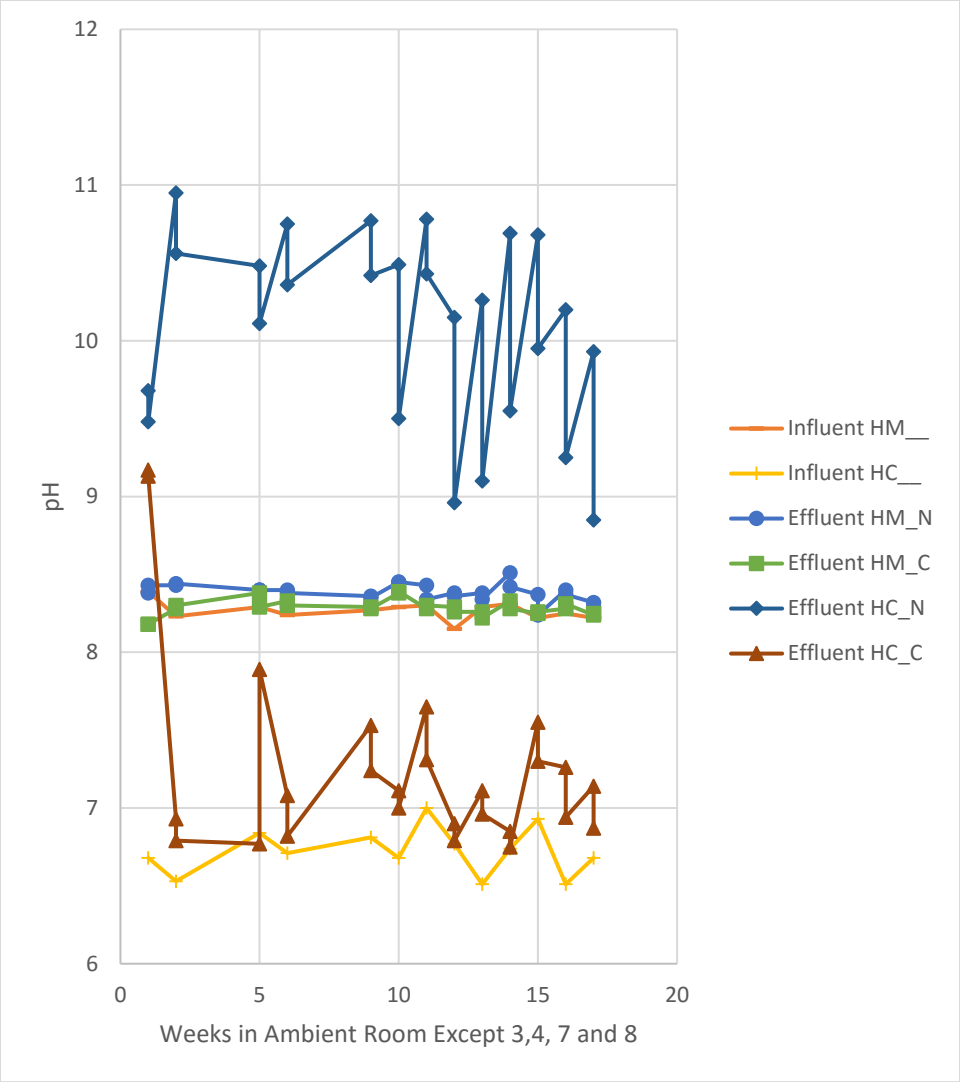

Figure 6.1: Composite pH levels for magnesium chloride and calcium chloride specimens in the ambient laboratory.

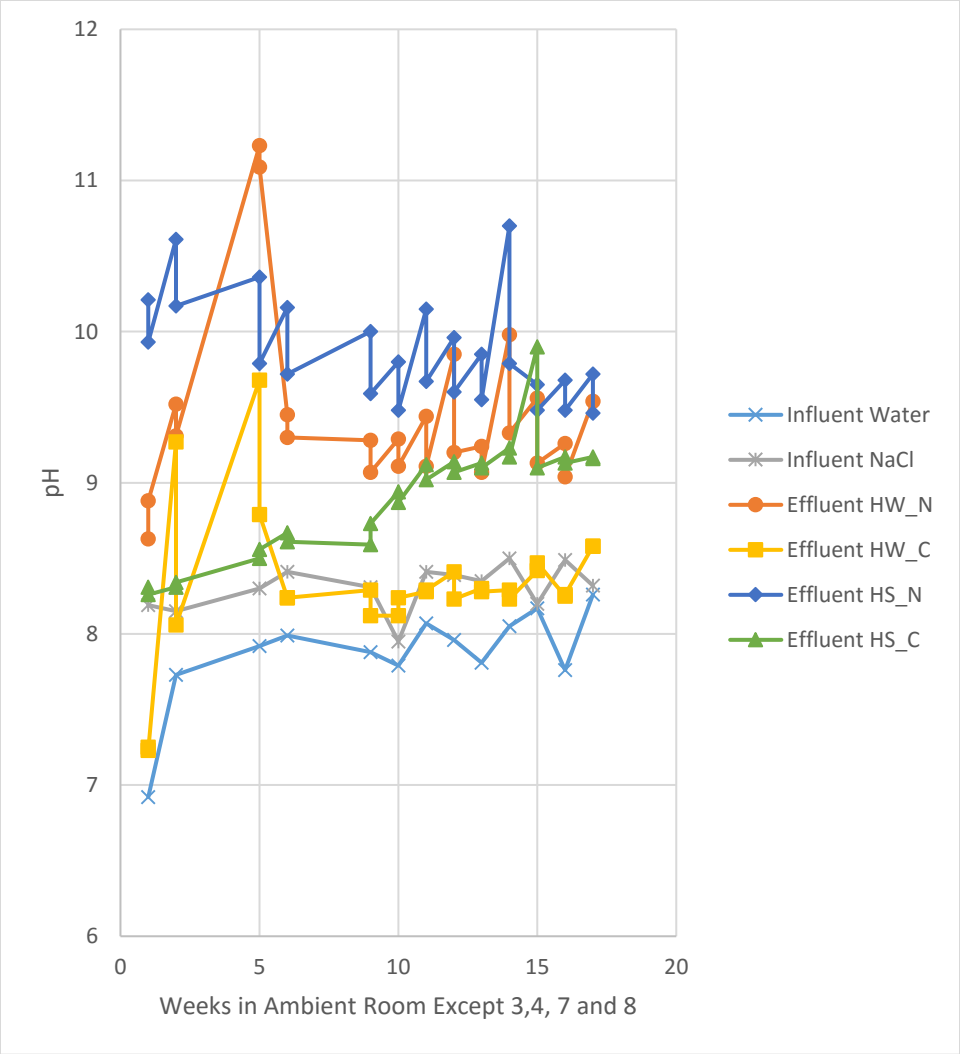

Figure 6.2: Composite pH levels for water and sodium chloride specimens in the ambient laboratory.

As can be seen in Figure 6.1, pH does not change significantly with time from influent to effluent for the magnesium chloride solutions. This was also evident in the data from the cold room. The pH in the effluent is typically lower for the carbonated specimens than the noncarbonated specimens, and significantly so for the calcium chloride specimens. As can be seen in Figures 6.1 and 6.2, the pH of the effluent from the noncarbonated specimens slowly decreased over the weeks for the water, sodium chloride and the calcium chloride specimens, most likely due to carbonation. Conversely, the pH of the effluent from the carbonated specimens receiving the sodium chloride treatment is increasing over time. There is no direct explanation for this from these tests. Perhaps this phenomenon has to do with a sodium carbonate or bicarbonate reaction. Thus, pH is not a good indicator for deicing resistance protocols as the pH may also decrease for the water, calcium and sodium solutions applied to the noncarbonated specimens over time due to a reaction with ambient air regardless of the number of these deicer applications, and also has the inverse trend over time for the carbonated specimens receiving the sodium based salt. Therefore, using pH as an indicator of resistance to deicer degradation is not expected to be reliable due to the many other causes of pH variation.

6.2. Ancillary Abrasion Tests

Abrasion testing was performed on three specimens from each of the four deicing treatment options in the ambient laboratory. In each case, two of the OPC noncarbonated and one of the OPC carbonated specimens were used. The test was based on an abrasion test specifically developed for pervious concrete (ASTM 2013). This test is intended to see if there is *less abrasion* in specimens that are made with different mixes and in different manners than what might be expected from a more traditional mix, such as with OPC only and no addition of sand or fibers or other special additives. However, in the cases herein, the interest is in determining if there is *more abrasion* of specimens subject to various deicer treatments. Therefore, the number of revolutions was reduced from 500 to 200 in an attempt to be in a range of some, but not full, degradation. Figure 6.3 is a photograph of the machine used for the abrasion testing. Figures 6.4, 6.5, 6.6 and 6.7 are photographs of the debris and remaining portions of the specimens after abrasion testing for the magnesium chloride, calcium chloride, sodium chloride and water treatments respectively. Very little difference was seen in the results for the magnesium chloride or the calcium chloride treatments versus the water or sodium chloride controls. In fact, the sodium chloride specimens had a 20.5%, the magnesium chloride specimens had a 19.8%, the calcium chloride had a 24.1% and the water specimens had a 26.7% loss in mass. It appears that variations in porosity might have more impact on abrasion mass loss than the deicer treatments. This is depicted in Figure 6.8 which is a plot of average porosity versus mass loss for the specimen types in the four treatments. Porosity appears to be the governing factor. Therefore, due to porosity variations, this abrasion test does not appear to be a good indicator of resistance to degradation for various options due to deicer applications after following the aforementioned testing protocols.

