Center for Environmentally Sustainable Transportation
in Cold Climates

Evaluation of Deicer Impacts on Pervious Concrete Specimens (Phase II)

Liv Haselbach, Sila Temizel-Sekeryan, Molly Ross, Nara Almeida
Department of Civil and Environmental Engineering
Lamar University

Date: May 31, 2018

Prepared by: Liv Haselbach, Sila Temizel-Sekeryan, Molly Ross, Nara Almeida

Center for Environmentally Sustainable
Transportation in Cold Climates
Duckering Building Room 245
P.O. Box 755900
Fairbanks, AK 99775

U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

INE/AUTC 18.10

REPORT DOCUMENTATION PAGE

Form approved OMB No.

1. AGENCY USE ONLY (LEAVE BLANK)	2. REPORT DATE 5/31/2018	3. REPORT TYPE AND DATES COVERED Final Report: 05/2017 – 05/2018

4. TITLE AND SUBTITLE
Evaluation of Deicer Impacts on Pervious Concrete Specimens (Phase II)

5. FUNDING NUMBERS
101622

6. AUTHOR(S)
Liv Haselbach, Chair and Professor, Lamar University
Sila Temizel-Sekeryan, Molly Ross, Nara Almeida, Students, Lamar University

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Civil and Environmental Engineering
Lamar University
P.O. Box 10024
Beaumont, TX 77710

8. PERFORMING ORGANIZATION REPORT NUMBER
INE/AUTC 18.10

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Center for Environmentally Sustainable Transportation in Cold Climates
University of Alaska Fairbanks
Duckering Building, Room 245
P.O. Box 755900
Fairbanks, AK 99775-5900

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLENMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
No restrictions

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words) This research examined the chemical degradation of pervious concrete due to calcium chloride or magnesium chloride deicers. The project consisted of Phase I, Phase IIa, and Phase IIb. Phase I was previous work where a testing protocol was developed to mimic deicer applications. Phases IIa and IIb are parts of this project. Phase IIa used split tensile testing on Phase I specimens and further evaluated the chemical data from Phase I magnesium chloride applications. Phase IIb repeated the Phase I protocol for a larger number of new ordinary Portland cement specimens and evaluated the impact on strength using the unconfined compressive strength test. The hypotheses were based on complexation and precipitation chemistry. Specimens subjected to calcium chloride showed visible degradation. Specimens exposed to magnesium chloride deicer showed a large increase in loss of calcium ions in Phase I. Both deicers showed a loss in strength compared with a water control in Phase IIb. Results from the split tensile testing were inconclusive. The protocol from Phase I with the unconfined compression test may be an effective testing procedure to determine if different designs might be more resistant to chemical degradation by these two deicing chemicals.

14- KEYWORDS : Please be sure they are searchable in the Transportation Research Thesaurus http://trt.trb.org/trt.asp?
Runoff, deicing chemicals, porous pavements, magnesium chloride, calcium chloride.

15. NUMBER OF PAGES
49

16. PRICE CODE
N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	N/A

NSN 7540-01-280-5500

STANDARD FORM 298 (Rev. 2-98)
Prescribed by ANSI Std. 239-18 298-1

DISCLAIMER

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
ºF	Fahrenheit temperature	5/9 (ºF-32)	Celsius temperature	ºC

ILLUMINATION

Symbol	When You Know	Multiply By	To Find	Symbol
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2

FORCE and PRESSURE or STRESS

Symbol	When You Know	Multiply By	To Find	Symbol
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS FROM SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	Miles (statute)	mi

AREA

mm^2 millimeters squared 0.0016 square inches in^2 m^2
meters squared 10.764 square feet ft^2 km^2 kilometers
squared 0.39 square miles mi^2 ha hectares (10,000
m^2) 2.471 acres ac

MASS (weight)

g grams 0.0353 Ounces (avdp) oz
kg kilograms 2.205 Pounds (avdp) lb mg
megagrams (1000 kg) 1.103 short tons T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3

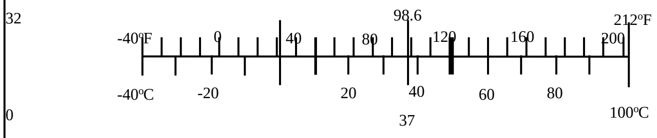
TEMPERATURE (exact)

ºC Celsius temperature 9/5 ºC+32 Fahrenheit ºF
temperature ILLUMINATION

Symbol	When You Know	Multiply By	To Find	Symbol
lx	lux	0.0929	foot-candles	fc
cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl

FORCE and PRESSURE or STRESS

N newtons 0.225 pound-force lbf
kPa kilopascals 0.145 pound-force per psi
square inch



ACKNOWLEDGMENTS

The authors are grateful for support from the Center for Environmentally Sustainable Transportation in Cold Climates (CESTiCC), the Ready Mixed Concrete (RMC) Research & Education Foundation, Washington State University, and Lamar University. We would like to thank Quinn Langfitt, Trace Sendele, and Sarah Pate for their previous contributions on experiments, and Holcim and Martin Marietta for their material donations.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This research examined the chemical degradation of pervious concrete due to calcium chloride or magnesium chloride deicer applications. The project consisted of three phases: Phase I, Phase IIa, and Phase IIb. During Phase I, previous work, a testing protocol was developed for mimicking deicer applications to pervious concrete. Phases IIa and IIb are parts of the present project. The focus in Phase IIa was on evaluating specimen resistance to chemical degradation using split tensile testing on Phase I specimens and on further evaluation of chemical data from the Phase I magnesium chloride applications. In Phase IIb, we repeated the Phase I protocol for a larger number of new ordinary Portland cement (OPC) specimens and evaluated the resistance of these specimens to chemical degradation using the unconfined compressive strength test. The hypotheses were based on complexation and precipitation chemistry.

The testing protocol covered a 17-week period during which water was used as a control for comparison purposes (sodium chloride was also a control in Phase I). Each week, treatments of 200 mL of water with approximately 3% by mass of deicers or the control were applied to pervious concrete specimens. The specimens were allowed to partially air dry between treatments.

Phase I, in which the testing protocol was developed on pervious concrete specimens of varying mix designs and under various conditions, is summarized in this report. In Phase I, the specimens exposed to calcium chloride deicer applications showed visible degradation. The specimens subjected to magnesium chloride deicer applications showed a large increase in calcium ions in the effluent.

Phase IIa consisted of two parts: (1) further evaluation of the chemical data from the magnesium chloride applications, and (2) evaluation of specimen resistance to chemical degradation using split tensile testing on Phase I specimens. Results support the hypotheses that

chemical attacks occur and that the changes might be explained by stability constants for the formation of complexes and precipitates. The second part of Phase IIa showed that the split tensile testing method may not be an efficient way to analyze chemical deterioration impacts, since location of voids in pervious concrete may vary on the randomly chosen stress plane, compounding the number of independent variables.

Phase IIb had two parts: (1) repetition of Phase I for a larger number of new OPC specimens only, and (2) evaluation of Phase II specimen resistance to chemical degradation using the unconfined compressive strength test. Results indicate that both of the deicing chemicals impacted the compressive strength of the specimens. Specimens subjected to the magnesium chloride treatment lost strength after the 17-week chemical treatment period despite a significant gain in mass. The specimens that were treated with calcium chloride showed an even greater loss in strength after the treatment period, in addition to visible degradation.

This final report is a compilation of results obtained from Phase I, Phase IIa, and Phase IIb. Various technology transfer and outreach activities are summarized throughout the report. The final conclusion is that the protocol as developed in Phase I, with the addition of the unconfined compression test used in Phase II, may be an effective testing procedure for use in determining if different mix designs or installation methods for pervious concrete are more or less resistant to chemical degradation by these two deicing chemicals.

CHAPTER 1 INTRODUCTION

Chemical deicers may have negative impacts on pervious concrete pavements in cold climate areas. This project aimed to develop a preliminary test method for researchers to use in evaluating the various chemical impacts of deicers on pervious concrete subject to various mix designs and/or preventive treatments. The foci were on magnesium chloride and calcium chloride deicers. The overall objectives were as follows:

- Phase I (previous work): Develop a testing protocol for pervious concrete specimens of varying mix designs and under various conditions (Haselbach 2017).
- Phase IIa (current project): Evaluate specimen resistance to chemical degradation caused by deicers using the split tensile test on Phase I specimens and further evaluate chemical data from the magnesium chloride applications.
- Phase IIb (current project): Repeat Phase I for a larger number of new ordinary Portland cement (OPC) specimens only and evaluate specimen resistance to the chemical degradation caused by deicers using the unconfined compressive strength test.

Table 1.1 provides an explanation of the naming schemes used to designate the various specimen types in Phases I and IIa. Names of the specimens differ according to

- temperature of the laboratory (ambient – H or cold – C),
- applied chemical treatment (water – W, sodium chloride – S, calcium chloride – C, or magnesium chloride – M),
- composition (OPC – O or OPC and 25% fly ash – F), and
- age (new and noncarbonated – N or older and more carbonated – C).

Table 1.1 Naming scheme for specimens Phases I and IIa (Sendele 2017)

Temperature of Storage	Ambient (Hot) Room		Cold Room	
	H		**C**	
Chemical Treatment	Calcium Chloride	Magnesium Chloride	Sodium Chloride	Water
	C	**M**	**S**	**W**
Composition	Ordinary Portland Cement		25% Fly Ash	
	O		**F**	
Age	2008/2009 (Carbonated)		2016 (Noncarbonated)	
	C		**N**	

Phase I was performed at Washington State University with support from the Ready Mixed Concrete (RMC) Research & Education Foundation. The main objective of Phase I was preliminary development of a testing method for use in comparing various pervious concrete mix designs or technologies that might be more resistant to chemical attack by deicing chemicals. Phase I used a larger set of variables in order to determine which variables were most important for the testing method. The main variables screened were temperature of the laboratory (ambient room temperature versus cold at around 4°C), new versus older specimens (to distinguish between little or more carbonation), and the use of fly ash as a supplement (only OPC or with 25% fly ash substitution). The results indicated that the most susceptible specimens would likely be those that are new, with only OPC and with the tests performed under ambient conditions. A brief summary of Phase I is found in Section 2.1. Phase I also considered four different treatments: water and sodium chloride as controls, and magnesium chloride and calcium chloride as the suspected deicing chemicals of most concern.

The testing method developed in Phase I seemed to be appropriate for evaluating the effects of chemical deicer degradation impacts. The calcium chloride treatment resulted in visual evidence of concrete deterioration on the bottom of many specimens. The magnesium chloride treatments had evidence of calcium leaching and internal mass gain. Because it is important to correlate these changes to impacts on durability and strength, in Phase IIa we conducted split tensile testing on the Phase I specimens and studied the mechanisms of magnesium chloride chemical changes.