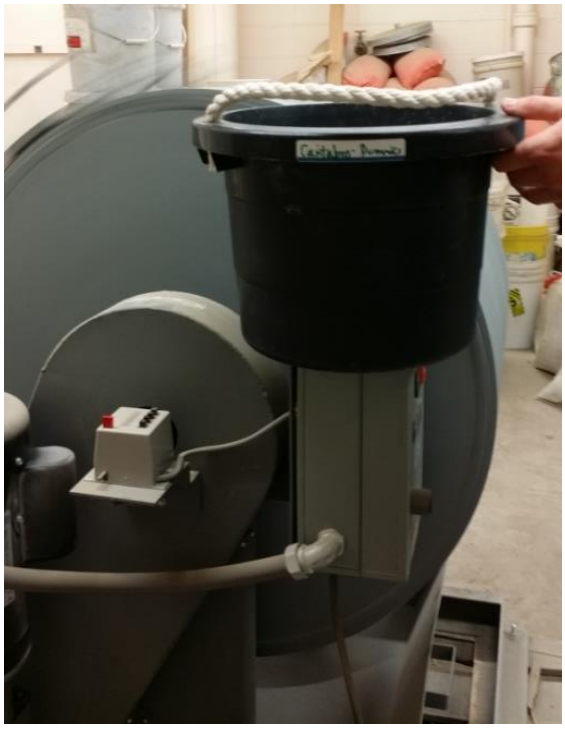

Figure 6.3: The machine used for the abrasion test.

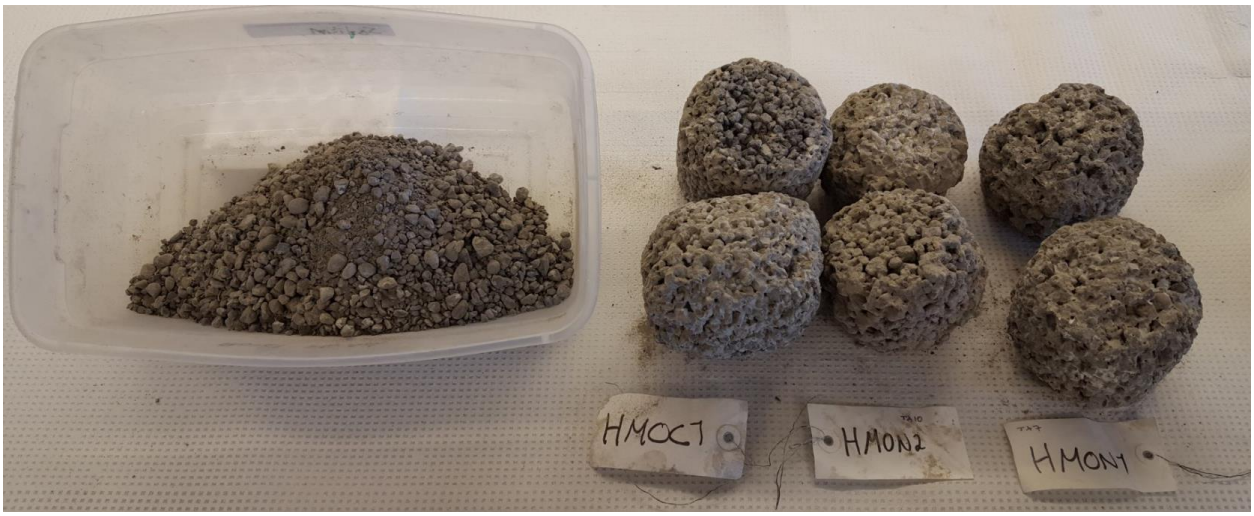

Figure 6.4: Abrasion test debris from three magnesium chloride specimens.

Figure 6.5: Abrasion test debris from three calcium chloride specimens.

Figure 6.6: Abrasion test debris from three sodium chloride specimens.

Figure 6.7: Abrasion test debris from three water specimens.

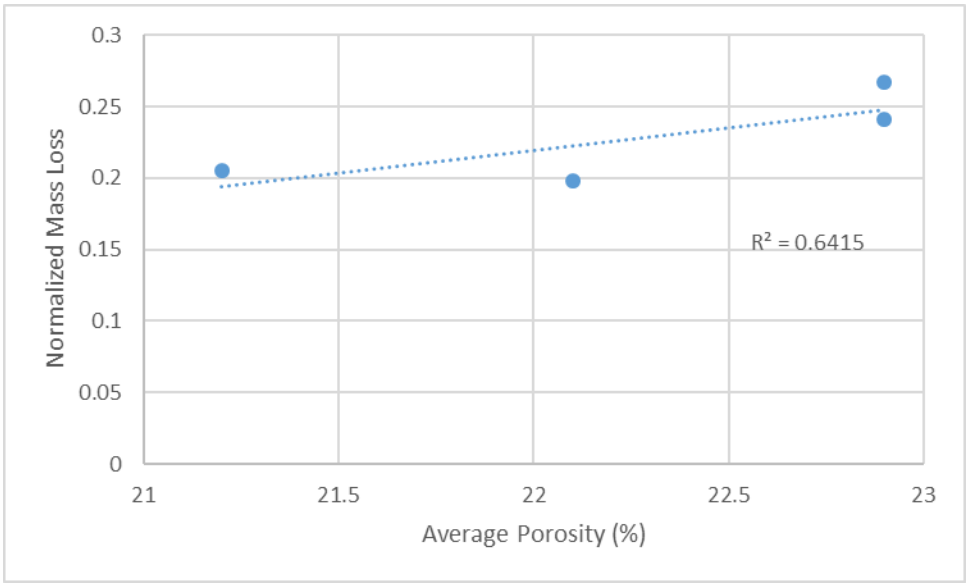

Figure 6.8: Mass loss versus porosity for specimen sets in abrasion test.

6.3. Summary

The proposed research was to develop a standardized laboratory procedure to evaluate the chemical impacts of various deicing methodologies on pervious concrete and would:

1: Set a standard laboratory specimen size.
2: Establish a range of 'loading' the specimen with various deicers applicable to the field methods.
3: Investigate a series of temperature related scenarios.

These three requirements were met with the following:

1: Size: 4 inch diameter specimens of a depth typical in many applications such as from 6 to 8 inches. The specimens would have shrinkwrap or other material around the cylindrical sides to form columns where solutions could be applied to the top and allowed to flow out the bottom. It is suggested that some control specimens be made from OPC without addition of supplementary cementitious materials. It is also suggested that the control and the test specimens be freshly made with little carbonation, at least when determining the deicer impacts for young placements.
2: Loading: Top applications of from 2% to 3% by mass of the deicer with 200 mL applications on a weekly basis over a period of approximately four months. In between the weekly applications, the specimens would be allowed to partially air dry, providing for the solutions to concentrate within the specimens.
3: Temperature: Testing was performed at both ambient laboratory conditions and in a cold room. The ambient laboratory setting had more visible deterioration for the calcium chloride tests, and more leaching of calcium from the concrete for the magnesium chloride tests than similar tests in the cold room. Therefore, it appears that ambient laboratory conditions will suffice for testing and that there is no need to have cold conditions included. Testing under cold conditions might take longer.

The results from the testing on the ***calcium chloride specimens*** suggest that the ambient room protocol using a similar setup and comparing 'modified' specimens to ordinary noncarbonated specimens may be a good method for evaluating resistance to calcium chloride deicer degradation. This could be performed with or without water controls, and the results after a similar or longer testing period would indicate whether there is visible debris falling off the 'modified' versus the control specimens. This loss of mass seen by the falling flakes or debris, as previously stated, appears to be based on concentrated (supersaturated) calcium chloride solutions that might result in a stripping of hydroxide ions from the concrete forming an aqueous calcium hydroxide species. It was also seen in the previous study by Jain et al. (2011) on traditional concrete with the wetting of specimens by concentrated (28%) calcium chloride solutions with mass loss and visual spalling. The study by Darwin et al. (2008) on traditional concrete also suggests a mass loss from concentrated calcium chloride applications and correlates this to a loss in strength. The Darwin et al. (2008) study used specimens that were recently cast, which supports the use of noncarbonated specimens as suggested herein.

The results from the testing on the ***magnesium chloride specimens*** suggest that the ambient room protocol using a similar setup and comparing 'modified' specimens to ordinary noncarbonated specimens may be a good method for evaluating resistance to magnesium chloride deicer degradation, particularly for leaching of calcium from the concrete. This could be performed with or without water controls. The testing is more complex than for the proposed calcium chloride testing in that it requires chemical analyses for calcium ion concentrations in both the influent and the effluent to determine if calcium is being stripped from the specimens during the applications. Evaluation of the calcium ion concentration in the effluent does not prove that a loss of strength or durability would occur, but the studies by Jain et al. (2011) and Darwin et al. (2008) on traditional concrete indicate that magnesium chloride exposure without freeze-thaw cycles can correlate to a loss in compressive strength. Again, the Darwin et al. (2008) study used specimens that were recently cast, which supports the use of noncarbonated

specimens as suggested herein. However, additional physical testing on pervious concrete may be needed to substantiate this.

Similarly, the results from the testing on the ***magnesium chloride specimens*** suggest that the ambient room protocol with the recording and comparison of the specimen masses over time may also be useful. An increased mass over time might indicate a buildup of precipitate in the specimens. A larger addition of mass over time during the ambient room experiments with magnesium chloride does not imply degradation of the specimens. However, the freeze-thaw study by Dang et al. (2016)on traditional concrete indicates that magnesium chloride specimens have a slight increase in mass and did not perform as well in split tensile tests. Additional physical testing on pervious concrete is needed to substantiate this.

Although some previous studies such as Jain et al. (2011) find that the addition of ***fly ash*** might aid in mitigating concerns over deicer impacts from magnesium chloride and calcium chloride, the results from the work herein were not conclusive in supporting this. For the calcium chloride deicer tests in the ambient laboratory, as can be seen in Figure 4.1, there was significant debris from some of the specimens with 25% fly ash substitution. However, the specimens with only OPC appeared to have earlier and more flaking and the fly ash ones appeared to have mostly aggregate pieces falling off. Speculation might be that there is less cementing of the aggregates in the fly ash specimens, but further testing would need to confirm this. Similarly, for magnesium chloride applications the results are not conclusive. In Figure 3.3, the masses of the specimens for the specimens in the ambient laboratory receiving magnesium chloride treatments show similar gains regardless of the addition of fly ash or not. In addition, Figure 5.3 indicates that there is similar leaching of the calcium ion as the treatments progress in the cold room for specimens with or without fly ash, even when the fly ash used had a low calcium content.

This research also supports the premise that there might be chemical impacts from certain deicer applications, not only physical or a combination of chemical and physical. The following comments are related to the four hypotheses presented in Section 1.3.

1. This hypothesis is supported by the work. The results of the testing on the calcium ion concentrations in the influent and the composite effluent samples for the magnesium chloride treatments versus the water and sodium chloride treatments indicate a larger increase in aqueous phase calcium ion concentration, which, under ambient laboratory conditions progressively becomes greater (Figure 5.1). In addition, the specimens receiving magnesium chloride treatments typically have a larger mass gain over time versus the other treatments (Figure 3.3). These two together indicate that there is an ion exchange between the magnesium and chloride ions as suggested by complexation and precipitation chemistry equilibria, and that probably the resultant magnesium species is precipitating within the pores of the specimens. If there was an ion exchange without precipitation, then there would be a mass loss, not a mass gain.

2. This hypothesis is supported by the work. The visual degradation of many of the specimens in the ambient room indicate that some of the cementing capacity of the concrete is being leached with the applications of the calcium chloride deicer. This was not indicated by mass losses, nor alkalinity, but instead visual degradation.

3. This hypothesis is partially supported by the work. The specimens receiving the sodium chloride treatment had less visible degradation than those receiving the calcium chloride treatment, however, this was not confirmed by chemical analyses.

4. This hypothesis is neither supported nor not supported by this research. Chloride ion concentrations were so high in the influents that small differences would have not been easily detectable between the influent and effluent samples.

The final observation is that both the visible degradation for the calcium chloride applications and the ion exchange between the magnesium and the calcium ion for the magnesium chloride treatments are time dependent. Neither became significantly apparent until after a couple of months of weekly deicer treatments. It is speculated that infrequent applications of deicing chemicals would not have similar results, particularly if precipitation events between applications flush the deicing chemicals out of the pores. The work herein is representative of frequent applications, with no flushing, over a period representing a long winter period.

6.4. Suggestions

The proposal indicated that this report would provide suggestions for a series of tests that could further evaluate field performance e.g. possibly compression test, freeze-thaw test, etc. The research did include an investigation into an abrasion test as summarized in Section 6.2, but this test appears to not be very useful due to the impacts of porosity variations. The chemical testing work included 58 specimens with close to a thousand applications, and numerous physical and chemical analyses related to the specimens, influents and effluents from these applications. The abrasion test performed left only a smaller group of specimens available for more physical testing, as this test is a destructive test. Some preliminary testing might be applied to these specimens for screening into other physical strength testing. However, for conclusive research additional specimens would need to be used after receiving similar treatments. Some options might be the following:

Dang et al. (2016) used *split tensile tests* on traditional concrete exposed to magnesium chloride. This test could be used on pervious concrete control and test specimens to see if the chemical changes noted herein might result in decreases in strength or durability. Many replicates of specimens would need to be tested as porosity variations and subsequent impacts on strength and durability would need to accounted for in the statistical analyses. After the specimens are split, there might also be evidence of interior precipitation of magnesium species as suggested by the mass increases noted herein. This same test might also be used to determine strength impacts of calcium chloride applications versus control specimens.

Based on the literature there is some indication that freeze-thaw cycles might affect the durability. Thus, it would be useful to subject sets of specimens that have been exposed to, and chemically changed by the aforementioned deicer applications, to *freeze-thaw testing*. It is suggested that these be performed under wetted, but not saturated conditions, as the large amounts of water in the large pores of pervious concrete might have impacts that mask the effects of chemical changes.

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APPENDIX A: ANCILLARY SPECIMEN CHARACTERIZATIONS

Table A.1: Infiltration Rates: Ambient Room Temperature Specimens: Noncarbonated

			ID	Prewet Time (s)	Average Time Test (s)	Infiltration Rate (in/hr)	Infiltration Rate (cm/hr)
NONCARBONATED	100% ORDINARY PORTLAND CEMENT	Water	HWON1	20.40	23.76	736	1869
			HWON2	16.49	16.38	1067	2711
			HWON3	17.74	20.90	836	2125
			HWON4	20.26	20.52	852	2164
		Calcium	HCON1	20.18	22.27	785	1994
			HCON2	19.10	19.39	902	2290
			HCON3	21.45	24.14	724	1839
			HCON4	17.48	17.12	1021	2594
		Magnesiu	HMON1	20.69	21.70	806	2046
			HMON2	20.67	23.05	758	1926
			HMON3	13.94	13.09	1336	3392
			HMON4	21.33	23.71	737	1873
		Sodium	HSON1	29.29	29.21	598	1520
			HSON2	20.75	20.60	849	2156
			HSON3	20.34	21.29	821	2086
			HSON4	18.77	18.32	954	2424
	25% FLY ASH	W	HWFN1	15.97	16.36	1069	2714
			HWFN2	18.38	17.30	1011	2567
		C	HCFN1	16.36	19.16	912	2318
			HCFN2	15.71	16.87	1036	2632
		M	HMFN1	23.75	22.01	794	2017
			HMFN2	18.03	18.12	965	2451
		S	HSFN1	23.93	29.87	585	1487
			HSFN2	23.21	23.14	755	1919

Table A.2: Infiltration Rates: Cold Room Temperature Specimens

			ID	Prewet Time (sec)	Average Infiltration Time (sec)	Average Infiltration Rate (in/hr)	Average Infiltration Rate (cm/hr)
NONCARBONATED	100% OPC	Water	CWON1	16.1	18.5	945	2403
			CWON2	21.0	23.0	762	1936
			CWON3	26.5	27.4	647	1624
			CWON4	20.5	21.1	827	2102
		Calcium	CCON1	26.0	28.2	619	1574
			CCON2	18.4	20.2	822	2205
			CCON3	22.0	22.8	772	1963
			CCON4	13.7	15.5	1125	2858
		Magnesiu	CMON1	26.1	27.6	634	1611
			CMON2	20.9	24.9	702	1784
			CMON3	16.5	21.0	833	2117
			CMON4	17.7	19.8	883	2244
CARBONATED	100% OPC	W	CWOC1	NA	13.9	1258	3197
			CWOC2	NA	11.7	1494	3798
		C	CCOC1	NA	11.7	1494	3796
			CCOC2	NA	16.7	1050	2668
		M	CMOC1	NA	11.4	1540	3914
			CMOC2	NA	13.0	1344	3416

*Noncarbonated data were provided by Trace Sendele and Brandon Werner in January 2016 while the carbonated data were provided by Brandon Werner as recorded in 2015

APPENDIX B: PHYSICAL DATA FROM DEICING APPLICATIONS

Table B.1: Effluents in the Ambient Room (*with DI Water)

		Effluent Mass (g) for Solution				Effluent Volume (mL)			
Week	**-ID**	**Water**	**$MgCl_2$**	**NaCl**	**$CaCl_2$**	**Water**	**$MgCl_2$**	**NaCl**	**$CaCl_2$**
A	ON1	N/A	N/A	N/A	N/A	N/A	130	122	128
	ON2	N/A	N/A	N/A	N/A	N/A	128	124	126
	ON3	N/A	N/A	N/A	N/A	N/A	130	118	120
	ON4	N/A	N/A	N/A	N/A	N/A	138	123	130
	FN1	N/A	N/A	N/A	N/A	N/A	120	126	106
	FN2	N/A	N/A	N/A	N/A	N/A	120	120	106
	OC1	N/A	N/A	N/A	N/A	N/A	134	136	152
	OC2	N/A	N/A	N/A	N/A	N/A	132	128	140
	FC1	N/A	N/A	N/A	N/A	N/A	152	150	146
	FC2	N/A	N/A	N/A	N/A	N/A	150	156	134
B	ON1	N/A	N/A	N/A	N/A	N/A	130	122	128
	ON2	N/A	N/A	N/A	N/A	N/A	128	124	126
	ON3	N/A	N/A	N/A	N/A	N/A	130	118	120
	ON4	N/A	N/A	N/A	N/A	N/A	138	123	130
	FN1	N/A	N/A	N/A	N/A	N/A	120	126	106
	FN2	N/A	N/A	N/A	N/A	N/A	120	120	106
	OC1	N/A	N/A	N/A	N/A	N/A	134	136	152
	OC2	N/A	N/A	N/A	N/A	N/A	132	128	140
	FC1	N/A	N/A	N/A	N/A	N/A	152	150	146
	FC2	N/A	N/A	N/A	N/A	N/A	150	156	134
C*	ON1	197.0	201.7	201.3	201.6	N/A	130	122	128
	ON2	198.5	202.1	201.7	202.5	N/A	128	124	126
	ON3	197.1	201.5	202.0	202.7	N/A	130	118	120
	ON4	197.6	201.0	200.7	202.3	N/A	138	123	130
	FN1	198.0	203.7	202.1	203.0	N/A	120	126	106
	FN2	198.4	202.9	201.9	202.6	N/A	120	120	106
	OC1	198.7	203.0	203.3	202.5	N/A	134	136	152
	OC2	200.0	202.7	202.7	202.3	N/A	132	128	140
	FC1	201.2	202.8	202.5	202.9	N/A	152	150	146
	FC2	201.6	203.0	202.1	203.3	N/A	150	156	134
D*	ON1	196.8	203.5	204.5	203.5	148	158	148	142
	ON2	197.8	202.3	202.4	203.0	150	158	149	151
	ON3	197.1	202.6	202.2	203.5	148	155	145	146
	ON4	197.0	202.9	202.5	203.1	150	151	149	149
	FN1	197.9	202.3	203.4	202.7	130	152	148	135
	FN2	197.0	203.0	202.7	202.9	140	148	140	139
	OC1	198.1	202.9	203.3	203.3	162	156	151	171
	OC2	198.7	202.6	202.9	203.4	172	162	157	153
	FC1	197.3	204.0	202.3	203.3	162	165	162	170
	FC2	197.7	203.2	201.6	204.0	162	163	164	169