During Phase IIa it was evident that split tensile testing of specimens with so many variables was inconclusive. Therefore, we modified Phase IIb, repeating the entire protocol on a larger set of specimens with fewer independent variables and performing unconfined compression testing for possible correlations to strength. The revised objectives of Phase II, covered in this report, are as follows:

Phase IIa:

1. Further evaluate data from the initial Phase I experimental protocol, particularly the impact of magnesium chloride on calcium in the concrete (see Section 2.2).
2. Enhance experiments with the performance of split tensile testing on Phase I specimens (see Section 2.3).

Phase IIb:

1. Perform the experiments again using a smaller set of variables (OPC, ambient room, and new pervious concrete) for water, magnesium chloride, and calcium chloride treatments, and using more specimens in order to provide better statistical analyses (see Section 3.1).
2. Perform unconfined compressive strength tests on the Phase IIb specimens to evaluate strength impact, as the split tensile tests were inconclusive and variable (see Section 3.2).

The following is a summary of the testing protocol developed in Phase I and used in both phases:

1. Make 4-inch-diameter specimens (7 to 8 inches in height)

2. Apply weekly treatments of 200 mL of water with approximately 3% by mass of deicers for 16 to 17 weeks.
3. Allow the specimens to partially dry in the laboratory between treatments.
4. Record the volumes and masses of the influents and effluents and weekly masses of the specimens.
5. Analyze the influent and effluent of the magnesium chloride treatment samples for calcium content if possible.
6. Look for visible signs of deterioration in the calcium chloride treatments.

An important part of any research is technology transfer and outreach. Chapters 2 and 3 mention technical products from this research. Chapter 4 summarizes various outreach activities performed by the project teams.

CHAPTER 2 RESEARCH APPROACH AND METHODOLOGY

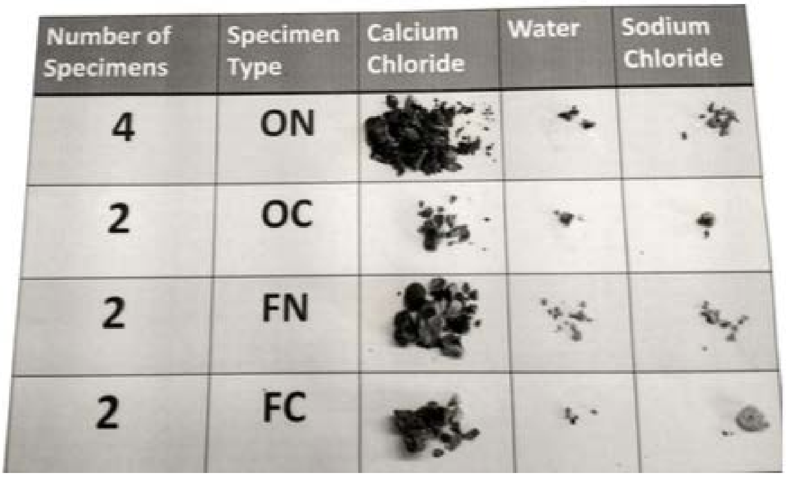
2.1 Phase I – Collecting Extensive Chemical Data and Refining a Preliminary Testing Protocol

This part of the project was funded by Ready Mixed Concrete (RMC) Research & Education Foundation. The effects of chemical deicers on traditional concrete pavements were researched by conducting a literature review. As a result of this review, test methods were developed for chemical treatments on pervious concrete specimens (Haselbach 2017).

According to the developed test method, the following steps were applied for each pervious concrete specimen made at Washington State University (WSU). All the specimens had been prepared previously with an approximately 4 to 1 aggregate-to-cementitious mass ratio. The aggregate was narrowly graded basalt (<1 cm), and the water-to-cementitious ratio was slightly higher than 0.30 (depending on weather conditions). For 17 weeks, the specimens were subjected to different treatments by pouring 200 mL solutions containing ~3% in mass of calcium chloride, magnesium chloride, sodium chloride, or water, as a control. Two parallel experiments were conducted both at room temperature and in a cold room (around 40°F). All specimens and influent solutions were usually weighed weekly before each chemical treatment. Effluent volumes and masses were recorded. Also, the presence of possible debris was checked periodically. As noted, each specimen was 7 to 8 inches in height and 4 inches in diameter, having different characteristics according to age (molded in 2016 or in 2008/2009) and composition (OPC or cement with 25% of fly ash).

A publication by Haselbach et al. (2018b) on calcium chloride deicer impacts on pervious concrete is one of the outcomes of Phase I. The paper provides a summary of the laboratory method used to examine different mixes and different types of treatments for improved chemical resistance to calcium chloride deicer applications, with water and sodium chloride as the controls. As described earlier, during Phase I, the experiments were conducted under two laboratory conditions: (1) ambient room temperature and (2) cold room (4°C). Two different specimen types were examined: ordinary Portland cement (OPC) pervious concrete specimens with 25% fly ash substitution and OPC pervious concrete specimens without 25% fly ash substitution. We tested 3% (by mass) calcium chloride solution by using water and 3% (by mass) sodium chloride solution as control. We applied 200 mL test solutions to the aforementioned specimens for 2 months and recorded the results. There were exceptions to the procedure applied (in both ambient and cold laboratory conditions). These exceptions included not performing the sodium chloride test or using specimens with fly ash in the cold room. Samples of the influents and effluents were collected, and pH was measured. Masses and volumes of the influents and the effluents were recorded. We used pervious concrete specimens made in 2008/2009 (Thomle and Haselbach 2011), and pervious concrete specimens made in 2016, in order to compare new specimens with little carbonation and older specimens that might be more highly carbonated.

Specimens that received calcium chloride treatment seemed to deteriorate near their bottom. The most deterioration occurred from OPC, noncarbonated (ON) specimens. Fly ash noncarbonated (FN) and carbonated specimens followed ON, respectively. Figure 2.1 from Haselbach et al. (2018b) is a depiction of these results. Since deterioration occurred in fly ash specimens also, it could be concluded that the substitution of fly ash may not dramatically benefit pervious concrete subjected to calcium chloride, especially when carbonated.



Number of Specimens	Specimen Type	Calcium Chloride	Water	Sodium Chloride
4	ON			
2	OC			
2	FN			
2	FC			

Figure 2.1 Debris collected in the ambient laboratory testing sequence from drying rack pads and when unwrapping the specimens (Haselbach et al. 2018b)

Based on the Phase I results, we recommend that screening tests be performed on new pervious concrete specimens, as these appear to be most susceptible to chemical attack.

The following publications resulted from Phase I (additional outreach activities performed by the project teams are given in Chapter 4:

- Haselbach, L. (2017). “Evaluation of the Effects of Deicer Chemical Methodologies on Pervious Concrete and Development of a Deicer Chemical Testing Method for Pervious Concrete.” Final Report to the RMC Research and Education Foundation, Silver Spring, MD. May 2017.
- Haselbach, L., Sendele, T., and Langfitt, Q. (2018b). “Screening Test for Improved Calcium Chloride Deicer Resistance in Pervious Concrete.” Proceedings: ASCE International Conference on Transportation and Development (ICTD), Pittsburgh, PA. July 2018.

2.2 Phase IIa, Part 1 – Further Evaluation of Data from Phase I: The Impact of Magnesium Chloride on the Calcium in the Concrete

The purpose of Phase IIa, Part 1, of the project was to further evaluate data from the initial Phase I experimental protocol, particularly the impact of magnesium chloride on calcium in the concrete. These laboratory experiments (Haselbach et al. 2018b) were performed by using a magnesium chloride deicer. The specimen types were OPC with and without 25% fly ash substitution, and the experimental condition was either ambient temperature or cold room. Additionally, since the specimens were made either in 2008/2009 or 2016, older specimens were considered "carbonated" and newer ones were considered "non-carbonated." Again, water or sodium chloride solutions were used as the control, and specimens were treated with these solutions for 4 months. The researchers hypothesized that ion exchange occurs between magnesium and calcium ions, which may affect the strength and durability of the specimens. Influent and effluent solutions were tested in terms of calcium concentration. We found that effluent collected from specimens treated with magnesium chloride had higher calcium concentration than both the specimens treated with control solutions and the influent after several weeks. This hypothesis was found to be relevant for the OPC specimens, as they tended to leach 20–30% more calcium than the fly ash specimens that had nearly 20% less calcium to exchange (Ross et al. n.d.).

Once 3% magnesium chloride solution passed through the specimens, effluents were collected. Calcium ion concentration seemed to have increased in the effluent solutions of the magnesium chloride-treated specimens, and the mass of these specimens increased more than the controls. Our interpretation of these results is that the magnesium ion exchanged with the calcium ion (higher effluent concentrations) and that magnesium hydroxide precipitated within the structure of pervious concrete (increased mass). Ross et al. (n.d.) recommended that further studies be conducted on the strength or durability impacts of these aforementioned chemical changes.

Figure 2.2 (Haselbach 2017) shows normalized (to initial masses) specimen masses for the calcium chloride and magnesium chloride applications in ambient laboratory conditions. For all four mix designs (ON, FN, OC, or FC), the specimens treated with magnesium chloride gained more mass than the specimens treated with calcium chloride, even though the atomic weight of calcium is greater than the atomic weight of magnesium. This result might imply internal precipitation, with magnesium hydroxide being the most likely species.