Week	-ID	Water	$MgCl_2$	NaCl	$CaCl_2$	Water	$MgCl_2$	NaCl	$CaCl_2$
E	ON1	200.5	202.8	201.7	202.3	142	157	139	136
	ON2	200.2	202.7	202.0	202.5	143	160	140	138
	ON3	199.5	202.2	202.2	202.9	142	153	137	140
	ON4	199.4	202.7	201.9	202.6	146	153	142	142
	FN1	199.2	202.7	202.8	202.9	140	152	142	138
	FN2	200.0	201.9	202.7	202.8	137	140	135	138
	OC1	200.1	202.2	203.2	202.6	162	154	154	167
	OC2	199.7	203.1	203.6	202.2	173	163	159	155
	FC1	200.0	203.0	203.7	203.2	164	160	168	165
	FC2	200.2	202.6	202.3	203.3	161	166	165	164
F	ON1	198.3	203.0	202.7	204.9	142	157	143	142
	ON2	198.4	202.9	202.2	204.9	140	160	140	140
	ON3	199.3	202.7	202.9	204.8	142	154	139	143
	ON4	198.8	202.6	202.6	204.4	148	154	143	146
	FN1	198.5	202.1	202.8	204.4	138	154	143	136
	FN2	198.4	202.4	202.2	204.2	140	150	133	134
	OC1	198.9	203.5	203.1	204.8	160	154	154	171
	OC2	199.3	203.7	202.1	203.4	173	162	158	159
	FC1	198.8	203.4	202.1	203.7	163	164	162	165
	FC2	199.2	203.5	202.4	203.8	168	166	162	163
G*	ON1	148.8	162.3	152.0	148.1	150	159	150	148
	ON2	145.5	164.2	149.8	152.5	146	161	148	149
	ON3	153.7	159.9	144.7	153.0	155	157	142	150
	ON4	151.9	159.8	151.7	152.8	153	157	150	150
	FN1	144.6	158.6	149.1	149.7	146	156	148	148
	FN2	141.4	153.2	148.1	148.6	143	151	146	146
	OC1	162.7	160.2	155.3	173.5	164	157	152	171
	OC2	173.2	165.2	162.5	163.9	175	162	149	161
	FC1	163.5	165.0	162.1	168.9	164	163	160	166
	FC2	165.2	167.5	168.4	168.5	166	165	166	165
H*	ON1	148.7	161.3	151.5	140.4	149	158	149	137
*except	ON2	145.4	159.8	152.6	146.7	146	157	150	134
$CaCl_2$	ON3	142.3	157.6	148.8	141.7	142	154	145	138
	ON4	152.9	158.0	152.7	144.6	153	155	150	141
	FN1	139.3	156.5	153.0	144.5	140	155	150	142
	FN2	139.9	152.0	149.9	143.3	140	150	146	140
	OC1	162.7	159.5	157.1	173.1	163	157	154	172
	OC2	172.7	166.3	161.8	164.8	173	164	159	162
	FC1	162.4	167.0	168.6	168.6	164	164	165	165
	FC2	163.4	168.5	168.0	166.0	165	165	165	162
I	ON1	144.1	158.4	142.8	146.73	143	156	140	143
	ON2	143.2	162.3	147.7	146.8	144	160	144	143
	ON3	141.1	156.5	140.8	150.5	142	154	138	147
	ON4	151.4	157.5	147.3	149.3	152	155	144	148
	FN1	140.5	156.2	141.3	140.2	141	154	139	137
	FN2	142.1	151.5	139.9	147.4	143	149	137	144
	OC1	163.1	159.7	153.8	150.1	163	156	150	147
	OC2	173.1	165.6	160.5	175.4	173	162	157	171
	FC1	164.1	168.5	166.6	166.4	165	166	164	165
	FC2	164.9	167.5	165.0	168.7	165	165	162	164

Week	-ID	Water	$MgCl_2$	NaCl	$CaCl_2$	Water	$MgCl_2$	NaCl	$CaCl_2$
J	ON1	142.5	162.1	143.8	142.6	144	160	140	140
	ON2	145.9	163.9	148.3	142.8	147	162	144	140
	ON3	143.7	160.5	140.9	145.6	145	148	138	143
	ON4	145.6	158.4	142.1	144.5	147	156	138	141
	FN1	141.5	158.2	145.5	148.5	142	154	143	145
	FN2	143.1	156.8	139.3	139.3	143	153	137	136
	OC1	162.3	158.2	153.0	174.4	162	155	150	170
	OC2	172.0	165.0	160.6	162.5	171	161	158	158
	FC1	158.2	171.0	162.9	165.5	158	168	160	163
	FC2	168.7	168.8	165.1	168.3	169	165	162	166
K	ON1	144.0	165.3	150.5	157.1	145	161	148	154
	ON2	141.0	165.7	155.9	162.5	142	162	153	159
	ON3	149.3	164.4	148.9	160.6	150	160	146	157
	ON4	149.9	163.0	151.4	162.3	150	158	148	159
	FN1	141.6	161.6	148.0	155.5	141	160	144	152
	FN2	140.2	157.2	144.2	151.7	140	155	141	148
	OC1	162.9	171.8	158.1	177.7	164	169	154	174
	OC2	169.9	178.7	163.1	167.5	172	173	160	164
	FC1	158.2	169.3	169.1	174.2	158	166	165	170
	FC2	160.9	171.7	172.1	172.8	161	169	168	168
L	ON1	157.0	164.1	146.1	147.3	159	161	144	144
	ON2	162.3	164.7	151.6	150.0	164	162	148	147
	ON3	161.5	161.5	147.1	150.6	163	158	144	148
	ON4	155.2	159.4	150.2	148.3	157	156	147	146
	FN1	142.8	158.1	147.2	143.7	144	154	144	141
	FN2	142.9	155.3	142.0	144.7	144	152	139	142
	OC1	165.7	157.4	155.3	174.2	166	154	152	171
	OC2	171.3	160.3	160.8	163.1	172	156	158	159
	FC1	165.8	167.4	164.6	167.5	166	164	161	164
	FC2	166.3	167.8	170.1	168.2	166	165	166	165
M	ON1	144.1	166.6	150.8	146.9	146	164	148	143
	ON2	146.3	168.4	153.0	151.3	148	165	150	137
	ON3	146.2	164.1	147.4	149.8	148	160	144	146
	ON4	151.3	162.2	154.5	153.1	153	158	151	149
	FN1	144.0	162.9	150.4	145.6	145	159	142	143
	FN2	147.1	161.7	141.6	144.8	NA	158	138	142
	OC1	162.1	167.0	159.3	176.8	163	164	156	173
	OC2	169.4	168.5	161.8	166.2	170	165	158	162
	FC1	162.5	172.8	168.8	169.2	164	169	166	165
	FC2	160.0	171.7	167.5	171.4	162	168	164	168
N	ON1	165.1	177.5	163.3	159.6	166	174	160	156
	ON2	167.2	174.9	155.2	161.2	168	172	152	158
	ON3	166.2	174.6	161.0	159.3	167	171	158	156
	ON4	162.2	169.4	159.3	154.2	163	166	156	151
	FN1	147.0	167.3	144.2	154.7	147	164	141	151
	FN2	149.2	171.2	154.3	152.5	149	168	151	149
	OC1	165.6	173.9	162.2	170.9	166	170	159	167
	OC2	175.0	179.4	165.5	174.6	176	176	163	171
	FC1	162.8	180.0	174.5	174.6	163	177	171	171
	FC2	164.1	177.0	172.9	171.8	165	174	169	168

Week	-ID	Water	$MgCl_2$	NaCl	$CaCl_2$	Water	$MgCl_2$	NaCl	$CaCl_2$
O	ON1	147.1	163.3	148.2	145.7	148	160	145	143
	ON2	148.3	163.7	150.5	147.1	149	160	157	144
	ON3	152.4	163.5	143.7	146.6	153	160	140	144
	ON4	150.4	160.0	152.1	145.9	151	156	149	143
	FN1	143.3	160.6	146.6	144.3	143	157	143	141
	FN2	142.3	158.6	142.2	142.8	142	155	140	139
	OC1	164.9	161.1	155.6	172.7	166	159	153	169
	OC2	172.0	166.2	159.3	162.3	173	164	156	159
	FC1	163.2	172.2	166.1	168.1	164	169	163	165
	FC2	165.2	170.8	169.5	166.8	166	168	166	164
P	ON1	147.8	164.3	147.4	155.3	149	160	145	151
	ON2	144.1	163.7	151.2	151.0	145	160	148	147
	ON3	143.7	158.6	145.5	151.5	145	155	143	147
	ON4	149.3	159.8	155.5	150.0	150	157	153	146
	FN1	139.6	159.6	147.1	146.2	141	156	144	142
	FN2	138.2	154.7	141.6	151.6	140	152	138	147
	OC1	159.8	159.7	156.8	166.4	160	156	154	162
	OC2	170.2	166.0	163.0	167.8	170	163	160	164
	FC1	159.4	170.4	167.0	171.4	160	167	164	168
	FC2	162.3	170.8	170.3	173.8	163	168	167	170
Q	ON1	146.3	166.0	152.4	146.2	146	162	149	143
	ON2	148.1	167.3	151.0	150.2	148	164	148	147
	ON3	147.3	164.3	150.0	154.4	147	161	146	151
	ON4	150.4	162.3	154.5	147.8	151	159	151	145
	FN1	140.6	159.4	146.2	150.7	140	156	143	147
	FN2	142.4	159.3	140.9	148.5	143	156	138	144
	OC1	162.0	164.3	156.9	176.0	161	160	154	173
	OC2	167.8	166.5	161.0	164.1	169	162	158	161
	FC1	161.6	174.8	167.5	169.5	162	171	164	166
	FC2	163.4	172.8	169.5	171.7	164	169	166	168

Table B.2: Influents in the Ambient Room (*with DI Water)

		Influent Mass (g) for Solution				Influent Volume (mL)			
Week	**-ID**	**Water**	**$MgCl_2$**	**NaCl**	**$CaCl_2$**	**Water**	**$MgCl_2$**	**NaCl**	**$CaCl_2$**
A	ON1	N/A	N/A	N/A	N/A	200	200	200	200
	ON2	N/A	N/A	N/A	N/A	200	200	200	200
	ON3	N/A	N/A	N/A	N/A	200	200	200	200
	ON4	N/A	N/A	N/A	N/A	200	200	200	200
	FN1	N/A	N/A	N/A	N/A	200	200	200	200
	FN2	N/A	N/A	N/A	N/A	200	200	200	200
	OC1	N/A	N/A	N/A	N/A	200	200	200	200
	OC2	N/A	N/A	N/A	N/A	200	200	200	200
	FC1	N/A	N/A	N/A	N/A	200	200	200	200
	FC2	N/A	N/A	N/A	N/A	200	200	200	200
B	ON1	N/A	N/A	N/A	N/A	200	200	200	200
	ON2	N/A	N/A	N/A	N/A	200	200	200	200
	ON3	N/A	N/A	N/A	N/A	200	200	200	200
	ON4	N/A	N/A	N/A	N/A	200	200	200	200
	FN1	N/A	N/A	N/A	N/A	200	200	200	200
	FN2	N/A	N/A	N/A	N/A	200	200	200	200
	OC1	N/A	N/A	N/A	N/A	200	200	200	200
	OC2	N/A	N/A	N/A	N/A	200	200	200	200
	FC1	N/A	N/A	N/A	N/A	200	200	200	200
	FC2	N/A	N/A	N/A	N/A	200	200	200	200
C*	ON1	197	201.7	201.3	201.6	200	200	200	200
	ON2	198.5	202.1	201.7	202.5	200	200	200	200
	ON3	197.1	201.5	202	202.7	200	200	200	200
	ON4	197.6	201	200.7	202.3	200	200	200	200
	FN1	198	203.7	202.1	203	200	200	200	200
	FN2	198.4	202.9	201.9	202.6	200	200	200	200
	OC1	198.7	203	203.3	202.5	200	200	200	200
	OC2	200	202.7	202.7	202.3	200	200	200	200
	FC1	201.2	202.8	202.5	202.9	200	200	200	200
	FC2	201.6	203	202.1	203.3	200	200	200	200
D*	ON1	196.8	203.5	204.5	203.5	200	200	200	200
	ON2	197.8	202.3	202.4	203	200	200	200	200
	ON3	197.1	202.6	202.2	203.5	200	200	200	200
	ON4	197	202.9	202.5	203.1	200	200	200	200
	FN1	197.9	202.3	203.4	202.7	200	200	200	200
	FN2	197	203	202.7	202.9	200	200	200	200
	OC1	198.1	202.9	203.3	203.3	200	200	200	200
	OC2	198.7	202.6	202.9	203.4	200	200	200	200
	FC1	197.3	204	202.3	203.3	200	200	200	200
	FC2	197.7	203.2	201.6	204	200	200	200	200

Week	-ID	Water	$MgCl_2$	NaCl	$CaCl_2$	Water	$MgCl_2$	NaCl	$CaCl_2$
E	ON1	200.5	202.8	201.7	202.3	200	200	200	200
	ON2	200.2	202.7	202	202.5	200	200	200	200
	ON3	199.5	202.2	202.2	202.9	200	200	200	200
	ON4	199.4	202.7	201.9	202.6	200	200	200	200
	FN1	199.2	202.7	202.8	202.9	200	200	200	200
	FN2	200	201.9	202.7	202.8	200	200	200	200
	OC1	200.1	202.2	203.2	202.6	200	200	200	200
	OC2	199.7	203.1	203.6	202.2	200	200	200	200
	FC1	200	203	203.7	203.2	200	200	200	200
	FC2	200.2	202.6	202.3	203.3	200	200	200	200
F	ON1	198.3	203	202.7	204.9	200	200	200	200
	ON2	198.4	202.9	202.2	204.9	200	200	200	200
	ON3	199.3	202.7	202.9	204.8	200	200	200	200
	ON4	198.8	202.6	202.6	204.4	200	200	200	200
	FN1	198.5	202.1	202.8	204.4	200	200	200	200
	FN2	198.4	202.4	202.2	204.2	200	200	200	200
	OC1	198.9	203.5	203.1	204.8	200	200	200	200
	OC2	199.3	203.7	202.1	203.4	200	200	200	200
	FC1	198.8	203.4	202.1	203.7	200	200	200	200
	FC2	199.2	203.5	202.4	203.8	200	200	200	200
G*	ON1	198.6	202.2	202.9	204.3	200	200	200	200
	ON2	198.7	202.2	201.2	204.8	200	200	200	200
	ON3	198.7	202.3	201.8	204.6	200	200	200	200
	ON4	198.8	202.2	201.3	204.9	200	200	200	200
	FN1	198.4	202.1	201.2	204.6	200	200	200	200
	FN2	198.5	202.3	202.3	204.5	200	200	200	200
	OC1	198.9	202.3	201.9	204.3	200	200	200	200
	OC2	198.6	201.8	201.6	204.5	200	200	200	200
	FC1	198.8	202.1	203.1	203.3	200	200	200	200
	FC2	198.9	202.2	203.4	204.4	200	200	200	200
H*	ON1	198.1	202.5	203	204	200	200	200	200
*except	ON2	198.2	202.1	202.9	204	200	200	200	200
$CaCl_2$	ON3	198.4	203	203.1	203.9	200	200	200	200
	ON4	198.4	202.7	202.8	203.9	200	200	200	200
	FN1	198.4	202.5	202.9	204.2	200	200	200	200
	FN2	198.2	202.4	202.8	204	200	200	200	200
	OC1	199.3	202.4	202.9	204.1	200	200	200	200
	OC2	199.2	203	202.7	203.4	200	200	200	200
	FC1	198.9	202.5	203	204.3	200	200	200	200
	FC2	199	202.6	202.7	204.1	200	200	200	200
I	ON1	199.7	203.9	202.7	204.7	200	200	200	200
	ON2	199.5	203.8	202.8	203.6	200	200	200	200
	ON3	199.9	203.8	202.7	204.2	200	200	200	200
	ON4	199.4	204.2	203.7	204.1	200	200	200	200
	FN1	199.8	203.7	202.7	204.4	200	200	200	200
	FN2	199.3	204	203.1	204.5	200	200	200	200
	OC1	199.3	203.5	203.2	204.5	200	200	200	200
	OC2	199.4	203.9	203	204.5	200	200	200	200
	FC1	199.4	204.1	202.9	204.8	200	200	200	200
	FC2	199.5	203.9	202.5	204.4	200	200	200	200

Week	-ID	Water	$MgCl_2$	NaCl	$CaCl_2$	Water	$MgCl_2$	NaCl	$CaCl_2$
J	ON1	199.5	203.4	202.4	203.3	200	200	200	200
	ON2	199.5	203.4	202.9	203.7	200	200	200	200
	ON3	199.9	203.7	202.5	203.4	200	200	200	200
	ON4	199.7	203.7	202.6	203.3	200	200	200	200
	FN1	199.7	203.4	202.7	203.8	200	200	200	200
	FN2	199.7	203.5	202.6	203.5	200	200	200	200
	OC1	199.6	203.7	202.6	203.9	200	200	200	200
	OC2	199.7	203.7	202.8	203.3	200	200	200	200
	FC1	200	204.3	202.6	203.4	200	200	200	200
	FC2	199.9	204.6	202.8	203.4	200	200	200	200
K	ON1	199.8	203.9	204.3	203.5	200	200	200	200
	ON2	199.8	203.7	204.7	204	200	200	200	200
	ON3	199.8	204	204.8	204.6	200	200	200	200
	ON4	200	203.9	204.3	204.3	200	200	200	200
	FN1	199.6	203.9	204.7	204.6	200	200	200	200
	FN2	199.6	203.8	204.4	204.6	200	200	200	200
	OC1	199.7	203.9	204.4	204.8	200	200	200	200
	OC2	199.5	203.8	204.6	204.7	200	200	200	200
	FC1	199.6	203.9	204.4	204.7	200	200	200	200
	FC2	199.8	N/A	204.7	204.7	200	200	200	200
L	ON1	199.5	204.9	203.7	204.7	200	200	200	200
	ON2	199.4	204.4	203.5	204.7	200	200	200	200
	ON3	199.5	204.9	203.5	204.8	200	200	200	200
	ON4	199.6	204.8	203.6	204.7	200	200	200	200
	FN1	199.3	204.5	203.6	204.5	200	200	200	200
	FN2	199.3	204.4	203.6	204.6	200	200	200	200
	OC1	199.6	204.5	203.6	204.6	200	200	200	200
	OC2	199.3	204.5	203.8	204.5	200	200	200	200
	FC1	199.6	204.4	203.8	204.8	200	200	200	200
	FC2	199.6	204.4	203.6	204.7	200	200	200	200
M	ON1	198.5	204.2	203.5	205	200	200	200	200
	ON2	198.7	204.5	203.7	205.5	200	200	200	200
	ON3	199.8	204.3	203.6	204.9	200	200	200	200
	ON4	198.8	204.3	203.7	205	200	200	200	200
	FN1	198.6	204.3	203.6	205	200	200	200	200
	FN2	198.6	204.3	203.6	205.1	200	200	200	200
	OC1	198.8	204.4	203.7	205	200	200	200	200
	OC2	199.4	204.4	203.7	205	200	200	200	200
	FC1	198.7	204.5	203.6	205.1	200	200	200	200
	FC2	198.6	204.6	203.6	205.1	200	200	200	200
N	ON1	199.3	204.4	204	204.6	200	200	200	200
	ON2	199.3	204.4	203.8	204.6	200	200	200	200
	ON3	199.3	204.3	204	204.6	200	200	200	200
	ON4	199.4	204.2	204	204.4	200	200	200	200
	FN1	199.3	204.3	204	204.6	200	200	200	200
	FN2	199.3	204.3	203.9	204.5	200	200	200	200
	OC1	199.4	204.3	203.9	204.6	200	200	200	200
	OC2	199.3	204.3	203.8	204.6	200	200	200	200
	FC1	199.4	204.3	203.8	204.6	200	200	200	200
	FC2	199.4	204.3	203.9	204.7	200	200	200	200