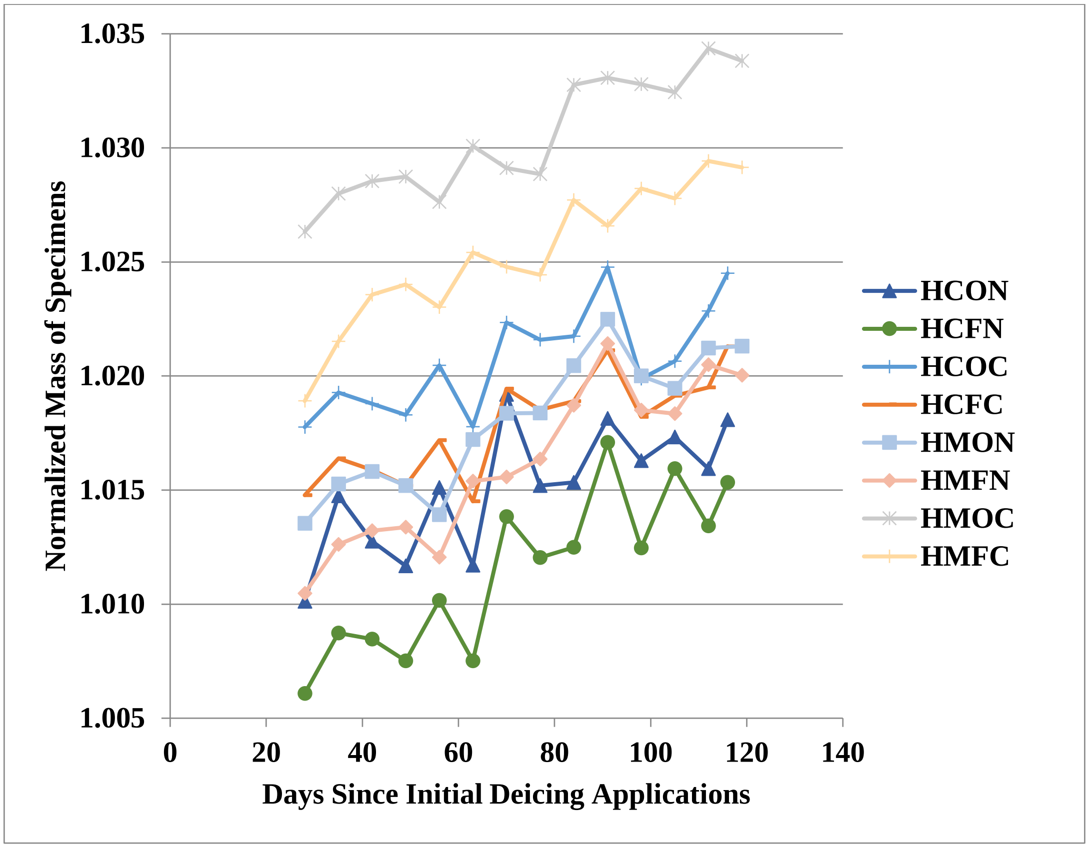


Figure 2.2 Ambient laboratory specimen masses for calcium chloride and magnesium chloride applications (Haselbach 2017)

Figure 2.3 is a depiction of the composite calcium ion concentrations in ambient laboratory conditions for the magnesium chloride, water, and sodium chloride applications (data are not available for the earlier weeks). It can be seen that influent calcium ion concentrations are generally lower than the effluent calcium ion concentrations for all three applications (Haselbach 2017). In addition, the effluent calcium concentrations from the specimens treated with magnesium chloride slowly increase substantially over time.

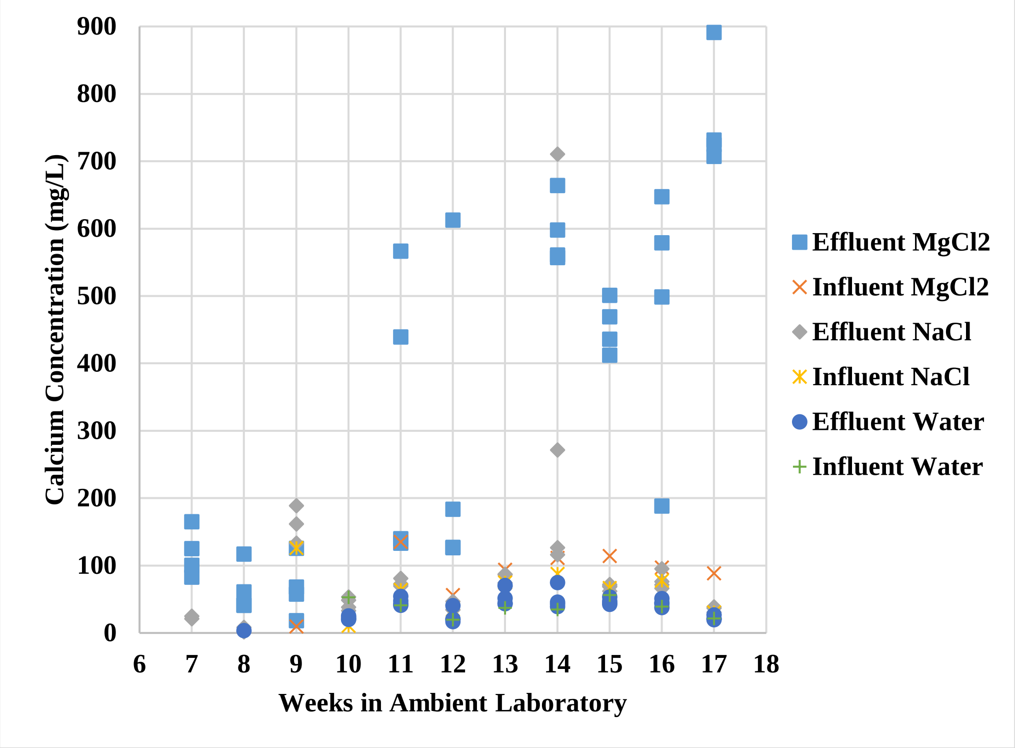


Figure 2.3 Composite calcium ion concentrations in the ambient laboratory of the influent and effluent of specimens receiving MgCl2, NaCl, or water treatments (Haselbach 2017)

A potential publication on Phase IIa, Part 1, is as follows (additional outreach activities performed by the project teams are given in Chapter 4):

- Ross, M., Haselbach, L., Sendele, T., Almeida, N. (n.d.) “Magnesium Chloride Deicer Chemical Effects on Pervious Concrete” (under review).

2.3 Phase IIa, Part 2 – Split Tensile Testing

Phase IIa, Part 2, of the project was developed at Lamar University during the summer of 2017. Split tensile testing using ASTM C496/C496M (ASTM 2011) was performed on selected specimens from Phase I to determine if chemical deterioration affected their structural performance, i.e., their strength.

Figure 2.4 Split tensile testing

Forty-six specimens were subjected to split tensile testing. All samples were weighed, and their dimensions were noted. Based on ASTM C1754/C1754M (ASTM 2012), Sendele (2017) had previously determined the porosities of the specimens. The standard procedures specified in ASTM C496/C496M (ASTM 2011) were used for split tensile testing, and the split tensile strength (psi) and peak load (lb) were found accordingly. After stress had been applied, the manner in which the specimens broke, i.e., the percentage of rubble and the percentage of larger pieces (> 500 gram/piece), were recorded, and the results were interpreted by plotting these results into graphs. The naming scheme used in this part of the study is given in Table 1.1.

Figure 2.5 Split tensile test procedure (left) and broken specimen examples

The graph in Figure 2.6 shows the correlation between split tensile strength (psi) and porosity (%) for all the specimens. We expected to see descending lines for all pervious concrete structures, since having more voids may result in lower strength (Meininger 1988); however, little correlation between split tensile strength and porosity is seen in Figure 2.6. In fact, the slopes are positive instead of negative for the three deicer treatment options.

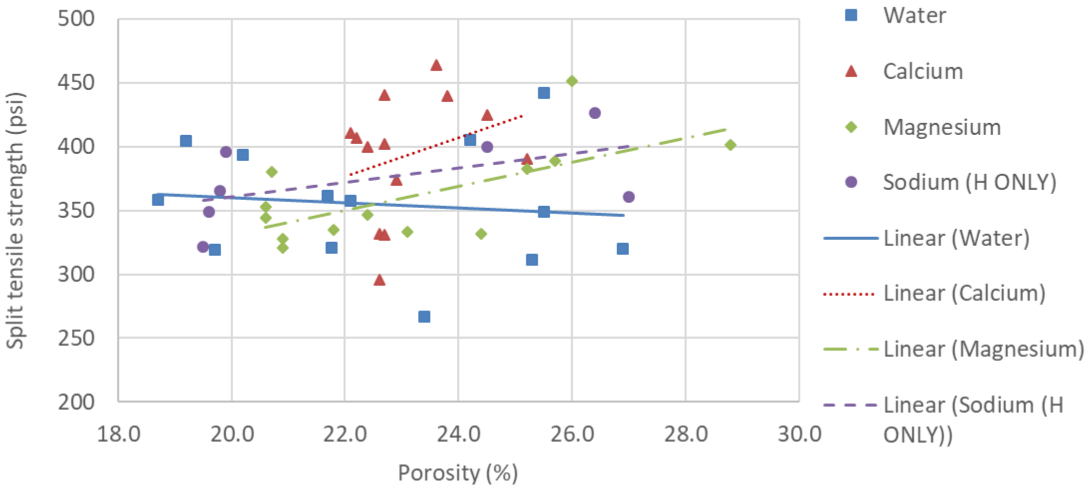


Figure 2.6 Split tensile strength (psi) vs. porosity (%) for all specimens in Phase IIb Part 2 (Haselbach et al. 2018a)

We investigated a relationship between the porosity of the concrete and the way the specimens broke after split tensile testing. The amount of rubble might be a function of strength, stress, deicer treatment, or porosity. To differentiate between the stress applied on the specimens as a function of porosity only, separate graphs were drawn as "tensile strength > 350 psi" and "tensile strength ≤ 350 psi" for water control specimens, since they did not have the treatment variability. Figure 2.7 shows an example graph for split tensile strength (psi) versus fraction of rubble pieces (%) where tensile strength is > 350 psi, and Figure 2.8 shows a similar frame but for tensile strength ≤ 350 psi.

Figure 2.7 shows an increase of fraction of rubble pieces with tensile strength for the water control specimens. In Figure 2.8, the data on tensile strength are more random, which could be interpreted as the tensile strength and the percent rubble being dependent variables. These data results might be due to the variability in distribution of voids in the specimens, which could impact their strength. Thus, those specimens which split at lower strengths may have too many factors impacting the experiments.