Week	-ID	Water	$MgCl_2$	NaCl	$CaCl_2$	Water	$MgCl_2$	NaCl	$CaCl_2$
O	ON1	199.3	204.3	203.9	204.6	200	200	200	200
	ON2	199.5	204.1	204.1	204.4	200	200	200	200
	ON3	199.6	204.2	204	204.7	200	200	200	200
	ON4	199.6	204.3	203.8	204.7	200	200	200	200
	FN1	199.5	204.1	204	204.5	200	200	200	200
	FN2	199.6	204.2	204	204.7	200	200	200	200
	OC1	199.6	204.1	203.9	204.7	200	200	200	200
	OC2	199.5	204.2	204.1	204.8	200	200	200	200
	FC1	199.6	204.3	204	204.7	200	200	200	200
	FC2	199.7	204.2	204.1	204.8	200	200	200	200
P	ON1	199.5	204.2	203.6	204.3	200	200	200	200
	ON2	199.4	204.2	203.5	204.3	200	200	200	200
	ON3	199.4	204.1	203.7	204.5	200	200	200	200
	ON4	199.5	204.1	203.5	204.5	200	200	200	200
	FN1	199.5	204.2	203.6	204.6	200	200	200	200
	FN2	199.5	204.3	203.6	204.5	200	200	200	200
	OC1	199.5	204.3	203.6	204.5	200	200	200	200
	OC2	199.5	204.2	203.6	204.5	200	200	200	200
	FC1	199.5	204.3	203.6	204.4	200	200	200	200
	FC2	199.5	204.2	203.7	204.4	200	200	200	200
Q	ON1	199.5	204.7	203.6	204.5	200	200	200	200
	ON2	199.3	204.8	203.6	204.4	200	200	200	200
	ON3	199.5	204.7	203.7	204.4	200	200	200	200
	ON4	199.4	204.7	203.7	204.4	200	200	200	200
	FN1	199.6	204.7	203.7	204.4	200	200	200	200
	FN2	199.5	204.8	203.7	204.4	200	200	200	200
	OC1	199.4	204.8	203.6	204.4	200	200	200	200
	OC2	199.4	204.7	203.7	204.4	200	200	200	200
	FC1	199.6	204.6	203.7	204.4	200	200	200	200
	FC2	199.6	204.7	203.7	204.4	200	200	200	200

Table B.3: Effluents in the Cold Room

		Effluent Mass (g) for Solution			Effluent Volume (mL)		
Week	**-ID**	**Water**	**$MgCl_2$**	**$CaCl_2$**	**Water**	**$MgCl_2$**	**$CaCl_2$**
I	ON1	111.6	130.6	125.2	113	127	123
	ON2	117.5	124.6	127.5	118	122	125
	ON3	117.9	134.1	126.2	118	131	124
	ON4	115.1	128.9	118.7	116	126	116
	OC1	147.5	169.3	154.6	149	165	151
	OC2	145.3	158.9	141.3	147	155	138
J	ON1	134.8	*81.1	153.0	136	*79	150
	ON2	137.2	155.0	156.6	139	152	153
	ON3	138.2	151.1	154.2	140	148	151
	ON4	140.0	152.3	148.6	141	149	145
	OC1	157.2	167.6	167.1	159	164	164
	OC2	163.1	165.1	160.9	165	162	158
K	ON1	161.7	180.3	173.6	163	178	170
	ON2	164.5	179.7	170.3	166	178	167
	ON3	158.8	183.7	165.1	160	182	162
	ON4	162.7	182.7	164.7	164	180	162
	OC1	173.5	176.6	175.8	172	173	172
	OC2	167.4	179.2	171.5	170	175	168
L	ON1	159.1	169.9	166.3	160	167	163
	ON2	161.4	167.3	159.5	162	164	156
	ON3	159.7	174.6	161.2	160	172	158
	ON4	156.5	172.7	159.8	157	170	157
	OC1	173.3	172.1	176.1	173	168	172
	OC2	171.5	177.2	167.1	172	174	163
M	ON1	162.0	167.8	166.9	163	164	163
	ON2	161.9	164.1	160.3	163	160	157
	ON3	161.0	167.6	156.8	162	163	153
	ON4	160.3	168.0	156.0	161	164	152
	OC1	169.0	171.0	176.3	169	167	172
	OC2	170.1	173.1	167.5	170	169	163
N	ON1	164.3	168.7	174.3	165	166	171
	ON2	164.2	164.8	165.6	165	162	162
	ON3	165.8	173.3	163.4	167	170	159
	ON4	167.5	172.3	158.5	168	169	155
	OC1	170.5	170.6	178.6	171	167	175
	OC2	171.4	177.2	171.3	172	173	167
O	ON1	153.9	167.2	168.0	154	163	164
	ON2	162.0	164.1	156.1	162	160	153
	ON3	161.7	171.8	159.1	162	168	156
	ON4	164.5	172.5	159.4	165	169	157
	OC1	173.5	171.4	176.8	174	168	172
	OC2	168.5	171.7	166.5	168	168	162

Week	-ID	Water	$MgCl_2$	$CaCl_2$	Water	$MgCl_2$	$CaCl_2$
P	ON1	162.0	168.6	171.6	162	165	167
	ON2	164.6	170.0	157.9	165	167	153
	ON3	160.5	174.3	160.9	160	171	156
	ON4	163.4	175.4	162.6	163	172	158
	OC1	171.5	172.8	178.2	171	169	174
	OC2	170.4	175.5	168.2	170	172	164
Q	ON1	166.8	171.2	170.7	167	168	166
	ON2	163.5	*NA	161.8	164	*NA	157
	ON3	170.9	181.1	163.4	171	177	159
	ON4	168.8	178.8	163.4	169	175	159
	OC1	177.3	173.0	178.8	178	170	174
	OC2	172.7	177.9	169.1	173	174	164
R	ON1	163.7	172.2	168.0	163	169	163
	ON2	164.1	171.9	159.2	164	169	155
	ON3	168.5	164.0	162.3	168	161	158
	ON4	169.3	172.9	162.1	169	170	158
	OC1	172.3	173.9	180.4	172	170	176
	OC2	170.0	174.6	170.7	170	171	166
S	ON1	165.4	174.5	168.7	166	171	165
	ON2	168.2	175.8	164.0	169	172	160
	ON3	167.2	182.3	162.8	168	178	159
	ON4	170.2	180.5	163.2	170	176	160
	OC1	176.8	174.5	177.9	177	171	173
	OC2	172.5	177.6	173.6	173	174	170
T	ON1	167.3	172.3	169.7	167	169	166
	ON2	165.8	176.8	159.8	166	173	156
	ON3	165.8	182.0	163.5	166	178	160
	ON4	169.9	179.6	165.3	170	176	*NA
	OC1	172.7	176.2	181.7	172	172	177
	OC2	174.7	177.3	173.3	175	174	169
U	ON1	168.1	175.8	169.1	168	172	165
	ON2	169.6	178.6	159.2	170	175	156
	ON3	167.1	183.5	163.4	168	180	160
	ON4	172.6	179.7	166.0	173	176	162
	OC1	175.3	175.0	182.0	176	172	177
	OC2	175.3	181.2	172.6	176	178	168
V	ON1	165.7	171.8	164.5	168	168	160
	ON2	164.3	176.6	156.9	164	172	153
	ON3	165.2	180.7	157.8	165	176	154
	ON4	169	178.5	162.0	169	174	158
	OC1	175.5	173.4	176.5	176	170	172
	OC2	170.2	174.6	166.8	171	171	162
W	ON1	168.2	174.7	167.6	168	171	163
	ON2	168.1	179.8	155.9	168	176	152
	ON3	166.4	183.8	159.8	166	180	155
	ON4	169.7	182.3	162.0	170	178	158
	OC1	175.9	174.8	177.6	176	171	173
	OC2	171.9	177.3	169.5	172	173	165

Week	-ID	Water	$MgCl_2$	$CaCl_2$	Water	$MgCl_2$	$CaCl_2$
X	ON1	163.5	171.3	164.8	164	168	160
	ON2	163.0	175.9	152.6	163	172	148
	ON3	168.0	180.1	159.0	168	176	154
	ON4	171.0	177.4	159.4	171	173	155
	OC1	172.9	170.3	177.9	173	166	173
	OC2	171.2	172.9	166.2	172	169	161
Y	ON1	161.2	171.6	161.6	161	168	157
	ON2	162.0	177.0	151.2	162	173	147
	ON3	161.5	178.5	155.2	161	174	147
	ON4	165.8	177.0	156.0	166	173	146
	OC1	172.3	173.2	173.1	174	170	162
	OC2	167.5	174.6	162.7	169	171	164

Table B.4: Influents in the Cold Room

		Influent Mass (g) for Solution			Influent Volume (mL)		
Week	**-ID**	**Water**	**$MgCl_2$**	**$CaCl_2$**	**Water**	**$MgCl_2$**	**$CaCl_2$**
I	ON1	199.5	204.7	205.1	200	200	200
	ON2	199.3	204.5	205.2	200	200	200
	ON3	199.9	204.8	204.7	200	200	200
	ON4	199.3	204.9	204.9	200	200	200
	OC1	198.2	204.5	205.2	200	200	200
	OC2	199.7	204.5	205.0	200	200	200
J	ON1	198.9	195.4	203.8	200	191	200
	ON2	198.9	204.3	203.8	200	200	200
	ON3	199.1	204.2	203.9	200	200	200
	ON4	199.1	204.2	204.1	200	200	200
	OC1	198.9	204.8	204.2	200	200	200
	OC2	199.0	204.7	203.9	200	200	200
K	ON1	200.2	204.6	204.2	200	200	200
	ON2	200.0	204.9	204.6	200	200	200
	ON3	200.2	204.9	204.2	200	200	200
	ON4	200.1	205.2	204.5	200	200	200
	OC1	200.8	205.1	204.8	200	200	200
	OC2	200.4	204.8	204.7	200	200	200
L	ON1	199.5	204.1	204.2	200	200	200
	ON2	199.9	204.1	204.0	200	200	200
	ON3	199.6	204.1	204.2	200	200	200
	ON4	200.0	204.4	204.2	200	200	200
	OC1	199.8	204.5	204.1	200	200	200
	OC2	199.9	204.5	204.2	200	200	200
M	ON1	199.9	203.5	204.9	200	200	200
	ON2	200.0	204.0	205.1	200	200	200
	ON3	199.8	204.3	205.3	200	200	200
	ON4	199.5	204.2	205.0	200	200	200
	OC1	199.8	203.9	205.2	200	200	200
	OC2	200.0	204.2	205.0	200	200	200
N	ON1	199.0	204.1	204.6	200	200	200
	ON2	199.7	204.3	204.4	200	200	200
	ON3	199.7	204.5	204.8	200	200	200
	ON4	199.4	204.3	204.9	200	200	200
	OC1	199.9	204.3	204.8	200	200	200
	OC2	199.9	204.4	204.8	200	200	200
O	ON1	199.6	203.8	204.3	200	200	200
	ON2	199.9	203.8	204.4	200	200	200
	ON3	199.5	204.4	204.6	200	200	200
	ON4	199.6	203.7	204.8	200	200	200
	OC1	199.7	203.7	204.6	200	200	200
	OC2	199.7	204.0	204.5	200	200	200