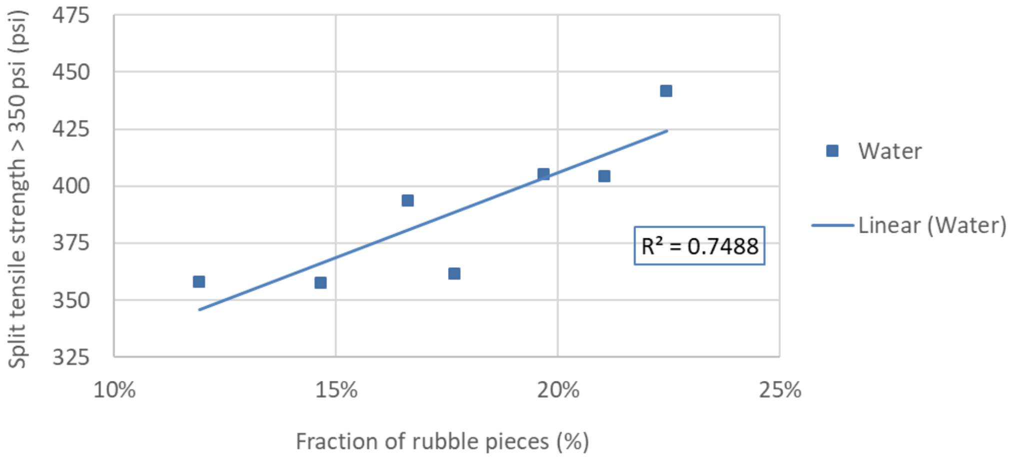


Figure 2.7 Water control for tensile strength > 350 psi. Split tensile strength (psi) versus fraction of rubble pieces (%) (Haselbach et al. 2018a)

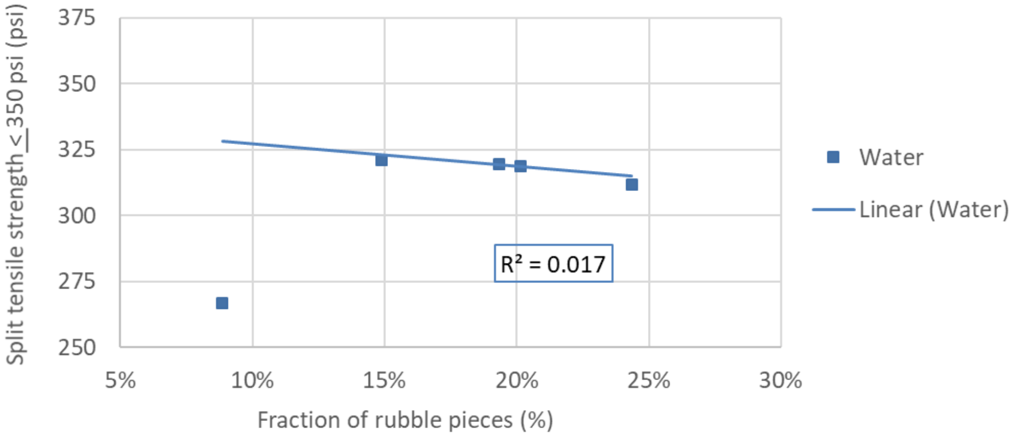


Figure 2.8 Water control for tensile strength ≤ 350 psi. Split tensile strength (psi) versus fraction of rubble pieces (%) (Haselbach et al. 2018a)

Figure 2.9 shows the correlation between the tensile strength (> 350 psi) and the fraction of rubble pieces for all the specimens. Statistical analysis (one-way ANOVA) was applied to understand the relationship between variables (split tensile strength, porosity, type of deicer treatment, and the amount of rubble). Some correlation was found between split tensile strength and porosity, with no evident correlation to the type of deicer treatment, most likely due to the small sample sets with multiple variables. Little correlation was found between porosity and the amount of rubble, since the rubble may also be dependent on the stress applied.

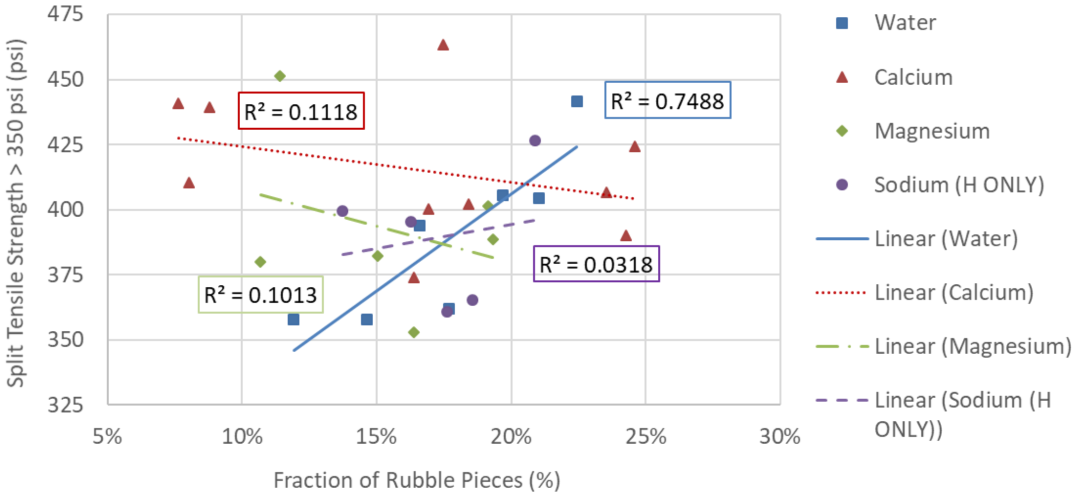


Figure 2.9 Split tensile strength versus fraction of rubble pieces (%) for tensile strength greater than 350 psi (Haselbach et al. 2018a)

As a result of these experiments, we found that the split tensile testing method may not be an efficient way to analyze chemical deterioration impacts on pervious concrete, since location of voids in pervious concrete may vary on the randomly chosen stress plane, compounding the number of independent variables. Further testing with fewer variables and a different strength test was recommended for Phase IIb.

CHAPTER 3 PHASE IIb

3.1 Phase IIb, Part 1 – Performing Deicer Tests on a Larger Set of Specimens with Fewer Mix Design Variables

In Phase IIb, the main objective was to redo the deicer applications with fewer variables. In this part of the research, hot (ambient condition) room specimens with OPC (non-carbonated) were subjected to calcium chloride (-CON), magnesium chloride (-MON), and water (-WON) treatments, as these were expected to be the most impactful conditions, and because carefully prepared specimens of an older age would take longer to obtain. The nomenclature for these specimens was preceded by the letter "L" referring to Lamar. Ten specimens for each type of treatment, thirty specimens in total, were used. All specimens were prepared with an approximately 4 to 1 aggregate-to-cementitious mass ratio. The aggregate was narrowly graded limestone (< 1 cm), and the water-to-cementitious ratio was slightly higher than 0.30 (depending on weather conditions). The chemical deicer testing procedure applied at Lamar University is presented in Appendix A. The testing procedure followed the protocols developed in Phase I.

Every week, the masses of the specimens, and the masses, pH, and volumes of the influent and effluent samples were recorded. The effluent samples were combined into three sets for each deicer treatment type, and segregated into groups of lower porosity, average porosity, and higher porosity (see Table A.1 in Appendix A). This grouping allowed for triplicate testing in order to distinguish between outliers. Noted periodically was the amount of debris that fell on the pads below the drying racks. (In a side experiment, calcium concentrations in both the influent and effluent samples for the magnesium chloride- and water-treated specimens are being analyzed using a Shimadzu ICPE-9820 Plasma Atomic Emission Spectrometer, and results are expected in the near future).

Table 3.1 gives the average infiltration rates measured prior to specimen deicer treatments based on porosity ranges. The table shows that, on average, water flows faster in specimens with higher porosity.

Table 3.1 Average infiltration rates based on porosity ranges for Phase IIb

Treatment Type	Porosities	Average Infiltration Rate (mm/s)
$MgCl_2$	**Low** (LMON1 to LMON3)	8.95
	Average (LMON4 to LMON7)	9.86
	High (LMON8 to LMON10)	9.84
$CaCl_2$	**Low** (LCON1 to LCON3)	7.97
	Average (LCON4 to LCON7)	8.37
	High (LCON8 to LCON10)	10.61
Water	**Low** (LWON1 to LWON3)	7.29
	Average (LWON4 to LWON7)	9.11
	High (LWON8 to LWON10)	9.65

Figures 3.1 through 3.3 provide, respectively, the typical pH values of influent and effluent for lower porosity, average porosity, and higher porosity specimens. The higher porosity specimens treated with calcium chloride trended slightly differently for pH over time. Water flowed through these specimens slightly faster, and the specimens, therefore, might not have had as much time for reactions to occur.

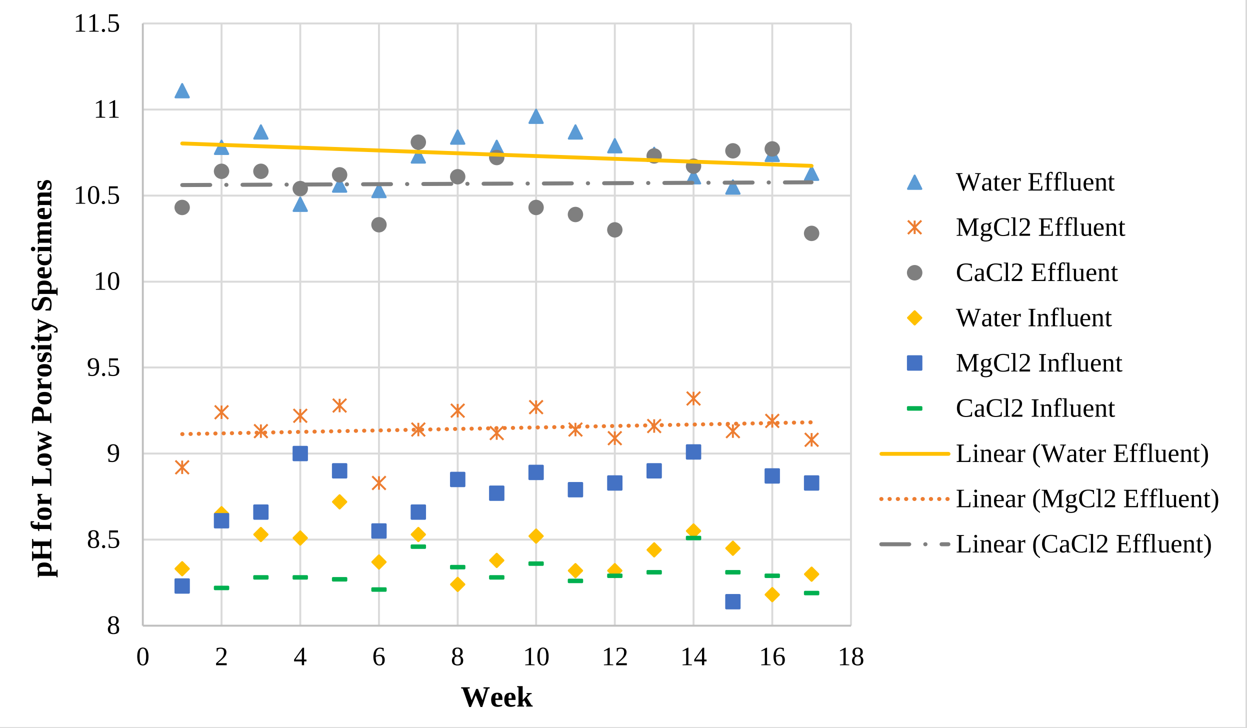


Figure 3.1 pH ranges of influents and effluents for lower porosity specimens: Phase IIb

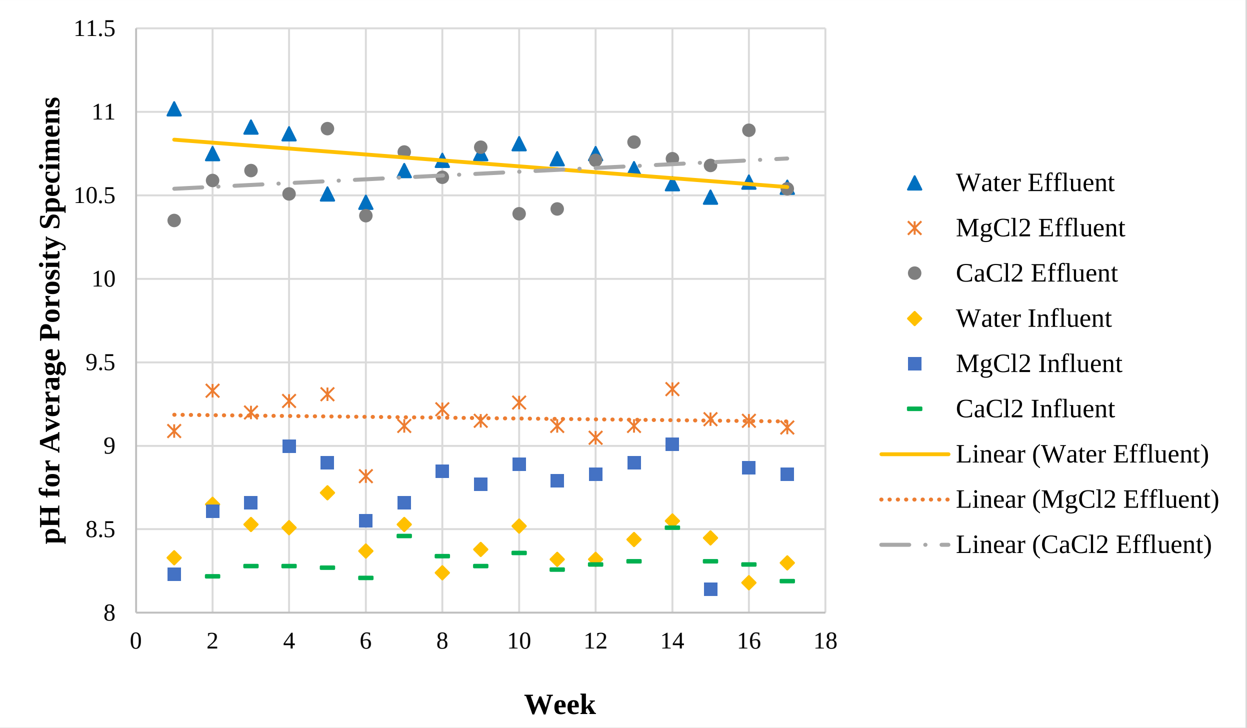


Figure 3.2 pH ranges of influents and effluents for average porosity specimens: Phase IIb

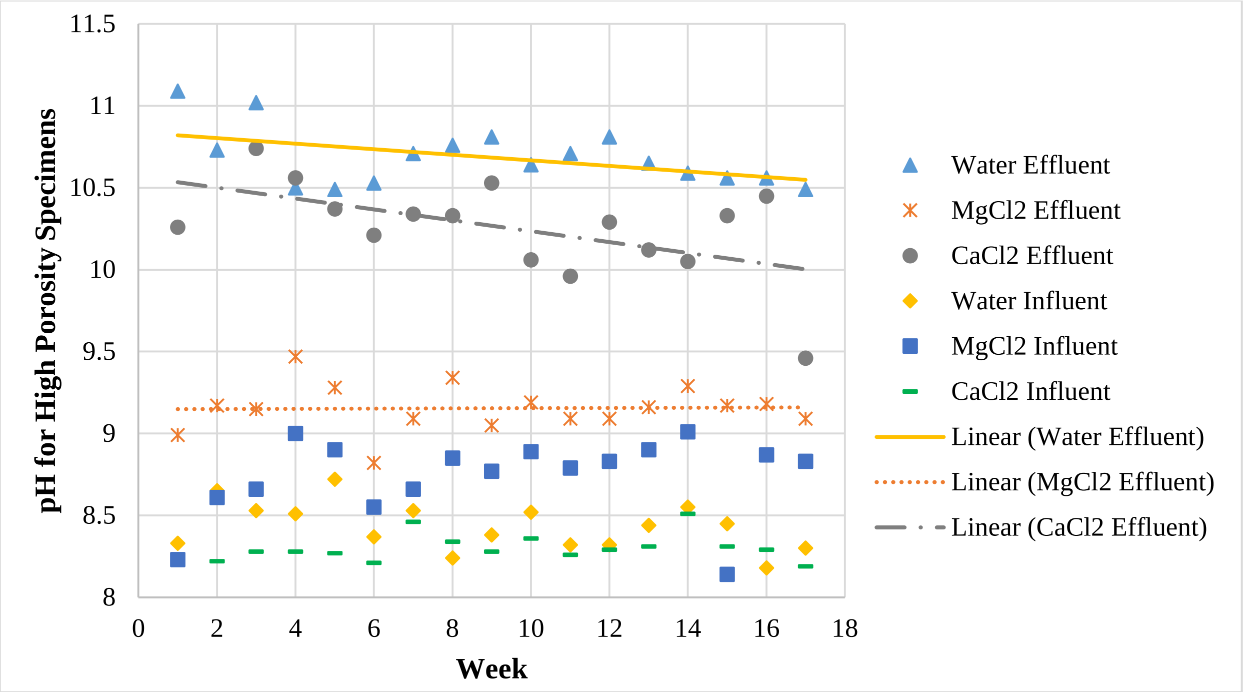


Figure 3.3 pH ranges of influents and effluents for higher porosity specimens: Phase IIb

Table 3.2 summarizes density values for the influent and effluent samples averaged over the 17-week period. Densities averaged separately for all the weeks are tabulated in Table B.1, Appendix B, along with the average volume of the influent and effluent samples. As expected, the specific gravity of the influent water samples hovered around 1 (0.996), while the influents of the specimens treated with magnesium chloride and calcium chloride were, on average, 1.025 and 1.027, respectively. These densities indicate that total dissolved solids in the influent solutions are close to the goal of 3%. The average densities of the effluent solutions were, in all cases, less than the average densities of the influent solutions, indicating that solids were retained within.

Table 3.2 Sample density values (g/mL) averaged over the 17-week period: Phase IIb

Solution	**Treatment Type**	**Average densities (g/mL)**
Influent	**$MgCl_2$**	1.025
	$CaCl_2$	1.027
	Water	0.996
Effluent	**$MgCl_2$**	1.019
	$CaCl_2$	1.022
	Water	0.991

Figures 3.4 and 3.5 present the masses of the specimens over the 17 weeks of the experiments as normalized to their initial masses and then averaged for each deicer treatment type. (Note that the shrink wrap on each specimen weighed approximately 7 grams and that the masses were corrected for this.) Figure 3.5 presents the same data as in Figure 3.4 except that the outliers around week 4 were excluded. This period was during the winter holiday break, and the treatments were more than a week apart between Weeks 3 and 4. Figures 3.4 and 3.5 indicate that the specimens receiving the deicer treatments were consistently gaining more mass than the specimens receiving the water control treatment, as is expected since the influent solutions contained more dissolved solids. This finding is consistent with the change in densities of the influents to the effluents, as noted in Table 3.2, indicating that solids are removed from the solution and retained within the specimens. Additional solids were also retained as some of the influent each week was retained within the specimens. (See Table B1 in Appendix B for the average influent and effluent volumes.) Some of the retained influent solution was then allowed to evaporate over each week, leaving additional solids behind.