Week	-ID	Water	$MgCl_2$	$CaCl_2$	Water	$MgCl_2$	$CaCl_2$
P	ON1	199.6	204.4	205.8	200	200	200
	ON2	199.7	204.8	205.3	200	200	200
	ON3	199.8	204.6	205.9	200	200	200
	ON4	199.7	204.7	205.5	200	200	200
	OC1	199.7	204.6	205.7	200	200	200
	OC2	199.5	204.5	205.7	200	200	200
Q	ON1	199.7	204.7	205.4	200	200	200
	ON2	199.6	204.6	205.2	200	200	200
	ON3	199.5	204.9	205.5	200	200	200
	ON4	199.7	205.0	205.4	200	200	200
	OC1	199.6	204.9	205.4	200	200	200
	OC2	199.6	205.0	205.5	200	200	200
R	ON1	200.3	204.6	205.6	200	200	200
	ON2	200.1	204.8	205.6	200	200	200
	ON3	200.3	204.8	205.7	200	200	200
	ON4	200.4	204.7	205.5	200	200	200
	OC1	200.3	204.5	205.3	200	200	200
	OC2	200.5	204.8	205.3	200	200	200
S	ON1	200.1	204.7	205.3	200	200	200
	ON2	199.9	204.9	205.6	200	200	200
	ON3	200.1	204.9	205.5	200	200	200
	ON4	200.3	204.7	205.3	200	200	200
	OC1	199.9	204.8	205.4	200	200	200
	OC2	200.1	205.0	205.4	200	200	200
T	ON1	200.2	204.9	205.5	200	200	200
	ON2	200.0	204.9	205.6	200	200	200
	ON3	200.0	205.0	205.6	200	200	200
	ON4	199.9	204.8	205.5	200	200	200
	OC1	200.1	204.9	205.7	200	200	200
	OC2	199.9	204.8	205.7	200	200	200
U	ON1	199.8	205.1	205.8	200	200	200
	ON2	200.1	205.3	206.3	200	200	200
	ON3	199.9	205.2	205.8	200	200	200
	ON4	199.8	205.0	205.6	200	200	200
	OC1	200.1	205.1	205.9	200	200	200
	OC2	199.8	205.2	205.7	200	200	200
V	ON1	200.2	204.5	204.2	200	200	200
	ON2	200.1	204.6	204.5	200	200	200
	ON3	199.9	204.7	204.9	200	200	200
	ON4	199.8	204.7	204.7	200	200	200
	OC1	200.0	204.7	204.7	200	200	200
	OC2	199.9	204.6	204.8	200	200	200
W	ON1	200.1	205.1	204.7	200	200	200
	ON2	200.0	205.5	204.8	200	200	200
	ON3	199.9	205.0	204.5	200	200	200
	ON4	200.1	205.0	204.5	200	200	200
	OC1	200.0	204.9	204.6	200	200	200
	OC2	199.9	204.9	204.7	200	200	200

Week	-ID	Water	$MgCl_2$	$CaCl_2$	Water	$MgCl_2$	$CaCl_2$
X	ON1	199.5	204.3	205.1	200	200	200
	ON2	199.6	204.2	205.0	200	200	200
	ON3	200.0	204.4	205.3	200	200	200
	ON4	199.9	204.4	205.3	200	200	200
	OC1	200.1	204.3	205.1	200	200	200
	OC2	199.9	204.4	205.3	200	200	200
Y	ON1	200.0	204.9	205.3	200	200	200
	ON2	199.9	205.0	205.2	200	200	200
	ON3	200.2	205.1	205.1	200	200	200
	ON4	199.9	205.1	205.1	200	200	200
	OC1	200.0	205.0	205.1	200	200	200
	OC2	199.9	204.9	205.0	200	200	200

APPENDIX C: CHEMICAL DATA FROM DEICING APPLICATIONS

Table C.1: Effluents and Influents in the Ambient Room: Calcium Ion (DL-detection limit)

		Concentration (mg/L)		
Week	**-ID-**	**Water**	**$MgCl_2$**	**NaCl**
A	Influent	N/A	N/A	N/A
	Effluent ON	N/A	N/A	N/A
	Effluent FN	N/A	N/A	N/A
	Effluent OC	N/A	N/A	N/A
	Effluent FC	N/A	N/A	N/A
B	Influent	N/A	N/A	N/A
	Effluent ON	N/A	N/A	N/A
	Effluent FN	N/A	N/A	N/A
	Effluent OC	N/A	N/A	N/A
	Effluent FC	N/A	N/A	N/A
C*	Influent	N/A	N/A	N/A
	Effluent ON	N/A	N/A	N/A
	Effluent FN	N/A	N/A	N/A
	Effluent OC	N/A	N/A	N/A
	Effluent FC	N/A	N/A	N/A
D*	Influent	N/A	N/A	N/A
	Effluent ON	N/A	N/A	N/A
	Effluent FN	N/A	N/A	N/A
	Effluent OC	N/A	N/A	N/A
	Effluent FC	N/A	N/A	N/A
E	Influent	N/A	N/A	N/A
	Effluent ON	N/A	N/A	N/A
	Effluent FN	N/A	N/A	N/A
	Effluent OC	N/A	N/A	N/A
	Effluent FC	N/A	N/A	N/A
F	Influent	N/A	N/A	N/A
	Effluent ON	N/A	N/A	N/A
	Effluent FN	N/A	N/A	N/A
	Effluent OC	N/A	N/A	N/A
	Effluent FC	N/A	N/A	N/A
G*	Influent	DL	DL	DL
	Effluent ON	DL	82.9	21.2
	Effluent FN	DL	100.3	24.6
	Effluent OC	DL	164.8	DL
	Effluent FC	DL	124.9	DL
H*	Influent	DL	DL	DL
*except	Effluent ON	3.6	40.8	8.3
$CaCl_2$	Effluent FN	DL	117.2	N/A
	Effluent OC	DL	60.9	1.5
	Effluent FC	DL	41.0	2.4
I	Influent	N/A	9.6	125.9
	Effluent ON	N/A	18.2	189.0
	Effluent FN	N/A	125.4	161.9
	Effluent OC	N/A	68.1	N/A
	Effluent FC	N/A	57.5	133.1

Week	-ID-	Water	$MgCl_2$	NaCl
J	Influent	53.0	N/A	10.5
	Effluent ON	25.2	N/A	48.5
	Effluent FN	20.3	N/A	53.4
	Effluent OC	20.7	N/A	38.3
	Effluent FC	22.7	N/A	33.0
K	Influent	41.2	135.0	63.7
	Effluent ON	54.5	566.4	72.8
	Effluent FN	43.1	439.1	71.3
	Effluent OC	47.8	139.7	69.3
	Effluent FC	40.8	133.2	80.8
L	Influent	19.4	56.3	34.9
	Effluent ON	40.4	612.7	46.5
	Effluent FN	20.3	183.6	41.6
	Effluent OC	20.5	126.9	34.2
	Effluent FC	16.8	126.6	34.1
M	Influent	37.2	93.6	74.7
	Effluent ON	43.5	N/A	86.9
	Effluent FN	51.5	N/A	74.2
	Effluent OC	70.3	N/A	69.2
	Effluent FC	44.0	N/A	86.5
N	Influent	34.8	111.2	87.4
	Effluent ON	74.6	598.0	115.9
	Effluent FN	42.8	664.2	126.5
	Effluent OC	45.7	560.8	271.4
	Effluent FC	39.1	556.8	710.6
O	Influent	56.1	114.2	66.6
	Effluent ON	53.3	501.2	71.7
	Effluent FN	44.2	412.3	69.8
	Effluent OC	42.4	436.3	62.0
	Effluent FC	47.4	469.2	68.4
P	Influent	39.0	96.9	77.6
	Effluent ON	43.4	647.2	95.2
	Effluent FN	44.6	498.6	71.3
	Effluent OC	51.0	578.9	66.1
	Effluent FC	37.8	188.5	76.1
Q	Influent	21.4	88.6	30.7
	Effluent ON	26.7	891.3	38.5
	Effluent FN	19.8	707.2	36.6
	Effluent OC	20.8	731.4	30.7
	Effluent FC	20.9	724.4	27.3

Table C.2: Effluents and Influents in the Cold Room: Calcium Ion (DL-detection limit)

		Concentration (mg/L)	
Week	**-ID-**	**Water**	**$MgCl_2$**
I	Influent	N/A	N/A
	Effluent ON	N/A	N/A
	Effluent OC	N/A	N/A
J	Influent	43.5	108.6
	Effluent ON	60.7	109.0
	Effluent OC	30.6	DL
K	Influent	N/A	N/A
	Effluent ON	N/A	N/A
	Effluent OC	N/A	N/A
L	Influent	37.5	111.8
	Effluent ON	N/A	171.0
	Effluent OC	57.7	124.5
M	Influent	50.7	111.0
	Effluent ON	73.3	173.2
	Effluent OC	29.3	139.8
N	Influent	40.8	115.8
	Effluent ON	56.2	168.8
	Effluent OC	37.0	180.0
O	Influent	38.1	116.7
	Effluent ON	32.6	154.0
	Effluent OC	38.7	132.1
P	Influent	45.2	99.7
	Effluent ON	37.8	171.0
	Effluent OC	30.5	135.4
Q	Influent	24.2	97.8
	Effluent ON	30.8	158.4
	Effluent OC	23.7	142.3
R	Influent	34.7	114.8
	Effluent ON	26.9	164.3
	Effluent OC	39.0	134.6
S	Influent	30.8	116.5
	Effluent ON	31.5	172.7
	Effluent OC	33.1	141.7
T	Influent	49.0	N/A
	Effluent ON	72.7	N/A
	Effluent OC	49.8	N/A
U	Influent	49.9	119.4
	Effluent ON	69.3	546.9
	Effluent OC	42.0	135.6
V	Influent	N/A	117.3
	Effluent ON	34.4	165.9
	Effluent OC	35.5	138.3
W	Influent	33.3	139.4
	Effluent ON	47.9	542.4
	Effluent OC	30.3	136.6