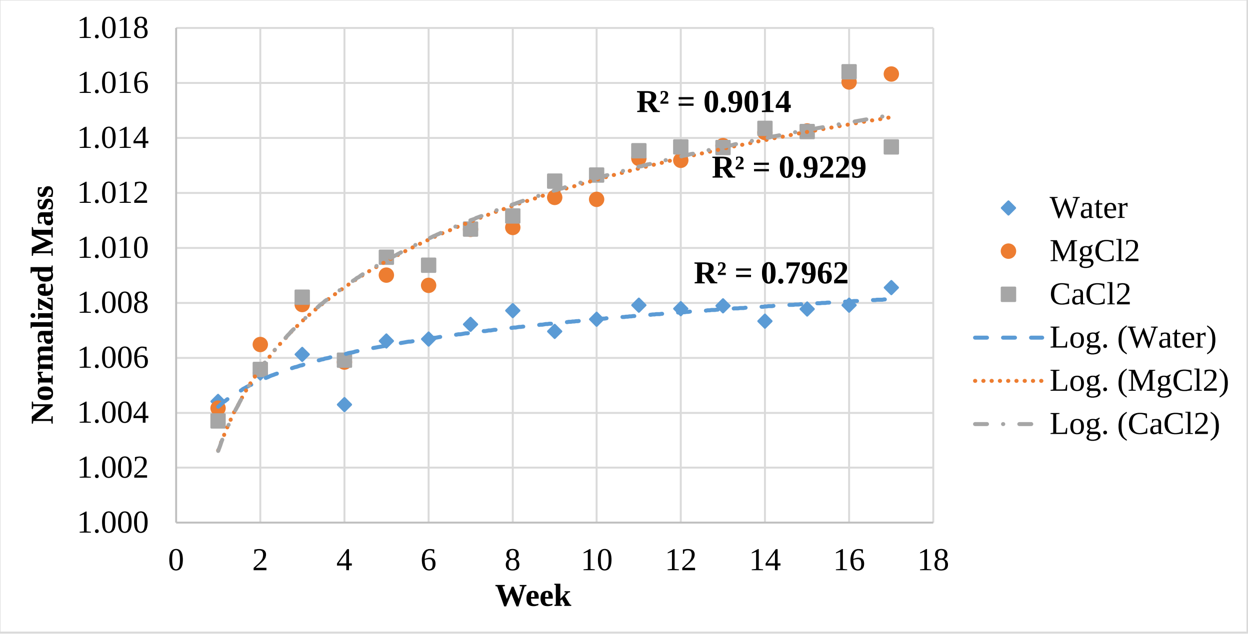


Figure 3.4 Normalized specimen masses: Phase IIb

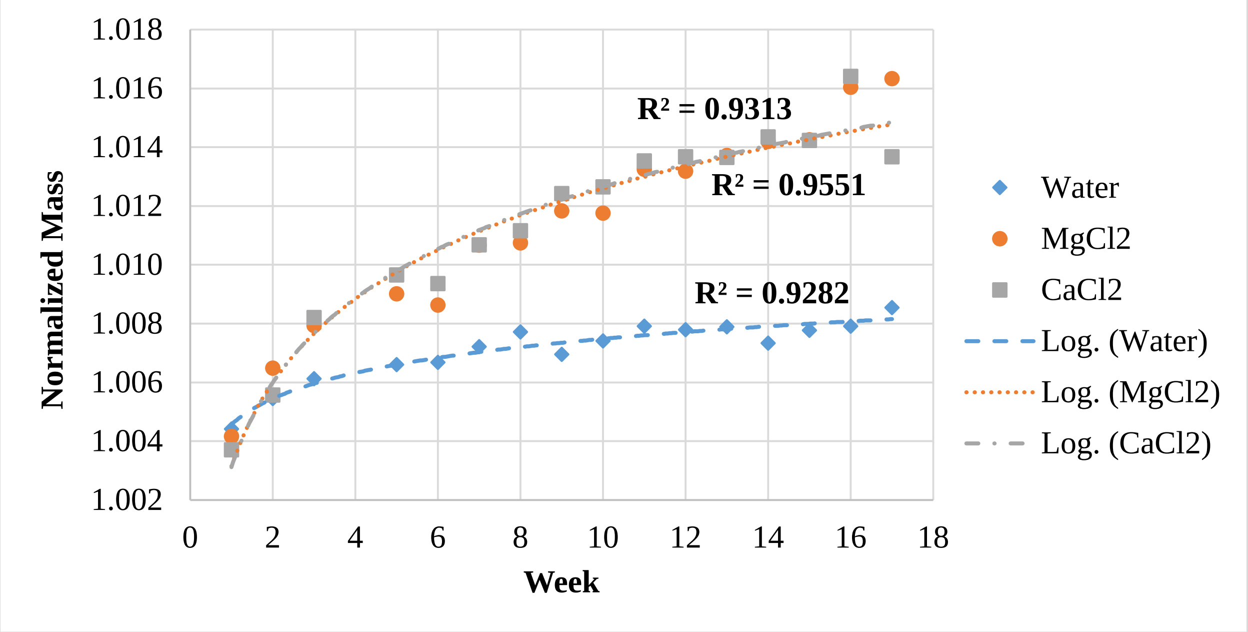


Figure 3.5 Normalized specimen masses without the outlier: Phase IIb

Figures 3.4 and 3.5 show that near the end of the experiment, the calcium chloride specimens had a possible drop in mass. This period was when an increasing amount of debris was found under these specimens, as will be described in the following paragraphs. In addition, more debris fell from the specimens as they were unwrapped. Table 3.3 provides a summary of the initial and final dry masses. Note how the specimens subjected to the magnesium chloride treatment gained more mass than the other specimens. The final average mass of the calcium chloride specimens contained both the increase in mass from the dissolved solids over the treatment period and the loss in mass from debris falling from the specimens during treatment and when unwrapped.

Table 3.3 Initial and final dry masses of specimens: Phase IIb

Treatment Type	Average Initial Mass (g)	Average Final Mass (g)
$MgCl_2$	2883	2922
$CaCl_2$	2882	2909
Water	2882	2903

Table 3.4 provides a summary of the masses of debris collected from under the ten specimens for each deicer treatment type. Figure 3.6 is a photograph of debris that fell onto the absorbent pad placed below the specimens that had received the calcium chloride treatment. Specimens that received the calcium chloride treatment were the only ones that had significant amounts of debris collect on the absorbent pads when treatments were performed and after unwrapping at the end of the experiments. This debris typically fell from the bottom of the specimens.

Table 3.4 Mass (g) of rubble/flakes collected in total for the 10 specimens: Phase IIb

	Weeks 1–10	Weeks 11–14	Weeks 15–17	Post-Treatment
$CaCl_2$	1.6	5.1	18.6	95.8
$MgCl_2$	-	-	0.3	< 0.1*
Water	-	1.3	-	0.4

* the scale (sensitive to 0.0) did not register the mass of this group, but flakes were still present.

Figure 3.6 Example of debris collected

3.2 Phase IIb Part 2: Unconfined Compressive Strength Tests on Phase IIb, Part 1, Specimens

During Phase IIb, Part 2, strength impacts were analyzed by applying unconfined compressive strength tests to the specimens from Phase IIb, Part 1. This part of the study consisted of two steps. The first step involved capping the specimens according to ASTM C617/C617M (ASTM 2015) by using USG Ultracal Brand 30 Gypsum Cement with a 0.27 water-to-cement ratio.

Both the bottoms and the tops of the pervious concrete specimens were capped using USG Ultracal Brand 30 Gypsum Cement. Prior to capping, aggregate visibly protruding from the tops or bottoms of the specimens was knocked off with a hammer to provide a more level surface from which to start. Since the tops were more uneven, more cement paste was used to cap them than the amount used on the bottoms. During capping, the bases and tops were leveled to three different planes by using a laser-level. Figure 3.7 is a photograph taken during capping and leveling the specimens. The waiting time for the paste to dry was approximately 1.5 hours, and the same procedure was applied for both the bottoms and the tops. Figure 3.8. shows some of the capped and labeled specimens.

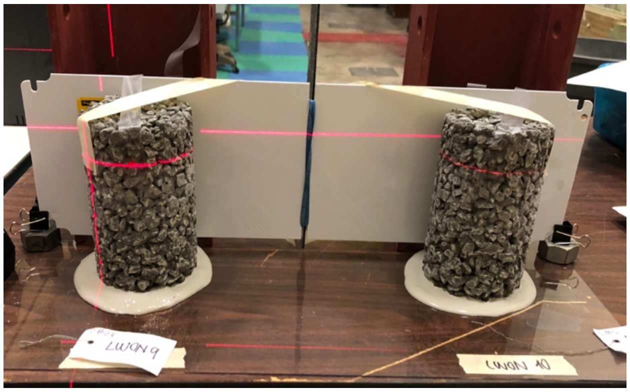


Figure 3.7 Capping and leveling specimens: Phase IIb

Figure 3.8 Capped specimens before unconfined compressive strength test: Phase IIb

The unconfined compressive strength test was performed with results displayed using the Humboldt HCM-5090.3F Digital Indicator for the Humboldt Compression Machines (Figure 3.9). ASTM C39/C39M Compressive Strength (ASTM 2018) was followed to conduct this test. This test was performed on eight of the ten specimens from each treatment group. Figure 3.10 shows a typical pervious concrete specimen after performing the compression test.

Figure 3.9 Unconfined compressive strength test machine (HCM-5090.3F): Phase IIb

Figure 3.10 Typical pervious concrete specimen after unconfined compressive strength test

Table 3.5 provides a summary of the average compressive strength and porosities for the three treatment types. Table C.1 in Appendix C gives the compressive strength and porosity for each of the 24 specimens tested. Figure 3.11 is a graph of compressive strength versus porosity for these 24 specimens.

Table 3.5 Average compressive strengths and porosities post-treatment: Phase IIb

Treatment Type	Average porosity (%)	Average Compressive Strength (psi)
$MgCl_2$	23.9	2644
$CaCl_2$	24.0	2166
Water	23.9	3031

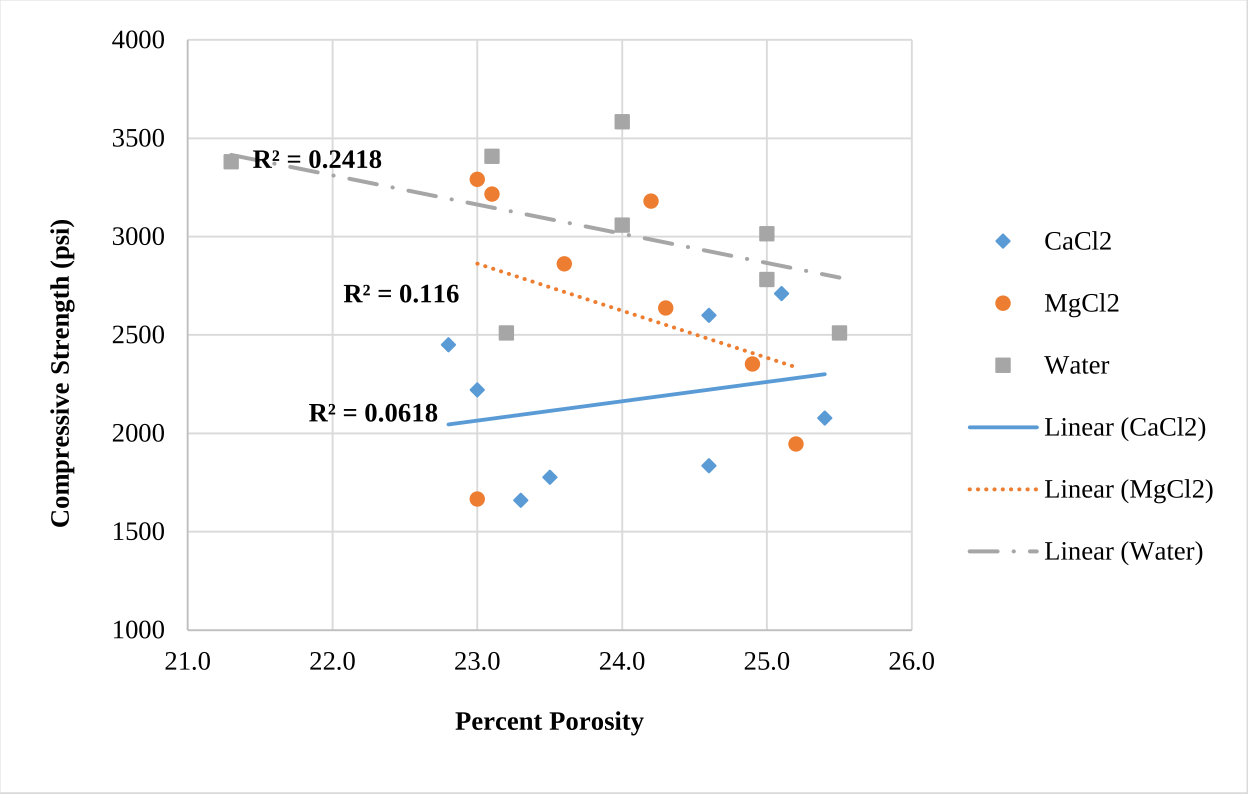


Figure 3.11 Compressive strength (psi) versus porosity (%). Phase IIb

As can be seen in Table 3.5, both of the deicing chemicals impacted the compressive strength of the specimens. No impact from the magnesium chloride treatment was visible, but the specimens lost strength after the 17-week chemical treatment period despite a significant gain in mass. The specimens that were treated with calcium chloride showed an even greater loss in strength after the treatment period. This loss might have been a result of the debris falling off the specimens, particularly at the bottom where the deicer solutions would settle and concentrate between treatments.

These results support the hypothesis that an ion exchange may be occurring between the magnesium in the deicer solution and the calcium in the pervious concrete from the magnesium chloride treatments. This ion exchange was hypothesized based on aquatic chemistry complexation stability constants. The loss of calcium from the concrete matrix would be expected to result in a loss in strength.

These results also support the hypothesis that calcium monohydroxide may be forming in concentrated solutions near the bottom of the specimens. This formation is based on aquatic chemistry complexation stability criteria. The formation of this aqueous complex might result in stripping of hydroxides from the concrete, although the exact mechanism is unknown. In addition, from visual inspection, it appears that significantly more debris fell off the specimens subjected to the calcium chloride treatment in Phase IIb than in Phase I for the newer specimens made with OPC (--ON). The difference between the two sets of specimens was only in the aggregate type used. For Phase I, the aggregate was basalt. For Phase IIb, the aggregate was limestone. Apparently, using basalt rather than limestone as the aggregate may aid in resistance to chemical attack from calcium chloride deicers.

CHAPTER 4 OUTREACH

In addition to producing the various publications previously mentioned, the research team participated in many presentations and other outreach activities. The presentations on pervious concrete are summarized in Table 4.1. Other outreach activities where pervious concrete was demonstrated as a part of civil and environmental engineering are summarized in Table 4.2.

Table 4.1 Presentations given

Event Name	Type of Presentation	Presenter	Topic of the Presentation	Date & Place
CESTiCC Workshop	Podium Presentation	Liv Haselbach	Evaluation of the Effects of Deicer Chemical Methodologies on Pervious Concrete	August 2017, Pullman, WA.
CESTiCC Workshop	Poster Presentation	Nara Almeida, Molly Ross	Deicer Chemical Effects on Pervious Concrete: Phase II	August 2017 Pullman, WA.
ASCE Texas Section Annual Civil Engineering (CECON) Conference	Podium Presentation	Liv Haselbach	Deicer Chemical Effects on Pervious Concrete: Phase II (updated version)	September 2017, San Marcos, TX.
ASCE Texas Section Annual Civil Engineering (CECON) Conference	Poster Presentation	Nara Almeida, Molly Ross	Deicer Chemical Effects on Pervious Concrete: Phase II (updated version)	September 2017, San Marcos, TX.
5th Annual Texas STEM Conference	Poster Presentation	Nara Almeida, Molly Ross	Deicer Impacts on Pervious Concrete Specimens: Phase IIa: Split Tensile Testing	October 2017, Beaumont, TX.
Permeable Pavement Workshop	Podium Presentation	Liv Haselbach	Impacts of a Pervious Concrete Retention System on Neighboring Clay Soils	November 2017, Davis, CA.
American Concrete Institute (ACI) Conference	Presentation in special session entitled Major Advances in Pervious Concrete	Liv Haselbach	Proposed Standard Method of Testing Effectiveness of Products Used to Fight Concrete Damage Caused by Chemical Deicing Products	March 2018, Salt Lake City, UT.

Event Name	Type of Presentation	Presenter	Topic of the Presentation	Date & Place
Coastal Science and Engineering Collaborative (CSEC) Workshop	Podium Presentation	Liv Haselbach	Introduction to Pervious Concrete	April 2018, Beaumont, TX.
ASCE International Conference on Transportation & Development (ICTD 2018)	Poster Presentation	Liv Haselbach	Screening Test for Improved Calcium Chloride Deicer Resistance in Pervious Concrete	Scheduled for July 2018, Pittsburgh, PA.
International Low Impact Development (LID) Conference	Presentation	Liv Haselbach	Deicer Impacts on Pervious Concrete Specimens: Phase IIa: Split Tensile Testing	Scheduled for August 2018, Nashville, TN.

Table 4.2 Outreach activities

Event Name	When	Where	Observations
High School Tours	September 13, 2017	Lamar University in Beaumont, TX.	Around 50 students visited Lamar University and stopped in the Structures Lab.
Cardinal View Day	November 4, 2017	Lamar University in Beaumont, TX.	Over 200 guests visited the engineering college which included a large civil engineering display.
Lumberton High School Tour	December 8, 2017	Lamar University in Beaumont, TX.	90 students from LHS visited and toured Lamar University Engineering including a demonstration in the Structures Lab
Pasadena Memorial HS Tour	January 24, 2018	Lamar University in Beaumont, TX.	Over 40 students visited LU and toured Lamar University Engineering including a demonstration in the Structures Lab
SE Texas Youth Career Expo	February 1, 2018	Ford Arena in Beaumont, TX.	Approximately 2000 students from the SETX area visited various booths. More than 50 students stopped by the Civil Engineering booth.

Event Name	When	Where	Observations
Cardinal View Day	February 10, 2018	Lamar University in Beaumont, TX.	Approximately 200 guests visited Lamar University Engineering, and more than 20 students stopped by the Civil Engineering booth.
Junior Achievement Job Shadow Tours	February 21, 2018	Lamar University in Beaumont, TX.	9 schools with over 200 students visited Lamar University Engineering for a tour including a demonstration in the Structures Lab.
Nederland High School Tour	April 3, 2018	Lamar University in Beaumont, TX.	Approximately 40 students visited Lamar University Engineering and stopped at the Structures Lab for a demonstration.
Discover Engineering	April 7, 2018	Boomtown Museum in Beaumont, TX	Free public event that attracted over 500 guests to see engineering demonstrations. ASCE was a large part of the event.
Cardinal View Day	April 14, 2018	Lamar University in Beaumont, TX.	Over 200 guests visited the engineering college which included a large civil engineering display.

CHAPTER 5 CONCLUSIONS

The results from Phase IIa indicate that the split tensile test may not be a good indicator of strength impacts from the deicing treatment protocol proposed herein. The successful repetition of the protocol on more specimens with fewer mix design variables in Phase IIb supports the use of the deicing treatment protocol for testing various alternative mix designs that might provide resistance to chemical degradation by magnesium chloride or calcium chloride deicers. The loss of mass due to visible debris from the calcium chloride treatments is a simple indicator of poor performance. For magnesium chloride treatments, we suggest that the compressive strength test be performed to validate impacts on strength.

Future research on various other mix designs, such as the addition of supplementary cementitious materials, would aid in our understanding of the chemical impacts of these deicers. Preliminary results imply that basalt aggregate may be more resistant to calcium chloride chemical impacts than limestone aggregate. We recommend additional research into the combination of chemical and physical (such as freeze–thaw) impacts on pervious concrete, especially due to the mass gains observed in the specimens.

CHAPTER 6 REFERENCES

ASTM. (2011). *ASTM C496/C496M Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.* ASTM International, West Conshohocken, PA.

ASTM. (2012). *ASTM C1754/C1754M Test Method for Density and Void Content of Hardened Pervious Concrete.* ASTM International, West Conshohocken, PA.

ASTM. (2015). *ASTM C617/C617M Standard Practice for Capping Cylindrical Concrete Specimens*. ASTM International, West Conshohocken, PA.

ASTM. (2018). *ASTM C39/C39M Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. ASTM International, West Conshohocken, PA.

Haselbach, L. (2017). "Evaluation of the Effects of Deicer Chemical Methodologies on Pervious Concrete and Development of a Deicer Chemical Testing Method for Pervious Concrete." Final Report to the Ready Mixed Concrete Research & Education Foundation, Silver Spring, MD. May 2017.

Haselbach, L., Almeida, N., Ross, M. (2018a). "Deicer Impacts on Pervious Concrete Specimens: Phase IIa: Split Tensile Testing." *Low Impact Development (LID) Conference,* Nashville, TN, August 2018.

Haselbach, L., Sendele, T., and Langfitt, Q. (2018b). "Screening Test for Improved Calcium Chloride Deicer Resistance in Pervious Concrete." *Proceedings: ASCE International Conference on Transportation & Development (ICTD),* Pittsburgh, PA, July 2018.

Meininger, R. C. (1988). "No-Fines Pervious Concrete for Paving." *Concrete International*. 10(8), 19–27.

Ross, M., Haselbach, L., Sendele, T., Almeida, N. (n.d.) "Magnesium Chloride Deicer Chemical Effects on Pervious Concrete" (under review).

Sendele, T. W. (2017). *Investigation into possible methods to screen for chemical degradation of pervious concrete due to common deicers*. Thesis, Washington State University. Pullman, WA.

Thomle, J., and Haselbach, L. (2011) “The Declining pH of Waters Exfiltrated through Pervious Concrete.” *ACI SP-282, The Leading Edge of Pervious Concrete*, American Concrete Institute, Farmington Hills, MI.

APPENDIX A: LU CHEMICAL DEICER TESTING PROCEDURE FOR PHASE IIb

A.1. Specimen Organization

Thirty specimens were subjected to one of three treatments including magnesium chloride, calcium chloride, and water as a control. A group of ten specimens was subjected to each treatment in which the specimens were grouped by similar porosity designated as low (L), average (A), or high (H) porosity. The labeling system for the influent and effluent samples to be collected is tabulated in Table A.1.

Table A.1 Labeling system for influent and effluent samples

<table>
<tr><th colspan="7">Deicer Treatment Sample Identification</th></tr>
<tr><td rowspan="2">Timeline</td><td colspan="6">17 Weeks</td></tr>
<tr><td colspan="6">Weeks A-Q</td></tr>
<tr><td rowspan="2">Deicer Treatment</td><td colspan="2">Water</td><td colspan="2">Magnesium Chloride</td><td colspan="2">Calcium Chloride</td></tr>
<tr><td colspan="2">W</td><td colspan="2">M</td><td colspan="2">C</td></tr>
<tr><td rowspan="2">Influent/Effluent</td><td colspan="3">Influent</td><td colspan="3">Effluent</td></tr>
<tr><td colspan="3">I</td><td colspan="3">E</td></tr>
<tr><td rowspan="2">Porosity (P)</td><td colspan="2">Low Porosity
P < 23.5%</td><td colspan="2">Average Porosity
23.5% < P < 25%</td><td colspan="2">High Porosity
P >25%</td></tr>
<tr><td colspan="2">L
(L_ON1 to L_ON3)</td><td colspan="2">A
(L_ON4 to L_ON7)</td><td colspan="2">H
(L_ON8 to L_ON10)</td></tr>
<tr><td rowspan="2">Duplicate*</td><td colspan="6">*only on duplicate samples for future chemical analyses</td></tr>
<tr><td colspan="6">d</td></tr>
</table>

A.2. Testing Procedure

1. Each week, one day was set aside to perform one of the three deicer treatments.
2. The appropriate specimens were removed from the drying rack, and their mass was recorded; then the specimens were hung securely on the beaker stands with a 1 liter beaker placed below.
3. The temperature and humidity in the laboratory were recorded.