Week	-ID-	Water	$MgCl_2$
X	Influent	38.9	N/A
	Effluent ON	109.3	166.2
	Effluent OC	32.9	128.7
Y	Influent	24.2	117.4
	Effluent ON	20.3	175.9
	Effluent OC	16.1	131.9

Table C.3: Effluents and Influents in the Ambient Room: pH

		Concentration (mg/L)			
Week	**-ID-**	**Water**	**$MgCl_2$**	**NaCl**	**$CaCl_2$**
A	Influent	6.92	8.39	8.19	6.68
	Effluent ON	8.63	8.38	10.21	9.68
	Effluent FN	8.88	8.43	9.93	9.48
	Effluent OC	7.25	8.18	8.31	9.17
	Effluent FC	7.23	8.18	8.26	9.13
B	Influent	7.73	8.23	8.15	6.53
	Effluent ON	9.52	8.43	10.61	10.95
	Effluent FN	9.31	8.44	10.17	10.56
	Effluent OC	9.27	8.28	8.31	6.93
	Effluent FC	8.06	8.30	8.34	6.79
C*	Influent	7.47	8.67	9.33	9.88
	Influent 2	N/A	8.63	9.31	9.90
	Effluent ON	11.48	8.80	11.35	11.35
	Effluent FN	11.24	8.80	11.23	11.26
	Effluent OC	9.67	8.70	9.36	9.82
	Effluent FC	9.16	8.66	9.40	9.76
D*	Influent 1	6.54	8.62	9.35	9.77
	Influent 2	6.10	8.63	9.30	9.78
	Effluent ON	11.23	8.77	11.33	11.34
	Effluent FN	11.09	8.79	11.07	11.12
	Effluent OC	9.68	8.68	9.34	9.82
	Effluent FC	8.79	8.60	9.32	9.68
E	Influent 1	7.92	8.29	8.30	6.84
	Influent 2	8.00	8.18	8.31	6.25
	Effluent ON	11.23	8.40	10.36	10.48
	Effluent FN	11.09	8.40	9.79	10.11
	Effluent OC	9.68	8.38	8.50	6.77
	Effluent FC	8.79	8.29	8.56	7.89
F	Influent 1	7.99	8.24	8.41	6.71
	Influent 2	N/A	8.25	8.34	6.62
	Effluent ON	9.45	8.40	10.16	10.75
	Effluent FN	9.30	8.38	9.72	10.36
	Effluent OC	8.24	8.33	8.67	7.08
	Effluent FC	8.24	8.30	8.61	6.82
G*	Influent 1	6.40	8.66	9.01	10.06
	Influent 2	5.56	8.62	N/A	10.05
	Effluent ON	11.20	8.78	11.13	11.26
	Effluent FN	10.82	8.72	10.83	11.04
	Effluent OC	8.81	8.65	9.38	10.03
	Effluent FC	8.28	8.62	9.26	9.79
H*	Influent 1	6.57	8.62	7.70	6.78
*except	Influent 2	5.85	8.62	7.62	6.69
$CaCl_2$	Effluent ON	11.07	8.77	10.85	10.45
	Effluent FN	10.69	8.73	10.36	9.60
	Effluent OC	8.16	8.65	9.00	6.37
	Effluent FC	8.61	8.62	8.92	6.70

Week	-ID-	Water	$MgCl_2$	NaCl	$CaCl_2$
I	Influent 1	7.88	8.27	8.31	6.81
	Influent 2	7.78	8.24	8.27	6.81
	Effluent ON	9.28	8.36	10.00	10.77
	Effluent FN	9.07	8.35	9.59	10.42
	Effluent OC	8.29	8.29	8.59	7.53
	Effluent FC	8.12	8.28	8.73	7.24
J	Influent 1	7.79	8.29	7.95	6.68
	Influent 2	7.82	8.33	7.95	6.79
	Effluent ON	9.29	8.45	9.80	10.49
	Effluent FN	9.11	8.45	9.48	9.50
	Effluent OC	8.12	8.38	8.94	7.11
	Effluent FC	8.24	8.39	8.87	7.00
K	Influent 1	8.07	8.30	8.41	7.00
	Influent 2	7.97	8.30	8.36	7.02
	Effluent ON	9.44	8.43	10.15	10.78
	Effluent FN	9.11	8.34	9.67	10.43
	Effluent OC	8.28	8.28	9.12	7.65
	Effluent FC	8.29	8.30	9.02	7.31
L	Influent 1	7.96	8.15	8.39	6.77
	Influent 2	8.00	8.19	8.38	6.72
	Effluent ON	9.85	8.38	9.96	10.15
	Effluent FN	9.20	8.36	9.60	8.96
	Effluent OC	8.41	8.29	9.14	6.90
	Effluent FC	8.23	8.26	9.07	6.79
M	Influent 1	7.81	8.29	8.35	6.51
	Influent 2	7.78	8.25	8.38	6.62
	Effluent ON	9.24	8.38	9.85	10.26
	Effluent FN	9.07	8.34	9.55	9.10
	Effluent OC	830	8.26	9.13	7.11
	Effluent FC	8.28	8.22	9.10	6.96
N	Influent 1	8.05	8.31	8.50	6.74
	Influent 2	7.97	8.34	8.40	6.71
	Effluent ON	9.98	8.51	10.70	10.69
	Effluent FN	9.33	8.42	9.79	9.55
	Effluent OC	8.29	8.33	9.23	6.85
	Effluent FC	8.23	8.28	9.17	6.75
O	Influent 1	8.17	8.22	8.20	6.93
	Influent 2	8.23	8.31	8.36	6.97
	Effluent ON	9.56	8.37	9.65	10.68
	Effluent FN	9.13	8.24	9.48	9.95
	Effluent OC	8.42	8.25	9.90	7.55
	Effluent FC	8.47	8.26	9.10	7.30
P	Influent 1	7.76	8.25	8.49	6.51
	Influent 2	7.84	8.28	8.52	6.58
	Effluent ON	9.26	8.40	9.68	10.20
	Effluent FN	9.04	8.37	9.48	9.25
	Effluent OC	8.25	8.28	9.17	7.26
	Effluent FC	8.26	8.31	9.13	6.94

Week	-ID-	Water	$MgCl_2$	NaCl	$CaCl_2$
Q	Influent 1	8.26	8.22	8.32	6.68
	Influent 2	8.39	8.27	8.34	6.79
	Effluent ON	9.54	8.32	9.72	9.93
	Effluent FN	9.18	8.29	9.46	8.85
	Effluent OC	8.58	8.24	9.17	7.14
	Effluent FC	8.58	8.25	9.16	6.87

Table C.4: Effluents and Influents in the Cold Room: pH

		Concentration (mg/L)		
Week	**-ID-**	**Water**	**$MgCl_2$**	**$CaCl_2$**
I	Influent 1	7.67	8.25	6.74
	Influent 2	7.82	8.30	N/A
	Effluent ON	9.11	8.37	9.12
	Effluent OC	7.84	8.32	6.88
J	Influent 1	7.77	8.23	6.75
	Influent 2	7.28	8.23	6.69
	Effluent ON	9.34	8.38	10.16
	Effluent OC	7.94	8.31	6.75
K	Influent 1	7.74	8.36	6.80
	Influent 2	7.73	8.36	6.70
	Effluent ON	10.25	8.69	10.42
	Effluent OC	8.49	8.40	7.46
L	Influent 1	7.83	8.22	6.85
	Influent 2	7.87	8.23	6.88
	Effluent ON	10.06	8.51	9.24
	Effluent OC	8.26	8.29	7.23
M	Influent 1	8.00	8.28	6.75
	Influent 2	7.97	8.29	6.79
	Effluent ON	10.02	8.53	10.09
	Effluent OC	8.33	8.33	7.27
N	Influent 1	8.02	8.02	6.87
	Influent 2	8.06	8.06	6.74
	Effluent ON	10.01	10.01	8.94
	Effluent OC	8.33	8.33	6.99
O	Influent 1	7.78	7.78	6.73
	Influent 2	7.82	7.82	6.76
	Effluent ON	9.74	9.74	8.46
	Effluent OC	8.25	8.25	7.06
P	Influent 1	8.03	8.33	6.74
	Influent 2	8.00	8.36	6.78
	Effluent ON	9.72	8.53	9.08
	Effluent OC	8.25	8.33	7.05
Q	Influent 1	7.79	8.27	6.32
	Influent 2	7.90	8.29	6.39
	Effluent ON	9.72	8.52	8.68
	Effluent OC	8.25	8.29	7.19
R	Influent 1	7.90	8.12	6.32
	Influent 2	7.99	8.17	6.56
	Effluent ON	9.66	8.43	10.07
	Effluent OC	8.45	8.22	7.32
S	Influent 1	7.82	8.22	6.78
	Influent 2	7.88	8.26	6.82
	Effluent ON	9.67	8.51	10.14
	Effluent OC	8.28	8.32	7.34

Week	-ID-	Water	$MgCl_2$	$CaCl_2$
T	Influent 1	6.56	8.25	6.42
	Influent 2	6.87	8.29	6.43
	Effluent ON	9.43	8.45	8.86
	Effluent OC	8.42	8.24	6.96
U	Influent 1	7.39	8.29	6.44
	Influent 2	7.42	8.29	6.46
	Effluent ON	9.52	8.49	9.54
	Effluent OC	8.37	8.34	7.42
V	Influent 1	7.80	8.26	6.58
	Influent 2	7.86	8.35	6.61
	Effluent ON	9.52	8.48	9.34
	Effluent OC	8.43	8.31	7.32
W	Influent 1	7.97	8.26	6.56
	Influent 2	8.27	8.32	6.50
	Effluent ON	9.55	8.49	9.34
	Effluent OC	8.62	8.32	7.33
X	Influent 1	7.77	8.15	6.48
	Influent 2	7.87	8.24	6.60
	Effluent ON	9.36	8.43	9.33
	Effluent OC	8.29	8.27	7.41
Y	Influent 1	7.94	8.14	6.68
	Influent 2	7.85	8.22	6.65
	Effluent ON	9.30	8.35	9.16
	Effluent OC	8.16	8.27	7.49