4. A 20 mL sample from the composite influent (prepared the day before) was set aside in a 50 mL beaker (at least 15.44 mm deep), and the pH was measured with the PHC30101 probe.
5. 200 mL of the influent solution was measured for each specimen (ten), and its mass was recorded.
6. 200 mL of the solution was poured on the top of each wrapped specimen, and the time was noted.
7. Each specimen drained for at least 10 minutes, and the effluent volume and masses were recorded.
8. Specimen effluents of similar porosity (low, average, or high) were combined, and a 20 mL sample of each effluent type was used to measure the pH with the PHC30101 probe.
9. The specimens were returned to the racks. (An absorbent pad was placed below the rack where the specimens had been placed, and any debris on these pads was noted weekly.)
10. The appropriate composite influent solution(s) (3% by mass) was prepared for the next day in the 4000 mL Erlenmeyer Flask using a stirring plate. Calculations for both deicer ($MgCl_2$, $CaCl_2$) influent solutions are given in Table A.2.

Table A.2 Deicer influent solution calculations

Deicer Influent Solution (Per Week)		
Deicer	**$MgCl_2$**	**$CaCl_2$**
Mass of Water (g)	3000	3000
Total Mass of Solution (g)	3192.2	3095.7
Deicer Mass Ratio	3.0%	3.0%
Pure Chemical Mass Required (g)	95.8	92.9
Purity of Deicer	46.83%	94.00%
Total Deicer Mass Required (g)	**204.5**	**98.8**

11. The testing procedure was followed for each treatment each week for 17 weeks. Figure A.1 summarizes the testing procedure for Week A, Water Treatment. Figure A.2 shows the specimens on the drying racks with the absorbent pads below.

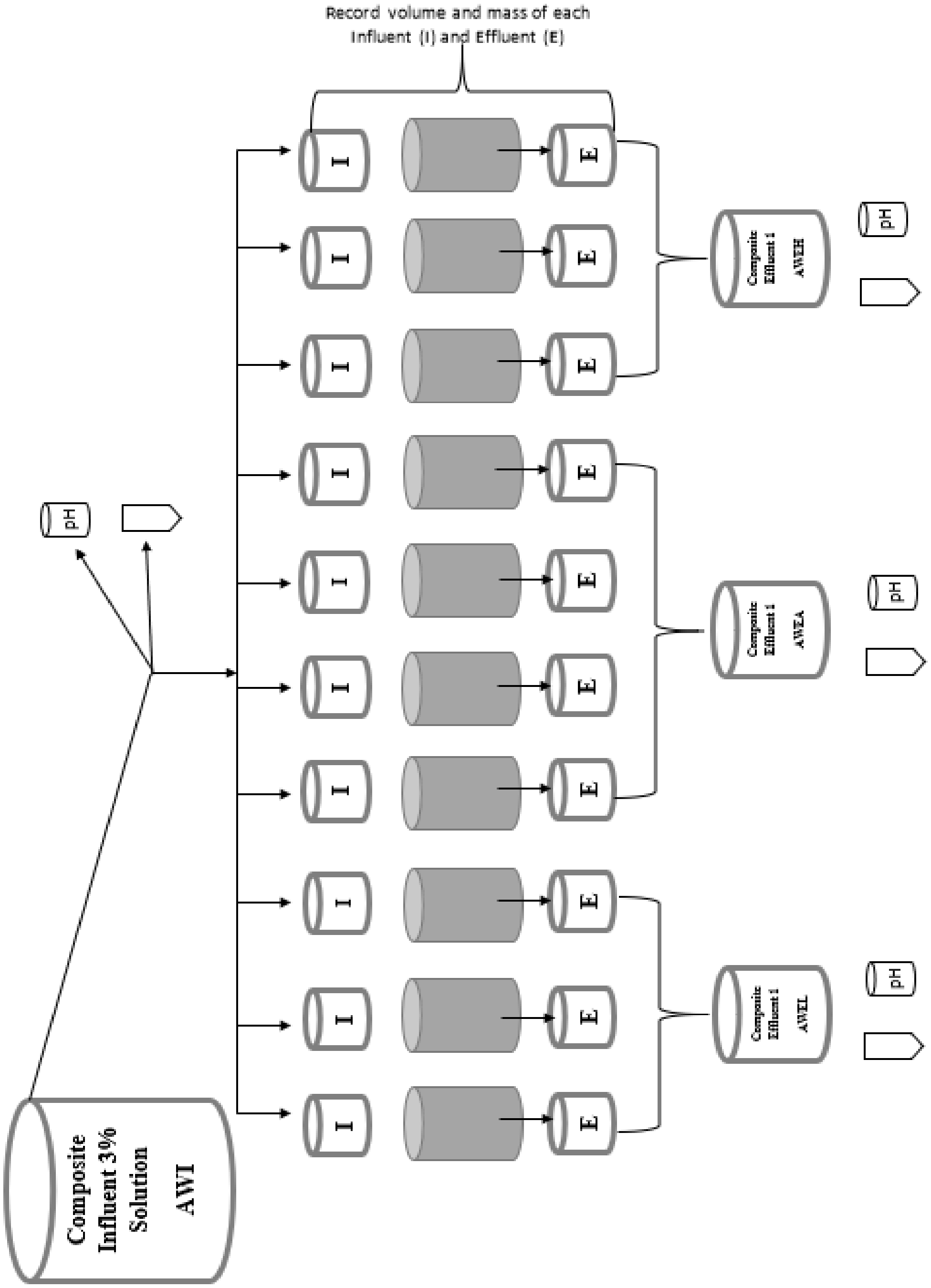


Figure A.1 Example of testing setup for Week A, Water Treatment

Figure A.2 Specimens on the drying racks with the absorbent pads below

APPENDIX B

Table B.1 Weekly average densities (g/mL) and volumes (mL) of the influent and effluent solutions for three treatments

Week	Treatment Type	Average Influent Volume (mL)	Average Influent Density (g/mL)	Average Effluent Volume (mL)	Average Effluent Density (g/mL)
A	**$MgCl_2$**	200	1.020	156.9	1.014
	$CaCl_2$	200	1.027	157.7	1.025
	Water	200	0.995	155.0	0.986
B	**$MgCl_2$**	200	1.024	159.7	1.018
	$CaCl_2$	200	1.028	157.4	1.020
	Water	200	0.992	156.2	0.990
C	**$MgCl_2$**	200	1.023	160.6	1.020
	$CaCl_2$	200	1.027	161.5	1.022
	Water	200	0.996	159.2	0.990
D	**$MgCl_2$**	200	1.022	157.3	1.016
	$CaCl_2$	200	1.026	157.9	1.019
	Water	200	0.995	155.1	0.985
E	**$MgCl_2$**	200	1.025	160.8	1.018
	$CaCl_2$	200	1.027	162.2	1.018
	Water	200	0.995	157.4	0.991
F	**$MgCl_2$**	200	1.025	158.8	1.018
	$CaCl_2$	200	1.027	159.8	1.021
	Water	200	0.997	157.6	0.988
G	**$MgCl_2$**	200	1.026	161.0	1.021
	$CaCl_2$	200	1.028	161.0	1.023
	Water	200	0.996	159.3	0.987
H	**$MgCl_2$**	200	1.026	161.4	1.020
	$CaCl_2$	200	1.025	162.2	1.021
	Water	200	0.997	157.6	0.993

I	**$MgCl_2$**	200	1.026	162.1	1.018
	$CaCl_2$	200	1.027	164.1	1.021
	Water	200	0.998	158.7	0.991
J	**$MgCl_2$**	200	1.025	161.7	1.018
	$CaCl_2$	200	1.028	163.9	1.022
	Water	200	0.997	158.5	0.991
K	**$MgCl_2$**	200	1.027	161.5	1.023
	$CaCl_2$	200	1.027	165.1	1.023
	Water	200	0.996	160.5	0.991
L	**$MgCl_2$**	200	1.027	161.9	1.021
	$CaCl_2$	200	1.027	164.7	1.025
	Water	200	0.997	160.4	0.992
M	**$MgCl_2$**	200	1.027	161.1	1.019
	$CaCl_2$	200	1.026	164.0	1.024
	Water	200	0.997	160.4	0.993
N	**$MgCl_2$**	200	1.026	161.7	1.019
	$CaCl_2$	200	1.027	165.4	1.022
	Water	200	0.997	160.2	0.993
O	**$MgCl_2$**	200	1.026	162.2	1.015
	$CaCl_2$	200	1.027	166.9	1.021
	Water	200	0.997	160.8	0.994
P	**$MgCl_2$**	200	1.027	163.9	1.022
	$CaCl_2$	200	1.028	168.5	1.025
	Water	200	0.998	159.8	0.997
Q	**$MgCl_2$**	200	1.027	163.5	1.019
	$CaCl_2$	200	1.028	164.0	1.023
	Water	200	0.998	160.5	0.991

APPENDIX C

Table C.1 Compressive strength (psi) and porosity (%) for each specimen

Treatment Type	Specimen ID	Porosity (%)	Compressive Strength (psi)
$MgCl_2$	**LMON1**	23.0	1666
	LMON2	23.0	3292
	LMON3	23.1	3216
	LMON4	23.6	2862
	LMON5	24.2	3181
	LMON6	24.3	2638
	LMON7	24.9	2353
	LMON8	25.2	1946
$CaCl_2$	**LCON1**	22.8	2450
	LCON2	23.0	2221
	LCON3	23.3	1660
	LCON4	23.5	1777
	LCON5	24.6	1836
	LCON6	24.6	2599
	LCON8	25.1	2711
	LCON9	25.4	2078
Water	**LWON1**	21.3	3381
	LWON2	23.1	3409
	LWON3	23.2	2510
	LWON4	24.0	3058
	LWON5	24.0	3584
	LWON8	25.0	2783
	LWON9	25.0	3014
	LWON10	25.5	2511